

PRE-1940

1941-1959

**1960-1974**

1975-1990

1991-PRESENT

OSA<sup>®</sup> | 100

## Introduction

Jeff Hecht

Physics as a whole boomed in the middle of the twentieth century, but optics remained a seemingly sleepy backwater compared with hot fields such as nuclear physics, electronics, and astronautics. Yet the seeds of two technological revolutions were growing quietly, fertilized by the generous government research funding that had fueled the rapid expansion of physics. One was the development of space optics for surveillance satellites, which in time would stabilize the uneasy balance of nuclear power. The other was the birth of the laser, which brought new excitement and ideas to optics.

The development of spy satellites was among the deepest of military secrets in 1960. The effort had begun quietly in 1955, as military and intelligence officials realized that satellites might offer a new window on the Soviet Union's nuclear activities. That priority grew more important with the Soviet Sputnik launch in 1957, which both showed that spaceflight was possible and established the precedent that satellites above the atmosphere could fly over countries without violating their airspace. Advanced optics were as crucial to the effort as rockets; without good optics, the satellites could not record images of the ground clearly enough for intelligence analysts to interpret them. Just weeks after Sputnik, the U.S. started a crash optics program called CORONA, described in this section by Kevin Thompson, which eventually succeeded in filming Soviet nuclear activity from space, helping to ease nuclear tensions. The Hexagon program that followed, described by Phil Pressel, built on CORONA's success.

The laser was an outgrowth of a military program seeking higher-frequency microwave sources that led Charles Townes to develop the maser, then to think of how to extend the principle of amplifying stimulated emission to even higher frequencies. Laser light brought dramatic new possibilities to optics—monochromatic and coherent light that could be concentrated into a beam of energy.

Irnee D'Haenens, who assisted Ted Maiman in making the first laser, may have been the first to call the laser “a solution looking for a problem,” and it was a cute joke in the early 1960s. But in reality the laser opened the door to solving a host of previously intractable problems. One series of articles in this section tells of the development of new varieties of lasers, made from gases, new types of solids, semiconductors, and organic dyes in solution. Another article tells how companies began manufacturing lasers for others to use.

The laser also opened up whole new fields of endeavor, covered in other articles in this section. The intensity of laser light revealed nonlinear effects that had previously been impossible to observe. The coherence of laser light made practical a radically new form of truly three-dimensional imaging called holography. Lasers offered precise new ways of measurement, from remote sensing to ultra-precise metrology. Laser beams could cut or drill materials, print words on paper or record data on optical disks, or read printed patterns to automate checkout at stores.

Lasers soon launched whole new government programs, described in other articles in this section. Concern about nuclear attack led to efforts to develop laser weapons that could destroy targets at the speed of light, a program that would wax and wane with the arms race and progress (or lack of it) in building high-power lasers until the present day. The laser's ability to focus intense energy onto pinpoint spots led to research on laser fusion, both as a way to generate

energy and to simulate nuclear weapons. The laser's narrow linewidth and tunability led to efforts to enrich isotopes, both for nuclear reactors and to make bombs.

And the echoes of laser ideas, stimulated in the early years of the laser revolution, also resonate through the remaining sections of this history.

# The Discovery of the Laser

Jeff Hecht

Albert Einstein planted the seed that grew into the laser when he realized the possibility of stimulated emission in 1916, the year The Optical Society (OSA) was founded. Experiments in the 1920s confirmed the existence of stimulated emission, then called “negative absorption,” but it seemed only a matter of academic interest. Russian physicist Valentin Fabrikant in 1939 proposed using stimulated emission to amplify light but did not pursue the idea at the time.

Charles Townes made the first major step toward the laser at Columbia University in 1951 when he proposed isolating excited ammonia molecules in a resonant cavity so stimulated emission could oscillate at microwave frequencies. In 1954, Townes and his student James Gordon demonstrated the first maser, shown in Fig. 1, a word he coined from “microwave amplification by the stimulated emission of radiation.” Microwave masers soon became important as high-frequency oscillators and low-noise amplifiers.

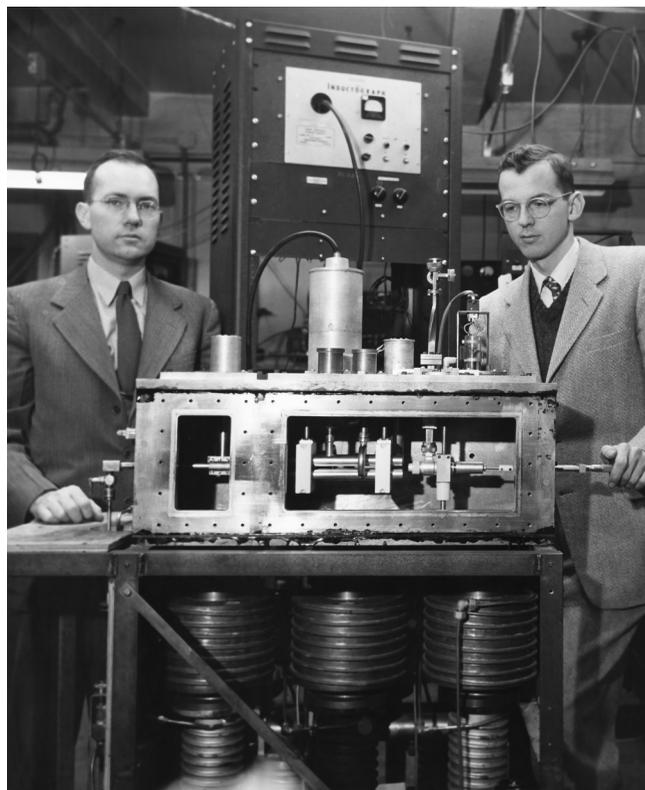
With millimeter waves and the far infrared then vast terra incognita, the next logical step was to develop stimulated emission at infrared and optical wavelengths. The key requirements were a medium with energy levels that could be inverted to produce stimulated emission in the optical band, a way to produce a population inversion, and a cavity in which the light waves could oscillate.

That took some serious rethinking, and in the summer of 1957 Townes began a systematic analysis of how to build what he called an “optical maser.” In essence, he formulated the physics problem that had to be solved to develop the laser. As part of his investigation, in late October Townes talked with Gordon Gould, a graduate student under Polykarp Kusch, about optical pumping, which Gould was using to excite thallium vapor for his dissertation research. Optical pumping was new, and Townes thought it might produce an optical population inversion. The two talked twice, then went their separate ways.

Townes enlisted the aid of his brother-in-law, Arthur Schawlow, who worked at Bell Labs and had experience in optics. Schawlow proposed using a pair of parallel mirrors to form a Fabry–Perot resonator for the laser. They initially considered using thallium vapor as the active medium, but Schawlow decided potassium vapor was more promising, so they focused their attention on that system, and also noted that solids could be optically pumped. Reviewers at Bell Labs, where Townes was a consultant, urged them to analyze cavity modes, which they included in their pioneering paper, “Infrared and optical masers,” in the 15 December 1958 *Physical Review* [1], which laid the groundwork for early laser development.

They did not know that Gould had jumped on the idea earlier. At age 37, he was growing impatient with his dissertation. Gould had worked with optics before, and within weeks after talking with Townes he described a Fabry–Perot laser resonator in a notebook that he had notarized on 13 November 1957, shown in Fig. 2. Filled with dreams of becoming an inventor, he left Columbia, talked with a patent lawyer, and holed up in his apartment with a pile of references to work out his plans for what he called the LASER. Gould had solved the laser problem on his own, and in time he would develop an extensive catalog of potential laser transitions. But neither he nor Townes and Schawlow were close to building a working laser. They had the blueprint, but finding the right material was a serious problem.

Alkali metal vapors were attractive because they are simple systems easy to describe in theory. They did not offer much gain, but they looked promising for a proof-of-principle physics experiment. Townes thought it would make a good dissertation project, as the microwave maser



▲ Fig. 1. Townes and Gordon with ammonia maser. (AIP Emilio Segre Visual Archives, Physics Today Collection.)

had been for Gordon, and put two of his students, Herman Cummins and Isaac Abella, to work on it.

Schawlow pursued optical pumping of solids, a natural because Bell Labs was deeply involved in solid-state physics. Schawlow initially focused on synthetic ruby, which was also being used in solid-state microwave masers and was readily available at Bell. However, the spectroscopy of ruby discouraged him. The red transitions which had looked attractive turned out to be three-level transitions terminating in the ground state, making it hard to invert the population. Moreover, other Bell researchers had found that the red emission was inefficient, so he began looking for other candidates.

As word of the laser circulated around Bell, others developed their own ideas. Ali Javan proposed a novel scheme for exciting a gas laser with an electric discharge in a mixture of helium and neon. The helium would absorb energy from the discharge, producing an excited state with energy very close to a neon transition. Collisions would excite the neon to a metastable upper laser level, which would then emit

on a transition to a level well above the ground state—a four-level system that looked attractive for continuous laser emission.

Gould, meanwhile, had gone to work at a defense contractor, Technical Research Group Inc., to support himself while working on his laser ideas. He had hoped to keep his ideas secret, but eventually worked out a deal to share patent rights with TRG, which helped him develop a patent and write a grant for research on building a laser. In early 1959, Gould and TRG president Larry Goldmuntz pitched their proposal to the Advanced Research Projects Agency, then less than a year old and chartered to explore daring new ideas. ARPA was so impressed that they approved a contract for \$999,000—more than triple the \$300,000 TRG had requested.

By then, publication of the Schawlow–Townes paper had put the laser into public view, interesting other researchers in trying to make one. The ARPA contract was serious money at the time, intended to support efforts to demonstrate laser action in a number of media. Laser development was becoming a race, but it would not be an easy one.

The first public reports on laser experiments came at a 15–18 June 1959 conference on optical pumping at the University of Michigan. Worried that the Pentagon might classify all laser research, not just its TRG project, Bell Labs management encouraged Javan to describe his work both at the meeting and in *Physical Review Letters*. Javan reported some progress in understanding energy transfer in helium–neon discharges in experiments he had begun with William Bennett. Gould described his ideas and hinted at the size of TRG’s military program but was vague on details. Meanwhile, Gould was having trouble getting the security clearance he needed to work on the TRG project because of his past involvement with communists.

September saw a meeting much better remembered, the first Quantum Electronics Conference at Shawanga Lodge in High View, New York. Sponsored by the Office of Naval Research, it was the first in a series of biennial meetings that became the International Quantum Electronics Conference. Only two speakers at the 1959 meeting talked about lasers. Javan described the early stages of his helium–neon

research, but had little to say beyond his *Physical Review Letters* report [2]. Schawlow wrote off pink ruby, with low chromium concentration, because as a three-level system he thought it would emit light too inefficiently for use in a laser.

Most speakers described microwave maser research. Among them was Theodore Maiman, who had built a surprisingly compact ruby maser at Hughes Research Laboratories in California, and was looking around for a new project. He had thought about optically pumping a microwave maser, but the optical laser caught his eye. Despite Schawlow's doubts, Maiman decided to start with ruby because he was familiar with it. He thought studying where ruby's energy went would help him identify a better material. But his careful measurements showed the quantum efficiency of ruby fluorescence was nearly 100%.

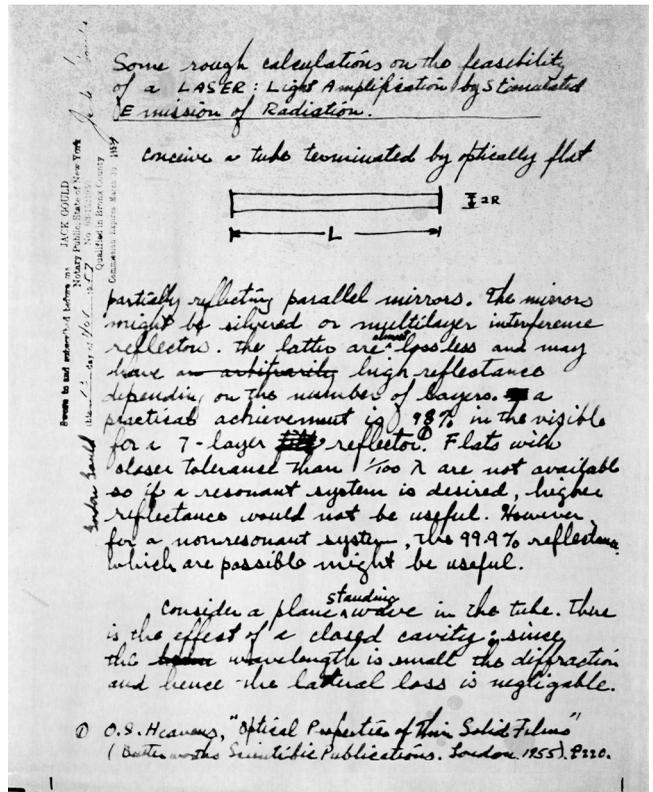
Ruby did have another problem: it was a three-level laser, with the ground state as the lower laser level. Four-level lasers were better for the continuous-wave lasers that most groups were trying to make. When Maiman sat down and calculated the pump power requirements for ruby, he found that even the brightest arc lamp available would make only a marginal continuous-wave laser.

Instead of giving up, he shifted gears and thought about making a pulsed laser to demonstrate the principle. He soon found that photographic flashlamps could emit peak power much higher than the brightest arc lamp and ordered a few coiled flashlamps in three different sizes, all of which he calculated could pump a ruby laser.

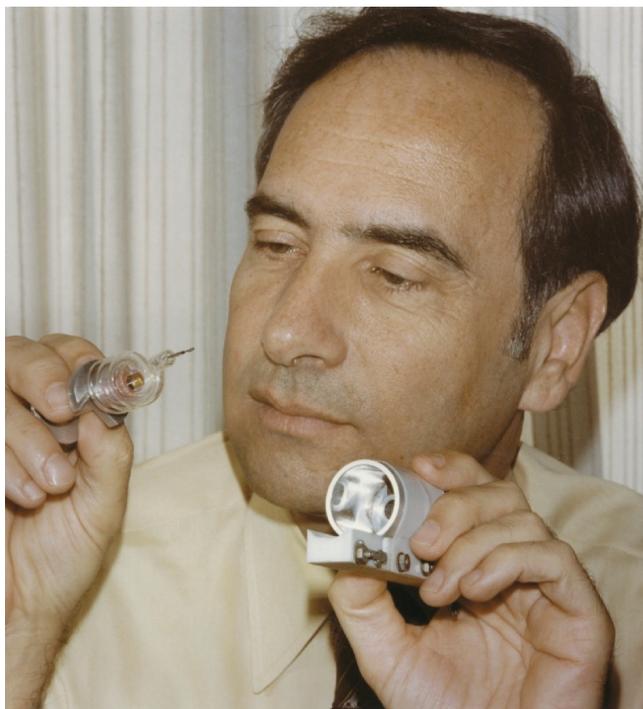
To test his ideas, Maiman silvered the ends of a fingertip-size stubby ruby rod and scraped a hole in the silver on one end for the beam to emerge. He slipped the ruby inside the coil of the smallest flashlamp, then slid the lamp inside a hollow metal cylinder, to reflect pump light back onto the rod and separate the pump light from the red pulse he hoped the ruby would emit (see Fig. 3). Then, on 16 May 1960, he and his assistant Irnee D'Haenens cranked up the voltage on the flashlamp power supply step by step. Initially, the ruby fluoresced when the flashlamp pulsed, growing brighter as voltage increased. When they exceeded 950 volts, the red pulses grew much brighter, and an oscilloscope screen displaying the pulse shape showed Maiman the changes he had expected for a laser.

Word of the success spread quickly through the lab, but Maiman insisted on performing further experiments to verify the results. When those tests confirmed the laser, word went up the management ladder, and Maiman wrote a paper, which he airmailed to *Physical Review Letters* on 22 June. PRL had just published his report of ruby fluorescence, and he was confident that the laser paper—a far more important achievement—would be quickly accepted.

He was stunned when editor Samuel Goudsmit summarily rejected the laser paper without sending it to referees. Maiman had violated two of Goudsmit's pet peeves. Tired of reports of minor progress on microwave masers, Goudsmit said he would run no more maser papers, but Maiman had titled his paper "Optical maser action in ruby." Goudsmit also disapproved of serial publication, and *Physics Review Letters* had just published Maiman's report on ruby fluorescence. Maiman protested that the paper was a major advance, but Goudsmit would not listen.



▲ Fig. 2. First page of Gould's notebook defines LASER. (AIP Emilio Segre Visual Archives, Hecht Collection.)



▲ **Fig. 3.** Maiman shows the simple structure of the world's first laser. (Reproduced by permission of Kathleen Maiman.)

Abella did not believe ruby could have lased, until the reporter explained Maiman had used a flashlamp. The laser quickly passed the acid test of replication; within three weeks, TRG had used press reports to demonstrate their own ruby laser—although they all showed Maiman with a laser design different than the one that worked. Bell Labs followed. By then, Maiman had received a ruby rod of much better optical quality that projected a bright spot on the wall.

The ruby laser excited the optics community, and The Optical Society invited Maiman to talk at the 1960 OSA Annual Meeting, held 12–14 October in Boston. It was his first report on the laser at a scientific conference, and the *New York Times* sent its top science writer, Walter Sullivan, to cover it.

His demonstration of flashlamp pumping inspired others. At the IBM Watson Research Center, Peter Sorokin and Mirek Stevenson had been trying to make four-level solid-state lasers with elaborate total-internal-reflection cavities. They bought flashlamps, had their crystals cut into rods, and soon demonstrated the second and third lasers, on lines of uranium and scandium in calcium fluoride. They were the first four-level lasers.

Bell Labs was close behind. On 12 December, Javan, Bennett, and Donald Herriott demonstrated the first helium-neon laser on a near-infrared line at 1.15  $\mu\text{m}$ . By the end of 1960, the laser age was launched.

Note: This essay is based on material from Ref. [4].

## References

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Rejection by *Physical Review Letters* was a serious blow in 1960, when it was the only physics journal offering rapid publication. To stake his claim to the laser, Maiman dashed off a short note to the weekly *Nature*, which quickly scheduled it for publication on 6 August [3]. He sent a longer paper to the letters section of the *Journal of Applied Physics*, which accepted it, but could not publish it for six months. (*Applied Physics Letters* did not begin publication until 1962.)

Hughes managers knew others were working on lasers, and were thinking about holding a press conference when Malcolm Stitch called from a Rochester conference warning that Columbia was close to making their laser work. In fact, they were not at all close; Oliver Heavens, on sabbatical at Columbia, had waxed much too enthusiastic at the meeting. But it was enough for Hughes to schedule a press conference in New York on 7 July.

The news made page 1 of the *New York Times*, and stunned other laser developers. Reached on the phone by a reporter,

# Postwar Employment Bubble Bursts

Jeff Hecht

Optics prospered along with other areas of physics and engineering as American research universities grew after World War II. Military programs encouraged universities to expand basic research, both in hope of developing new defense technology and to train specialists for defense research at government agencies or defense contractors. Over the years from 1938 to 1953, military support of university physics research soared by a factor of 20 to 25, after adjusting for inflation.

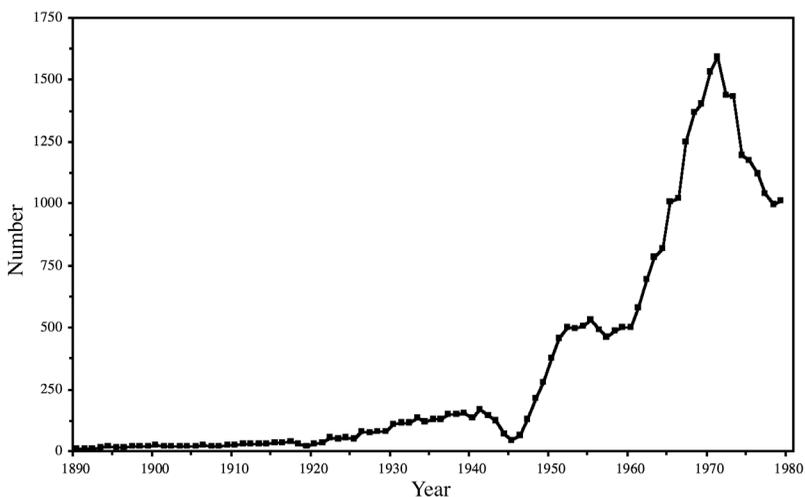
These programs provided both bright new ideas and bright people to help launch the laser era in optics. The Columbia Radiation Laboratory, founded in 1942 at Columbia University to develop new microwave tubes for 30-GHz radar, received \$250,000 a year after the war from the Army Signal Corps to continue microwave research in Columbia's physics department. At the time, that was enough to support a staff of 20 and nearly as many graduate students, as well as to pay several faculty members over the summer. Charles Townes headed the radiation lab from 1950 to 1952, during the time he conceived of the microwave maser.

Military research dollars also produced new physicists. American universities had graduated about 150 new physics Ph.D.s annually just before the war, and the number dropped steeply during the conflict. But from 1945 to 1951 the number of physics Ph.D. graduates doubled every 1.7 years, reaching about 500 per year, as shown in Fig. 1. Seeing where the jobs were, postwar students concentrated on experimental physics. Engineering likewise boomed in the postwar years, with 159,600 bachelor's degrees awarded from 1946 to 1950, more than from 1926 through 1940.

Dwight Eisenhower had seen part of that growth as president of Columbia University from 1948 to 1951, but as President of the United States he cut military research spending in 1953, and the number of physics Ph.D.s remained in the 500–600 range through the 1950s. The cuts led universities to scale down their programs. Boston University went further, shutting the optics lab it had inherited from Harvard; veterans of that group became the nucleus of the Itek Corporation, founded in 1957 by Richard Leghorn with funding from the Rockefeller family.

Eisenhower changed course after the Soviet launch of Sputnik 1 on 4 October 1957 stunned the American physics community, the Pentagon, and politicians. Fearing the U.S. was falling behind in an arms race in space, his administration boosted funding for physics and engineering research and education. The money brought quick results. The number of Ph.D.s graduating from American universities rose exponentially from about 500 in 1960 to some 1600 in 1970, faster than the growth of Ph.D.s in any other field. The number of American universities offering Ph.D.s in physics climbed from 52 in 1950 to 78 in 1960 and reached 148 in 1970. The number of undergraduate degrees in physics also climbed, from 1000 in 1945 to a peak above 6000 in 1968. Engineering degrees also increased. The numbers reflected both growth in overall college enrollment and an increase in the fraction of students studying physics and engineering. It did not include the Postwar baby boom, who started to graduate from college in 1968.

The arms race, the space race, fast-growing industrial labs, and a booming technology industry created unprecedented demand, particularly for physicists. A 1964 report from the American Institute of Physics found that in 1960 only 17,300 trained physicists were available to fill some 29,000 physics-related jobs in the U.S. It's not clear how many of the excess jobs went unfilled or were filled by people lacking physics degrees, but the deficit seemed formidable—and the gap was projected to reach 20,000 by 1970.



◀ **Fig. 1.** Number of Ph.D. physicists graduating from American universities annually, showing the dramatic postwar boom and post-1970 decline. (© 2002 by The Regents of the University of California. All rights reserved [1].)

A tripling of government research and development funding from 1955 to 1965 helped propel the boom, with defense and space programs leading the way. The birth of the laser and increasing military use of electro-optics pumped up spending on optical research and development, and in 1962 OSA's Needs in Optics Committee concluded that existing training programs could fill only a quarter of the need for 3500 new optics specialists in the coming five years [2].

Yet by the mid-1960s, the well-oiled machinery of growth had begun hitting serious bumps in the road. Doubts were growing about America's escalating involvement in Vietnam, and opponents were raising questions about the presence of military research on university campuses. Budget watchers worried that the country could not afford to continue pumping more money into basic research while fighting a war. Pentagon auditors found that military spending on basic research yielded a disappointing return on investment and urged focusing narrowly on mission-oriented research and development.

Congress began pressing to cut military spending on basic research, and spending on new research buildings was stopped in early 1967, forcing some creative financing to build the new Optical Sciences Center at the University of Arizona [2]. Congress complained that too much research money was going to a few elite universities, and too little to other Congressional districts. Topping off the trend, the Mansfield amendment in 1969 barred Pentagon spending on research lacking direct military applications, although those restrictions were later eased.

Universities also began re-examining their military research policies, pushed by faculty and student protests. In 1967 Columbia, an early hotbed of protests, divested its Electronics Research Laboratory, which became the Riverside Research Institute. More would follow. Stanford in 1970 split off the Stanford Research Institute, later SRI International, and in 1972 MIT divested its Instrumentation Laboratory, which became the Charles Stark Draper Laboratory. The most important split for the optics world probably was the University of Michigan's 1972 divestiture of its off-campus Willow Run Laboratories, the birthplace of laser holography and optical signal processing.

In retrospect, it should have been obvious that the rapid growth powered by the space and arms races could not continue, but students recruited with promises of well-paying jobs were caught by surprise. Recruitment advertisements, which had fattened campus newspapers at elite schools like Caltech, began evaporating after 1967. Job fairs at physics conferences shrank. Only 253 jobs were advertised at the American Physical Society's 1968 annual meeting, but nearly 1000 applicants showed up, and over 1500 people received Ph.D.s that year. Two years later, 1010 job-hunters chased 63 jobs at the APS April meeting. "American physics had indeed reached a crisis by 1970, exactly when the 1964 report had predicted," wrote MIT historian David Kaiser [1]. But the crisis was a shortage of jobs rather than of physics graduates.

Inevitably, graduate enrollment shrank, and the number of new physics Ph.D.s dropped from a peak of 1600 at the start of the 1970s to about 1000 per year at the end. Physics research continued growing, but at a much slower pace. One measure of research, the number of abstracts published each year in *Physics Abstracts*, increased about 3% a year from 1971 to 1999—only a quarter of the 12%

annual growth from 1945 to 1971. Optics in general fared better than many other specialties, leading some physicists in hard-hit fields to move into optics.

Engineers were caught in a similar crunch. Ph.D.s in electrical engineering, the major most related to optics, peaked at 858 in 1971, then slid steadily to 451 in 1978, a 47% drop—larger than the 37% drop in physics Ph.D.s. The decline in bachelor's degrees, which in the 1970s were typically the terminal degree in engineering, was much less. Electrical engineering undergraduate degrees peaked at 12,288 in 1970–1971, then bottomed out at 9874 in 1976, only a 20% drop [3]. Many of those engineers, and some physicists, wound up in the fast-growing computer industry. Others ended up in optics.

Optics also felt the slowdown of the late 1960s and early 1970s, but with only a handful of schools training optical engineers and physicists, optics still offered opportunities for young physicists and engineers. Many of the newcomers adapted their skills to work on lasers and fiber optics, the fastest-growing fields in optics in the 1970s and 1980s. The newcomers brought new skills, and helped optics grow into new areas as they developed their careers.

## References

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# Gas Lasers—The Golden Decades, 1960–1980

William B. Bridges

By all rights, gas lasers should have been discovered long before 1961, likely by accident. Einstein's 1917 classic paper derived the relationship among spontaneous emission, stimulated emission, and absorption, but only considered a system in thermodynamic equilibrium (guaranteed *not* to oscillate). It remained only to ask: "What if the system were *not* in thermodynamic equilibrium?" Yet despite countless experiments looking at the absorption of radiation in gas discharge tubes (not in thermodynamic equilibrium), the first gas laser had to wait for Ali Javan of Bell Telephone Laboratories.

## First Gas Laser

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In 1959 Javan proposed four different ways to make a gas laser:

- (1) A gas discharge in pure neon.
- (2) A gas discharge in pure helium.
- (3) Resonant collisions in between excited krypton and mercury atoms in a discharge exciting the Hg ( $9^1P$ ) or Hg ( $6^1F$ ) levels, creating an inversion in the mercury levels.
- (4) Helium atoms in the ( $2^3S$ ) level in a gas discharge exciting Ne ( $2s$ ) levels to create an inversion in neon levels.

The first three systems do not actually work, but fortunately Javan and his Bell coworkers Bill Bennett and Don Herriott did the fourth experiment. They excited a mixture of helium and neon with a radio-frequency discharge in a gas tube with flat end mirrors coated for maximum reflectivity near 1- $\mu\text{m}$  wavelength, as depicted in Fig. 1. Oscillation of the neon transition  $2s_2 \rightarrow 2p_4$  at 1.1523  $\mu\text{m}$  made the first gas laser.

## Gas Lasers Using Neutral Atoms

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Once the word was out, everybody had to have a helium–neon laser, and a war-surplus night vision 'scope to see the infrared laser output. Hughes Research Laboratories was no exception, and the author found himself in the queue to get one from a mini production line that Hughes had set up. The author had been interested in developing a microwave traveling wave tube (his former professional interest) as a high-frequency photodetector for laser communications and had already done experiments with a pulsed ruby laser. The continuous operation of the He–Ne laser was more attractive for communications, despite the need for a new detector. But fate intervened.

The author had planned to attend the annual Conference on Electron Device Research in late June with his boss, Don Forster, and Hughes Associate Director, Mal Currie. Currie decided they should visit Bell Labs on the way to see what was new and interesting. They were astounded to see a *red* He–Ne laser operating at about 10 mW, in the lab shown in Fig. 2. The three researchers saw the now familiar "red sandpaper" speckle of truly coherent light (which was not very evident in the IR He–Ne laser viewed with a night-vision 'scope). Alan White and J. Dane Rigden had found *another*

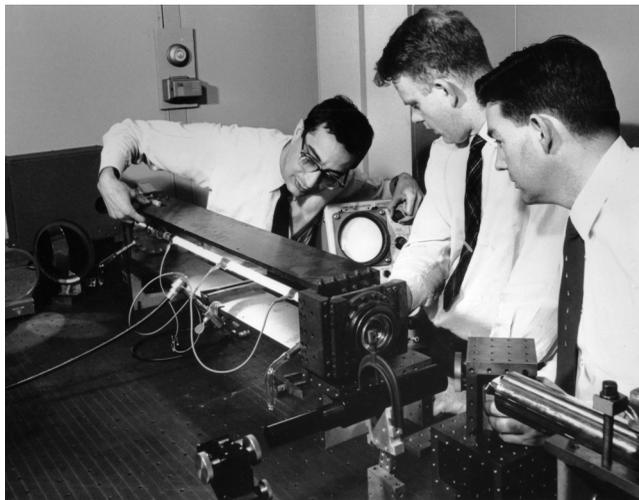
metastable level in helium, the  $2s^1S_0$ , that collected population from higher-lying helium levels, and was near resonance with the  $3s_2$  level in neon. That created a population inversion with the  $2p_4$  level on the red laser line at  $0.6328\ \mu\text{m}$  and oscillation when red-reflecting mirrors were used for feedback. White and Rigden were in a different Bell technical group from Javan, Bennett, and Herriot, and enjoyed the rivalry. When they announced the red laser the next week at the conference, the rivalry between the two groups was quite evident.

That night on the drive back from Bell in New Jersey to our hotel in New York, the group discussed the new red laser. Currie (who was driving) ended by saying “We have to have one!” The author sensed that he had just received a battlefield promotion to “Gas Laser Researcher.”

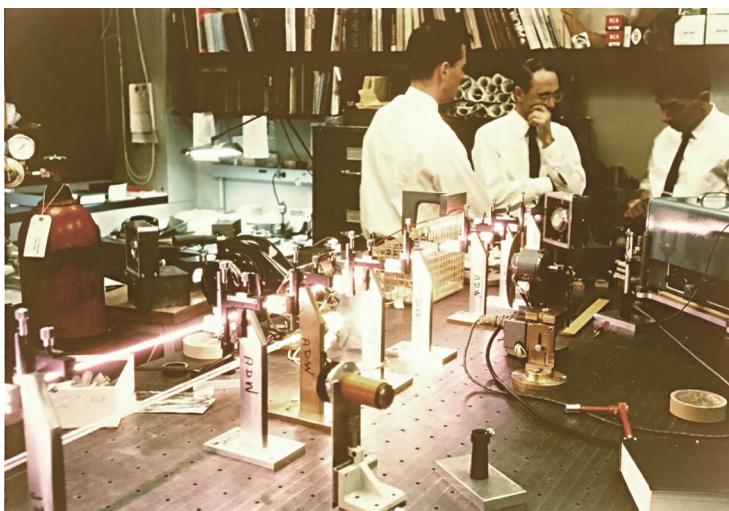
Helium–neon gas mixtures turn out to have several infrared lines from  $2s$  levels to  $2p$  levels, and several lines from green to deep red between the  $3s_2$  level and  $2p$  levels. In addition, several infrared lines in the  $3\text{-}\mu\text{m}$  range have so much gain that they can easily suppress the red laser line. Arnold Bloom, Earl Bell, and Bob Rempel of Spectra-Physics found that they could prevent  $3\text{-}\mu\text{m}$  emission by adding an intracavity prism.

Other researchers rushed to extend these results. Another Bell Labs group built a 10-m discharge tube to obtain oscillation on many more infrared lines to wavelengths beyond  $100\ \mu\text{m}$  in various noble-gas mixtures. This early burst of research showed that oscillation was possible in pure noble gas discharges, without adding helium. That led to a burst of research on the noble gases, which are easy to investigate because they do not interact with the discharge tube walls or electrodes.

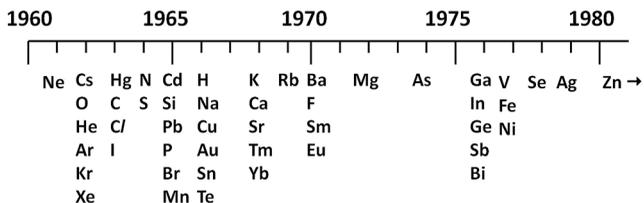
Interest soon turned to other materials, starting with the permanent gases such as oxygen, nitrogen, and chlorine, which dissociate into atoms in a discharge, and expanding to easily vaporized elements such as mercury, iodine, and sulfur. Reports of new lasers multiplied, and it seemed that almost *anything* that you could vaporize and put in a gas discharge would lase. Figure 3 shows how the ranks of lasing elements grew during the first two decades, the “golden age” of gas laser research. The author



▲ Fig. 1. Ali Javan, W. Bennett, and D. Herriott with the first He–Ne laser at Bell Laboratories. (Reprinted with permission of Alcatel-Lucent USA Inc., courtesy AIP Emilio Segre Visual Archives, Physics Today Collection.)



► Fig. 2. J. D. Rigden, A. D. White, and W. W. Rigrod with the first red He–Ne laser at Bell Laboratories. (Courtesy of Alan White.)



▲ Fig. 3. Timeline for the discovery of laser oscillation in neutral atoms during “the golden age” of gas laser research, 1962 to the 1980s.



▲ Fig. 4. A simple helium–neon gas laser typical of those in supermarket optical scanners. The cavity mirrors are attached directly to the ends of the small diameter discharge tube. An aluminum cold cathode surrounds the discharge tube. Tubes like this sold for about \$100, and typically lasted for over 10,000 hours.

The first commercial He–Ne lasers sold for about \$20,000, but the prices quickly dropped as commercial manufacturers learned the tricks, and large-scale applications developed. By 1970, the 2-mW-output lasers of the type shown in Fig. 4 that were used in early supermarket checkout scanners sold for about \$100 (plus power supply). The mirrors were sealed directly on the ends of the glass envelope with a low-melting-temperature glass frit. Millions of such He–Ne lasers were manufactured, but now this application has all but been taken over by red diode lasers, and He–Ne lasers will soon become collector’s items.

## Ionized Gas Lasers

In the course of investigating new gas lasers in 1963, W. Earl Bell and Arnold Bloom of Spectra-Physics discovered the first gas laser that oscillated on energy levels of ions while testing mixtures of helium and mercury. Like the early He–Ne laser, they used a simple glass discharge tube, a few millimeters in diameter and about a meter long. The key difference was using high current pulses of a few tens of amperes, rather than a constant current of few mA. This produced laser pulses with peak power of a few watts at wavelengths of 0.5677 and 0.6150  $\mu\text{m}$  in the green and orange—an important milestone because the green line at the time was the shortest visible wavelength yet produced by a laser. Figure 5 shows Bell in his laboratory at Spectra-Physics with an early pulsed He–Hg<sup>+</sup> laser.

The excitation mechanisms behind the He–Hg<sup>+</sup> laser were unclear at the time, and at least four groups tried to pin it down, including Bloom and Bell; Rigden (who had moved to Perkin-Elmer); G. Convert, M. Armand, and P. Martinot-Lagarde at CSF in France; and the author at Hughes. Independent experiments by Rigden and the author showed that a neon–mercury discharge could also produce the orange mercury-ion line, ruling out simple charge exchange as the mechanism.

personally had no doubt that you could make a gas laser from such hard to vaporize elements as tungsten, osmium, rhenium, and iridium if you could put a discharge through them in vapor form, but the technical community so far has not felt it was worth the effort.

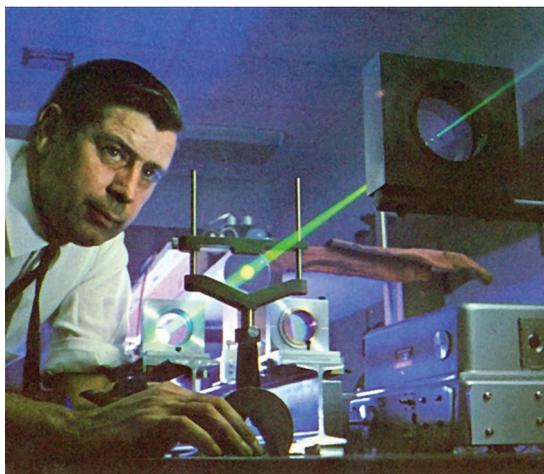
The technology for He–Ne lasers is actually pretty simple; think “neon sign.” A simple glass tube, 2 to 10 mm in diameter and 100 to 2000 mm in length, was commonly used. A DC discharge of 2 to 10 mA is typically required. (A radio-frequency discharge at 27 MHz was used in the first He–Ne laser, but DC is simpler.) The gain of a typical red He–Ne laser is quite low, only a few percent per meter. But the optical gain of a 3.39- $\mu\text{m}$  He–Ne laser can be tens of decibels per meter, so a meter-long discharge tube might well oscillate with the feedback from the first surface reflection of an uncoated glass window perpendicular to the optical path. A simple discharge tube in pure xenon may easily exhibit 20-dB gain at 3.508  $\mu\text{m}$ . This is the author’s argument that the gas laser should have been discovered by accident long ago (but no one records such an event).

To put an extra nail in the coffin of charge exchange, the author tried an argon–mercury discharge. (Argon has an ionization potential well below that of neon.) This initially did not produce the orange and green Hg II laser lines, so the mixture was pumped out. After the tube was refilled with a helium–mercury mixture, the discharge again produced the orange and green Hg II laser lines—plus a turquoise blue laser output, which turned out to be ionized argon, shown in Fig. 6. The blue pulse coincided with the electron current, not the discharge afterglow, suggesting that electron collision was the mechanism behind the argon-ion oscillation. That system, similar to the one shown with the author in Fig. 6, opened up a new chapter. It was Valentine’s Day, 14 February 1964.

It turned out that the groups at Spectra-Physics, CSF, and Hughes had independently discovered the Ar II 0.4879- $\mu\text{m}$  laser. So had W. R. Bennett, Jr., J. W. Knutson, Jr., G. N. Mercer, and J. L. Detch at Yale University, who had not been studying mercury-ion lasers but were trying to make an argon-ion laser! It was clearly an idea whose time had come. Another group at Bell Laboratories, E. I. Gordon, E. F. Labuda, and R. C. Miller, found that the argon-ion laser could emit continuously, unlike the mercury-ion laser. In a matter of months, water-cooled discharge tubes were emitting more than 2 W continuously. The efficiency was below 0.1%, so several kilowatts of input was needed, requiring major improvements in discharge tubes.

Other noble-gas ion lasers followed quickly. More than two dozen laser lines in krypton and xenon ions were discovered within a week of the argon laser. Neon oscillation followed in a couple of months, the time needed to obtain cavity mirrors at the right wavelengths. Spectrographic plates recorded laser oscillation on lines of oxygen, nitrogen, and carbon left as impurities in the discharge tubes. Further spectroscopic research discovered laser emission from multiply ionized species at higher peak currents.

Watts of continuous-wave blue laser light opened the possibility of new applications. Among the first was improving coagulation to repair detached retinas, which had been done with high-power xenon lamps and later ruby lasers. Krypton-ion lasers, able to emit red, yellow, green, and blue light simultaneously, were quickly adopted for light shows. Their use at rock concerts introduced new types of customers to laser companies that were used to scientists; one customer arrived at Spectra-Physics with a wad of hundred-dollar bills to buy a krypton laser, put the laser in his station wagon, and drove off to a show that night. By far the largest application for ion lasers became high-power pumps for dye lasers, making ion lasers the “power supply” for much science.



▲ Fig. 5. W. E. Bell in his laboratory at Spectra-Physics with an early pulsed helium–mercury ion laser. (AIP Emilio Segre Visual Archives, gift of W. Earl Bell.)



▲ Fig. 6. Photograph of the author with a pulsed argon-ion laser in his laboratory in February 1964: an air-cooled fused silica discharge tube with Brewster’s angle windows and external mirrors. Pulse lengths of a few microseconds with a simple capacitor discharge and rates of a few hundred per second were used.

# Molecular Gas Lasers

Nobel Laureate and former Optical Society President Arthur Schawlow once said, “A diatomic molecule is a molecule with one atom too many.” However, for molecular lasers this author would say instead, “If one atom is good, then several must be better.” Molecules have more degrees of freedom than atoms or ions, including the number and kind of atoms, the molecular structure, the nature of energy levels, and type of pumping, leading to the demonstration of thousands of molecular lasers. The first was carbon monoxide, which L. E. S. Mathias and J. T. Parker made oscillate on electronic transitions in a pulsed discharge at 0.8 to 1.2  $\mu\text{m}$ . Close behind it was the 0.337- $\mu\text{m}$   $\text{N}_2$  laser demonstrated by H. G. Heard. The third molecular laser would be the charm—and most successful—the 9- to 11- $\mu\text{m}$   $\text{CO}_2$  laser, discovered at Bell by C. K. N. Patel, W. L. Faust, and R. A. McFarlane.

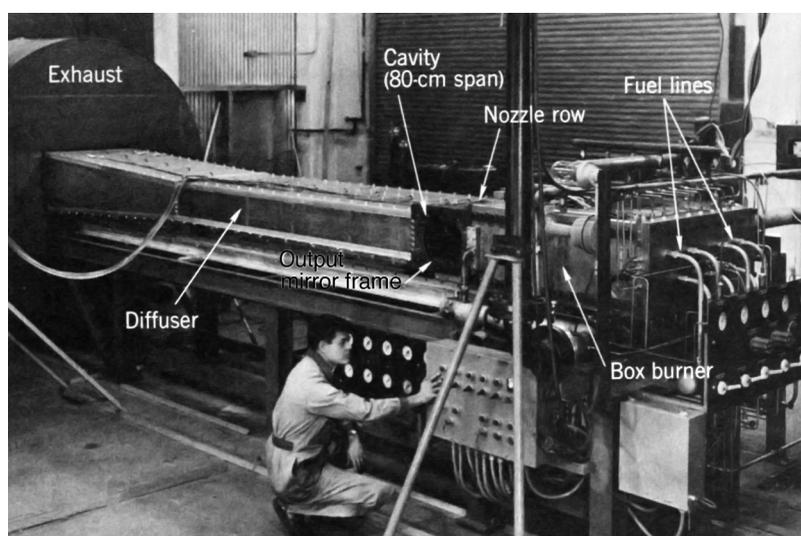
The diatomic noble gases, noble-gas halides, and noble-gas oxides in the list exist only in an electronically excited state, called an “excimer.” The population inversion occurs because the molecule quickly falls apart into atoms when it drops to the ground state. The rare gas-halide excimers have become commercially important because they produce powerful pulses in the vacuum ultraviolet. The 193-nm argon-fluoride laser is used in laser ablation of the cornea to correct vision defects and in high-resolution lithography to make silicon integrated circuits.

Larger and more complex gas molecules also have been made to oscillate, mostly by optical pumping with the 9- to 11- $\mu\text{m}$  light from  $\text{CO}_2$  lasers. These larger molecules have hundreds of rotational/vibrational transitions in the far-infrared region, and to make matters more complicated, the wavelengths depend on the hydrogen, carbon, nitrogen, and oxygen isotopes in the molecule.

The most important molecular gas laser,  $\text{CO}_2$ , like the He-Ne laser, depends on energy transfer from a more abundant species to the light emitter, so it might better be called the nitrogen- $\text{CO}_2$  laser. Typically a discharge excites a gas mixture of ten parts  $\text{N}_2$  and one part  $\text{CO}_2$ , with most energy going to excite  $\text{N}_2$  molecules to their lowest vibrational level, which is metastable so it cannot radiate. However, they can transfer energy by colliding with  $\text{CO}_2$  molecules, which have a near-resonant energy level that produces a vibrational population inversion.  $\text{CO}_2$  oscillation occurs on rotational sublevels of the inverted vibrational level, which can be selected by tuning the cavity.

Carbon dioxide lasers can have efficiency of 10% or more, among the highest of any gas laser, and a factor of 100 higher than most atomic or ionic lasers. That makes  $\text{CO}_2$  the gas laser of choice when power is important. Applications including burning date codes or other identification on plastic bottles, cutting sheet metal, or even cutting the special glass used in cell phone displays.

In the mid-1960s, the AVCO Everett Research Laboratory produced record continuous  $\text{CO}_2$  output of 50 kW, shown in Fig. 7. This “gas-dynamic laser” burned fuel at high temperature



◀ Fig. 7. An experimental gas-dynamic  $\text{CO}_2$  laser developed by AVCO Corporation circa 1968. The output was over 50 kW.

(2000°F) and pressure (20 atm.) and then exhausted the mixture of 89% nitrogen, 10% CO<sub>2</sub> and 1% water vapor through a supersonic expansion nozzle. This produced a CO<sub>2</sub> population inversion downstream, which could oscillate when passed through an optical cavity. The black circle above and to the right of the technician's head was the beam output. The combustion chamber is at the right of the device, and the exhaust to the atmosphere is to the left of the picture. (The combustion exhaust was relatively harmless to the environment, but the highly poisonous cyanogen C<sub>2</sub>N<sub>2</sub> was used as fuel to keep the exhaust low in hydrogen, so extreme care was needed to make the fuel burn properly.) Later, a 400-kW version was installed in the Airborne Laser Laboratory, a laser-weapon testbed built in the 1970s.

Hydrogen–fluoride (HF) chemical lasers, which burn hydrogen and fluorine to produce HF gas that lases in a system similar to the gas-dynamic laser, have reached megawatt-class powers in demonstrations on the ground. These are described by Jeff Hecht in his chapter on laser weapons.

## Summary

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The two decades ending in the 1980s were the heyday of gas laser development. Today, the world of gas lasers is much quieter, with only a few types remaining, with mostly carbon dioxide in the factory and some excimers and argon ion lasers in ophthalmologists' offices.

A list of literature citations for the thousands of gas lasers implied by this chapter would be longer than the chapter itself. The interested reader is referred to guides to that literature, such as [1].

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# Discovery of the Tunable Dye Laser

Jeff Hecht

The narrow-emission bandwidth of laser light quickly attracted the attention of spectroscopists in the early 1960s, but that narrow linewidth came at a cost—the wavelength was fixed. Laser researchers found that they could shift the fixed wavelength somewhat by applying magnetic fields to the laser, they developed tunable parametric oscillators, and eventually they found a few laser lines that were tunable. But those arrangements were cumbersome and their range limited. As a student in the mid-1960s, spectroscopist Theodor Hänsch felt “a sense of frustration” that he had no way to tune lasers “to wavelengths that were interesting.”

What spectroscopists really wanted was a laser that could be tuned across a broad range of interesting wavelengths. The first such tunable laser, the organic dye laser, was discovered by accident in research on Q-switching ruby lasers. The first Q switches were active devices based on Kerr cells or rotating mirrors, but in early 1964 the first passive Q switches were developed using saturable absorbers. Later that year, Peter Sorokin at the IBM Watson Research Center showed that certain organic dyes dissolved in solvents made simpler and more convenient saturable absorbers.

After that success, Sorokin found himself with a large collection of dye compounds that had been prepared for the saturable absorber experiments. The dyes had interesting properties including strong fluorescence, so he decided to try producing stimulated Raman scattering. He fired pulses from a big Korad ruby laser into a dye that had never been tested in Q switching. The first experiment produced a black smudge on a photographic plate, but it was late Friday afternoon and he had to leave. Monday morning, 7 February 1966, he told his assistant Jack Lankard they should try aligning a pair of mirrors with the dye cell before they fired the laser again. “Jack came back from developing the plate with a big grin on his face. There was one place in the plate that the emulsion was actually burnt,” Sorokin later recalled. They knew it was laser action because the bright line was at the peak of the dye fluorescence

Word of their experiments traveled slowly; Sorokin chose to publish his results in the March 1966 issue of the *IBM Journal of Research and Development* because he liked the editor, but it was not widely read. That gave two other groups a chance to independently invent the dye laser.

The idea of a dye laser came to Mary Spaeth, then at Hughes Aircraft Co., about the same time Sorokin was working on his experiment. She recalls, “I was sitting on my bed with my two year old daughter on my lap, two months pregnant with my second daughter, and about 20 papers spread out in front of me. I had been studying dyes that had been used for many years for photographic purposes. In particular, I was studying models for how they are excited and how they transfer energy from one molecule to another in the photographic process. The excited states of these dyes have a geometry very similar to their ground states, so they have very strong absorption spectra. I suddenly realized that if a dye could be put in a suitable solvent, you could have an enormous population inversion after illumination by a short-pulse laser. It was just like the light bulb pictures you see in the funny books. Boing! There it was, clear as day.”

She also realized that because dyes have huge numbers of rotational states, they should have a broad gain bandwidth, so that placing dispersive optics in a laser cavity with the dye solution should allow wavelength tuning. But first she wanted to try exciting the dye with pulses from a

ruby laser. It was not part of her job, so it took her months to make arrangements to pump dyes with a ruby laser in Dave Bortfeld's lab. As she sat epoxying a dye cell together, Bortfeld entered the room and threw a paper airplane at her. She recalls, "I looked at him to try to figure out why he had done that. As I unfolded the airplane, I found it was a copy of Sorokin's paper," which Bortfeld had just spotted. She knew the dyes, so she instantly realized what it was about. "We decided, what the heck, we were working independently, and we continued on our way."

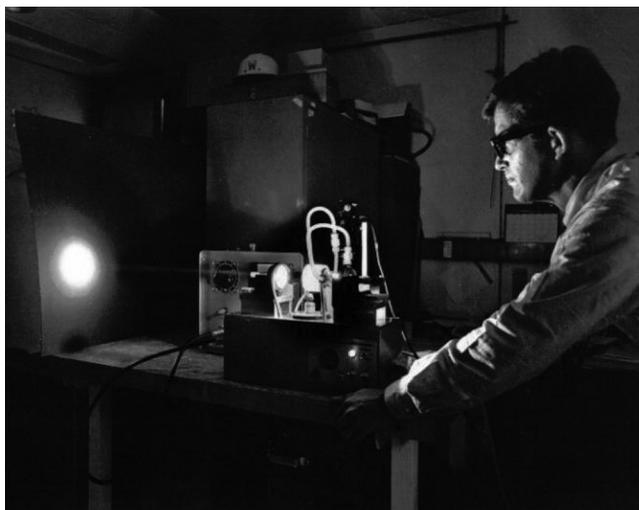
Expecting the dye to emit at a wavelength a little longer than 700 nm, she did not set up a detector, figuring she would be able to see the laser spot on a magnesium oxide block. However she didn't see anything. "I was about eight months pregnant, I had trouble reaching the knobs on the oscilloscope, it was 7 in the evening, and I was very tired," she recalls. Bortfeld told her to go home, while he set up a photodetector and tried again. He called later that evening to tell her it had worked.

In further tests, they changed dye cells and moved their optics and found the oscillation wavelength of one dye changed from 761 to 789 nm when they tried cells from 8 mm to 10 cm long, and mirror spacing from 10 to 40 cm. They sent a paper to *Applied Physics Letters*, which received it 11 July 1966 and published it in the 1 September issue. It was the first report to show that dye laser wavelength could be changed, although it was not yet practical tuning. Spaeth did not get the chance to explore tuning further. Hughes management had no interest in dye lasers, and she had a difficult childbirth, so her immediate priorities became recovering and dealing with two small children.

Fritz Schaefer wrote that his group at the Max Planck Institute in Germany was unaware of either effort when they stumbled upon the dye laser while studying saturation in a different group of organic dyes. A student was testing the effects of increasing the dye concentration by firing ruby pulses into the solution, Schaefer wrote, when "he obtained signals about one thousand times stronger than expected, with instrument-limited risetime[s] that at a first glance were suggestive of a defective cable. Very soon, however, it became clear that this was laser action." They may have learned of Sorokin's work after submitting a paper on their results which *Applied Physics Letters* received on 25 July, two weeks after Spaeth's paper. (After revisions received by APL on 12 September, Schaefer's paper was published in the 15 October 1966 issue, citing Sorokin's paper but not Spaeth's.) Like Spaeth, they reported wavelength changes, in their case arising from changes in dye concentration.

Sorokin soon demonstrated flashlamp pumping, shown in Fig. 1, which proved important because it could pump dyes across a broader range of wavelengths than the ruby laser. In 1967 Bernard Soffer and Bill McFarland at Korad replaced one cavity mirror with an adjustable diffraction grating to make the first continuously tunable dye laser. They tuned across 40 nm and also reduced emission linewidth by a factor of 100. At last, spectroscopists had a broadly tunable laser, and they soon were busy exploring the possibilities.

Triplet-state absorption in the dyes limited pulse duration to nanoseconds in those early pulsed lasers, but in 1969 Ben Snavelly from Eastman Kodak and Schaefer found that adding oxygen to the solvent could quench triplet absorption. Snavelly then teamed with Kodak colleagues Otis Peterson and Sam Tuccio to develop a continuous-wave (CW) dye laser. They first investigated prospects for pumping with intense plasma light sources, then tried pumping with an argon-ion laser. That required longitudinal excitation and liquid flow to keep the dye solution cool, deplete triplet states, and avoid



▲ Fig. 1. Peter Sorokin with the flashlamp-pumped dye laser in 1968. (Courtesy of International Business Machines, © International Business Machines Corporation.)



▲ Fig. 2. Mary Spaeth at Livermore. (Courtesy of Lawrence Livermore National Laboratory.)

thermal lensing. In 1970, they produced CW output of about 30 mW at 597 nm when pumping a dye solution flowing between a pair of dichroic mirrors with a 1-W argon-ion laser.

Further refinements followed. Trying to increase CW dye output by increasing the pump power and focusing it onto a smaller spot tended to burn the coatings off the quartz windows covering the dye. That problem was solved when Peter Runge and R. Rosenberg at Bell Labs developed a way to flow a jet of dye solution through the pump beam in a laser cavity without confining it, so there was no glass or coating to be damaged.

Pulsed dye lasers had launched tunable laser spectroscopy. CW dye lasers and higher powers led to a series of landmark experiments. Conger Gabel and Mike Herscher at Rochester reached tunable single-mode dye power of 250 mW between 520

and 630 nm and used intracavity harmonic generation to produce tunable ultraviolet power of up to 10 mW. Felix Schuda, Herscher, and Carlos Stroud at Rochester stabilized a CW dye laser to 10 to 15 MHz to measure the hyperfine absorption spectrum of the sodium D line, showing that dye lasers could do important experiments in fundamental physics.

Spectroscopy with CW dye lasers advanced rapidly. Two-photon Doppler free spectroscopy with dye lasers, which allows extremely precise wavelength measurement, was developed independently in 1974 by David Pritchard at MIT and by Arthur Schawlow and Theodor Hänsch at Stanford.

CW operation of broadband dyes also opened the way to ultrashort laser pulses. In 1964, Willis Lamb had showed that mode locking could generate extremely short laser pulses with duration limited by the Fourier transform of the laser bandwidth. As long as laser bandwidth was limited, mode locking could not generate very short pulses. However, with suitable optics a CW dye laser could oscillate across most of the dye's emission bandwidth, allowing mode locking to generate ultrashort pulses. In 1972, Erich Ippen and Charles Shank generated 1.5-ps pulses by passive mode locking of a dye laser, and in 1974 they generated subpicosecond pulses with kilowatt peak power. That launched the growth of ultrafast technology, described in a later section by Wayne Knox.

As Schawlow wrote in the speech he gave when receiving the 1981 Nobel Prize in Physics, "spectroscopy with the new [laser] light is illuminating many things we could not even hope to explore previously." One of the amazing things was the small shifts of transition wavelengths between different isotopes of elements such as uranium. Tunable narrow-line dye lasers could resolve those shifts, offering the possibility of selectively exciting the fissionable isotope U-235. As described in another article in this section, the Lawrence Livermore National Laboratory used banks of dye lasers, pumped by large copper-vapor lasers, to enrich both uranium and plutonium. At Livermore, Spaeth (Fig. 2) found support for her interest in dye lasers, and managed development of massive CW dye lasers that generated kilowatts for Livermore's uranium-enrichment demonstrations.

# Remembrances of Spectra-Physics

David Hardwick

It was a cold February morning in Minnesota—really cold! The year was 1963 at the Honeywell Research Center, and the author, only recently graduated from college, helped some visitors bring in their product to demonstrate. Herb Dwight, one of the five founders of Spectra-Physics, and Gene Watson, their star salesman, had stayed overnight in Minneapolis and left their laser in the back of a station wagon. When their Model 110 He–Ne laser was brought into the lab, “steam” was pouring off every surface, befitting the change from below zero to room temperature. The unit was turned on and, miracle of miracles, a sharp red 632.8-nm beam emerged. It does not seem like much now, but the author was blown away—having only too recently tried to build such a laser himself. With the optics of the time and his limited understanding of the process, achieving the necessary alignment proved difficult indeed. And here were these guys, tanned by the California sun and braving the frigid temperatures, showing us pallid northerners in the depth of winter a commercial product that worked.

Some months later, convinced that he wanted to join the world of lasers, the author headed west to join the company. Just before he set out, a call came in requesting that he stop at the JILA lab in Boulder, Colorado, to demonstrate a laser to Dr. John Hall, a future Nobelist. That laser, drop shipped to the author in Denver, did not work. It turned out that the power supply “on” switch was not wired in and the author was too clueless to determine the problem. The next day another laser arrived and was demonstrated to Dr. Hall and his staff, thus completing the author’s first sales call.

Early Spectra-Physics lasers consisted of a tube filled with a He–Ne gas mixture at a pressure of a few Torr placed in an optical cavity with mirrors at either end and a power source, which was radio-frequency (RF) coupled into the gas. Radio-frequency coupling avoided the necessity of placing anodes and cathodes in the tube itself; cathodes available at the time quickly deteriorated, and the tube would go from a healthy pink glow to a sickly blue—death by gas poisoning!

The Model 130 was introduced in 1963, a foot-long ten-pound laser that looked for all the world like a lunch box complete with leather handle. Cost considerations demanded that DC power be used instead of RF coupling. The tube was terminated with optical windows set at Brewster’s angle, and the confocal mirror cavity was protected from the outside world with flexible rubber boots. The problem was the cathodes were “borrowed” from neon sign technology and were designed for use at pressures 10× that of the laser tube. These little metal tubes, terminated with a ceramic disc and filled with some rare-earth oxide mixture, simply did not last very long; the neon was quickly “sputtered” away, and a few-hundred-hour lifetime was considered good. What to do?

The author’s bosses, Arnold Bloom and Earl Bell, asked him to follow up on a paper by Urs Hochuli of the University of Maryland in College Park describing aluminum cathodes for use in He–Ne lasers. This assignment led to the author’s first real project at Spectra. A visit to Hochuli in College Park resulted in Spectra’s machine shop fabricating a few aluminum cathodes, tubes a few inches long and an inch in diameter, allowing some He–Ne tubes to be made. The results were very promising. So promising, in fact, that in a few months, the neon sign cathodes were abandoned and only aluminum cathodes were used. Some 50 years have passed, He–Ne lasers are still being manufactured, and to the author’s knowledge aluminum cathodes remain the standby.

That technology became the Model 130, which had quite a long life as a Spectra product. Early devices delivered about 0.5 mW at 632.8 nm; they cost \$1525, a solid value at the time, although today a laser pointer producing much more power can be purchased for a few dollars. The Model 130 found many applications, ranging from serving as a pointer in Arthur Schawlow's lecture room to guiding a gigantic borer with a ten-foot-diameter cutting face in a tunnel being drilled through a hillside in Llanelli, Wales.

Spectra-Physics was a wonderful place to "grow up" in the laser world. The five founders provided leadership, presented real opportunities to those younger and dumber, and created an enjoyable work environment. As an example, when it came time to crate the hundredth laser for shipment, work was halted, a keg of beer was produced, significant others were invited, and the factory floor witnessed a party celebrating the event. Now, when millions of lasers in thousands of different configurations are produced worldwide, it is fun to remember when coherent light was rare and customers clamored for the first chance to employ it in their experiments.

Spectra-Physics was also a place where the workdays seemed to run on forever—it was the employees' choice to work overtime, not a company demand. The author recalls fiddling in his lab late one night in 1964 when Earl Bell, a company founder, called out and asked him to come next door to his lab. He had a three-meter-long, large-diameter laser tube attached to a vacuum system and fitted with various gas sources. As usual, he was experimenting with different gases to investigate their laser potential. There was a very bright beam coming out of the tube and Earl asked what color it was. The answer was obvious—a very intense green! Earl said, "I thought so but couldn't really tell as I am quite color blind!" Thus the author was the second person, after Earl, to see an ion laser—a mercury-ion laser. The gain was amazing—Earl took a Kennedy half-dollar out of his pocket and held it in the mirror position at the end of the tube, and the laser flickered on and off as he brought the "mirror" into alignment.

After Earl's discovery, Bill Bridges at Hughes built a pulsed argon-ion laser. Earl quickly followed, and soon the continuous wave argon-ion laser, now ubiquitous, came on the scene. Spectra quickly commercialized it with the refrigerator-sized Model 135 argon-ion laser and power supply. Only a few dozen were made; they were RF-coupled, temperamental, and short-lived. The author remembers many miserable days at a Paris university trying to coax usable power out of one of these monsters during the dog days of August 1968, when all the more intelligent Parisians had left town for the seaside.

Spectra-Physics actively sought to sell their lasers in Europe from very early days. They employed a salesman stationed in Switzerland who visited universities and company laboratories, selling many large He-Ne lasers at prices favorable to the company. However, there was a problem: European countries had firm tariff barriers that greatly increased the costs of buying American lasers. The solution was to set up manufacturing inside the tariff borders. When Herb Dwight asked if anyone was interested in setting up such an assembly operation, the author quickly volunteered and, in a couple of months, moved to Scotland with his small family to do so, choosing a site in Glenrothes Fife, just north of Edinburgh. With the help of the Spectra team, friends of Herb at the local Hewlett-Packard factory, Scottish government representatives and a host of others, Spectra's first Scottish-built Model 130 was shipped three months later, in late 1967. During three years based in Scotland, the team demonstrated and sold Spectra lasers throughout Europe, from nearby England to far-off Athens and north to Stockholm. It was a great adventure!

Back to Mountain View, California, and the author had a new assignment to be product manager for the Spectra-Physics Geodolite Laser Distance Rangefinder, working with Ken Ruddock, one of the five company founders. The Geodolite was based on a 25-mW He-Ne laser that was amplitude modulated at five different frequencies while the return from the target was phase-detected. A one-inch telescope broadcast the beam, and an eight-inch Cassegrain telescope gathered the return signal.

The team used the Geodolite for several ground-based and aerial applications, including ice roughness measurement and wave height determination from various air platforms including a Lockheed TriStar, Convair 990, and Douglas DC-3. For the author, it was the travel gig of a lifetime. He was in Barbados with the BOMEX project and a NASA team when Neil Armstrong landed on the moon. Unfortunately, there was no live television feed to the island, so the team listened on the radio and celebrated with the local brew! As an aside, the very next day Thor Heyerdahl pulled into

Bridgetown Harbor after having been rescued from the failed Ra rafting attempt across the Atlantic, and the team was there to greet him. Other remote sites visited with the Geodolite included Ireland, the Shetland Islands, Hawaii, the north slope of Alaska, and Brazil. On the ground, the team used the Geodolite to survey in the primary markers for the Batavia, Illinois, accelerator.

Ken Ruddock was a great director and a lot of fun to work with. The Spectra team was testing the Geodolite in airborne applications using the open cargo bay of a rented DC-3 on a hot day flying over the central California valley. Unfortunately, the plane was owned by a chicken raiser, who used it to ship many thousands of baby chicks from his farm to customers located all over the western United States. These chicks leave a powerful odor, which was endured for many flight hours, but there was compensation: the team was on one of those flights the day Spectra-Physics became a public company. Ken turned to the author and said, "I think I have just become a millionaire!"

The author also worked for Bob Rempel, a founder and our first president. Bob was a Ph.D. physicist by degree but a tinkerer and mechanical engineer in his heart. He had strong ideas as to how products should be built and expected all those in his sway to follow his lead. The author's favorite vignette about Bob was his deep love of the Allen head bolt. Such fasteners were used in every possible configuration in all Spectra products. Of course, to use such a bolt, one needed to have the correct Allen head driver on hand. Somehow they were never at hand, and this dearth of drivers drove Bob up the wall. One day, in a fit of pique, he showed up in the lab areas with many boxes of these small drivers and scattered them loosely over every conceivable work surface. With a satisfied smile, he took his leave, saying as he left, "there, that should fix the problem!"

Life at Spectra-Physics was full, challenging, and instructional. The author worked at one time or another for each of the five founders. Though young and dumb, he was treated as an equal partner and was generously given the right to make mistakes and the encouragement to contribute ideas and energy to build a successful Spectra-Physics. The founders of Spectra-Physics are owed a debt of gratitude that cannot be fully paid off.

# The Birth of the Laser Industry: Overview

Jeff Hecht

Companies large and small began making lasers after Ted Maiman announced the ruby laser. The big companies had large industrial research laboratories and the resources needed to develop a new technology. The little companies, many formed after Maiman's report, had energy, enthusiasm, and flexibility. Both would play important roles in the laser industry.

Money, expertise, and military contracts gave some companies a head start. Hughes Aircraft started with Maiman's design, as well as an Air Force contract to develop laser radars and rangefinders. The much smaller Technical Research Group already had an ARPA contract to develop lasers based on Gordon Gould's patent applications and were the first outside group to replicate Maiman's laser. Bell Labs had a formidable laser research group. Other big companies including American Optical, IBM, General Electric, Raytheon, Varian, and Westinghouse began investigating lasers, with their own funds or with military contracts.

American Optical, Hughes, and Raytheon became important early laser manufacturers, but most other big companies never made many lasers. As part of the AT&T regulated phone monopoly, Bell Labs had to license its patents. GE, IBM, Varian, and Westinghouse focused on other products.

A wave of small companies also set out to build lasers. Maiman left Hughes to found a laser group at a short-lived company called Quantatron in Santa Monica. When Quantatron's backers soured on lasers, Maiman founded Korad Inc. with investment from Union Carbide and key people from Hughes and Quantatron. Lowell Cross, Lee Cross (no relation), and Doug Linn left the University of Michigan's Willow Run Laboratory in 1961 to establish Trion Instruments Inc. in Ann Arbor to build ruby lasers they had developed while at Michigan. Narinder Kapany added lasers to the product line of Optics Technology, which he founded in 1960 to make optical fibers and other optical equipment.

Several books and articles, listed below, tell about the early days of laser development. In the essays that follow, two industry veterans recount their adventures as young men working in the very young laser industry in the early 1960s.

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# Lasers at American Optical and Laser Incorporated

Bill Shiner

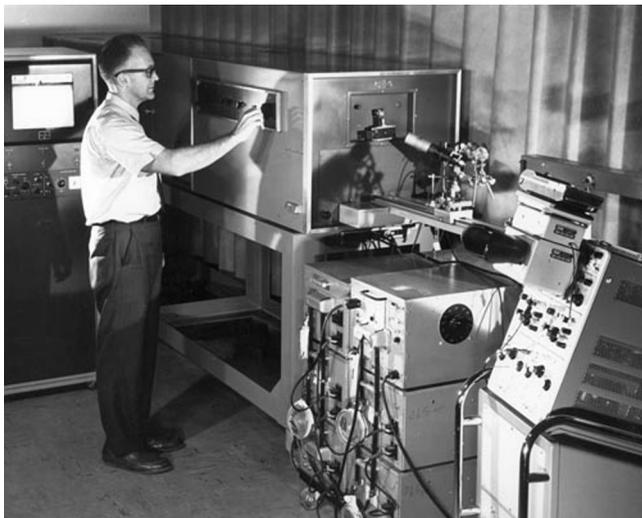
American Optical (AO) entered the laser business early through its interests in optical glass and optical fibers. Elias Snitzer, whom AO had hired to work on fiber optics, made the first glass laser in 1961 by doping glass with neodymium, drawing it into a long, thin rod and cladding the rod with lower-index glass to guide light along the rod by total internal reflection, just as in an optical fiber.

The author started at AO in 1962 as a technician working for the company's chief metallurgist, George Granitsis, who was investigating potential use of lasers for welding. They were in the same building in Southbridge, Massachusetts, as Eli Snitzer, so the author also was assigned the task of testing new laser glasses for Eli. Everyone was excited about lasers, and the author remembers AO putting out a press release touting that the company would become the IBM of the laser industry.

Those were fun days. Glass was easier to make in large rods than other solid-state lasers, so larger and larger powered lasers were made, such as the one Eli is working on in Fig. 1. When Shiner worked in Eli's laser lab, they had two big metal wastebaskets. One said "Eli" and one said "Bill." The flashlamps that pumped the glass lasers sometimes blew up, so when they charged the power supplies for them, they put the wastebaskets over their heads in case the lamp failed. When the lamps exploded, the glass would hit the metal wastebasket. These wastebaskets were also the first form of laser eye protection.

AO made the first Sun-powered laser, using a huge mirror to focus sunlight onto a neodymium-glass rod. AO produced the first laser capable of ranging off the Moon with a group from Harvard University, using a glass laser and an amplifier. The company also had a lot of early military contracts and for a time held the world's record for producing the most energy in a single laser pulse, 5000 J, which was classified at the time. The author's lab had glass lasers that put out 1500 to 3000 J per pulse, and they had to pump the rod with many times that energy, as the efficiency was about 2% wall plug. The resulting heat caused thermal expansion that sometimes blew up the glass rods. They also built the first large glass oscillator-amplifier systems for KMS Fusion and the Lawrence Livermore National Laboratory to use in the first laser fusion experiments back in the late 1960s.

The author also did some early medical laser applications work with Dr. Charles Koester, some of which in retrospect was rather weird. He worked with a doctor at the Delaware Veteran's Hospital who was working on a new procedure to stop ringing in the ear that was plaguing Vietnam veterans. The standard procedure was to drill a hole to the brain with the patient alert and knock out brain audio receivers until the ringing stopped. Many times more brain tissue was destroyed than required. The laser application was to map the cochlea of the inner ear with a fiber laser to knock out the receptors rather than to knock out the receivers in the brain. Monkeys were trained to respond to sound by pulling on a lever when they heard a sound at a certain frequency to avoid receiving a slight shock. This technique thus established a map of the threshold of sound as a function of frequency for the monkey. The side of the monkey's face was shaved, the diaphragm was folded back, and the fiber laser was inserted in the inner ear of the monkey. The procedure was to locate the fiber laser at a precise location and fire it to eliminate a receptor. In the cochlea the receptors are at a precise location as a function of



▲ Fig. 1. Elias Snitzer with glass laser. (Courtesy of the Snitzer family.)

enhance and protect the physical senses: animal groups from all over the country were calling, complaining about the photos showing the author with the poor monkey with a shaved head and distorted face.

AO later bought a small company called Laser Incorporated in Briarcliff Manor, New York, headed by Tom Polanyi, which had developed an industrial carbon dioxide laser. They moved the personnel to Framingham, Massachusetts, and consolidated it with AO's laser group. However, like most other large companies, AO found it hard to make enough money from lasers to generate a profit and decided to close the laser division. At that time in June of 1973 the author was application manager and Albert Battista was engineering manager in the AO Laser Division. The two of them teamed up and purchased the business from AO and renamed it Laser Inc. They did quite well and grew sales to several million dollars, making the company quite profitable. In 1980 they sold Laser Inc. to Coherent, and it became the most profitable division of Coherent for the next three years.

This article was adapted from an interview by Jeff Hecht, 18 May 2012.

frequency. After the procedure the monkey was tested to determine which receptor was eliminated. Many times as the diaphragm was removed to reach the inner ear, the seventh cranial nerve would be damaged, creating distortion of the monkey's face. The experiments went very well and the Veterans hospital called in the press. Photos were taken of the doctor, the monkey, the laser, and the author.

The author was very proud of his contribution to the project; the photos went out over the Associated Press wire. When he came back to AO he was called into the president's office, and the author thought he was going to be congratulated for his contribution. Instead, he almost got fired. The company made eyeglasses, and the company slogan was about products to

# Solid-State Lasers

William Krupke and Robert Byer

16 May 1960 marks the beginning of the laser era, in particular the era of the solid-state laser. On this date Dr. Ted Maiman and his colleagues at the Hughes Research Laboratories in Malibu, California, demonstrated the first ever laser, a ruby laser. The work leading up to this event is described elsewhere in this section, and in more detail in Joan Lisa Bromberg's *The Laser in America, 1950–1970*, published in 1991 [1]. Ruby would be the first in a large family of solid-state lasers.

George F. Smith [2], a Hughes manager at the time, wrote the following: “Maiman felt that a solid state laser offered some advantages: (1) the relatively simple spectroscopy made the analysis tractable, and (2) construction of a practical device should be simple.” Maiman initially considered making a gadolinium laser in a gadolinium salt, but soon turned to synthetic ruby, a form of sapphire ( $\text{Al}_2\text{O}_3$ ) doped with trivalent chromium ions, which he knew from his earlier work on microwave masers.

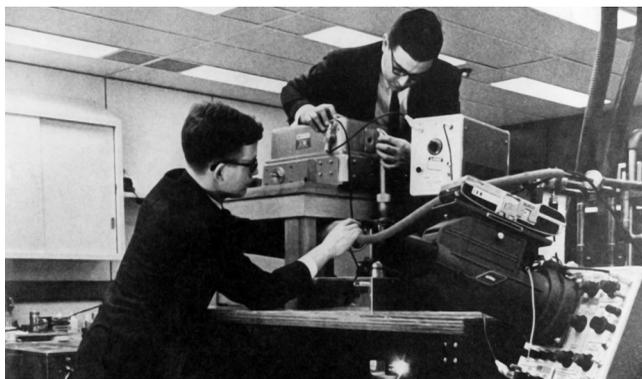
Maiman resolved doubts about ruby's quantum efficiency, but producing a population inversion was a problem because the laser transition terminated in the ground state. When he calculated requirements for laser operation based on gain per pass and mirror reflectivity, Smith wrote, “He concluded that the brightest continuous lamp readily available, a high pressure mercury vapor arc lamp, would be marginal. A pulsed xenon flash lamp, on the other hand, appeared promising.”

Crucially, ruby offered a way to demonstrate the laser principle using commercially available materials, a ruby crystal made for use in precision watches, and a helically coiled flash lamp made for photography. Maiman's success surprised many others working on the laser. Looking back, Arthur L. Schawlow wrote, “I was surprised that lasers were so easy to make. Since they had never been made, it seemed likely that the conditions needed might prove to be very special and difficult to attain. It was also surprising that the earliest laser was so powerful” [3]. He told *Optics News* [4], “I thought if you could get it to work at all it might put out a few microwatts or something like that, and here he was getting kilowatts.”

Schawlow and others had realized the attractions of a solid-state laser, but had focused their attention on continuous-wave (CW) lasers, which consisted of a four-level system, with the lower laser level above the ground state. Maiman showed that pulsed operation could be easier and could produce attractively high instantaneous power. His ruby laser was reproduced within weeks at other labs, and use of his flashlamp-pumping approach quickly led to the demonstration of other solid-state lasers.

Peter P. Sorokin and Mirek Stevenson at IBM had been working on their own approach to solid-state lasers at the IBM Watson Research Laboratory. In Sorokin's words [5]: “The most valuable and stimulating aspect of the Schawlow–Townes article [6] was the derivation of a simple, explicit formula applicable to a general system, showing the minimum rate at which atoms must be supplied to an excited state for coherent generation of light to occur. The formula showed that this rate (actually a measure of the necessary pump power) was inversely proportional to the longest time that fluorescence from the excited state could be contained between the two cavity end mirrors in the parallel-plate geometry proposed by Schawlow and Townes.”

When Sorokin searched for suitable materials, he concentrated on those suitable for four-level laser action. Fluorite ( $\text{CaF}_2$ ) looked attractive as host material because of its optical quality, so he searched the literature for suitable emission lines from ions doped into  $\text{CaF}_2$ . Looking back,



▲ **Fig. 1.** Peter Sorokin and Mirek Stevenson adjust their uranium laser at IBM. (Courtesy of AIP Emilio Segre Visual Archives, Hecht Collection.)

he wrote, “It was strongly felt that a suitable ionic candidate should display luminescence primarily concentrated in a transition terminating on a thermally unoccupied state. It was also felt that there should be broad, strong absorption bands that could be utilized to populate the fluorescing state efficiently with broadband incoherent light. These two requirements generally define a four-level optical pumping scheme.”

His search found spectral data that identified two promising four-level systems in  $\text{CaF}_2$ : trivalent uranium and divalent samarium. He and Stevenson ordered custom-grown crystals of uranium- and

samarium-doped  $\text{CaF}_2$  grown by outside vendors, and started experimenting with them. Then hearing Maiman’s results stimulated a change in course.

Sorokin recalled, “We quickly had  $\text{CaF}_2:\text{U}^{3+}$  and  $\text{CaF}_2:\text{Sm}^{2+}$  samples still in hand fabricated into rods with plane-parallel silvered ends, purchased a xenon flashlamp apparatus, and within a few months’ time successfully demonstrated stimulated emission with both materials. The materials  $\text{CaF}_2:\text{U}^{3+}$  and  $\text{CaF}_2:\text{Sm}^{2+}$  thus became the second and third lasers on record. When cooled to cryogenic temperatures, both systems operated in a striking manner as true four-level lasers. Threshold pumping energies were reduced from that required for ruby by two or three orders of magnitude. Our demonstration of this important feature stimulated subsequent intensive research efforts in several laboratories to find a suitable rare earth ion for four-level laser operation at room temperature.” (See Fig. 1.)

Heavily-doped dark or “red” ruby (as opposed to the “pink” ruby used by Maiman) also has four-level transitions, on satellite lines arising from interactions of chromium atoms. In 1959, Schawlow had recognized the lower levels could be depopulated at cryogenic temperatures, but did not pursue it for a laser at the time. He and others returned to the system, and in February 1961, after the four-level uranium and samarium lasers were reported, Schawlow and G. E. Devlin [7] and, independently, Irwin Wieder and L. R. Sarles [8] reported achieving four-level laser action in the satellite lines of dark ruby at cryogenic temperatures.

The trivalent neodymium ion,  $\text{Nd}^{3+}$ , first demonstrated in late 1961, proved to be the preferred ion for constructing a room temperature four-level laser. L. F. Johnson and K. Nassau at Bell Telephone Laboratories [9] first demonstrated laser emission on that line in a neodymium-doped calcium tungstate crystal. In the same year Elias Snitzer at American Optical Company [10] reported achieving similar room temperature laser action in neodymium-doped glass. Interestingly, Snitzer’s laser was in a glass rod clad with a lower-index glass—a large-core optical fiber—but the importance of that innovation would not be realized for many years. Not until 1964 did J. E. Geusic (Fig. 2) and his colleagues at Bell Laboratories [11] report robust room temperature laser action in neodymium-doped yttrium aluminum garnet (YAG), the crystal destined to be the dominant solid-state laser material for commercial and industrial laser applications to the present time.

Once rare earth ions were identified as a particularly fertile group of materials for near-infrared and visible lasers because of their characteristically narrow-band fluorescence transitions, an explosion of demonstrations of optically pumped solid-state lasers ensued, beginning in 1963. Rare-earth ions included the trivalent thulium, holmium, erbium, praseodymium, ytterbium, europium, terbium, samarium ions, as well as divalent dysprosium and thulium ions; these ions were doped into a variety of crystalline host materials. Z. J. Kiss and R. J. Pressley [12] give an excellent review of solid state laser development up to 1966.

All of the early solid-state lasers described so far have relatively narrowband laser transitions offering very limited spectral tunability. There also was growing interest in developing solid-state

► **Fig. 2.** Joseph Geusic with a solid-state laser and two amplifier stages at Bell Labs. (Reprinted with permission of Alcatel-Lucent USA Inc. Bell Laboratories/Alcatel-Lucent USA Inc., courtesy AIP Emilio Segre Visual Archives, Hecht Collection.)



lasers, preferably four-level lasers operating at room temperature, with broadband laser transitions that would allow wide spectral tunability for scientific and commercial laser applications. The first such solid-state lasers were realized in 1963, when L. F. Johnson, R. E. Dietz, and H. J. Guggenheim [13] of Bell Telephone Laboratories identified divalent nickel, cobalt, and vanadium in magnesium fluoride crystals as four-level laser gain media for widely tunable lasers in the near-infrared spectral range. Peter Moulton details the development of these and later tunable solid state lasers elsewhere in this section.

The five or six years after Maiman’s successful demonstration were immensely fruitful for solid-state and other lasers, recalled Anthony Siegman of Stanford University. “The field was just exploding. And it turns out if you look into it, essentially every major laser that we have today had actually been demonstrated or invented in at least some kind of primitive form by 1966” (OSA Oral History Project, May 2008).

The latter part of the 1960s and the 1970s saw the identification of many new crystalline host materials doped with rare-earth and transition metal ions, described by A. A. Kaminskii [14]. Over the same periods, the most promising of these solid-state lasers were developed technologically and industrialized.

The next seminal advance in the history of solid-state lasers was replacing the pulsed or CW discharge lamps used to pump the first generation of solid state lasers with emerging semiconductor light sources, including light-emitting diodes (LEDs) and later semiconductor laser diodes (LDs). Lamps are inherently broadband pump sources, generally spanning the whole visible spectrum, so they can pump many different materials, but solid-state laser materials have distinct pump bands, so inevitably much of the light would not excite the laser transition. In contrast, LEDs have bandwidths of about 20 nm, and laser diodes of about 2 nm. Adjusting the mixture of elements in a compound semiconductor can shift the peak emission wavelength to match many absorption lines, such as the 808-nm absorption line of neodymium. As long as a suitable pump band is available, this generally increases coupling of pump radiation to the laser gain medium and significantly decreases deposition of waste heat in the gain medium. Generally, diode lasers are preferred for their higher efficiency and output power.

Diode pumping has a long history. In 1964 R. J. Keyes and T. M. Quist [15] reported transversely pumping a  $U^{3+}:\text{CaF}_2$  crystal rod with a pulsed GaAs laser diode, with the entire laser enclosed within a liquid helium-filled dewar. M. Ross [16] was the first to report diode pumping of a Nd:YAG laser in 1968, using a single GaAs diode in a transverse geometry. Reinberg and colleagues at Texas Instruments [17] used a solid-state LED to pump a YAG crystal doped with trivalent ytterbium at cryogenic temperatures.

Early progress in diode laser-pumped solid-state lasers was limited by the need for cryogenic cooling and by the low powers of the diode lasers. It was not until 1972, nearly a decade after the pioneering experiments, that Danielmeyer and Ostermayer [18] demonstrated diode laser pumping of Nd:YAG at room temperature. Room temperature CW operation was first demonstrated in 1976. Powers of diode-pumped solid-state lasers increased with the powers of the pump diodes and with the development of monolithic arrays of phase-locked diodes in 1978.

Initial development of diode-pumped solid-state lasers centered on neodymium because the 808-nm pump line was readily generated by gallium arsenide, the first high-power diode material. Further development of other compound semiconductors in the 900- to 1000-nm band allowed pumping of erbium- and ytterbium-doped lasers.

Development of higher-power diodes also allowed end pumping of optical fibers. Doped with erbium, they became optical amplifiers that powered the boom in long-haul fiber-optic communications. Doped with ytterbium, they became high-power fiber lasers used in a growing range of industrial applications, as described in another chapter.

## References

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# Semiconductor Diode Lasers: Early History

Marshall I. Nathan

In 1958 Arthur Schawlow and Charles Townes [1] published a seminal paper suggesting how to extend maser action to the visible spectrum to make a laser. Only two years later in 1960 Ted Maiman [2] made the first working laser by exciting R-line emission of ruby with a flashlamp. Shortly thereafter Peter Sorokin and Mirek Stevenson [3] reported a four-level laser in uranium-doped calcium fluoride, which had a much lower excitation threshold, and Ali Javan [4] reported the helium-neon gas laser, which used radio frequency (RF) excitation.

All these lasers suffered from inherent shortcomings, they were large, bulky, and very inefficient at transforming excitation energy into coherent light. Overcoming these difficulties would be crucial because most applications of lasers require compact, highly efficient devices.

Semiconductors offered the possibility of high efficiency and compactness, but it was by no means obvious how to make a semiconductor laser. Many people proposed ideas, but there was no experimental work. John von Neumann was the first to suggest light amplification by stimulated emission in a semiconductor in an unpublished paper in 1953 [5], five years before Schawlow and Townes's groundbreaking paper. Von Neumann suggested using a  $p$ - $n$  junction to inject electrons and holes into the same region to achieve stimulated emission, but the scientific community was unaware of his idea. In 1958, months before Schawlow and Townes, Pierre Aigran also proposed stimulated emission from semiconductors in an unpublished talk [6]. At about the same time N. G. Basov, R. M. Vul, and Yu. M. Popov [7] made a similar suggestion. None of these ideas led to any experiments, perhaps because they did not specify what semiconductor or structure or electronic transitions to use.

M. G. Bernard and G. Durafforg [8] then put forth a condition for lasing when electrons dropped from the conduction band to the valence band: the difference between the quasi-Fermi level of electrons in the conduction band,  $E_{Fn}$ , and that of the holes in the valence band,  $E_{Fp}$ , must be greater than the photon energy ( $E_{Fn} - E_{Fp} > h\nu$ ). More to the point, Basov and co-workers [9] suggested that recombining electrons and holes could produce stimulated emission. However, their work attracted little attention because they said nothing about the crucial matter of which semiconductor to use.

W. P. Dumke [10] in early 1962 pointed out that indirect semiconductors such as silicon and germanium would not work as lasers because the gain from conduction to valence band transitions is not sufficient to overcome the loss from free carrier absorption, which is intrinsic to the material. In contrast, the gain for interband transitions in direct materials such as GaAs is large enough to overcome the loss. That prediction has stood up until the present time, notwithstanding the work of Kimerling and co-workers [11] who made a laser in Ge, which was made quasi-direct by stress caused by epitaxial growth on Si.

By far the most influential work leading to the GaAs injection laser was the observation of interband emission from forward biased GaAs  $p$ - $n$  junctions at 900 nm at room temperature and at 840 nm at 77 K. This was first reported at the March 1962 American Physical Society Meeting by J. I. Pankove and M. J. Massoulié [12]. At the same meeting Sumner Mayburg and co-workers [13] presented a post-deadline paper claiming 100% emission efficiency of 840 nm radiation from a  $p$ - $n$  junction at 77 K. However, their evidence was indirect—that the light at 840 nm was visible to the eye, indicating that it was very intense, and its intensity was linear with injection

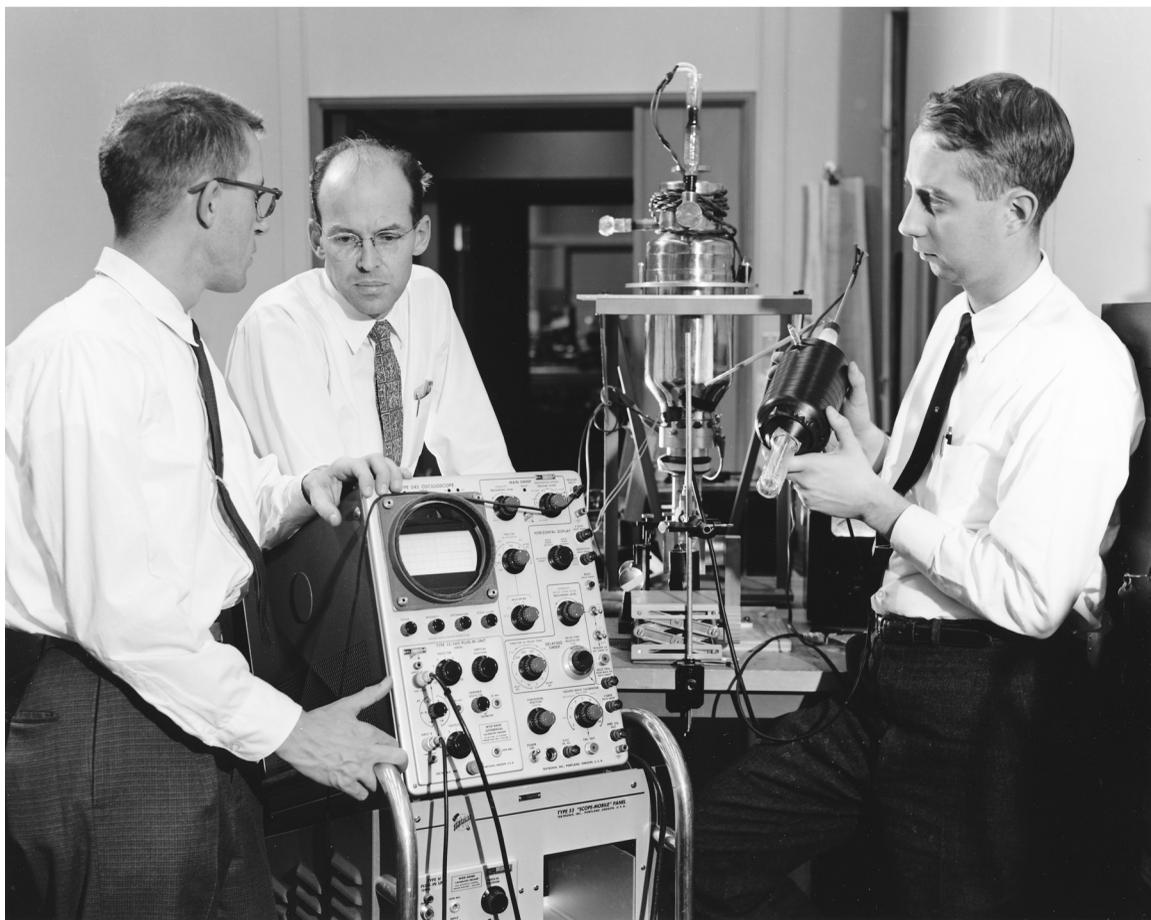


◀ **Fig. 1.** IBM scientists observe electronic characteristics of their new gallium arsenide direct injection laser. From left to right: Gordon J. Lasher, William P. Dumke, Gerald Burns, Marshall I. Nathan, and Frederick H. Dill, Jr. The picture was taken on 1 November 1962. (Courtesy of International Business Machines Corporation, © International Business Machines Corporation.)

current—and less than totally convincing. At about the same time D. N. Nasledov and co-workers [14] in the Soviet Union reported about 20% line narrowing of the radiation from a forward biased GaAs  $p$ - $n$  junction. It was an interesting result but was not stimulated emission.

A few months later in June 1962 R. J. Keyes and T. M. Quist [15] presented direct evidence of the high efficiency of the GaAs  $p$ - $n$  junction light at the Durham, New Hampshire, Device Research Conference. They measured light intensity as a function of current with a calibrated light detector and found near 100% efficiency for the conversion of electrical energy to optical energy. This work got wide attention, with an account published the day after the conference presentation in *The New York Times*. The management at several industrial research laboratories took notice, and activity in GaAs emission increased substantially.

It was barely four months later that laser action in GaAs was reported at four separate laboratories within five weeks of one another. The first two reports were published simultaneously on 1 November 1962. R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson [16] from General Electric in Schenectady, New York, had a received date 11 days before M. I. Nathan, W. P. Dumke, G. Burns, F. H. Dill, Jr., and G. J. Lasher [17] from IBM in Yorktown Heights, New York (see Figs. 1, 2, and 3). The GE paper was more complete in that it demonstrated an actual laser structure, shown in Fig. 1(a) of that paper (not reproduced here). The laser oscillated in the plane of the junction and emitted coherent light from the polished end faces. On the other hand the IBM paper reported line narrowing in an etched diode. One and a half months later two more



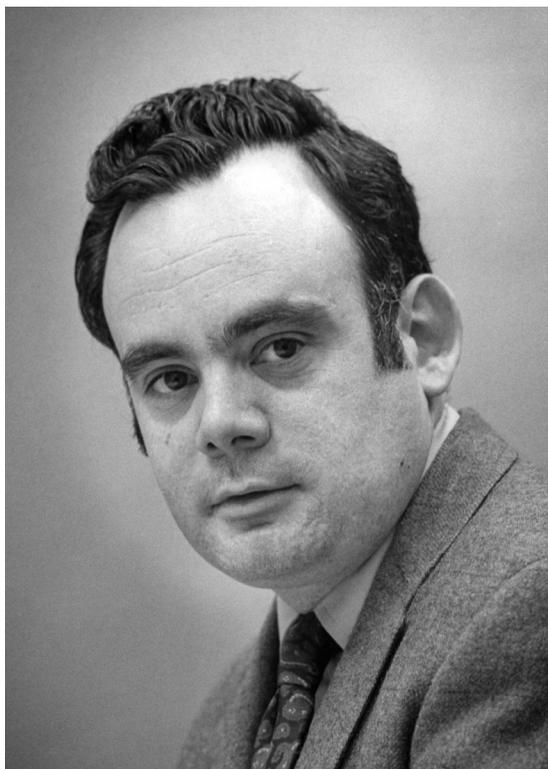
▲ **Fig. 2.** Gunther Fenner, Robert N. Hall, and Jack Kingsley at GE Research & Development Laboratories with the first diode laser, which operated in the dewar that Kingsley is holding. (General Electric Research Laboratories, courtesy AIP Emilio Segre Visual Archives, Hecht Collection.)

papers from different laboratories were published: N. Holonyak, Jr., and S. F. Bevacqua [18] from General Electric in Syracuse, New York, and T. M. Quist, R. H. Rediker, R. J. Keyes, W. E. Krag, B. Lax, A. L. McWhorter, and H. J. Zeiger [19] from Lincoln Laboratory in Lexington, Massachusetts.

All four lasers operated at 77 K in a pulsed mode with a pulse length of about 100 ns and a repetition rate of about 100 Hz, and the emission of three of them was about 840 nm. The GE Syracuse work was different from the others in that the laser light was visible, near 660 nm, and the laser material was a semiconductor alloy, GaPAs. It was remarkable in that the GaPAs material was polycrystalline, but still recombination radiation was so efficient that it lased. The IBM group achieved full-fledged pulsed laser operation at room temperature and continuous operation at 2 K in short order as reported in several papers in the January 1963 issue of the *IBM Journal of Research and Development* [20–26]. A key advance of the IBM group was the first use of cleaved ends of the lasers by R. F. Rutz and F. H. Dill [27]. This greatly simplified the fabrication process.

The publication of the four papers from GE, IBM, and Lincoln Lab launched a tidal wave of research activity on semiconductor lasers. Just about every industrial and government research laboratory and many university laboratories initiated work in the area.

The threshold current density of early semiconductor lasers operating at 77 K was several thousand A/cm<sup>2</sup>. The threshold current was so high that the laser could operate only under short (~100 ns) excitation. When the lasers [28] were cooled to 4.2 K, the threshold went down to less than 100 A/cm<sup>2</sup> and the laser operated continuous wave (CW). As the temperature was increased, the threshold current



▲ Fig. 3. Marshall I. Nathan. (Courtesy AIP Emilio Segre Visual Archives, Physics Today Collection.)

increased rapidly until at room temperature it approached  $10^5 \text{ A/cm}^2$ . Work to reduce the threshold current by improving the geometric structure and the impurity doping profile proceeded. By heroic efforts at heat sinking and optimizing the laser structure limited CW operation was obtained at temperatures as high as 205 K [29]. However, the high threshold and the pulsed operation placed serious limitations on the possible application of semiconductor lasers. Much work needed to be done.

It was clear that poor guiding of the laser light in the active region  $p$ - $n$  junction caused the high threshold. The light was spreading out into the inactive regions of the structure, where it was being lost to diffraction and being reabsorbed. The guiding due to the population inversion was very weak. Manipulating the junction profile improved the situation some, but not enough to get to CW operation at room temperature. Better guiding could be obtained for modes perpendicular to the  $p$ - $n$  junction because of the larger cross-sectional area. However the active region is so thin for this direction of propagation that the overall gain would be very low, and the losses in the unexcited regions of the laser would be very large. At that time a laser of this type was impractical.

In 1963 Herb Kroemer [30] suggested that improved guiding could be obtained by using different materials for the active layer and the adjacent cladding layers, creating heterojunctions on either side of the active layer. This structure came to be known as the double heterojunction laser. If the cladding layers had a lower index of refraction than the active layer, the guiding would be improved substantially. This could be accomplished by using a material with a higher energy gap for the cladding layers since the index decreases with increasing energy gap. This index difference would be much larger, and hence, the wave guiding would be much better in the heterojunctions than in a homojunction. Furthermore, the loss due to re-absorption of the laser light in inactive cladding layers would be reduced because of the higher energy gap in the inactive cladding.

One material choice Kroemer suggested was using Ge, an indirect semiconductor, as the active layer and GaAs in the cladding layers. This is an excellent choice for crystal growth because Ge and GaAs have the same lattice constant. With the direct gap in GaAs only 0.14 eV higher than the indirect gap in Ge, Kroemer hoped the population in the direct gap material would be sufficient to get lasing. This turns out not to be the case, although as mentioned earlier Kimmerling and co-workers [11] made a Ge laser by using growth-induced stress to make the direct gap closer to the indirect gap.

Alferov and R. F. Kazarinov [31,32] in the Soviet Union had similar ideas for heterojunctions. They made lasers with GaAs active regions and GaPAs cladding layers, but the lattice mismatch between the two materials made their lasers polycrystalline so they had high-threshold current densities.

Clearly, what were needed were direct gap materials with sufficiently different energy gaps so as to provide a single crystal heterojunction with good mode guiding for the laser. This came in 1967 from Jerry Woodall and Hans Rupperecht [33] at IBM, who were working on solar cells, where they wanted a large energy gap to let more light into the  $p$ - $n$  junction in smaller-gap material. Using the alloy system AlGaAs, which has a good lattice match to GaAs, they made single-crystal AlGaAs/GaAs heterojunctions. They grew their crystals with liquid phase epitaxy, which had been invented by H. Nelson [34] several years earlier and later became commercially important. They observed efficient electroluminescence. However, they did not apply their technique to lasers.



▲ Fig. 4. Future Nobel Laureate Zhores Alferov (lower right) with colleagues (clockwise) Vladimir I. Koro'kov, Dmitry Z. Garbuzov, Vyacheslev M. Andreev, and Dmitry N. Tret'yakov, the group that made the first CW diode laser. (Zhores I. Alferov, courtesy AIP Emilio Segre Visual Archives, Hecht Collection.)

This was left to H. Kressel and H. Nelson [35], who in 1967 reported an AlGaAs/GaAs single-heterojunction laser (structure shown in Fig. 1(b) from that paper [not reproduced here]) with its active region in the  $p$ -type region of the GaAs. Because of the improved guiding and reduced absorption of the AlGaAs the laser's threshold current density was  $8000 \text{ A/cm}^2$ , a factor of two to three times lower than the best homojunction lasers at the time. Shortly thereafter similar work was done by Hayashi, Panish, Foy, and Sumki [36,37], who obtained a threshold current density as low as  $5000 \text{ A/cm}^2$ . However, these results were not good enough to obtain CW operation at room temperature.

Room-temperature continuous operation would take a further advance, namely, the double-heterojunction laser, shown in Fig. 1(c) from that paper (not reproduced here), in which the large-gap AlGaAs material is on both sides of the junction, providing better mode guiding and reduced loss on both sides of the junction. The heterojunctions also confine the electrons and holes to a thin region, yielding higher gain. The first double-heterojunction lasers were made by Alferov, Andreev, Portnoi, and Trukan [38] in 1968. These lasers had threshold current density as low as  $4300$  but were not yet CW. In 1969 Hayashi, Panish, and Sumski [36] reported the achievement of double-heterostructure AlGaAs/GaAs lasers with a threshold as low as  $2300 \text{ A/cm}^2$  [39] By the following year (1970) they had reduced the threshold down to  $1600 \text{ A/cm}^2$  and obtained CW operation at room temperature [40]. Alferov's group (see Fig. 4) achieved CW room temperature operation at about the same time in a stripe-geometry laser [41].

At this point it was clear that the semiconductor laser was a device with many important applications. Research and development toward this end have continued and expanded since then.

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# Lasers and the Growth of Nonlinear Optics

Jeff Hecht

**N**onlinear optical effects were seen long before the laser was invented. In 1926, Russians Sergey Vavilov and Vadim L. Levishin observed optical saturation of absorption when they focused bright microsecond pulses to power densities of kilowatts per square centimeter. Vavilov introduced the term “nonlinear optics” in 1944, and during World War II Brian O’Brien put saturation to practical use in his Icaroscope to spot Japanese bombers attacking with the sun behind them. The bright coherent light from the laser opened new possibilities.

Peter Franken (Fig. 1) realized them as he sat in packed sessions on lasers at OSA’s spring meeting in early March of 1961. His mind wandered as speakers droned about applications in communications and eye surgery. Seeking something really unusual, he calculated the intensity of a 5-kW laser pulse focused onto a 10- $\mu\text{m}$  spot. His answer was megawatts per square centimeter, with electric fields of 100,000 V/cm—only three or four orders of magnitude below the electric field inside an atom.

“I realized then that you could do something with it,” Franken recalled in a 1985 interview [1]. Further calculations showed the fields should be able to produce detectable amounts of the second harmonic. Excited, he left the meeting and hurried back to the University of Michigan, where he and solid-state physicist Gabriel (Gaby) Weinreich began planning an experiment. He rented a ruby laser from Trion Instruments, a small Ann Arbor company that was the first to manufacture them, and got Wilbur “Pete” Peters to set up a spectrograph and camera for measurements. Weinreich told him to fire the laser into crystalline quartz, which can produce the second harmonic because it lacks a center of inversion.

They needed a long time to get usable results. Alignment requirements were demanding, and harmonic conversion was so inefficient that 3-J, 1-ms pulses containing about  $10^{19}$  photons yielded only about  $10^{11}$  second harmonic photons. Nonetheless, their photographic plate clearly showed the small second harmonic spot. They submitted their paper in mid-July, a little over four months after the meeting, and it appeared in the 15 August *Physical Review Letters*—without the faint second harmonic spot, which an engraver had removed because it looked like a flaw in the photo [2].

Optical harmonic generation experienced a breakthrough in 1961. “At that time, we were all thinking photons, and you can’t change the frequency of a photon,” recalled Franken. But working with Willis Lamb at Oxford University in 1959 had taught Franken that classical electromagnetic wave theory applied to light, so he had realized that nonlinearities might generate optical harmonics. The faint second harmonic spot that never made it into print launched modern nonlinear optics.

Franken’s results caught the eye of Joe Giordmaine, who just two months earlier had begun exploring the effects of ruby laser pulses on various materials at Bell Labs. He began testing Bell’s large stock of crystals left from World War II research and within a few weeks was seeing more harmonic power than Franken had. When he tested crystals of potassium dihydrogen phosphate (KDP) he was surprised to find that second harmonic emission was not just in the direction of the ruby beam, but in a ring centered on a different direction, and that the second harmonic was many times higher at some angles than others. He had discovered the importance of phase

matching the fundamental and second harmonic beams. It did not work in quartz, but it did in birefringent crystals such as KDP. Bob Terhune independently discovered phase matching at the same time at the Ford Motor Co. Research Laboratory.

At Harvard, Nicolaas Bloembergen (Fig. 2) gathered John Armstrong, Peter Pershan, and Jacques Ducuing to work on nonlinear optics after he saw a preprint of Franken's paper. Armstrong and Ducuing began experiments, and all four worked on theory. Bloembergen wrote the differential equations describing harmonic generation, but solving the nonlinear problems posed a formidable task. The group spent several intense and exciting months from July 1961 to early 1962, dividing the task among themselves and working closely with Bloembergen.

The result was a 22-page detailed analysis of light interactions in nonlinear dielectrics, published in *Physical Review* in September 1962 [3]. "It was by no means the last word, but it was a very complete first word," says Armstrong, whose name was first in alphabetical order. The codification of nonlinear interactions including harmonic generation and parametric conversion had a huge impact in the young field.

Meanwhile, experiments with high-power, single-pulse Q-switched ruby lasers at Hughes Aircraft's Aerospace group revealed an unexpected nonlinear anomaly. In early 1962, Eric Woodbury and Won Ng measured output power at several hundred megawatts, far more than expected, when they used a Kerr-cell Q-switch filled with nitrobenzene. Puzzled, they did other experiments, but the light finally dawned when measured power dropped to the expected level after they inserted narrow-pass filters centered on the 694.3- $\mu\text{m}$  ruby line. Further measurements revealed unexpected light on three near-infrared lines, the strongest at 766 nm, a weaker one at 851.5 nm, and a barely detectable line at 961 nm. The increments were roughly equal in frequency units.

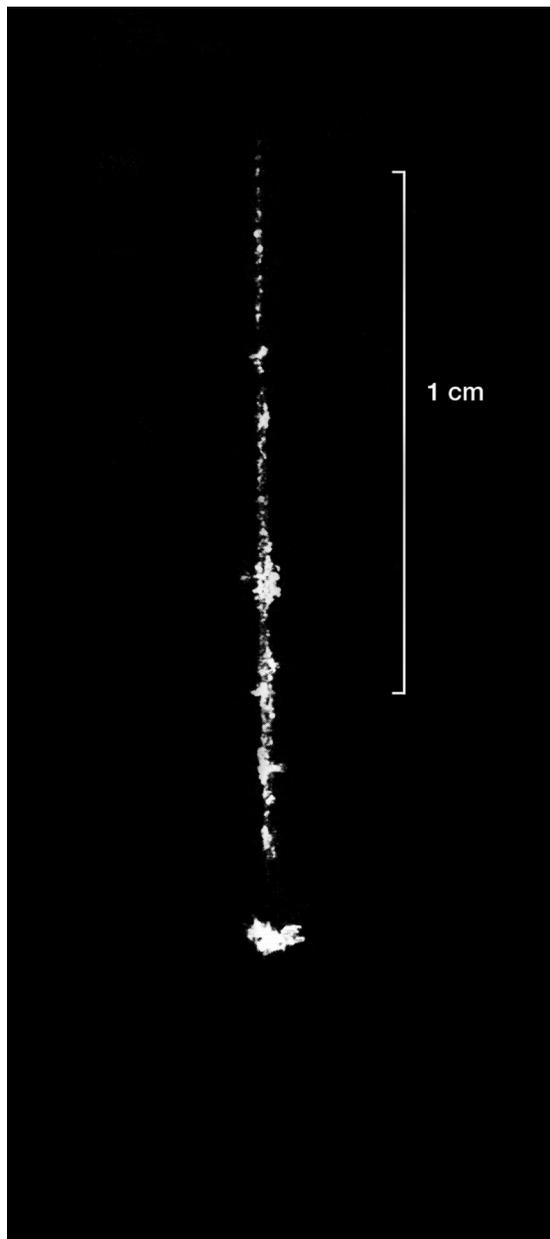
They reported what they thought was a new type of laser action, but it was up to Robert Hellwarth and Gisela Eckhardt of Hughes Research Labs to suggest the infrared lines were coming from stimulated Raman scattering by the nitrobenzene in the Q-switch. Experiments quickly confirmed that, and Hellwarth later developed a full theoretical model. It was a landmark discovery in nonlinear optics, showing that light interacted with molecular vibrations to stimulate scattering at Stokes-shifted wavelengths. Soon afterward, Terhune and Boris Stoicheff separately observed anti-Stokes emission.



▲ Fig. 1. Peter Franken. (OSA Historical Archives.)



▲ Fig. 2. Nicolaas Bloembergen. (Photograph by Norton Hintz, courtesy AIP Emilio Segre Visual Archives, Hintz Collection.)



▲ Fig. 3. Trace of damage caused by a Q-switched ruby laser pulse. (Courtesy of Michael Hercher.)

nearly the same time Giordmaine (Fig. 4) and crystal expert Robert Miller demonstrated one at Bell Labs. Both pumped with the second harmonic of neodymium lasers, with the Moscow lab using KTP and Bell using lithium niobate as the nonlinear crystals. The experiments were difficult, and Bell Labs achieved only 5% conversion efficiency, but output was tunable across 70 nm, an impressive figure in 1965.

Self-focusing led to self-phase modulation. When Kelley and MIT student Ken Gustafson studied shock-wave generation in nonlinear materials, they found a phase shift that depended on the square of the field intensity. They did not make much of it at the time, but in 1967 Fujio Shimizu at the University of Toronto demonstrated that self-phase modulation in liquids could spread the spectral bandwidth of a

Charles Townes, then at MIT, analyzed Stoicheff's results and wondered whether lasers could also stimulate Brillouin scattering. In just two weeks, graduate student Ray Chiao, Townes, and Stoicheff used a ruby laser to demonstrate Brillouin scattering in a solid. Soon another student, Elsa Garmire, demonstrated Brillouin scattering in a liquid. It took years to work out the details, and in 1972 Boris Ya. Zel'dovich—the son of noted Soviet nuclear physicist Yakov B. Zel'dovich—showed that stimulated Brillouin scattering could produce phase conjugation.

Townes suggested another research direction after seeing thin filaments of optical damage in glass exposed to Q-switched megawatt pulses from a ruby laser (see Fig. 3) by Michael Hercher of the University of Rochester. Townes suspected that optical nonlinearities were self-trapping the beam and with Chiao and Garmire described how the intense beam changed the refractive index to create a waveguide. At the MIT Lincoln Laboratory, Paul Kelley developed a theory of self-focusing showing scale lengths and the effects of beam power. Unknown to U.S. researchers, Vladimir Talanov was working on the same idea in the closed Soviet city of Gorky.

Rem V. Khokhlov and Sergey A. Akhmanov founded Russia's first nonlinear optics laboratory at Moscow State University in 1962, but Cold War tensions allowed little communication with American groups. During that year, they proposed a theory to extend parametric oscillation from radio frequencies to light, offering a way to generate tunable output from fixed-wavelength lasers. Khokhlov and Akhmanov's *Problems in Nonlinear Optics* was the first book on the topic when it was published in Russian in 1964, but it did not appear in English until 1972. Bloembergen's *Nonlinear Optics* was published in 1965.

The Moscow lab soon developed efficient ways of generating second, third, fourth, and fifth harmonics. A long series of experiments with Alexander Kovrigin demonstrated an optical parametric oscillator in the spring of 1965, at

► **Fig. 4.** David Kleinman and Joe Giordmaine. (Courtesy of AT&T Archives and History Center.)



pulse [4]. In 1970 Bob Alfano and Stan Shapiro at GTE Laboratories in Bayside, New York, demonstrated more frequency spreading in glass and crystals [5]. The higher the power, the broader the bandwidth, and over the years the effect spread the spectrum enough to make white-light supercontinua.

In 1973, Akira Hasegawa and F. Tappert took another important step, extending the concept of self-trapping to describe optical temporal solitons in optical fibers [6]. Nonlinear phase modulation and dispersion interact such that pulse duration and frequency chirp increase and decrease cyclically along the length of the fiber, periodically reconstructing the original pulse. Hasegawa, Linn Mollenauer, and others later showed that solitons could transmit signals through optical fibers.

Modern nonlinear optics has come a long way from its roots, yet the fundamental groundwork remains solid. “To this day, every time I make a discovery in nonlinear optics, I look at [Bloembergen’s] paper and he’s done it,” says Robert Boyd of Rochester. “He put the whole field together in 18 months.” That feat earned Bloembergen the 1981 Nobel Prize in Physics.

Nonlinear optics is used in consumer products. Second harmonic generation turns the invisible 1.06- $\mu\text{m}$  line of neodymium into a bright 532-nm green beam. “It’s hard to believe you can buy these things. If you think of what’s inside, it’s just amazing,” says Garmire. Harmonic generation also finds cutting-edge laboratory applications, generating pulses of attosecond duration or with wavelengths in the extreme ultraviolet or x-ray bands. Self-phase modulation together with mode locking produces femtosecond pulses and frequency combs. The more we try to do with optics, the more we have to think about nonlinearities. Like the laser that was essential to its birth and its applications, nonlinear optics seems to be everywhere.

Note: This chapter was adapted from [7].

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# Early Years of Holography

Jeff Hecht

The idea of holography came to Dennis Gabor while he was waiting for a tennis court on Easter Day in 1947. Born in Hungary in 1900, Gabor had earned a Ph.D. in electrical engineering from the Technical University of Berlin, then moved to Britain when Hitler came to power. In 1947, he was working at the British Thoms-Houston Company in Rugby and wondering how to improve the resolution of electron microscopes.

Waiting for his tennis match, he wondered how to overcome the imperfections in electron optics that limited resolution. “Why not take a bad electron picture, but one that contains the whole information, and correct it by optical means?” he recalled later. He first thought of illuminating an object with coherent electrons, so interference between electrons scattered from the object and those not deflected would record the phase and intensity of the wavefront. If he recorded the interference pattern and illuminated it with coherent light, he thought he could reconstruct the electron wavefront and generate a high-resolution image.

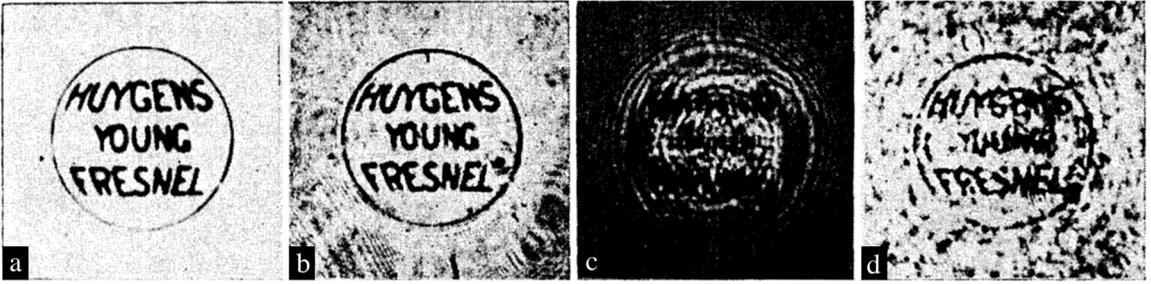
Lacking a way to record electron interference patterns, Gabor tried using light as a model, although he had not worked with optics before. The best available coherent source at the time was a high-pressure mercury lamp, but its coherence length was only 0.1 mm, and filtering it through a pinhole left only enough light to make 1-cm holograms of 1-mm transparencies. Nonetheless, he made recognizable holographic images in 1948 (Fig. 1), a dozen years before Theodore Maiman made the first laser.

Gabor’s report in *Nature* in 1948 [1] raised the possibility of three-dimensional (3D) imaging, generating considerable attention, and helped him land a professorship at Imperial College in London; but progress was slow, his design generated twin overlapping images, and the short coherence lengths of available light sources limited imaging to small transparencies. By the mid-1950s, Gabor and most others had largely abandoned holography.

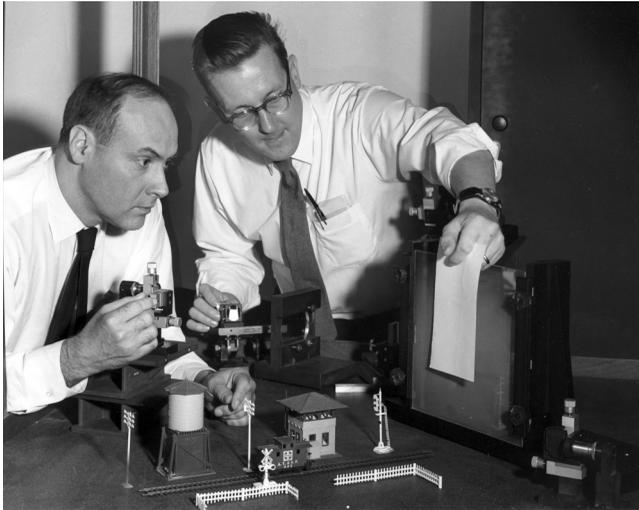
The revival of holography grew from a completely independent direction: classified military research on synthetic aperture radar launched in 1953 at the University of Michigan’s Willow Run Laboratory. The following year, a young engineer named Emmett Leith who had studied optics at Wayne State University began developing an optical system to perform Fourier transforms of radar data collected by flying over the target terrain. He and Wendell Blikken started with incoherent optics, but Leith later said many of their problems “just melted away” when they considered coherent light in 1955. They did not need much coherence and they eventually found that focusing all the light from a point source onto another point would suffice for radar processing.

In September 1955, Leith realized that the light waves diffracted from the data record were replicas of the original radar signals converted to optical wavelengths. That led him to a theory that mirrored Gabor’s wavefront-reconstruction holography but shrank the radio waves to optical wavelengths rather than stretching electron waves to optical lengths. He knew nothing about other research in holography until a year later, when he discovered a paper by Paul Kirkpatrick and Hussein M. A. El-Sum in the *Journal of The Optical Society of America* (JOSA) [2].

Holography intrigued Leith, but the radar project kept him too busy to experiment until 1960, when Willow Run hired Juris Upatnieks as a research assistant in the optics group. Born in Latvia in 1936, Upatnieks fled with his family when Soviet troops occupied Latvia in 1944. They spent years as refugees in Germany before moving to the U.S. in 1951. He had a fresh degree in electrical engineering from the University of Akron (Ohio) but lacked a security clearance, so he could not work on the radar project.



▲ Fig. 1. Dennis Gabor's first hologram. (Reprinted by permission from Macmillan Publishers Ltd.: *Nature* © 1948.)



▲ Fig. 2. Emmett Leith and Juris Upatnieks in 1965. (Courtesy of Juris Upatnieks.)

Leith put Upatnieks to work making Gabor-style holograms while they waited for his clearance. Despite lacking optics experience, Upatnieks succeeded. The reconstructed images were fascinating but had the same twin-image problem as Gabor's.

However, Leith's theory of holography offered a crucial insight because it described a signal modulating a carrier wave, which produces sidebands at the sum and difference frequencies, above and below the carrier frequency. Leith realized that Gabor's twin images were the two sidebands. Eliminating one of them should leave a single clear image. (Figure 2 shows them with their holographic setup.)

Leith suggested separating the object and reference beams so that they reached

the photographic plate at different angles. However, that proved hard until they used a diffraction grating to split light from a mercury-vapor lamp into different diffraction orders, and using one as the reference beam and the other as the object beam. That yielded the first off-axis holograms, and Upatnieks's experiments confirmed Leith's theory. Leith described the results at OSA's October 1961 meeting in Los Angeles and submitted a paper to *JOSA* [3].

By then, the military had called Upatnieks to fulfill his obligations from ROTC in college. When he returned to Willow Run in November 1962, he started a new round of holography experiments with a mercury lamp, but an early commercial helium-neon laser was sitting temptingly in a nearby laboratory where Anthony VanderLugt was using it in image-recognition experiments. Inevitably, as Upatnieks says, "We kind of talked him into letting us borrow his beam. We put a mirror in his room, and bounced the beam off to our setup."

Based on a standard optical bench, their new setup expanded the laser beam and split it by passing it through a wedge prism. Recording good holograms required extra-flat glass plates that Kodak had developed for spectroscopy. Exposure was very slow, so the laser's higher intensity was a big advantage. Leith and Upatnieks reported a dramatic improvement in hologram quality at the March 1963 OSA meeting in Jacksonville and in a paper in the December 1963 issue of *JOSA* [4]. The holographic reconstruction of a 1.5-cm slide in the published version is hard to tell from the original. Holographic reconstructions of slides of a child in an outdoor scene and an adult portrait are speckled but clear.

Lasers brought speckle to holography, but their higher power and longer coherence length made experiments easier. More important in the long run, laser coherence allowed fully 3D holography of

opaque objects. Leith and Upatnieks spent a couple of days trying 3D holography in July 1963 but failed and turned to other work.

They returned to 3D holography after the JOSA paper came out and reporters asked Leith what might come next. “He offhand mentioned that 3D objects could be recorded and they would be three dimensional, and no one believed it,” Upatnieks recalled. “Since Emmett said it would be done, we had to show it,” and they went back to 3D holography.

They faced tough technical problems such as isolating their holographic setup from wavelength-scale vibrations. Moving to a massive granite optical bench improved image clarity, but the 3D images did not seem dramatic until Leith and Upatnieks started using objects a few inches across, large enough for the eye to see as three dimensional. Holograms recorded on 4- by 5-in. plates were “incredible, just totally incredible, the one thing that excited us most,” Leith recalled.

Their first image was a pile of loose objects they obtained from the laboratory; it looked like a pile of junk, interesting only because it was a hologram. As they refined their technique, they found an iconic object that made a striking hologram—an HO-gauge toy train engine that they filled with epoxy and glued to the tracks to stabilize it (Fig. 3). They recorded two holograms on the same photographic plate mounted at different angles, then reconstructed the two images separately without crosstalk by illuminating the plate at the proper angles.

Visitors streamed through the lab to see the holograms, but the floodgates opened in April at OSA’s 1964 spring meeting. Upatnieks presented a 15-minute paper on Friday afternoon, the last day of the meeting, titled “Lensless, three-dimensional photography by wavefront reconstruction,” but the talk could not match a demonstration. Attendees lined up in the hall to see a He-Ne laser illuminate a hologram in a hotel suite rented by Spectra-Physics. They stood and studied the holographic toy train floating in space, then looked around to find the hidden projector that was fooling them. Leith called that “the high point in the dissemination of holography” [5].

The optics world was enchanted by holography, and specialists hurried home to try to make their own holograms. Most failed on their first attempts and called Leith and Upatnieks for help. “Those calls kept us quite busy for a while, but that was how holography took off,” Leith recalled.

Enthusiasm spread fast, as it had for the laser. It was a boom time for technology, and, like the ruby laser, holography could be duplicated in a well-equipped optics lab. Could holography be the problem that the laser was searching to solve?

It took time to assimilate the concept. The first issue of *Laser Focus* in January 1965 called it “3-D lasography” [6]. Others called it lensless photography or wavefront reconstruction. *Scientific American* called its June 1965 article “Photography by laser” and showed two holographic chess pieces on the cover [7]. Leith and Upatnieks used Gabor’s term, hologram. By any name, holography had potential. Its images shimmering in mid-air looked so real that people reached out to touch them.

Among the burst of innovations in the holographic boom was the rediscovery of reflection holography invented by Yuri Denisjuk at the Vavilov State Optical Institute in the Soviet Union. Instead of directing the object and reference beams onto the same side of the photographic plate, Denisjuk illuminated the object *through* the plate, with the reflected object light interfering with the reference beam in the plane of the plate. He demonstrated the technique with mercury lamps; but his experiments ended in 1961, and his two papers published in Russian in 1962 were ignored until three American labs stumbled upon the effect independently in 1965. Importantly, Denisjuk reflection holograms can be viewed in white light.



▲ Fig. 3. Iconic photo of holographic toy train. (Courtesy of Juris Upatnieks.)



▲ Fig. 4. “Mini Kiss II”: Pam Brazier in holographic stereogram. (Courtesy of MIT Museum. Mini Kiss II, Lloyd G. Cross, 1975. <http://web.museum.mit.edu/imagerequest.php?imageidnumberMOH-1978.52.01> [all three views].)

Another major imaging advance came was the invention of “rainbow” holograms by Steve Benton at Polaroid in 1969. Seeking to make brighter images, he produced reflection holograms that displayed depth only in the horizontal plane, the only one in which our eyes see parallax. This allows the hologram to diffract the whole visible spectrum, spread across a range of angles to produce a rainbow of colors. Easily visible under normal lighting, such holograms can be embossed onto metal films and they have become the most widely used holograms.

In the early 1970s in San Francisco, Lloyd Cross developed a variation on rainbow holography that offered an illusion of motion. He produced the holograms in a two-stage process. First, he took conventional photographic transparencies as he moved around a person or object, and then he recorded rainbow holograms of the series of transparencies as successive narrow stripes on film. Finally, the film was mounted in a 120-deg arc or a 360-deg cylinder.

The viewer’s eyes saw different frames, giving the parallax that the brain interprets as depth. If the model moved between frames, a viewer saw the movement while moving around the curved hologram. Cross formed a company called Multiplex to make the holograms; the best known one shows Pam Brazier blowing a kiss to the viewer (Fig. 4).

In October 1971, when the holographic imaging boom was in full flower, Dennis Gabor received the Nobel Prize for “his invention and development of the holographic method.” Many in the optics community felt that Leith and Upatnieks should have shared the prize for reviving holography with lasers and their solution of the twin image problem.

In his book *Holographic Visions* [8], science historian Sean Johnston blames George W. Stroke, who in 1963 started a holography program on the Michigan campus that came to compete with Leith’s work at Willow Run. Stroke eventually left Michigan carrying a grudge and claiming that his work was more important. This was long a common view in the optics community.

However, in her dissertation on the history of holography written at Cambridge University [9], holographer Susan Gamble argues that the problem was that Leith and Upatnieks worked at a military lab. Michigan students had protested Willow Run’s military projects, and in 1971 opposition to the Vietnam War was widespread in Europe. The Nobel committee may well have decided that awarding a Nobel Prize for military work would send the world the wrong message.

If some optical Rip Van Winkle from 1970 woke up today after his long nap, he might ask, “Whatever happened to holography?” Holographic imaging never came to movies or television, and the “holographic telepresence” of convention speakers is based on the old “Pepper’s Ghost” illusion rather than real holograms. Yet holographic displays have found some specialized niches. Furthermore, holograms are used in industry in many ways that go unrecognized, such as holographic optics, and security imprints on packaging and some currencies. We may never watch wide-screen movies in glorious holo-vision, but who would have expected us to be carrying holograms in our pockets on credit cards?

Note: This chapter is adapted from [10].

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# History of Laser Materials Processing

David A. Belforte

In the 100 years of OSA, laser technology has played a part for more than 50 years and industrial laser materials processing has played a part for more than 40 years. This capsule view presents the highlights of these years.

Prior to 1970, a handful of commercial laser suppliers, located mostly in the United States, attempted to satisfy requests from a number of industrial manufacturers that showed an interest in the possibility of a laser materials processing solution to a unique production problem. A 1966 publication stated, “This year will mark the beginning of an accelerated growth for lasers. Many of the early problems involved in their use are nearing solution. In the commercial markets, the applications will center on welding and other high-power CO<sub>2</sub> and neodymium YAG (yttrium aluminum garnet) lasers . . .” [1]. Interestingly, this otherwise optimistic report ended with the statement, “The markets for lasers will gradually develop over the next few years, but they are not nearly as imminent or as large as is frequently quoted.”

One reason behind this disparity may be found in the premise that the laser was “born fully grown,” a view held by many who read about the amazing possibilities for this powerful energy source, as evidenced by the commonly quoted line that “lasers are a solution looking for a problem” [2]. Industrial manufacturers that approached these scientific laser companies were from many different industries: glass, with interest in cutting flat plate glass [3]; mining, with interest in rock drilling [4]; packaging, with interest in cutting steel rule dies [5]; aircraft engines, with interest in processing turbine engine components [6]; sheet metal cutting [7]; paper, for cutting and slitting paper [8]; and microelectronics, with accelerating interest in trimming resistors and printed circuits [9] and cutting/scribing ceramic substrates [10]. Of these, only the latter two advanced to widespread industrial utilization stages in the late 1960s, pushed by soaring growth in the microelectronics industry. The others, all technically good applications, languished for a few years, fulfilling the prophecy cited above, as the laser suppliers struggled to develop devices with more power or better beam quality with improved reliability and maintenance procedures.

The most economically successful applications drawing attention from a wide segment of the world’s media were the use of a CO<sub>2</sub> laser beam to cut woven fabric for made-to-order men’s suits [11] and the use of a pulsed ruby laser beam to drill holes in diamond dies used as wire drawing dies [12]. The latter was the first industrial laser processing machine to be exhibited in the Smithsonian Museum in Washington, D.C.

While technical and economic cases can be built to explain the slow commercial success of the laser as a manufacturing process tool, widespread implementation of laser processes was inhibited to a degree by published articles. These articles were headlined, for example, “Death rays benefit mankind,” a phrase that can be attributed to a number of journalists searching for attention-grabbing headlines in the early 1970s. Implementation was also stalled because of the unfortunate labeling, by engineering societies and the U.S. government, of laser processing systems as a nonconventional materials processing technology.

One anecdote that illustrates the former is this author’s personal experience. While negotiating the purchase of a high-power CO<sub>2</sub> laser welding machine by a Fortune 500 company, he was startled to hear a company official sanction the purchase because he was impressed by successful laser cataract surgery performed on his brother-in-law.

Thus, the industrial laser suppliers of the early 1970s were faced with an additional selling burden, easing the concerns of uninformed, risk-wary buyers, and reassuring potential buyers that their lasers were reliable and safe. A common selling tactic was to identify a laser “champion” as the potential customer and to educate this person to be an inside sales advocate. Many of these champions became laser industry advocates through their willingness to publish complimentary articles.

Overcoming the nonconventional tag took many years [13], and it was not until the late 1980s that this sobriquet was dropped by those charged with producing industry statistics. The 1970s, a period that saw the blooming of several industrial laser suppliers, is considered by most analysts to be the beginning of the industrial laser market, with annual revenues for laser sales ramping from \$2 million to \$20 million in the first decade of the market, an almost 26% compound annual growth rate (CAGR). Several applications drove this growth: thin gauge sheet metal cutting [14], microelectronic package sealing [15], cooling hole drilling in aircraft turbine engine blades and vanes [16], steel-rule die board cutting [17], and semiconductor wafer dicing [18]—all applications that continue successfully today.

An interesting footnote to the early beginnings of the industrial laser material processing era is that these applications, and many that rose to prominence later, were accomplished using lasers that can best be called “industrialized scientific lasers,” which were controlled by analog programmable controllers or tape reader numerical control (NC) devices. MIT scientists developed numerical control for machining in the 1970s, and it became commonly used in the 1980s. This technology was a major contributor to the growth of lasers for industrial material processing applications. The evolution to computer numerical control (CNC) [19] and the industrial development of minicomputers in the 1980s and the microprocessor in the 1990s vaulted the industrial use of lasers to annual growth rates in the mid-teens.

Through the 1980s and 1990s, solid-state lasers led by Nd:YAG devices and ultra-reliable low-power, sealed-off CO<sub>2</sub> units remained the backbone of the industrial laser materials processing industry. On a smaller scale, excimer lasers were used mostly in semiconductor processing [20] and metal [21] and non-metal applications in the manufacture of medical devices. These lasers had evolved from the scientific designs of the 1970s into ruggedized, reliable, low-maintenance products that were being integrated by system manufacturers into material processing products acceptable to a broad range of global consumer product manufacturing companies.

The utilization of industrial lasers, very much advanced in the U.S. in the first two decades of the technology, was due in great part to the marketing prowess of domestic equipment suppliers. This is counter to some international views, mainly in Europe, that the U.S. government, through the Department of Defense (DOD), funded the development of the laser products that were being used in commercial industrial applications. In reality, the industrial laser and systems suppliers of the 1970s and 1980s were essentially a part of a bootstrap industry, self-funded in terms of equipment and applications development. What little funding flowed from the U.S. government through its DOD Manufacturing Technology programs was focused on laser applications that could improve or repair defense products. In part, this lack of a national initiative to support progress in manufacturing stultified the growth of the industrial laser economy.

Stepping into the void left by this modest industrial laser program, the government of Japan in the 1980s and Germany (supported in part by the European Union) undertook university-based efforts to understand and improve the laser beam/material interaction on a broad range of materials. In Japan, most of the effort focused on defining and improving the process of laser cutting sheet metals [22], specifically stainless steel, at that time a major industry in that country. As a result, increased output power from new types of CO<sub>2</sub> lasers, improved gas-assist nozzle signs, and purpose-built cutting systems entered the market from a number of suppliers, first in Japan to a large number of custom cutting job shops and then exported to the international markets. In addition to this effort, the Japanese government funded a major program for flexible manufacturing, which had as a part the development of a very-high-power CO<sub>2</sub> laser that vaulted the selected supplier to the top of the CO<sub>2</sub> power chain.

In the late 1980s, almost concurrent with the laser cutting development in Japan, European CO<sub>2</sub> laser suppliers [23] made efforts to expand their markets by improving their product lines. This

spawned the development of RF excited high-power CO<sub>2</sub> lasers and the consequent alliances with system integrators while educating the market about laser technology. In several countries, a “make it with lasers” program found eager interest among manufacturers. In Germany, the federal and state governments funded programs to improve the process of laser cutting, and one effort was designed to improve the manufacturing capability of small- to medium-sized manufacturers so they could become global competitors. As a consequence, the technology of laser material processing became familiar to manufacturers [24], paving the way for future employment of these processes in their manufacturing operations. European industry became “laser aware,” a situation that prompted the government to heavily sponsor laser and applications development, which has led Europe to become the major center of industrial laser and material processing and development today.

The late 1980s and the 1990s have been judged as the “golden” years of industrial laser materials processing. Abundant, pertinent, and beneficial development of laser applications, and the lasers and systems to achieve the processes, occurred during this period, led by institutions such as the various Fraunhofers [25] that built upon the basic understandings necessary to expand the use of these processes throughout the manufacturing world. As a consequence, industrial laser sales grew by more than a factor of eight in the period from 1985 to 1999. Driving market growth were global industries such as automotive, aerospace, agriculture, and shipbuilding for high-power lasers, and semiconductor, microelectronics, and medical devices for low-power units. The lasers being used remained those that had been introduced in the 1970s: Nd:YAG lamp and diode pumped at both the fundamental and the frequency-shifted wavelengths, CO<sub>2</sub> with output power up to 8 kW, and excimer that had a major redesign into more reliable products.

The turn of the century marked the thirtieth year for industrial laser materials processing, and the total industrial laser system market was then approaching \$3 billion and laser sales were almost \$1 billion, both experiencing a 23% CAGR [26]. The technology of laser applications was centered in Europe as was much of high-power laser development, while the U.S. retained leadership in the solid-state laser and microprocessing sectors and Japan, as a consequence of national economic conditions, slipped from a leadership role in the industrial laser market.

At this point, laser materials processing had become accepted by mainstream global manufacturing industries and the technology no longer was classified as unconventional machining, perhaps due in part to the fact that in 2000, laser machines represented about 10% of the total machine tools sold globally.

In the first decade of the new century, industrial laser growth showed a dramatic increase until the great recession of 2008/2009. After this major setback, the industry rebounded to prerecession levels, rapidly led by surging sales of high-power fiber lasers that were replacing high-power CO<sub>2</sub> lasers in sheet metal cutting applications. The rise of fiber lasers in this decade as replacements for other lasers used in established applications was the first major shift in the types of industrial lasers selected to satisfy industrial market demands. Low-power fiber lasers replaced solid-state lasers for marking and engraving applications, substituting for diode-pumped rod type devices in this market that installs more than 20,000 units per year. In 2012, fiber lasers represented 27% of the laser materials processing systems installed [26].

Also appearing in this period were high-power direct diode lasers with improved beam quality that increased the market for this efficient compact laser. Although output power for these focused beam devices had yet to reach the multikilowatt level, these lasers created interest among the many cutting system suppliers that had already converted to high-power fiber lasers.

As this is being written, the market for industrial lasers for material processing is well on the way to breaking the \$10 billion/year mark. In 2012, 50% of the world market for industrial lasers was in Asia. Major markets have been established in China and Southeast Asia, and looming on the horizon are markets in South America, Russia, and India, which are expected to add to growth opportunities for industrial lasers.

Further, a new generation of laser and system suppliers is appearing in Asia with companies first serving domestic needs but eventually entering the global markets, establishing competition for the old line sellers that have dominated the market for decades.

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## Brief History of Barcode Scanning

Jay Eastman

### Introduction

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It is not an overstatement to say that barcodes are nearly everywhere you look—virtually every product you purchase at a supermarket, hardware store, liquor store, book store, or elsewhere carries a universal product code (UPC) barcode printed on the package or an attached label. Most package delivery services, including Federal Express, UPS, and the United States Postal Service, use barcodes on packages for tracking purposes. As a consequence we can track whether the book we ordered from Amazon has shipped, and at any time we please, know where our book is on the route from Amazon to our front door.

Barcode scanners are equally ubiquitous. Scanners are at most check-out counters where we shop. Some of us even carry a barcode scanner with us wherever we go—in the form of an app on our smartphone. One smartphone app can build a grocery shopping list by simply scanning barcodes on empty packages before they go into the recycling bin.

This article provides an illustrated overview of the history of barcode scanning, beginning with the development of the various barcode symbologies, and following through the development of the scanning devices used to read the barcodes. Since the barcode industry has been very competitive, little information was published in technical journals. Inventions were either patented or treated as trade secrets. This article will illustrate the history of barcode scanning based on key patents issued in the field. Figure 1 illustrates by year the number of patents issued that include either of the terms “barcode” or “bar code.” Issued barcode patents rose from a trickle in the early 1980s to a high of 265 patents in 2003.

### Barcode Symbologies

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The first mention of encoding information into printed dark bars and white spaces was disclosed in U.S. patent 1,985,035 submitted by Kermode, Young, and Sparks in 1930. The patent was ultimately issued on 18 December 1934 and assigned to Westinghouse. The invention described a card sorting system for organizing electric bill payments by geographic region, thus simplifying the work of accurately tabulating customer payments.

The first true barcode was a circular “bullseye” symbol invented by Silver and Woodland (see Fig. 2). The two disclosed their invention to the U.S. Patent Office in 1949 and their patent, numbered 2,612,994, was issued on 7 October 1952. The patent contained claims covering a circular bullseye symbol on an item and an apparatus to read the symbol.

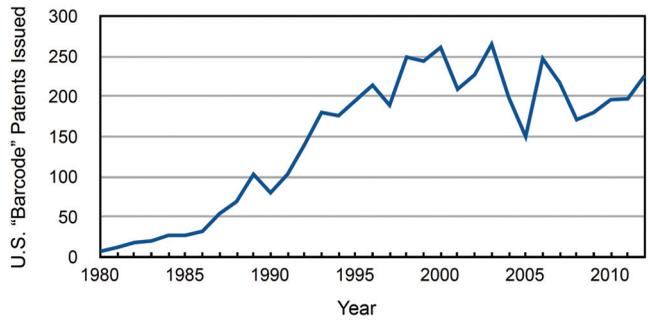
In the late 1960s a group of supermarket chains began to realize efficiencies could be gained with a more automated checkout process. Several checkout methodologies were formulated and subsequently studied resulting in a recommendation to adopt an 11-digit product identification code. This effort ultimately resulted in the formation of the UPC Symbology Committee in March 1971. The committee was charged with selecting a symbology concept and providing a detailed specification for the selected symbology. The Symbology Committee also worked with suppliers of optical readers for the selected symbology.

The symbol ultimately adopted was the UPC symbol found on most products today, as shown in Fig. 3. In the U.S. the leading digits of a symbol, which identify a manufacturer, are

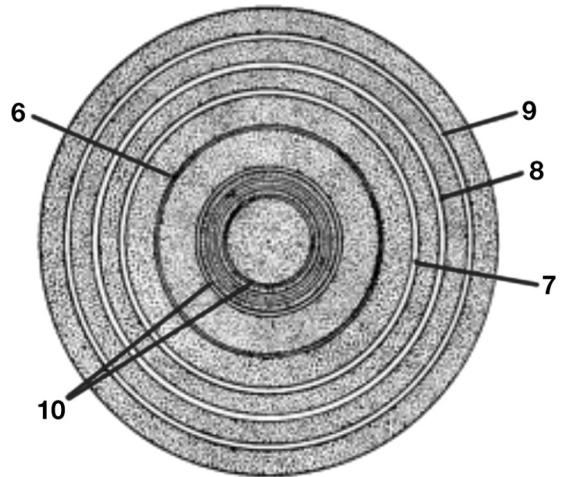
licensed by GS1 US, a private firm responsible for maintaining the assignment of manufacturers' identification numbers. The following five digits are assigned by a manufacturer for each product it produces. The final check sum digit is used to ensure the data integrity of the scanning and decoding processes.

Numerous other symbologies have been developed over the years for other applications ranging from inventory control through military logistics to package tracking by delivery companies. Some of these, such as Code 3 of 9 (aka Code 39) and Interleaved 2 of 5, are purely numeric codes. Others, such as Code 93 and Code 128, are full alphanumeric codes. Examples of these one-dimensional (1D) symbologies are illustrated in Fig. 4.

The need for labels containing ever-increasing amounts of data led to the development of stacked codes and two-dimensional (2D) codes. A complete discussion of these higher information density symbologies is beyond the scope of this article. Examples of higher information density 2D symbologies are shown in Fig. 5.



▲ Fig. 1. Number of patents issued (including either of the terms “barcode” or “bar code”).



**Note: LINES 6, 7, 8, AND 9 ARE LESS REFLECTIVE THAN LINES 10.**

▲ Fig. 2. First true barcode using a circular “bullseye” symbol.

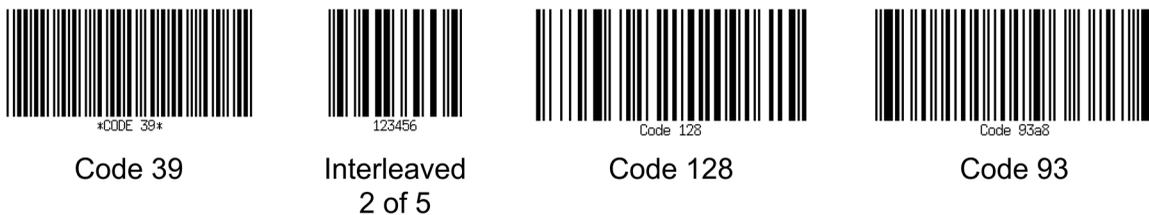
## Supermarket Barcode Scanners

In 1971, RCA began the first system test of a bullseye scanner at a Kroger supermarket in Cincinnati, Ohio. This test and others continued through early 1974. The first full-scale implementation of supermarket checkout scanning began at Marsh Supermarkets in Troy, Ohio, when a pack of Wrigley’s chewing gum was scanned by a laser checkout scanner on 26 June 1974. The scanner, jointly developed by NCR and Spectra Physics, Inc., is described in U.S. patent 4,064,390 (the “390 patent”) issued on 20 December 1977 and assigned to Spectra Physics. One of the original scanners, Spectra Physics serial number 006, from the first Marsh Supermarket installation is now on display at the Smithsonian Institute in Washington, D.C.

These initial supermarket scanners were enormous in comparison to the laser scanners common in today’s checkout counters. The scanner was very large and sat directly on the floor. Its scanning window was at the end of a grocery conveyor that sat on top of the checkout counter. The scanner’s dimensions were 30 inches high × 12 inches wide × 18 inches



▲ Fig. 3. UPC symbol.



▲ Fig. 4. Examples of 1D symbologies.



▲ Fig. 5. Examples of higher information density 2D symbologies.

deep. The scanner is aptly described as being about equally comprised of optics, mechanics, and electronics.

Before beginning a discussion of the optical path through this scanner, is it useful to consider factors involved in scanning a UPC barcode symbol. The UPC symbol was designed so that it could be scanned by a simple X configuration scanning pattern. As a result, the UPC symbol is split into two halves that can be scanned in two separate scanning passes. In order to ensure that the two halves are assembled in the correct order, a check digit and design features such as differing “start” and “stop” bar patterns for the left- and right-hand halves of the symbol are included in the UPC symbology specification. Figure 6 illustrates that the beam labeled “A” scans through the entire left half of the label, while the beam scanning down and to the right (“B”) scans through the complete right half of the label. In principle, these two scans produce a scanning signal which allows the entire label to be decoded by the scanning system.

Figure 7 from the “390 patent” illustrates a portion of the optical path in the Spectra-Physics scanner. A 24-facet optical polygon, denoted by “R,” provides a mechanism that produces orthogonal horizontal and vertical scan lines on a product (the cube at the top of the illustration). A laser beam entering at the bottom right of the figure is directed by mirror 60 through a slot in the polygon mirror assembly to mirror 82. This mirror subsequently sends the beam to mirror 84, through beamsplitter 86 and lens 88 to mirror 42 and on to lens 90. Lenses 88 and 90 form a relay telescope used in generating vertical scan lines. After lens 90, the beam is deflected by the polygon mirror and reflected by fold mirror 94 through the scanner window 34 to impinge on the product. Light scattered from the barcode label on the product follows a retro-directive path back through the optical system and ultimately impinges on a photodetector (not shown).

Vertical scan lines are generated in a similar manner and follow a similar beam path as the horizontal scan lines, however, each beam from beamsplitter assembly 54, 56, 58 makes two reflections from two separate polygon mirrors. An ingenious arrangement of facet tilt angles of sequential polygon mirrors results in three vertical scan lines for each horizontal scan line. The slots in the face of the polygon assembly are designed so that only one horizontal or vertical scan line passes through the scanning window at any given time.

A large fractional horsepower AC motor rotated the “390” scanner polygon at 3400 RPM producing scanning speeds of 8000 in./min. The retro-directive light collection path utilized aspheric collection optics to minimize spherical aberration and coma. Narrow-band optical filters rejected ambient light. These design features resulted in breathtaking, state-of-the-art, scanning performance. It was possible to literally throw a five-stick pack of chewing gum spinning across the scanning window and have its barcode label decode on the first pass! Now, nearly 40 years later, present day supermarket

checkout scanners are hard pressed to achieve this degree of scanning performance, but they are cheaper, much smaller, and draw substantially less electrical power, all of which add to the bottom line of the supermarket.

## Handheld Barcode Scanners

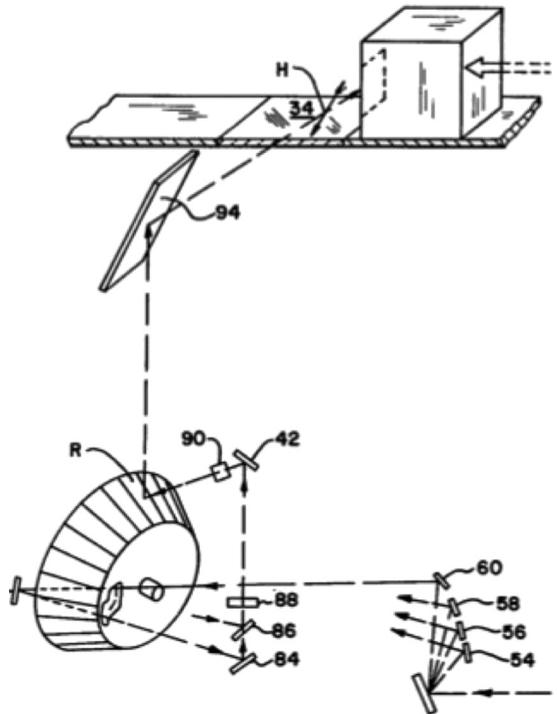
Scanners used in supermarket applications quickly moved to laser scanning due to the high scanning speed and large depth of focus available from such devices. Initial industrial applications of barcodes, such as inventory control and tracking work in process, had significantly lower performance requirements and required lower price points. Initially simple barcode “wands” were used for these purposes. An early barcode wand is described by Turner and Elia in U.S. patent 3,916,184 assigned to Welch Allyn, Inc. (the “184 wand”). The “184 wand” utilized an incandescent bulb or LED and a fiber optic bundle to illuminate the barcode symbol through an opening in the case. A simple two-lens system and photocell or photodiode produced an electrical signal representative of the barcode symbol as the wand was manually scanned across the label. Apertures in the two-lens system controlled the depth of field and field of view (i.e., resolution of the barcode label) of the wand.

Since wands were in contact with the label during scanning, the label became degraded when scanned multiple times. Another common problem with wands was that paper “lint” would accumulate in the entrance opening and degrade scanning performance. To improve on early wands, Bayley of Hewlett Packard suggested the use of a sapphire ball lens in the opening of the wand in U.S. patent 4,855,582. Hewlett Packard’s commercial product based on this patent had a compact hermetic electronic package that housed the illumination LED and a photosensor. The highly integrated design was cost effective and very rugged, an important requirement for any handheld device in an industrial or warehouse environment.

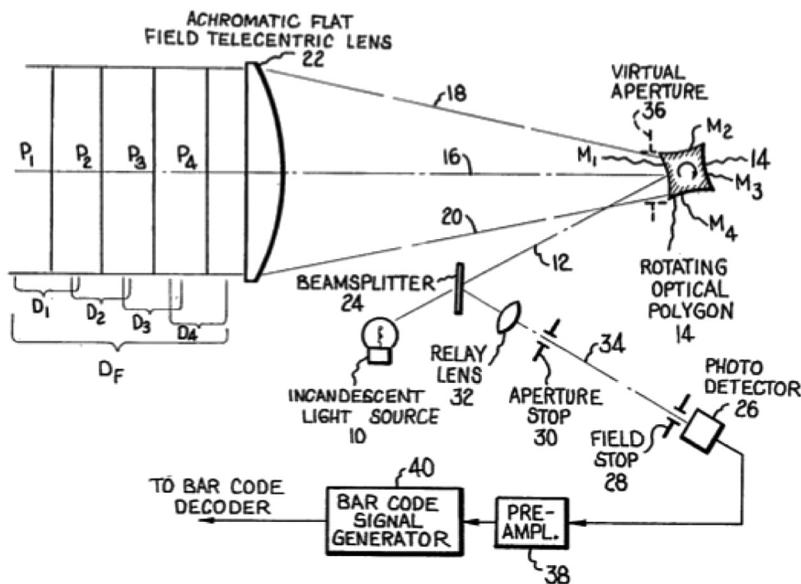
The contact nature of barcode wands was a disadvantage in many industrial environments since the label was often read several times during a manufacturing or inventory process, or in package tracking. These applications drove the development of non-contact handheld scanners. An early example is described in U.S. patent 4,560,862, first disclosed to the Patent Office in 1983. The concept of this patent is illustrated Fig. 8. A rotating polygon with concave mirrors scans an image of an incandescent source across a barcode symbol. The illuminated scanning plane is then imaged back along the optical path to a beamsplitter which directs the returning light through a relay lens, aperture stop and field stop to a photodetector. The curved mirrors on the polygon have various radii, thus producing multiple temporally multiplexed focal planes on the photodetector due to rotation of the



▲ Fig. 6. Simple X configuration scanning pattern.



▲ Fig. 7. A portion of the optical path in the Spectra-Physics scanner.



◀ Fig. 8. Concept of U.S. patent 4,560,862: A rotating polygon with concave mirrors scans an image of an incandescent source across a barcode symbol.



◀ Fig. 9. Examples of visible laser diode barcode scanners, in approximate chronological order from left to right. (Courtesy of Cybarcode, Inc.)

polygon. The commercial device utilized eight spherical mirrors on the polygon and was housed in a gun shaped housing for convenient handling, and used a trigger for selection of a barcode label to be read.

Eastman and Boles disclosed the first laser diode based fixed-beam handheld laser scanner to the patent office in 1983, resulting in issuance of U.S. patent 4,603,262 in July 1986. The fixed-beam scanner, similar in size to a child's squirt gun and the first to use surface mount electronics to reduce size and weight, was scanned by the user's wrist motion. The laser diode operated at 780 nm, so its light was not readily visible to a user. Consequently a visible "marker beam" propagated coaxially with the laser beam to enable the user to point the scanner at a barcode label. The scanner had no moving parts other than its trigger button, so it was very rugged and capable of operating after a drop from a second-story window onto a concrete sidewalk with no ill effects.

Both of the above devices were quickly eclipsed by He-Ne-based moving beam handheld laser scanners. U.S. patent 4,409,470 by Shepard, Barkan, and Swartz disclosed a "narrow-bodied" laser barcode scanner that became successful in the early to mid-1980s as Symbol Technologies' LS-7000. The advent of low-cost visible laser diodes quickly led to the availability of rugged handheld laser scanners in the late 1980s and early 1990s, as described in U.S. patents 4,760,248; 4,820,911; and 5,200,579. In order to avoid the strong patent position of Symbol Technologies in handheld laser barcode scanners, Rockstein, Knowles, and their colleagues invented a "triggerless" handheld barcode scanner as described in U.S. patent 5,260,553. This device automatically began scanning when a barcode symbol was in close proximity. Several examples of visible laser diode barcode scanners are shown in Fig. 9, in approximate chronological order from left to right.

# Imaging Barcode Scanners

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As higher-density stacked and matrix (i.e., “2D”) codes became prevalent, the need for handheld scanners capable of quickly and reliably reading these symbologies became important. Although laser scanner manufacturers attempted to adapt laser scanners to reading 2D codes using two dimensional raster scanning (see, for example, U.S. patent 5,235,167) these devices never achieved the level of performance laser line scanners could achieve reading 1D barcodes. Thus, in the mid-1990s patents began to appear for scanners that imaged the barcode symbol onto a CCD or CMOS array for detection. Broad-area illumination of the symbol was provided using LEDs. Three early examples of handheld 2D imaging bar code scanning technology were disclosed by Wang and Ju in U.S. patents 5,521,366 and 5,572,006, and by Krichever and Metlitsky in U.S. patent 5,396,054.

Details from patent 5,572,006 illustrate the basic configuration of an early handheld 2D imaging barcode scanner. The barcode is illuminated by an illumination array that typically comprised a circuit board, on which LEDs are mounted to broadly illuminate the target area in which the barcode symbol is located. A lens images the illuminated barcode symbol onto a sensor array, which may be either a CCD or CMOS imaging array.

Numerous patents disclosed various techniques for decoding 2D barcode symbologies, but discussion of these techniques is beyond the scope of this short historical article. Readers interested in this aspect of the technology are encouraged to read an excellent text specifically on barcode symbologies: *The Bar Code Book* by Roger C. Palmer. Imaging scanners have several advantages over laser scanners in that they are capable of capturing images of objects and people. Of course, this functionality is dependent on the firmware built into the device. Image quality from a scanner may not rival that of today’s low-cost digital point and shoot cameras.

Many of us today routinely carry devices that can serve as 1D and 2D scanners—our smartphones. For example, there are currently at least 100 barcode scanning apps for an iPhone, most of which are available as free downloads. A search of either the Google Play or the Microsoft Marketplace app store lists numerous barcode scanning programs, many of which are also free. Some barcode scanning apps can decode a barcode, search the Internet to find product pricing, list nearby stores that carry the product, and display a map with directions to the store of your choice.

Use of these scanning apps is as simple as pointing your smartphone’s camera at the barcode symbol. That’s it—no focusing, no careful alignment, and no tapping the screen to capture a picture. The app auto-focuses, auto-recognizes that a barcode is present, decodes the symbol, and finally searches the Internet for available information. Nothing could be simpler; this is truly shopping made easy—and very impulsive!

# Developing the Laser Printer

Gary Starkweather

**I**nventors usually realize that any good idea owes some debt to earlier technological developments. The laser printer is no exception. In 1938, Chester Carlson, a struggling patent attorney, needed a way to copy patents other than by hand. That led him to develop a technology now known as “xerography” from which the company Xerox was born. The word xerography comes from the Greek words “xeros” and “graphein” which mean respectively “dry” and “writing.” The laser printer, as we now know it, depends on this wonderful imaging capability.

Xerox introduced the first real copier in 1959 and called it the “914,” with the number standing for the largest paper the machine could copy. Despite warnings by “market experts” to the contrary, the 914 became one of the most profitable products ever produced in the Western world. Xerox started developing many different kinds of imaging machines. One of the most interesting and advanced for its time was a limited-volume product called LDX for Long Distance Xerography.

As a young engineer coming to Xerox in 1964, one of the challenges the author was given was to see if the LDX system could be made faster. The LDX system as built in the middle 1960s was a design with limited extensibility. A line scan cathode ray tube (CRT) was used with an imaging lens to scan an original document. The light was picked up by a light sensor and sent over a 56-kilobaud (kBd) line to a receiver at a location perhaps hundreds of miles away. This sort of bandwidth was not readily available but could be purchased if needed. The receiving station also had a line scan CRT whose beam was modulated to generate a variable-intensity light signal that a lens imaged to expose a xerographic drum similar to that used in a copier. The problem was that the CRT used for exposure was pushed hard to get enough light output. It took many seconds to print a document, and there was a real desire to go much faster. The immediate challenge was to find a better way.

Being a graduate student at the University of Rochester Institute of Optics, the author was using a new light source: the helium–neon (He–Ne) laser, invented in 1961. Its main advantage was its brightness or radiance. Because the laser beam was highly confined rather than a Lambertian radiator, its radiance was thousands of times higher than the CRT. The red beam was a concern for current photoreceptors in the copiers, but as a bright, deflectable light source, it had no peer. The author set about to see what might be done with the laser as an illuminator for the print and perhaps even the scan station.

A key advantage of the CRT was the fact that magnetic or electrostatic fields could deflect the electron beam on the screen. Laser beams, as someone has described them, are “stiff” and so they need something to deflect them. The only practical solution was putting several mirror facets on a rotating disk. Using 10 to 20 or more facets greatly reduced the required rotational speed. However, the mirror facets and rotational axis had to be kept within a very few arc seconds of each other while rotating at several thousand revolutions per minute. This is an exceedingly difficult requirement for a cost-effective commercial product. The author built a laser facsimile prototype with a modified 914 (720 series) copier to scan an original and print the results. His skilled colleague Robert Kowalski built electronics generating about 1000 V to drive a special Pockels-cell beam modulator. Switching 1000 V in a small fraction of a microsecond even with a small capacitance was not trivial.

The two researchers clamped, taped, and otherwise assembled a scan and print breadboard to the 720 copier with a special red-sensitive drum and made some laser fax copies in 1968–1969.

The lack of precision in the scanning mirror left bands in the images, but the demonstration showed what a laser system could do. However, a way had to be found to make a precise scanner without spending \$20,000 each.

After thinking about the precision requirements for several days, the author came upon an idea while sketching the problem on a piece of paper. It looked as though a cylinder lens would solve the problem. If it would, it was puzzling why no one else had discovered it. A 12-in. (30.48-cm)-long cylinder lens was ordered, which arrived the next day by air. What was the result? Eureka! It solved the scanner problem. A scanner with perhaps 1 or 2 arc min of error could perform a task that would have required 1 arc sec precision. The scanner was now going to be very inexpensive. Today, such a simple six-sided polygon and motor system for a personal laser printer costs less than \$5–\$10.

About this time, the author began to wonder about an idea after talking with a couple of other people. Why not forget the input scanner and use a computer to generate the signal patterns for a print station only?

Up to this time, every part the author and Robert Kowalski had used was already part of their laboratory equipment since no spending on this effort was permitted. Furthermore, about this time a more serious, non-technical issue arose.

The author's immediate manager got wind of his idea and stated in no uncertain terms that this was a bad idea and that he wanted all work on it stopped. This was the beginning of a real challenge: To continue the project or let it go? The author decided to continue working on it less obviously. The situation was heading to a real confrontation when, one day in early 1970, the author read in the company newsletter about a new research center being started in Palo Alto, California. He called one person he knew in the starting group to ask how to tell them about the project and described what was being worked on. They decided to fly the author out to California to make a case for the new printer technology.

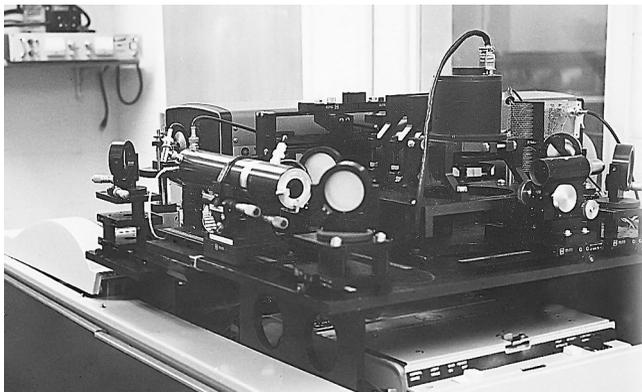
The trip was a rousing success. A group also becoming part of the new Palo Alto Research Center (PARC) was working on a personal computer that "bit-mapped" text and graphics onto a display much like today's Macs and PCs. They needed a way to render their pixel-oriented screen image to paper. The new laser printer was a natural fit to their needs. They were willing to take the author into their organization, but there was one "problem": management in Rochester would have to approve a transfer. The author promised to find a way to get this done.

Upon the author's return to Rochester, his manager refused to permit the transfer to PARC. Technically, this was a violation of company policy. After some stressful discussions the author took the issue to a more senior level. Eventually, after some tense but productive discussions, George White, an energetic and future-oriented Xerox vice president, approved the transfer to PARC, and the author moved his young family to California in early January of 1971. Thus began work in earnest on the laser printer.

Spearheaded by the visionary genius of Jack Goldman, PARC was a great place to build this machine as well as being a font of other great technologies. The invaluable Bob Kowalski from the Webster, New York, Xerox facilities was hired. John Urbach, now deceased, provided a lot of encouragement as well as financial support. He reported to one of the best managers and mentors anyone could have, Bill Gunning, who helped the author set realistic and important goals for the first printer and provided very wise counsel.

The group decided to build a prototype that would print at one page per second and at a spatial density of 500 laser points per inch in both the fast and slow scan directions. A solution to the poor red sensitivity of standard Xerox photoreceptors emerged from a major optical system design error in the Xerox 7000 duplicator that did not show up until early production. The only practical way to remedy this optical system problem was to replace the usual blue–green-sensitive photoreceptor with one more sensitive in the red part of the spectrum on the drum of the 7000. This error was a truly fortuitous event allowing the laser printer work to proceed. It is unlikely that the printer would have had the necessary backing if it alone had required a special photoreceptor.

The Xerox 7000 with the red-sensitive drum was going to be used to print one page per second using a He–Ne laser. This meant generating at least 20 million points per second from the scanner. The



▲ Fig. 1. First PARC prototype laser printer.



▲ Fig. 2. Dover printer with covers open.

scanner was more than capable of doing this, and the author designed an optical system that would scan a 60–75  $\mu\text{m}$  spot across an 11-in. page in under 200  $\mu\text{s}$ . Bob Kowalski and others began building a test-pattern generator that would produce grid patterns and some character forms that would drive the laser modulator at the required data rate. The actual operational data rate was closer to 30 Mb/s due to scan inefficiencies and other factors in the prototype.

In November 1971, after putting together the prototype shown in Fig. 1, the group was able to print grid patterns and some simple text lines at one page/s.

The results were exciting. There were some competing efforts using other technologies for computer printing, but the laser printer won out as it used what George White liked to call “zero dimensional” imaging. When you print with points, you can print any arbitrary pattern at quality levels the technology will permit. No more fixed letter formats as in a typewriter or line printer. Alan Kay and others built an experimental character generator to drive the prototype printer through a cable running from the character generator in the computer science lab to the laser printer lab because the character generator also had other uses.

PARC’s expansion as the prototype was developed further created another problem. The computer science lab was moved to a newly acquired building half a mile away, and with a freeway in between, no cable could be run directly between the character generator (CG) and laser printer. How could the system be tested in the next one to two years before the group was all back together again in the new PARC facility on Coyote Hill Road? Fortunately, there was a clear line of sight between the two buildings. Four 8-in. astronomical telescopes were bought, and two were placed in weatherized boxes on the roof of one building and two on the other. That way, a modulated He–Ne laser at each end sent signals between the laser printer and the CG. For over a year the printer sent the start of the scan signals to the CG and the CG sent us data back in synchronism with the critical start of the scan signal from the printer. A 6- $\mu\text{s}$  delay in the light travel time yielded a 1-in. (2.54 cm.) extra margin on the printed sheet, but that was quite tolerable for the development work. The group was back in business for the year they were apart. In California, rain actually cleared the air, and measurements of the path transmission efficiency showed improvements when it rained!

Once the group was back together in 1973, a new laser printer was built for general employee use at PARC, called EARS, for Electronic Array Raster Scanner. Ron Rider designed a hardware character generator remarkable for its speed and capability. Everyone with an Alto computer at PARC could have their documents printed on this machine at 1 page/s. Over the 15 to 18 months or so that it was in service, over four million pages were printed.

The next big step after EARS was to take advantage of the novel image generation capabilities of the Alto II computer and develop a 60-page/min. laser printer named Dover built on the same 7000 copier base in 1976–1977. Figure 2 shows a Dover printer with the top covers open.

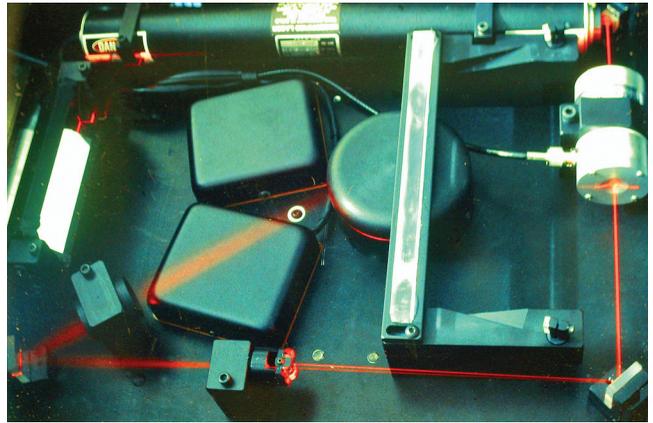
Figure 3 shows the Dover laser head with the laser beam light path. This machine ran with a software image generator combined with a novel hardware board resident in the Alto computer itself. Data were printed at a spatial pixel density of 384 pixels/in. This permitted a much lower cost system, and 35 of these machines were built for selected users in conjunction with Electro Optical Systems in Pasadena.

The Dover printers had digital controls rather than the relay logic of the 7000, yielding a streamlined design and a reproducible configuration at a modest price for a machine with such novel capabilities. One of these machines can be seen in the new Computer History Museum in Mountain View, California.

In 1977, Xerox introduced the 9700 Electronic Printing System, which printed 2 pages/s at 300 pixels/inch. The paper supplies were big enough to permit over 40 minutes of printing without paper reloading, and the paper trays could be refilled while printing. Xerox management had hoped that these printers would generate at least 250,000 prints per month on average. In actuality, they averaged well over one million prints per month! Now that the technology has come down in cost, one can readily buy low-cost personal monochrome or color laser printers. Fast, high-end color laser printers now challenge traditional ink-on-paper printing technologies. In fact, digital copiers today are really a return to the original laser fax idea. Some things just seem to require time and patience to properly unfold.

It is hard to be thankful enough for the opportunity of working at Xerox and PARC in developing this technology. These were exciting times in a beautiful location. What was once a nearly career-limiting idea has become commonplace. A statement by Michelangelo is pertinent:

“I saw the angel in the marble, and I carved until I set him free.”



▲ Fig. 3. Dover printer laser head.

# History of the Optical Disc

Paul J. Wehrenberg

American inventors including David Paul Gregg and James Russell originated some key optical storage concepts in the late 1950s and early 1960s, but initially envisioned writing with electron beams and reading by directing laser beams through the material to detectors on the other side. The concepts of a rotating disc and reflective media made optical storage a real possibility [1]. Rotating the disc and moving the optical pick-up (OPU) radially gave the required two-dimensional access to the data surface. Reflective media meant the emitters and detectors could be on the same side of the disc, greatly easing optical alignment. Burying the data surface in a transparent disc made the media robust in the hands of the consumer.

By the early 1970s, growing interest in read-only optical discs for Hollywood movie distribution led to product development. A partnership between MCA and Philips, MCA DiscoVision, introduced the first consumer laser video disc (later called Laservision) in the United States at the end of 1978. It used He–Ne gas lasers to read molded or embossed pits on a 30-cm disc, the size of a vinyl LP record. Video information was encoded as a variable distance between the edges of pits in a spiral track, yielding a frequency-modulated analog signal as the disc rotated past the laser spot.

The details of the tracking process were quite complex, and it took longer than expected to develop a reliable and low-cost process to mass produce the discs. Philips made the first fully playable disk in 1976, but it took an intense engineering effort to launch the first qualified mass production started at a factory in Blackburn, England, in 1981. The discs showed less wear than VHS tape, and image quality was better, but those advantages were not enough for Laservision to outcompete tape, which was less expensive and recordable (although most customers did not use that aspect). In the end, VHS tape thoroughly dominated consumer video distribution until the arrival of DVD in the mid-1990s.

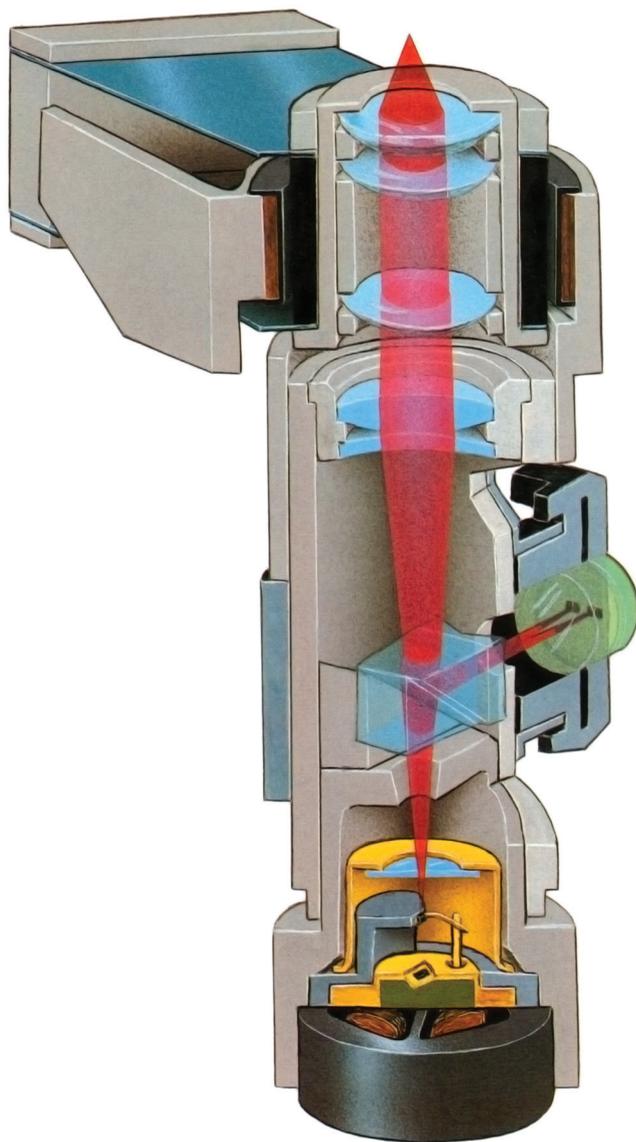
In 1974 Philips Research Laboratories and the Philips Audio Division began developing an optical audio-disc system. Their design thinking, further detailed below, is an excellent example of system integration using the best of current technologies and additionally anticipating probable future developments in component technology, specifically digital processing power of consumer integrated circuits and wavelength reduction of solid state lasers. The project grew internally in Philips, and it was decided that analog signal recording would not work well enough and that a fully digital technique was a better approach. The magnitude of the development effort made it attractive to have partners, and after some negotiation, an agreement was reached with Sony in 1979. In-depth technical discussions were started, focusing primarily on the error-correction signal processing. The contributions from both companies resulted in a system standard which forms the physical basis of the compact disc (CD) as we know it today.

Early in the project the disc size was chosen as 120 mm and called “compact disk” because it was smaller than the 300-mm Laservision disc. They knew that the available and affordable solid state lasers for the playback devices would give them about 1 mW at approximately 800 nm, and designed the optical system accordingly (see Fig. 1) [2]. The laser beam passed through a 1.2-mm transparent substrate to read data marks embossed onto the aluminized disk surface. The embossing makes the data marks reflective phase objects.

After defining the CD-A disc standard, Philips and Sony set up a licensing organization which Philips still administers. Licensees receive a copy of the “Red Book” which details the

standard and optical performance metrics. The physical standard focuses entirely on the removable optical disc. The only constraint on the disc player is that it must be able to read and play back standard-format discs. A great advantage of this sort of standard is that it allowed open-ended growth in the capabilities of disc players. For example, today's inexpensive players transfer data at 16 times the 1.41 Mb per second of initial players. The optics, servos, and electronics could handle twice that rate, but that would require spinning the polycarbonate disk at 6400 to 16,000 revolutions per minute, reaching speeds where the centrifugal force could shatter the plastic disc, a very disconcerting experience for the user.

Several aspects of optical disc system design are brilliant. One example is writing data tracks as a very long spiral rather than concentric circles, allowing mass-produced players to read data by following the track rather than creating it. Injection molding can replicate discs accurately and inexpensively, so this shifts the costs of achieving the required precision to the mastering machine, which is amortized over millions of replicated discs. That also allowed most players to play discs with track pitch reduced to squeeze up to 99 minutes of music onto a disc originally designed for 74 minutes. Inspired choices of eight-to-fourteen modulation coding and cross-interleaved Reed–Solomon error-correction code made the system resilient to random bit errors that if uncorrected could blow out speakers—vital because replicated discs had raw byte error rates of  $10^{-4}$  to  $10^{-5}$ . Establishing 2352-byte blocks for CD-audio discs left room for the error-correction codes needed to meet computer requirements of bit-error rates less than  $10^{-12}$ , allowing development of CD-ROM for computer storage.



▲ **Fig. 1.** Artist's rendering of playback optics in first Philips CD product, CD100. Size was 12 mm x 45 mm. Philips Technical Review **40**(6), 150 (1982).

## Writable and Re-Writable Discs

Research on write-once and rewritable optical discs accelerated in the 1970s in the U.S., Europe, and Japan as read-only discs were being developed as products. A big challenge was the limited laser power available. In France, Thomson-CSF and later Alcatel Thomson Gigadisc developed glass-substrate discs coated with thin layers of a proprietary material probably similar to nitrocellulose, plus metals including a final malleable layer of gold. It was a clever way to write

data, as microscopic bumps in the gold layer, were formed by exploding the proprietary layer, but repeated laser readout deformed the gold bumps, increasing the error rate to an unacceptable level.

A more successful approach for write-once read-many-times (WORM) media was spin-coating dye-polymer mixtures onto a glass or plastic substrate. The optics in the drive are the same as for read-only discs, so the only added requirement is a more powerful delivery of peak powers of 50–100 mW peak. Philips and Sony specified the write-once CD, later called CD-R, in their 1988 Orange Book, and by the late 1990s the required lasers had become available and writing CD-R became the norm for optical drives in computer systems. The wide variety of write-once media soon became a challenge, forcing optical drive developers to develop different writing strategies for various disks and install them in player firmware.

Magneto-optic (M-O) and phase change recording were the major contenders for rewritable optical disks. Magneto-optics got off to a promising start in the early 1970s, based on synchronizing laser heating (to the Curie point) of a magnetic recording medium with modulation of the magnetic field in the heated area. The write/read heads were complex, but the media offered an essentially unlimited number of write/read cycles, so the systems could easily fit with existing computer memory management.

Phase-change media are purely optical systems based on a thin layer of a chalcogenide alloy, such as AgInSbTe or GeSbTe, which can be stable in both amorphous and microcrystalline states with different reflectivities. Illumination by a short high-energy laser pulse melts the chalcogenide layer, which cools to an amorphous state. A longer, lower-energy pulse heats the film but does not reach the melting point, causing crystallization of the amorphous layer, thus control of the laser profile rewrites the material. A great deal of research from the 1970s through the 1990s went into finding the best alloy compositions and deposition procedures.

## Industry Anecdotes

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The author was deeply involved in developing those systems, so he saw the dynamics that shaped their history. As a Senior Researcher in the R&D Division of Ampex Corporation in the 1970s, he was offered the opportunity to lead technical development of a either re-writable magneto-optic media or write-once media. He chose the write-once group because it seemed that write-once media were certainly as useful as ink and paper and that the dye polymer media and drives could be produced at much lower cost than the M-O media and drives. These guesses turned out to be correct in the long run. What was not realized at the time was that the changes in computer operating systems required to manage read-only and write-once media would be very slow in coming. Those file-system enhancements were not standardized and implemented until the late 1980 and 1990s, when software developers finally understood that the utility and low cost of CD-ROM, and later CD-R, made them necessary system components.

By the mid-1980s the author was on “the other side of the fence,” as Manager of Optical Storage at Apple Computer. His initial goal in joining Apple had been to develop CD-A and CD-ROM for use with Apple’s computers. Steve Jobs really liked optical storage and therefore provided good support to the CD effort. At the time, M-O developers believed the unlimited re-writability and removability of M-O media made it more attractive than conventional magnetic hard disk drives for computer use. After Steve left Apple, rumors spread that his new company called NeXT was going to use M-O drives instead of magnetic discs in its new computer. That worried Apple management, which had great respect for Steve’s product judgment, so the author’s group began working with a major Japanese electronics company on M-O drives for Apple computers. As the possible performance and costs were learned, analysis showed that computer performance would not be adequate with only a M-O drive. The slower access time and transfer rates of M-O drives would make the computers too sluggish for the market. Subsequent developments indicate that dropping the M-O disc was the correct choice.

# DVD and Blu-Ray, the 120-mm Optical Disc Drive beyond CD

When 650-nm diode lasers became available, a group including Philips, Sony, Toshiba, and Matsushita developed 120-mm dual-layer discs with capacities of nearly 5 GB on a single-layer disc and 8.5 GB on a dual-layer disc. New video codecs could generate decent NTSC/PAL video from an average bit rate of 4 Mb/s and a maximum bit rate of 11 Mb/s. The new standard also transported video data in blocks just like computer data, avoiding the differences that had existed between CD-A and CD-ROM. After resolving some “last minute” engineering issues regarding copy protection, Hollywood put their content on the new discs, and DVD became an incredibly successful consumer product for all concerned.

The DVD standard is almost purely “raising all the bars” from CDs. Shorter-wavelength lasers, better error correction codes, and more powerful VLSI chips are all evolutionary developments resulting from many person years of R&D. This history shows that evolutionary engineering developments can produce revolutionary effects. CD capacity is not large enough to support video; DVD can support video. A modern personal computer operating system will just fit on a dual-layer DVD; it would require 12 CDs or 5400 floppy disks.

Because CD usage remained quite strong, the new optical drives needed optics and electronics to support both 780 nm for CD and 650 nm for DVD. Typically the multi-wavelength optics use dichroic beamsplitters to combine optical axes through a single objective lens. In some



▲ Fig. 2. Twenty-year evolution of optical disc product capabilities.

**Table 1.** Twenty-Year Evolution of Optical Disc Product Capabilities

### 1988 Optical Disc Drive (AppleCD SC)

Volume of optical drive mechanism and electronics 122.2 cu"  
Volume of OPU 1.5 cu"

Media types	Maximum Read Speed	No Writing Capability
CD-A	1× audio play only	
CD-ROM	2×	

### 2008 Optical Disc Drive (Apple Superdrive)

Volume of optical drive mechanism and electronics 11 cu"  
Volume of OPU 0.3 cu"

Media types	Max. Read Speed	Max. Write Speed
CD-A	24×	
CD-ROM	24×	
CD-R	24×	24×
CD-RW	24×	16×
DVD Video one layer	8×	
DVD-Video dual layer	8×	
DVD-ROM one layer	8×	
DVD-ROM dual layer	8×	
DVD-R one layer	8×	8×
DVD-R dual layer	8×	6×
DVD+R one layer	8×	8×
DVD+R dual layer	8×	6×
DVD-RW	8×	6×
DVD+RW	8×	8×

**Table 2.** History of 120-mm Disc Physical Parameters by Standard

Standard Name	CD	DVD	Blu-Ray
Product Introduction	1982	1995	2003
Laser Wavelength	780 nm	650 nm	405 nm
Objective Numerical Aperture	0.5	0.6	0.85
Cover Layer Thickness	1.2 mm	0.6 mm	0.1 mm
Track Pitch	1.6 $\mu\text{m}$	0.74 $\mu\text{m}$	0.32 $\mu\text{m}$
Minimum Mark Length	0.80 $\mu\text{m}$	0.40 $\mu\text{m}$	0.15 $\mu\text{m}$
Single Layer Capacity	0.80 GB	4.7 GB	25 GB
Number of layers	1	2	2
Disc Capacity	0.74 GB	8.5 GB	50 GB

cases the “lens” is actually a dual optic with a high-numerical-aperture (NA) annular zone giving a small 650-nm spot and a smaller-NA region focusing 780 nm light to a larger spot.

Decades of research and development have dramatically reduced size and increased capabilities. Figure 2 and Tables 1 and 2 compare size and specifications of optical drives from 1988 to 2010. For demonstration, the top lid of the 2008 drive has been removed, and an unfinished 120 mm disc (metallization layer not yet applied) has been placed on the spindle. The optical pickup is visible through the still transparent disc.

The bar was raised even further in 2006 with introduction of the Blu-Ray drive product, based on the development with 405-nm lasers. Evolution in every aspect of the technology, as shown in Table 2, created a dual-layer 120-mm disc with 50-gigabyte capacity—which would have been unthinkable four decades earlier. Blu-Ray can support high definition video with four times as many pixels as NTSC/PAL video.

The future of optical disc use and development will be strongly affected by other technologies. Will consumers accept the lower-quality video distributed over the Internet or insist on the quality delivered by a 120-mm HD Blu-Ray disc? Optical discs with properly made media are as archival as silver halide, so what role will they play in archiving the data our society continues to generate at an accelerating rate?

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# Interferometric Optical Metrology

James C. Wyant

**L**asers have made truly revolutionary changes in optical metrology. The laser's small source size and narrow linewidth made it so much easier to obtain good contrast interference fringes that applications of interferometric optical metrology have increased immensely during the 50 years since the laser was first developed. Single-mode frequency-stabilized lasers provided a standard for dimensional metrology, while ultra-short pulsed lasers have enabled high-resolution range finding.

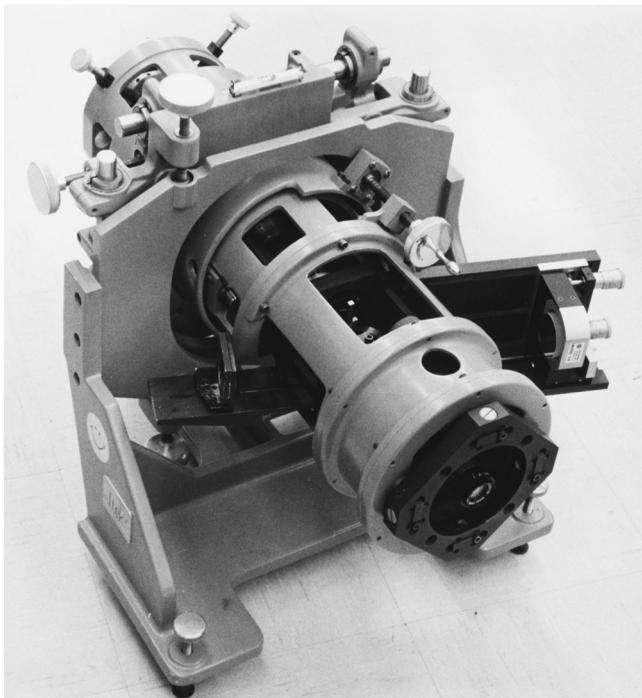
The laser has greatly enhanced the testing of optical components and systems. Before the laser, the use of interferometry in optical testing was limited because either the interferometer paths had to be matched or the source size had to be very small to have good spatial coherence, and the filters needed to reduce spectral width left very little light for measurements. Once the laser was introduced, Bob Hopkins from the Institute of Optics at the University of Rochester was quick to realize how much laser light could improve the testing of optical components [1], and he encouraged other researchers to design laser source optical interferometers [2–6]. By 1967 lasers had become common in optical testing [7,8]. Figure 1 shows a laser unequal path interferometer (LUPI) designed by John Buccini and manufactured by Itek in the late 1960s and early 1970s.

Abe Offner from Perkin Elmer was quick to realize that adding null correctors to laser interferometers would allow measurements of optical components with aspheric surfaces [9]. Null correctors are a combination of lenses and mirrors having spherical surfaces, but when used in the proper way they produce an aspheric wavefront that matches the surface of an aspheric optic, producing interferograms with straight equally spaced fringes when the tested aspheric surface is perfect. Unfortunately, that use of null correctors received horrible publicity after initial orbital tests of the Hubble Space Telescope showed its optics could not be brought to the expected sharp focus. Analysis of the flawed images showed that the primary mirror had an incorrect shape. A commission headed by Lew Allen, director of the Jet Propulsion Laboratory, determined that the null corrector used to test the primary mirror had been assembled incorrectly—one lens was 1.3 mm from its proper position [10]. That caused the null corrector to produce an incorrect aspheric wavefront, so using it to test the primary mirror led to fabricating the mirror with the wrong shape. In correcting the error, the cost was more than a billion dollars to design and fabricate additional optics and install them on the Hubble telescope from the space shuttle.

## Heterodyne and Homodyne Interferometry

Heterodyne interferometry using the beat signal between two different laser frequencies permits the measurement of changes in distances or variations of surface height in the nanometer or angstrom range. The two frequencies are commonly obtained from a Zeeman split laser [11], rotating polarization components [12], or Bragg cells [13].

Homodyne interferometry using either a phase-shifting [14,15] or spatial-carrier [16] technique is now widely used to test optics. In phase-shifting interferometry three or more interferograms are captured where the phase difference between the two interfering beams changes by some amount, typically 90 degrees, between consecutive interferograms. From these three or more interferograms the phase difference between the two interfering beams can be



▲ Fig. 1. Laser unequal path Twyman–Green interferometer, often called a LUPI (1970).



▲ Fig. 2. Laser-based phase-shifting Fizeau interferometer having both a 6-in. and a 12-in. aperture (late 1980s).

ern addition of electronics, computers, and software make the technique much more powerful and useful for a wider variety of applications.

## Holographic Interferometry and Speckle Metrology

The laser allowed optical interferometry to expand to include interference of random optical fields scattered from diffuse surfaces. For example, the coherence of laser light is essential in holographic interferometry [21] and speckle metrology [22]. One example is using holographic interferometry to

determined. In spatial-carrier interferometry a large amount of tilt is introduced between the two interfering beams, and the resulting interferogram is sampled such that three or more measurements are made per fringe.

Adding a computer to an interferometer creates a great metrology tool for use in manufacturing many types of components including optics, hard disk drives, machined parts, and semiconductors [17]. Figure 2 shows a phase-shifting laser-based Fizeau interferometer manufactured by the WYKO Corporation in the late 1980s, and Fig. 3 shows a phase-shifting interference microscope also manufactured by WYKO in the mid-1980s for measuring surface microstructure.

The great feature of phase-shifting interferometry is that it can measure distances to nanometer or even angstrom accuracy, but it only measures phase over a range of  $2\pi$  and wraps if the phase varies by more than  $2\pi$ . The phase can be unwrapped if it varies slowly, but not if the surface has large steps or discontinuities. The problem arises from the monochromaticity of the laser light used in the measurement. One way to get around the unwrapping problem is to measure a surface at two or more wavelengths and observe how the phase changes when the wavelength is changed [18]. A second approach is to observe how the phase changes as the frequency changes when using a tunable laser source [19]. A third approach is to reduce temporal coherence of the source and observe how fringe visibility changes as the path difference between the two interfering beams changes [20]. It is interesting that the use of a low-coherence-length source, essentially white light, is the same approach Michelson used more than a hundred years ago. The mod-

measure deformation, first discovered and described by Karl Stetson [23]. First a hologram is recorded of a three-dimensional (3D) object, and then the object is deformed so light from the reconstructed hologram can interfere with the optical field from the deformed object to yield interference fringes showing how the object was deformed. One particularly good application of such holographic nondestructive testing is the testing of automotive and aircraft tires pioneered by Gordon Brown [24]. Changing tire pressure slightly between two holographic exposures causes small bulges in weak areas that show up very clearly in the resulting holographic interferogram.

Time-averaged holography effectively measures surface vibration [25]. A hologram is made of a vibrating surface over a time long compared with the vibration period. Interference fringes are recorded from the nodes of the vibration but are washed out by movement of the vibrating part of the surface. The result is a fringe contour map showing the location of the vibration nodes.

Two-wavelength holography can be used to contour surfaces [26]. One technique starts by recording a hologram of a surface using a wavelength,  $\lambda_1$ . Then both the surface being contoured and the hologram are illuminated with a second wavelength,  $\lambda_2$ , and the optical wavefront reconstructed by the hologram is interfered with the optical wavefront from the object being illuminated with wavelength  $\lambda_2$ . The resulting interference pattern gives the shape of the surface being measured at a synthetic wavelength,  $\lambda_{eq}$  given by  $\lambda_1 \lambda_2 / (\lambda_1 - \lambda_2)$ . Diffuse surfaces can be contoured as long as  $\lambda_{eq}$  is large compared with surface roughness.

Solid-state detectors now have sufficient resolution to record a hologram on a high-resolution image detector, and a computer can reconstruct the optical field [27]. Phase-shifting interferometric holography can measure deformation and vibrations and can contour complex surfaces by using multiple wavelengths.

Computer generated holograms (CGHs), invented by Adolf Lohmann [28], have become common in the laser interferometric testing of aspheric surfaces [29]. Aspheric surfaces have become common in optical systems because they can produce better images with fewer optical elements than spherical surfaces. A computer can calculate a CGH to provide a reference wavefront, and an electron-beam recorder can fabricate the CHG. Then the CGH is put into the laser interferometer to produce the required reference wavefront. The use of CGHs with laser interferometers has helped to greatly improve modern optical systems.

Speckle photography and the interferometer are closely related to holographic interferometry. Illuminating a rough surface with a laser beam produces a grainy distribution of light, resulting from coherent superposition of the random optical fields scattered by the rough surface. Originally considered a nuisance, this speckle pattern was later recognized as containing information about the light-scattering surface. For example, the contrast of the speckles can give information about the roughness of the surface [30]. Speckle contrast as a function of position can give vibration information [31]. Deforming the surface changes the speckle pattern by changing optical pathlengths, and comparing speckle patterns before and after deformation can determine distribution of the deformation [32].

Speckle metrology has become more and more useful as high-resolution image sensors and software analysis programs have improved.

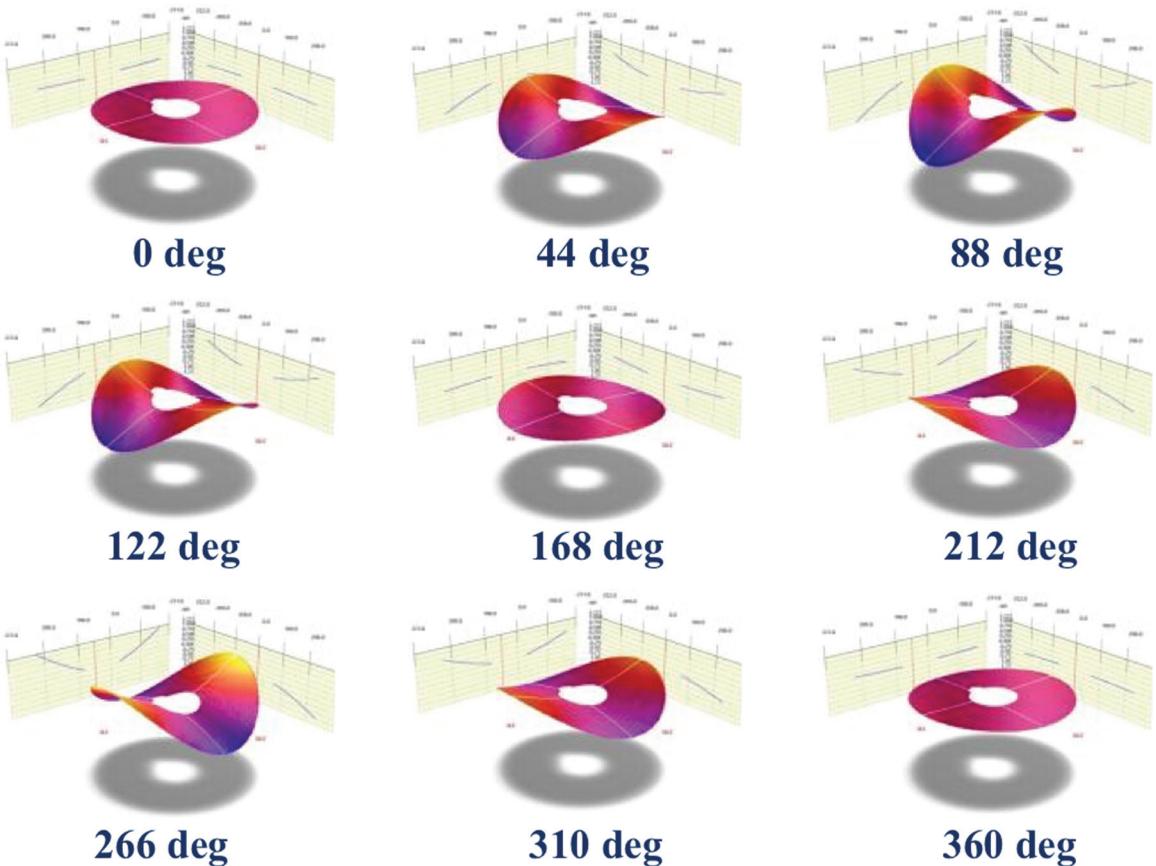


▲ Fig. 3. Phase-shifting interference microscope for measuring surface microstructure (1985).

# Improved Measurement Capability

Lasers make it easy to get interference fringes, but sometimes they can generate fringes from stray beams in an interferometric setup. For example, surface reflections during the transmission measurement of a glass plate can produce spurious interference fringes that greatly reduce accuracy. Using a low-temporal-coherence source and matching the two arms of the interferometer can get around this, but matching the lengths of the two arms can be difficult and reduce the usefulness of the interferometer. A better approach is to add an optical delay line that splits the source beam into two components and allows a controllable path difference between the two beams. That eliminates both the spurious interference fringes and the need to match the test and reference beam pathlengths [33].

The environment affects phase-shifting interferometry, and in many cases, especially in manufacturing situations or testing large telescope optics, it can limit accuracy or sometimes even prevent measurements. The problem is that in conventional phase-shifting interferometry three or more interferograms are obtained at different times for which the phase difference between the two interfering beams changes by 90 degrees between consecutive interferograms. Vibrations can cause incorrect phase changes between consecutive interferograms. However, vibration effects can be reduced by taking all of the phase-shifted frames simultaneously, and now high-resolution image sensors offer several ways to obtain all of the phase-shifted frames simultaneously. One technique that works very well is to have the test and reference beams have orthogonal circular polarizations and to put a polarizer in front of each detector pixel. The array of polarizers are arranged in groups of four where the axis of the polarizers are at 0, 45, 90, and 135 degrees [34]. It can be shown that the phase shift between the two interfering beams goes as twice the angle of the polarizer [35]. In this way, four phase-shifted beams are obtained simultaneously. As long as there is enough light to make a short exposure, the effects of



▲ Fig. 4. Three-dimension contour maps showing shape of vibrating surface as a function of time.

vibration are eliminated and precise measurements can be performed in the presence of vibration; many measurements can be averaged to reduce the effects of air turbulence. Also, if surface shape is changing with time, the changes in surface shape can be measured and movies can be made showing how the surface shape changes as a function of time, as shown in Fig. 4. Techniques such as this are extremely useful for increasing the applications of laser-based interferometric metrology.

## Frequency Combs

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An important recent development is the use of frequency comb lasers for determining the absolute distance to an object. In 2005 John Hall and Theodor Hänsch shared half the Nobel Prize in physics for development of laser-based precision spectroscopy, including the use of frequency comb lasers.

Frequency comb lasers [36] have the potential to revolutionize long-distance absolute measurements by allowing better than sub-micrometer accuracy of distances up to, and possibly beyond, 10,000 km. Comb lasers are pulsed (ultrafast) mode-locked lasers with a precisely controlled repetition rate and pulse phase. Stabilizing the output of a femtosecond laser provides a spectrum of well-defined frequencies. The periodic pulse train of a femtosecond laser generates a comb of equally spaced frequencies for multi-wavelength interferometry. It is possible to link the time-of-flight domain of long-distance measurement with an interferometric measurement to obtain nanometer accuracy. The basic concept is to use this incredibly regular pulse structure to measure a distance in units of the pulse separation length. For accuracies down to the 10- $\mu\text{m}$  level, it is sufficient to use Time of Flight measurement [37,38]. Sub-wavelength accuracy in the nanometer range can be obtained using spectral interferometry where the distance is obtained by determining the slope of the phase as a function of the optical frequency [39,40]. It is believed that distances of 500 km can be measured to accuracies better than 50 nm.

It continues to be a very exciting time for the use of lasers in optical metrology. With the combination of new lasers, modern detectors, computers, and software, the capabilities and applications of metrology are astonishing.

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# Half a Century of Laser Weapons

Jeff Hecht

The laser concept emerged at an ideal time to stimulate the emission of military research contracts. In early 1958, President Dwight Eisenhower established the Advanced Research Projects Agency (ARPA) to handle the high-risk, high-payoff projects that cautious military bureaucrats had been avoiding. That May, ARPA director Roy Johnson told Congress that his agency's work "might lead to a death ray. That would be the weapon of tomorrow," a step beyond the hydrogen bomb, able to destroy nuclear-armed ballistic missiles before they reached their targets.

Thus it was no wonder that ARPA welcomed Gordon Gould and Lawrence Goldmuntz with open arms when they came bearing a proposal to build a laser in early 1959. As Gould told the author many years later, "Ray guns and so on were part of science fiction, but somebody actually proposing to build this thing? And he has theoretical grounds for believing it's going to work? Wow! That set them off, and, those colonels, they were just too eager to believe." (See Fig. 1.)

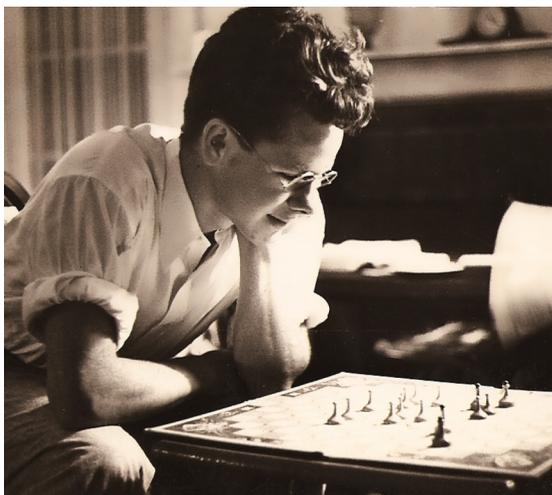
Charles Townes and Arthur Schawlow were the first to propose the laser publicly, but their vision was a modest-power oscillator. Gould had realized that the amplification of stimulated emission in an oscillator might allow a laser to generate high power and concentrate light to a high intensity. His pitch to ARPA was laden with bold ideas. He said a laser pulse could mark military targets and measure their ranges for other weapons. He predicted that laser beams could be focused to be 10,000 times brighter than the Sun, enough to trigger chemical reactions. Ultimately, he suggested, lasers might be powerful enough to destroy targets or ignite nuclear fusion.

Paul Adams, who handled ARPA's optics projects, loved the plan, and a review panel thought prospects for laser communications, target designation, and range finding were good enough to justify the \$300,000 grant requested. Adams was so enthusiastic that he pushed through a \$999,000 contract for a bigger program at TRG Inc., the company Goldmuntz headed. Then the Pentagon tossed a monkey wrench into the works by classifying the laser project and denying Gould a security clearance because of his youthful dalliance with communism. He could not work on the project he had created.

The press also focused on the idea of laser weapons. When Ted Maiman announced he had made the first laser, reporters asked if the laser was a "death ray." After trying to duck the question, he finally admitted he could not rule out the possibility. When he returned to California, he found the *Los Angeles Herald* carrying a headline in two-inch red type: "L.A. Man Discovers Science Fiction Death Ray."

After Maiman's success, ARPA expanded its program to study laser mechanisms, materials, and beam interactions with targets. The Air Force gave Maiman a contract to develop ruby lasers, and other military labs started their own laser projects. The armed services focused on near-term applications in missile guidance and communications; ARPA focused on high-energy laser weapons.

Although many physicists were skeptical, they also hesitated to oppose Pentagon plans. After weapon scientists said nuclear re-entry vehicles were so sensitive to thermal shock that laser heating might shatter them, ARPA's laser-weapon budget was boosted to \$5 million. Air Force Chief of Staff General Curtis LeMay jumped on the laser bandwagon, saying on 28 March 1962 that "beam directed energy weapons would be able to transmit energy across space with the



▲ Fig. 1. Gordon Gould. Courtesy of Geoffrey Gould, 1940.

continuous wave from CO<sub>2</sub> at 10 μm in mid-1965. That was enough to satisfy his research needs, but it only whet the appetites of military labs, which began scaling CO<sub>2</sub> lasers to impractical sizes. Hughes reached 1.5 kW using a 10-m oscillator followed by a 54-m amplifier.

The real breakthrough to high-energy lasers was the gasdynamic laser, developed by Arthur Kantrowitz and Ed Gerry at the Avco Everett Research Laboratory near Boston. They knew that sustained laser power would have to reach a megawatt to damage a military target—and figured they might reach that level by drawing 0.1% of the energy from a rocket engine, which could generate a gigawatt by burning chemical fuel to generate hot CO<sub>2</sub>. Expanding the gas through special nozzles at supersonic speed produced a population inversion. “It was a very simple thing, but not a very efficient laser,” recalled Gerry. First demonstrated in 1966, the gasdynamic laser was kept classified until 1970. By then Avco had exceeded 100 kW, although Gerry was only allowed to report 50 kW at the time.

That power level attracted interest from the armed forces, and Avco built three 150-kW gasdynamic lasers, one for each of them. Moving targets proved a challenge. When the Air Force tried to hit a drone flying figure-eight patterns, the beam locked onto a weather tower and melted it. In 1973, the laser finally shot down a weakened drone. The next step was squeezing a 400-kW gasdynamic laser into a military version of a Boeing 707 to make the Airborne Laser Laboratory. Two years after an embarrassingly public failure in 1981, it finally shot down an air-to-air missile over the Naval Weapons Center in China Lake, California. That was the end of the line for the gasdynamic laser, a monster of such size and complexity that critics called it a ten-ton watch.



▲ Fig. 2. MIRACL. Courtesy of U.S. Army Space and Missile Defense Command.

speed of light and bring about the technological disarmament of nuclear weapons.” The Air Force Systems Command budgeted \$27 million for a five-year “Project Blackeye” to develop ground-based anti-satellite lasers and perhaps a space-based laser weapon.

But early laser technology was not up to the task. American Optical pushed neodymium-glass lasers to generate 35-J pulses, but thermal effects shattered the rods. The same happened to ruby rods when Westinghouse pushed Q-switched pulse energy to 60 to 80 J. Discouraged, ARPA scaled down its solid-state laser weapon program around 1965.

By that time, the carbon-dioxide laser was showing hints that gas lasers could reach high powers—and could conduct away troublesome heat. C. Kumar N. Patel generated 200 watts

After the Big Demonstration Laser built by TRW exceeded 100 kW, the Navy focused its attention on chemical lasers because moist air transmits better at the 3.6- to 4.0-μm band of deuterium fluoride. In 1978, the 400-kW Navy ARPA Chemical Laser (NACL) became the first chemical laser to shoot down a missile in flight. TRW then built the first megawatt-class laser, the Mid-Infrared Advanced Chemical Laser (MIRACL) (Fig. 2). The giant laser, finished in 1980, could emit 2 MW, but only for seconds at a time. Focusing that tremendous power through the air to a moving target proved an overwhelming challenge, and by the early 1980s the armed services

had lost their enthusiasm for deploying laser weapons.

DARPA, renamed the Defense Advanced Research Projects Agency in 1972, had spent the 1970s trying to develop high-energy lasers at short wavelengths. Projects included x-ray, free-electron, and excimer lasers. At the end of the decade, DARPA proposed building three testbeds for testing space-based defense against a nuclear missile attack: a high-frequency laser called Alpha emitting 5 MW at  $2.7 \mu\text{m}$ , a 4-m high-power space mirror called the Large Optics Demonstration Experiment (LODE), and a pointing and tracking system called Talon Gold.

Then Lockheed engineer Max Hunter proposed an even bolder plan, using that technology to build a fleet of 18 orbiting chemical laser battle stations to block a Soviet nuclear attack. He claimed that 17,000-kg satellites could carry the laser, the optics, and enough fuel to fire 1000 shots at targets up to 5000 km away, and proposed launching them on the space shuttle. Senator Malcolm Wallop embraced the plan and in 1979 claimed it could be built for \$10 billion.

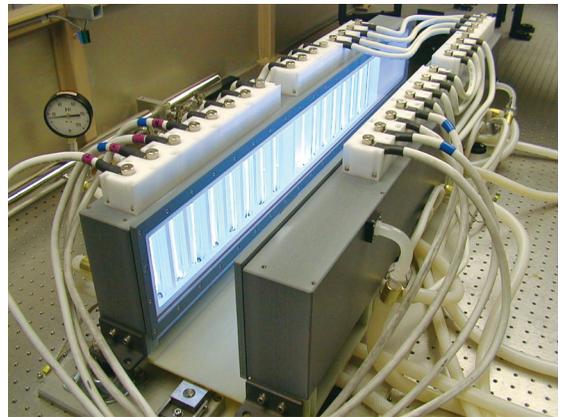
Ronald Reagan's Strategic Defense Initiative took over the DARPA space laser projects in 1983, envisioning them as part of a multi-layer defense system designed to block a Soviet nuclear attack. SDI also poured money into plans for space-based x-ray lasers (Fig. 3) and massive ground-based free-electron lasers to be paired with orbiting relay mirrors. Most of the laser community was skeptical—to say the least—but SDI spending on optics peaked around \$1 billion a year in the mid-1980s, including optics for beam direction, target tracking and other purposes, as well as high-energy lasers.

A ground-based demonstration of the Alpha laser achieved megawatt-class output in 1991, but after the end of the Cold War, most of the big high-energy laser missile defense programs faded away. They were replaced by a missile defense program that at the time seemed more realistic than orbiting laser battle stations: the Airborne Laser. The plan called for installing a megawatt-class chemical oxygen-iodine laser (COIL) in a modified Boeing 747 to defend against a few missiles launched by a “rogue state” such as North Korea. Emitting at  $1.3 \mu\text{m}$ , the COIL included an adaptive optics system designed to deliver lethal power to missiles rising through the atmosphere up to a few hundred kilometers away. After falling several years behind schedule, it destroyed two test missiles in February 2010, but results fell far short of operational requirements, and the program was canceled.

Ironically, as the Airborne Laser faltered in the 2000s, dramatic advances in diode-pumped solid-state lasers opened the door to a new class of laser weapons, vehicle-mounted systems powered electrically rather than by special chemical fuels. They are designed to stop rocket, artillery, and mortar attacks by detonating the munitions in the air at ranges to a few kilometers. A key demonstration was the Joint High Power Solid State Laser (JHPSSL) (Fig. 4), a diode-pumped neodymium-slab laser built by Northrop Grumman, which fired 100 kW continuous wave for five minutes in March 2009. More recently, the multi-kilowatt beams from several industrial fiber lasers have been combined and used to shoot down rockets.



▲ Fig. 3. Space-based x-ray laser art. Courtesy of Lawrence Livermore National Laboratory.



▲ Fig. 4. Inside view of Joint High Power Solid State Laser (JHPSSL). Courtesy of U.S. Army Space and Missile Defense Command.

Big challenges remain in making high-energy lasers that can fire reliably on the battlefield, with key issues including keeping the optics clean, avoiding optical damage, building durable cooling systems, and making the lasers reliable and affordable. But the task is also vastly easier than SDI's goal of building orbiting battle stations capable of blocking a massive Soviet nuclear attack.

Note: This article was adapted from [1].

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# KH-9 Hexagon Spy in the Sky Reconnaissance Satellite

Phil Pressel

In 1965, Central Intelligence Agency Director John McCone laid down a challenge to a selected few companies with experience in designing cameras for the intelligence community. He wanted a new generation of surveillance satellites that combined the broad area coverage of CORONA with the high resolution of the KH-7 GAMBIT.

Thus was born what would eventually become the KH-9 Hexagon spy satellite. It was the last film-based orbiting reconnaissance camera for the United States government. It was a marvel of engineering achievements that resulted in a fine optical instrument that was capable of taking stereo photographs of the entire earth as well as concentrating on small areas of interest and able to distinguish objects two to three feet in size from an altitude of 90 miles above the earth. The system would become an invaluable asset and provided intelligence information credited with persuading President Nixon to sign the SALT-1 treaty in 1972. It was also acknowledged at the time to have been “the most complicated system ever put into orbit.” The first launch was on 15 June 1971 and the last of 19 successful missions sadly exploded 800 feet above the pad on 18 April 1986 just a few months after the tragic *Challenger* explosion.

The vehicle weighed 30,000 pounds, was 60 feet long and 10 feet in diameter, and each of the two cameras carried 30 miles of film. The film traveled at speeds up to 204 in./s at the focal plane and was perfectly synchronized to the optical image captured by a constantly rotating scanning camera. The exposed film was periodically returned to Earth in four re-entry vehicles caught by an Air Force C-130 over the Pacific. A photograph of the entire vehicle and a schematic diagram of the vehicle are shown in Figs. 1 and 2, respectively.

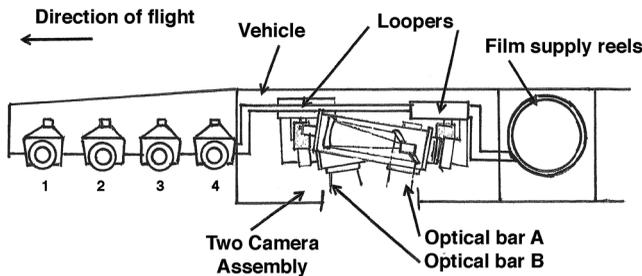
The story started out as the author was working for the Perkin-Elmer Corporation, and with a small group who studied the concept for over a year. The results were presented to the CIA at night in an innocuous-looking safe house in Washington, DC. Albert “Bud” Wheelon, the first CIA Deputy Director of Science and Technology (from 1963 to 1966) said that the agency thought highly of the group’s concept.

The group then spent an extremely intense six weeks writing a proposal. It culminated in May 1966 when Perkin-Elmer CEO Chester Nimitz, Jr., the son of the famous World War II admiral, stood up at the end of the final proposal presentation to the CIA, put his foot up on a table and said, “We want this f—g job and we’re gonna get every f—g agency and every f—g engineer from here to Florida. We recognize the importance to national security and we’re capable of doing the job.” It was a memorable event.

A second memorable event came five months later on 10 October 1966, when the group was told to gather at 10 a.m. in the large engineering room, in an isolated and secure area across the street from one of Perkin-Elmer’s two main plants. Group vice president Dick Werner, the group’s program manager Mike Maguire, and contract specialist Charley Hall walked in shortly after 10. They were all dressed in stylish suits. In those days everyone wore ties and jackets, although the latter were soon discarded as each day progressed. As they reached the front of the room Dick reached into his right inside jacket pocket and took out one of the longest cigars imaginable. The first words out of his mouth were “We won.” A great cheer went up from the



▲ Fig. 1. Photo of the Hexagon vehicle (minus 2 re-entry film capsules).



▲ Fig. 2. Schematic of the entire Hexagon vehicle.

heard, and it turned out to be a lucrative investment, especially for those who had the courage to invest “serious” funds. The company stock split seven times in the next dozen years.

Hiring a skilled technical staff was difficult because the program was top secret, so potential candidates could not be told the nature of the program or the specific tasks to which they would be assigned. In addition, completing the required background and security checks took from four months to a year, and permanent employment depended on clearing security screening.

New hires were told not to discuss or even speculate with others what the program was about. While awaiting their clearances, most of them worked on unclassified projects in a non-secure part of the building called “the tank.” It also was called “the mushroom patch,” because the people working there were kept in the dark and fed a lot of crap.

Everyone in the tank eagerly awaited their security clearance. Dick Carritol, a systems and servomechanism engineer, recalls being called to the security office. “I was given a bunch of documents to read and sign. I remember being awed by the words I was reading. It seemed like I was being told more than I needed to know. After 40 years the memory is a little hazy, but I do remember something like this: ‘... a study program leading to the design and development of a photo reconnaissance satellite, to conduct covert operations for the CIA, under cover as the Discoverer Program. This high resolution system is to carry out search and surveillance missions over the Sino-Soviet Bloc... the program name is FULCRUM.’” (It later was changed to Hexagon.)

Carritol continues: “The documents droned on about not revealing, acknowledging, or commenting on the existence of the program, the program name, the customer’s name, or any of the participants in the program. This ban on discussion included everyone from one’s family and friends all the way to others on the program with the proper security clearance but without an explicit need to know.”

“When I had finished all the reading and signing, the security officer asked if I was surprised. I didn’t have a feeling of surprise. I felt numb. I had just read a lot of words and concepts that I had never considered before. Covert Operations, Under Cover, Search and Surveillance of the Sino-Soviet Bloc, and compartmentalized security clearances were all new and quite foreign to me. I had a lot to learn! No, I didn’t feel surprise, I felt like I had just joined the ‘Big Leagues.’”

The design environment in the late 1960s was very different from that of today. Computers were large general-purpose mainframes which received input on punched cards and produced output on magnetic tape or an impact printer. Analysis programs were limited to early versions of NASTRAN (for mechanical structural analysis) and SINDA (for thermal analysis).

group. Dick and Mike then each spoke a few words of praise for the great team effort along with wishes for success in this new adventure.

As soon as the meeting broke up, group members immediately made phone calls. Many called their wives to say that the group had won a big program that would keep them employed for a long time.

Some employees called their stockbrokers to buy as much Perkin-Elmer stock as they could afford. Of course, this was illegal as it was trading using insider information. The next day a secretary went around asking everyone if they had purchased shares and if so, how many. This list was eventually given to the Perkin-Elmer legal department, and all who had bought stock expected to be reprimanded and possibly made to sell the shares or void the purchases. But nothing further was

There were no CAD (computer aided design) systems. Designs were drawn on drafting boards using pencils, and major changes required much erasing or starting a new drawing from scratch. Large machines that used ammonia and other chemicals copied the drawings to make real “blueprints.” The smell of ammonia permeated the blueprinting department, and copies retained the odor for quite a while. There were no graphic printers or displays, and drawings could not be rotated on a screen and nor parts observed in three dimensions. Most engineers did math on slide rules or desktop calculators; pocket electronic calculators did not arrive until the early 1970s. By modern standards, the tools used for testing, visualizing, and analyzing, and in some cases for fabrication, were antiques.

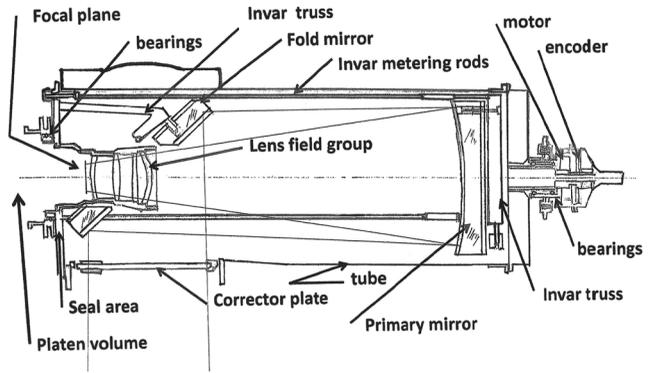
Each camera, called the optical bar, was an  $f/3$  folded Wright optical system with a focal length of 60 in (152.4 cm). Its configuration is shown in Fig. 3.

Each of the two identical optical bars contained an entrance window, a fold-flat mirror, a 26-in. primary mirror, and a field group of lenses. The mirrors were 4 in. thick and made of two faceplates fused to a hollowed-out core and made by the Heraeus Corporation. Perkin-Elmer polished them to an rms wavefront quality of  $1/50$ th of a wave. The image was imposed on the focal plane located 1 in. behind the last lens. One optical bar was tilted 10 deg to look forward, and the other 10 deg to look back, creating a 20-degree stereo angle. A two-camera-assembly isometric is shown in Fig. 4.

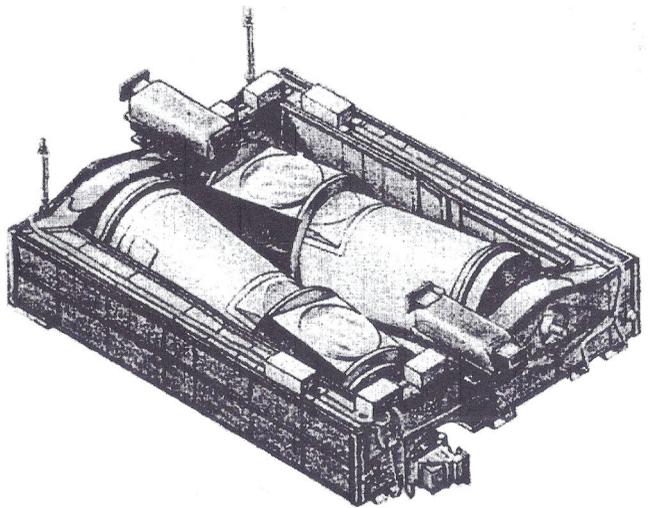
The optical bars rotated continuously in opposite directions during photography, as did the other major rotating components of the vehicle, for momentum compensation. They rotated at a constant speed depending on  $V/h$  (the orbital velocity divided by the altitude above the earth). Photographic imaging occurred only during scans of  $\pm 60$  degrees or less on either side of nadir (looking straight down). During photographic scans the film’s linear velocity and rotational speed (that was also a function of  $V/h$ ) in the platen had to be synchronized exactly with the moving image.

The film exited the supply reels at a constant velocity of 70 in./s. After the film left the supply, it had to be moved in accordance with a prescribed film velocity profile to enable photography to occur at the proper time and to utilize as much of the film as possible. The film path, shown in Fig. 5, was approximately 100 feet long and contained many rollers over which the film traveled. The film was accelerated to photographic speed in the platen.

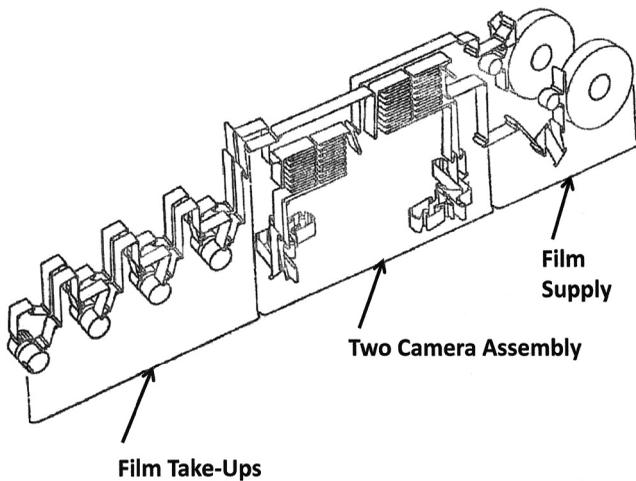
The platen was the assembly that controlled film speed and synchronization with the image at the focal plane. At perigee, the lowest point in the satellite’s orbit, the film speed was 204 in./s. After the exposure occurred, the film was decelerated and driven backward so that the next exposure was made with only 2 in. of film between exposures. The film was then stopped so that an electronic data block could be inscribed on the film in this narrow space. At altitudes higher than perigee, all of the film and camera rotational speeds slowed down proportionately.



▲ Fig. 3. The optical bar.



▲ Fig. 4. Two-camera-assembly isometric.



▲ Fig. 5. Overall system film path schematic (cameras not shown).

film during the non-photographic cycle (240 deg or more) of the optical bar was accomplished by means of a film storage device called the looper. It contained a carriage and many rollers. The carriage traveled linearly back and forth. During motion in one direction it drew the proper quantity of film from the supply reels into the entrance side of the looper while simultaneously feeding film into the platen for exposure.

After exposure the film during the reverse motion was stored in the exit side of the looper. It was then wound up at constant velocity again at 70 in./s onto the take-up assembly in the forward section of the vehicle. After the first of four take-up reels (each in its own re-entry vehicle) was filled, the film was wound and cinched onto the core of the next take-up reel then cut. At the appropriate time during one of the next orbits the filled re-entry vehicle was jettisoned and returned to earth.

It took almost five years of development and testing to reach the next big date, which was 15 June 1971. The author sat next to Mike Maguire, the group's director and general manager, and several others in the "war room" listening to the Vandenberg launch controller countdown to ignition and liftoff of a Titan 3D rocket with about 3 million pounds of thrust. Silence followed, then periodic updates on altitude and speed. Eventually the controller confirmed that the payload had reached orbit. It would be the first of 19 successful launches.

Known to the public as "Big Bird," Hexagon succeeded beyond anyone's dreams. The program helped ease Cold War tensions and became the most successful film-based spy satellite the United States ever orbited. It was eventually succeeded by electronic digital imaging systems that could deliver images to the ground much faster than possible with film.

The last date etched in the author's memory was 18 April 1986. For the twentieth time, the countdown was heard: "Ten, nine, eight, seven, six, five, four, three, two, one, launch, we have liftoff." A noisy and powerful exhaust came from the rocket as it rose off the pad at Vandenberg Air Force Base in California. Then disaster happened. The rocket exploded in a fiery blast before it reached 1,000 feet, destroying the last Hexagon. Those who worked on the program could not share their stories for another quarter century, until the National Reconnaissance Office finally declassified the program in a 17 September 2011 ceremony attended by the author along with many colleagues who had worked on the Hexagon project.

This chapter was based on [1].

## Reference

1. P. Pressel, "Spy in the sky: the KH-9 Hexagon," *Opt. Photon. News* 24(10), 28–35 (2013).

# CORONA Reconnaissance Satellite

Kevin Thompson

The CORONA program came at a time when classified optics programs were in their steepest ascent toward a mission to literally save the world. But very few people realized it at the time because it was among the most classified of all classified programs. Outside of a team of fewer than 100 scientists, at one point only six people, including President Eisenhower, were aware of the work that together with the U2 surveillance plane helped save the world from nuclear war. Significantly, a single person was behind the success of both CORONA and the U2 missions: Richard Bissell of the CIA.

Initiated just weeks after the Soviet *Sputnik* launch, CORONA was at the cutting edge of technology and a remarkably visionary program. It anticipated that the high-altitude U2 could be brought down, as it would be in 1960. Its crucial role was to cast the light of knowledge onto the dangerous shadows of speculation about Soviet capabilities. At one point, advisors told Eisenhower that the U.S. needed 10,000 nuclear warheads to catch up. The U2 and CORONA together provided hard evidence that if there was a “missile gap,” it was the Soviets who were behind. The first successful CORONA mission acquired ten times more information than all of the preceding U2 missions combined. Eisenhower’s visionary program was a credit to his presidency, and kept President Kennedy from overreacting to the Cuban missile crisis in 1962.

The saga of CORONA has been the subject of a number of good books since its declassification in 2004. A major reference for this article was *ITEK and the CIA* [1], which offers a substantial, factual account of the CORONA program. The most readable history of CORONA, which covers many of the technical and operational issues, is *Eye in the Sky: The Story of the CORONA Spy Satellites* edited by Day, Logsdon, and Latell [2], in the Smithsonian History of Aviation Series. Another important resource for this essay was a plenary talk given at the 2004 SPIE annual meeting by (the late) Robert S. Hilbert, one of the principal optical engineers on CORONA for nearly a decade before becoming the leader of Optical Research Associates. The author worked with him for nearly 20 years.

CORONA, like the U2, proceeded from concept to flight hardware in a matter of months, an incomprehensible pace today. The multidisciplinary team of engineers and scientists were armed primarily with slide rules and engineering judgment, and they had only limited computer simulation capabilities. But they were unencumbered by any significant management or budget constraints and were driven by genuine personal urgency to move ahead at a pace that was perhaps matched only by the earlier U2 program at the Burbank Skunk Works. The engineering team, fortuitously, had been together for some years. Nearly all had worked at a reconnaissance research facility at Boston University. The university was in a financial crisis when Eisenhower commissioned CORONA and was disbanding the reconnaissance group, which was quickly bought by the newly formed Itek Corporation, formed with funding from David Rockefeller.

Rockefeller was an outspoken conservative who decided that if he would not implement his vision of a better world politically, he would create it by backing key technologies that enabled his goals. He was a visionary who saw that gaining knowledge of the unknown was a key to ensuring the future. At the time, Eisenhower was crippled by having no information at all about vast expanses of adversarial countries. This lack of knowledge led to speculation that potential adversaries had vast arsenals, as well as strong pressure from the military, the press, and the public to arm the U.S. well beyond its means. Eisenhower made a key decision, that knowledge at any monetary cost was the best option.

Rockefeller's role was vital because the president could not directly ensure that Itek had the financial resources needed for the program. Because Eisenhower's key military advisors knew nothing about CORONA, he was continually challenged as being indecisive in ways that were clearly rational in light of the super-secret project. As one of the six people briefed on the program outside of Itek, Rockefeller understood this. However, he was the only Rockefeller briefed, and Itek needed so much financing that he had to involve his brothers. This led to some suspense in the story of Itek, but in the end all the Rockefellers invested—and reaped the financial benefits by a timely exit from Itek before Perkin-Elmer won a vital contract for the follow-on Hexagon (“Big Bird”) program.

Edwin Land, the founder of Polaroid, was a second key technology advisor and an important link between the optics community and the president. At a time when the Air Force was pushing for a first-of-its-kind crash program in electronic imagery from space, it is likely, but unverified, that Land kept the CORONA mission firmly based in film (although the film was to come from Kodak). Although the program was Eisenhower's highest priority, its classification level made it impossible to get priority access to new technology, in particular a critical polyester base film from Kodak. After the project stalled because it lacked the special film they needed, Bissell quietly intervened and a large batch suddenly arrived.

The exposed film had to be returned to Earth for processing, so it was jettisoned in a capsule that was supposed to be caught in the air by a C-130 aircraft. To make sure the film did not fall into the wrong hands, the capsules had salt plug seals that dissolved in an hour to drop them to the bottom of the sea. Only the film returned to earth, so each mission needed a new camera. The logistics of this were staggering.

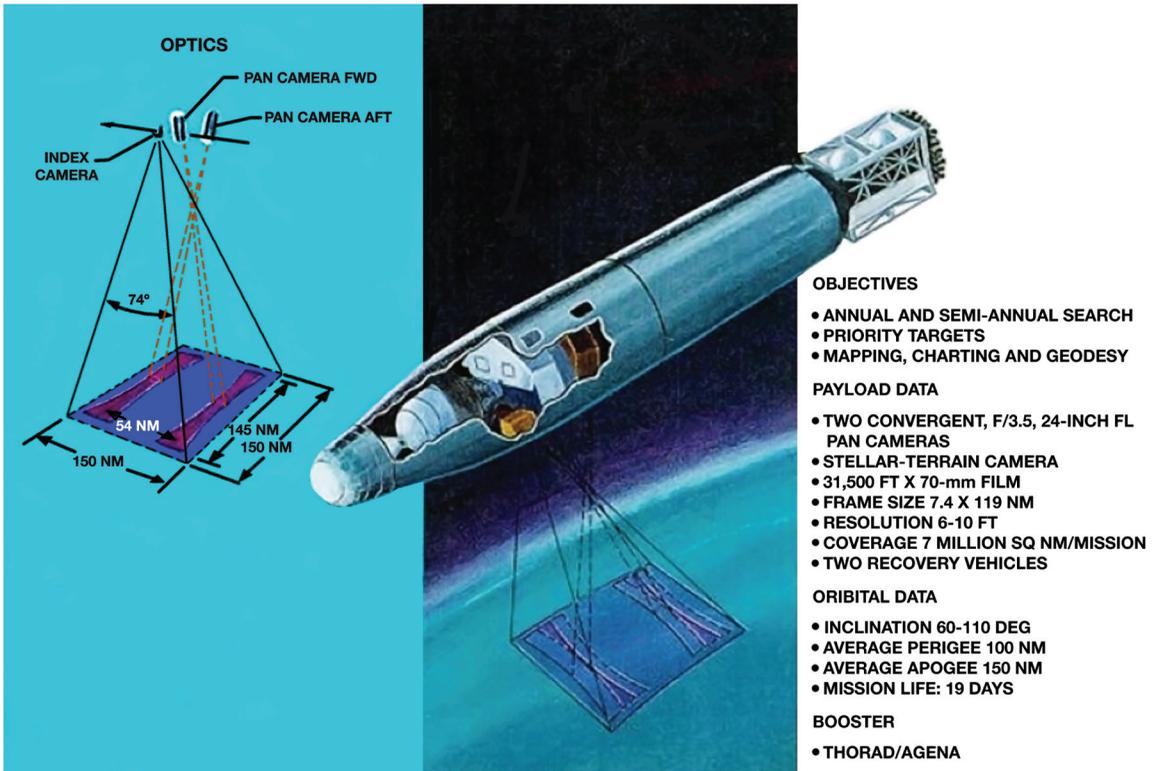
The CORONA program became the definition of perseverance, determination, and perhaps desperation. The crash program went through a long series of failures, often with the rocket simply blowing up on the launch pad, a problem not related to CORONA. That might be expected at the beginning of the space age, but for a year it set a grueling pace for the scientists. Bob Hilbert would typically arrive at the office between 10 a.m. and noon for technical meetings and exchanges and then work through to midnight. At midnight, he would put on his optics engineer hat and work on computer simulations until 4 a.m. because the computer time was too expensive at other hours. His wife always had his dinner prepared when he arrived, at 4:15 a.m., seven days a week.

The stakes were raised after the Soviet Union shot down a U-2 over Siberia on 1 May 1960, stopping flights that had been the best source of surveillance data. On 10 August, the fourteenth CORONA launch successfully orbited a capsule carrying an American flag, but the recovery aircraft flew in the wrong direction. Fortunately, a Navy ship was able to retrieve the capsule. The next launch came on 18 August, carrying a camera that operated successfully and ejected film that was successfully recovered.

The composite graphic in Fig. 1 gives a good overview of the CORONA equipment. Instead of stabilizing the capsule by spinning it in orbit, which would make photography difficult, Itek scientists stabilized it with small microjets. The camera itself needed to move back and forth in a pendulum-like motion to image from side to side. These requirements prevented use of the Fairchild camera used for imaging in the Korean War, so Itek had to design their own based on earlier ideas for a panoramic camera for imaging large swaths of the ground by sweeping in a cross-track direction as the satellite orbited.

The chosen orbit was a north–south one synchronous with the sun to provide maximum high-latitude coverage during daylight. Initial designs used an oscillating lens to focus the image onto a curved platen carrying the photographic film. Traditional aerial photography generally used long focal lengths to produce large-scale images to record sufficient detail with the limited resolution of photographic film. However, the size and weight restrictions of early satellite systems limited the focal length and the amount of film that could be carried to orbit. CORONA had to achieve very high resolution in a compact system constrained by film handling and dynamic limitations.

Robert Hopkins of the Institute of Optics suggested a Petzval-type design to meet the camera resolution requirements. Itek engineers directed by Walter Levison, Frank Madden, and Dow Smith generated a novel Petzval design that mounted primary and large-aperture imaging components in a constantly rotating lens barrel and put the lower-tolerance field flattening components near the focal surface in a lightweight oscillating arm that defined the image location. These two assemblies operated



▲ **Fig. 1.** A pair of convergent f/3.5 cameras produce stereo images of the ground on 70-mm film, with each frame covering 7.4 by 119 nautical miles. (Courtesy of Bob Hilbert, Itek.)

synchronously to “wipe” the image across the photographic film. The film was advanced when the lens was rotating in a non-image collecting part of the cycle and was dynamically located relative to the lens just at the time of exposure by rollers attached to the oscillating field flattener assembly.

The result was a minimum-weight camera that could fit across the width of the spacecraft and allowed the inclusion of two cameras to provide stereo coverage of the entire imaging swath. The optical components also needed to exhibit appropriate lateral shifts during the panoramic scan to provide image motion compensation and reduce along track blur in the recorded image. Additional optics recorded stellar index images on the film to aid geo-location of targets. The result was a remarkable synthesis of optical, mechanical, and electrical systems that were the most complicated, and eventually reliable, systems of their kind to be incorporated in a spacecraft at the time.

Figure 2 shows a test exposure taken from an aircraft flying over Manhattan, which illustrates the strong distortion of the wide-panorama photos. One of Bob Hilbert’s key responsibilities was the optical design and manufacture of the “rectifier” lens based on a concept credited to Claus

► **Fig. 2.** Stereo cameras used in Corona have high resolution combined with large intrinsic distortion, shown in this image of Manhattan taken from 10,000 feet. (Courtesy of Bob Hilbert, Itek.)



Aschenbrenner. The idea was to construct a lens that exactly reverses the distortion of the taking lens, a very effective approach still used in cinematography. The rectifier lens imaged returned film onto a second film image that was corrected for panoramic scan distortion.

Once it was finally successful, CORONA went on 85 successful missions, the last launched in 1972. Its career, and that of Itek and Itek's scientists and engineers, was ended somewhat unceremoniously when the follow-on program was canceled in what was primarily a political battle and passed on to Perkin-Elmer, who successfully developed a wide area photographic imaging system with a new name, Hexagon, nicknamed "Big Bird." Itek did later develop a precision large-format mapping camera which flew along with many of the Hexagon missions.

CORONA optics presented challenges, but the complex film transports represent impressive engineering feats. The preceding article by Phil Pressel describes the film transports used in the larger Hexagon program, sort of a CORONA on steroids.

These pioneering optical systems are now on display. You can view a CORONA camera at the National Air and Space Museum in Washington, D.C. Samples of the Hexagon and GAMBIT systems are viewable at the National Museum of the U.S. Air Force in Dayton, Ohio.

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# Laser Isotope Enrichment

Jeff Hecht

The idea of laser isotope enrichment grew from the laser's ability to concentrate its output power in a narrow range of wavelengths. Different isotopes of the same element are very hard or impossible to separate chemically, but the difference in their masses leads to differences in their spectra, which in principle can be used to selectively excite one isotope and isolate it by some photo-induced process.

The first proposal came from the Atomic Energy Commission's (AEC's) Mound Laboratories in Miamisburg, Ohio, which in 1961 began a classified investigation of using lasers to enrich the concentration of fissionable uranium-235. Others independently proposed laser uranium enrichment. A company called Radioptics proposed it to the AEC in 1963 and later unsuccessfully sued the AEC for violating their trade secrets. A French group received a patent in France in 1965, and by the time a U.S. version of the patent issued in 1969 the idea was looking attractive.

The impetus came from the development of the tunable dye laser and the growth of nuclear power. The U.S. depended on the gaseous diffusion process developed during World War II to enrich U-235 concentration to the levels needed for atomic bombs. Gaseous diffusion is energy-intensive, expensive, and raises U-235 concentration only a small amount on each pass. Laser enrichment offered to reduce cost, improve efficiency, and increase recovery of U-235.

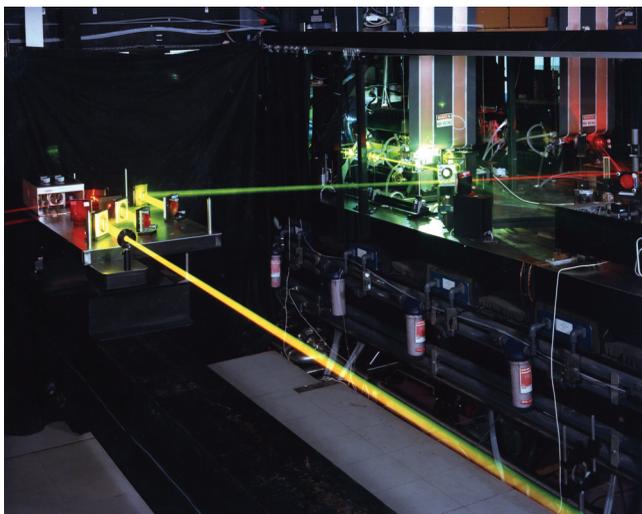
At the Avco-Everett Research Laboratory, Richard Levy and G. Sargent Janes developed a two-step process to enrich U-235. First a dye laser would selectively excite U-235 atoms in uranium vapor, then an ultraviolet laser would ionize the excited U-235 atoms, so they could be collected [1]. (Figure 1 shows the process.) Avco lacked money to develop the technology, so they formed a joint venture with Exxon Nuclear, hoping to build a private uranium enrichment business.

Avco-Everett founder Arthur Kantrowitz initially worried that laser enrichment might open the door to nuclear proliferation. "At first glimpse it seems like it's a garage operation. A garage operation for separating uranium isotopes is a frightening thing," he recalled in a 1985 interview. He imposed special security restrictions but eventually realized "this is not an easy way to make a bomb. It might be an easy way to make 1000 bombs, but it is not a terrorist operation" because of its technical complexity [2].

In 1972 the AEC launched competing laser uranium enrichment projects at its Los Alamos and Livermore laboratories.

John Emmett, director of Livermore's laser program, chose to try selective excitation of U-235 atoms in uranium vapor with the relatively well-developed tunable dye laser. That paralleled the Avco approach but was based on earlier work by Ray Kidder of Livermore. They proposed a two-step process, starting with using visible output of a narrow-band dye laser tuned to excite U-235, then ionizing the excited uranium atoms. In early 1973 Livermore hired three developers of the first continuous-wave dye laser from Eastman Kodak, Ben Snavely, Otis Peterson, and Sam Tuccio, to start and manage the program. "It seemed like an exciting thing to do at the time," Snavely recalled many years later, an opinion echoed by the other two.

At Los Alamos, Reed Jensen and John Lyman chose to try selective enrichment in  $\text{UF}_6$ , the compound used in gaseous diffusion, which sublimates at about 55 deg Celsius and is easier to handle than uranium vapor. They found a large isotope shift in a 16- $\mu\text{m}$  absorption band of  $\text{UF}_6$  and discovered that ultraviolet photons could photodissociate excited  $\text{UF}_6$  molecules, precipitating solid  $\text{UF}_5$  from the gas phase reaction and releasing free fluorine into the gas. Developing



▲ **Fig. 1.** The Avco-Everett scheme for laser enrichment of uranium required the combination of four laser beams to produce the desired wavelengths to select U-235. (AVCO Research Laboratory, courtesy AIP Emilio Segre Visual Archives, Physics Today Collection.)



▲ **Fig. 2.** Four milligrams of uranium with its U-235 concentration enriched to 3% by a dye laser process at Livermore is visible at the bottom of this test tube—the first time this much uranium was enriched by lasers. 1975 photo from the Lawrence Livermore National Laboratory. (Lawrence Livermore National Laboratory.)

the process would require finding a narrowband 16- $\mu\text{m}$  laser that could generate enough power to dissociate  $^{235}\text{UF}_6$ . Los Alamos chose C. Paul Robinson to be the director of the program to solve all those problems.

At Livermore, Snively clashed with Edward Teller and particularly recalled Teller's disapproval of a metal-vapor process that eventually was adopted for the Atomic-Vapor Laser Isotope Separation (AVLIS) program (see Fig. 3). When Snively told him he expected the process to succeed by the end of September, Teller grumbled, "You mean by the 31st of September?" Snively ignored him, and Teller pointedly said, "You know September has only 30 days." Snively then replied, "Yes, I knew that, but I wasn't sure that everybody knew it," and Teller threw him out of his office. Yet Snively recalled that after he succeeded, Teller made a point of congratulating him when they met at a University of California ceremony.

Livermore was the first to report uranium enrichment in June 1974 at the International Quantum Electronics Conference in San Francisco. They illuminated a beam of hot uranium vapor with a dye laser emitting near 590 nm, selectively exciting U-235 atoms that then were ionized with ultraviolet light from a mercury arc lamp [3]. Figure 2 shows the enriched uranium oxidized to form "yellowcake" visible in the bottom of a test tube. That process would not scale to mass production, but Richard W. Solarz and Jeffery A. Paisner later found a way to coherently pump the selected isotope all the way from the ground state to an autoionization state (Rydberg level), permitting cost-effective isotope separation.

Meanwhile, Los Alamos developed a two-step process in which a 16- $\mu\text{m}$  source first excited vibration of cooled  $\text{UF}_6$  molecules containing U-235 and then a 308-nm xenon-chloride laser removed a fluorine atom from the excited  $\text{UF}_6$ . The resulting  $\text{UF}_5$  precipitated as a solid that could be filtered from the gas. Developing the cooling process was a major accomplishment; it required flowing  $\text{UF}_6$  diluted with a noble gas through a supersonic nozzle to

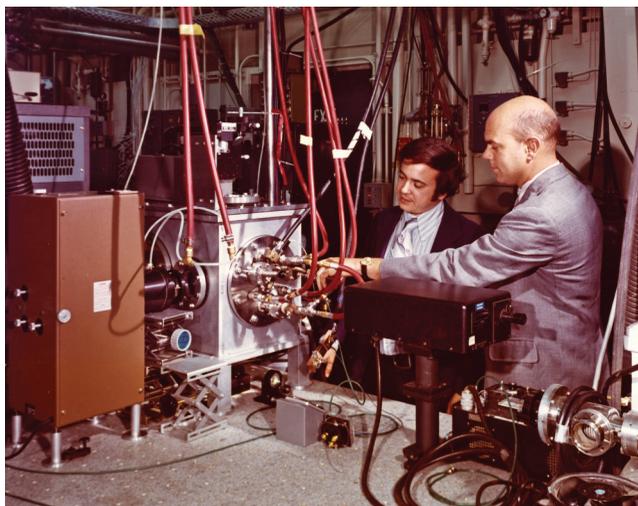
cool it while keeping it in the gas state to maintain a narrow line spectrum, and pulsing the gas flow in synchronization with the laser pulses.

Los Alamos first demonstrated enrichment in 1976, but the details were kept classified until 1978, when the news was released to *Laser Focus* in a remarkably roundabout way. A reporter first visited the lab, but researchers who showed him around the lab told him nothing about uranium enrichment results. A few days after his visit, a university researcher phoned the author to suggest that he call Los Alamos and ask, “Have you enriched macroscopic quantities of uranium?” The author did, and it was as if he had said “open sesame.” Los Alamos officials were delighted to answer “yes” and provide details on their two-step process [4]. Evidently security had authorized the disclosure only in response to those exact words.

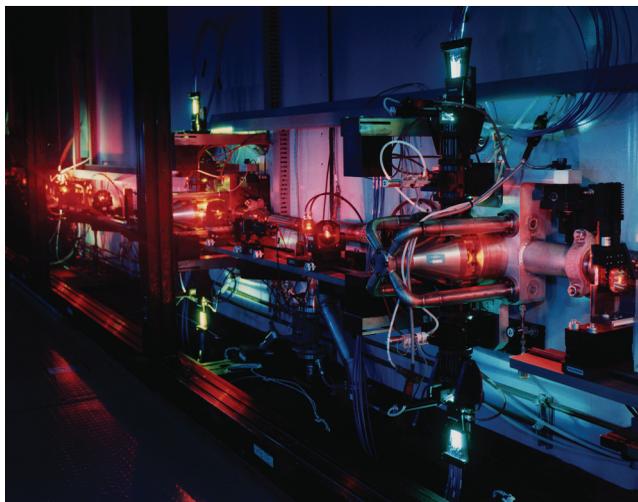
By the late 1970s, uranium enrichment was a major research program. The two competing government programs consumed a total of about a hundred million dollars a year. Jersey Nuclear-Avco Isotopes continued its atomic uranium enrichment research, spending a total of over \$70 million before shutting it down in 1981 after the government refused to fund a demonstration plant [5].

The laser community tended to see selective laser excitation as the big challenge and focused its attention on the lasers. Livermore had the more straightforward problem, and built a bank of high-power copper-vapor lasers to pump large dye lasers for its AVLIS program. By 1982, Livermore had a master oscillator/power amplifier (MOPA) array of copper-vapor lasers emitting 7 kW, pumping a dye-laser MOPA array emitting 2.5 kW day in and day out (see Fig. 4). Los Alamos needed to develop a 16- $\mu\text{m}$  source, which it achieved by Raman-shifting the output of carbon-dioxide lasers. Although details of that technology were kept under security wraps, Los Alamos was able to generate the required power and linewidth with efficiency considered reasonable at the time. The heart of that system was a hydrogen-fluoride optical parametric oscillator, developed by George Arnold and Robert Wenzel. That oscillator was originally used to perfect the spectroscopic data and was subsequently used as the seed source for the Raman-shifted carbon-dioxide laser amplifier.

Little mentioned at the time was a parallel, classified program aimed at purifying plutonium for use in nuclear weapons. Fissionable plutonium-239 is produced by irradiating U-238 with neutrons in a special reactor. However, some U-238 atoms absorb a second neutron, producing Pu-240, which



▲ Fig. 3. Benjamin Snavely (right) and Sam Tuccio examine the laser system used to enrich U-235 concentration in hot uranium vapor at Livermore. (Lawrence Livermore National Laboratory.)



▲ Fig. 4. Copper-vapor pumped dye lasers scaled for uranium enrichment at Livermore. Most of the green light from the copper lasers was tightly confined so it could efficiently pump dye lasers, which emitted red-orange light tuned to three absorption lines of U-235 vapor. (Lawrence Livermore National Laboratory.)

fissions spontaneously so only low levels can be tolerated in nuclear weapons. The “special isotope separation” program launched in 1975 was intended to produce essentially pure plutonium-239. It remained small for a few years, reaching only about \$5 million in 1980, but funding jumped in 1981, and the Reagan Administration boosted the budget to \$76 million in 1983 in a plan to assemble more than 14,000 additional nuclear warheads in the next decade. Livermore and Los Alamos each had their own plutonium projects, based on adapting their preferred processes for use with plutonium.

Although public statements stressed progress in selective laser excitation of U-235, both labs faced problems in producing a final product. The fundamental problem with both programs was that chemical and physical reactions after the successful laser-induced chemistry or ionization quickly scrambled the isotopes, making it difficult to collect the initially enriched U-235 or isotopically purified plutonium. In the Molecular Laser Isotope Separation (MLIS) program, the pentafluoride molecule could easily steal a fluorine atom from another hexafluoride molecule before it condensed on the collector. In the AVLIS case, the laser-generated ion could steal an electron during the plasma extraction process and be lost from the enriched stream.

Those problems did not deter the Department of Energy’s (DOE’s) support for laser enrichment, and in 1982, DOE picked the Livermore atomic-vapor approach for uranium and shuttered the molecular separation program at Los Alamos. As would be expected in such decisions, both scientific and political considerations affected the final outcome.

However, a slowdown in nuclear power development after the 1979 Three Mile Island reactor accident reduced concerns about supplies of enriched uranium. As fears of oil shortages eased, new technology for producing reactor fuel became a lower priority. DOE delayed its decision to build a pilot AVLIS uranium plant at Livermore until 1985. The main rationale was economic: DOE calculated that AVLIS could produce separative work units (SWUs), a measure of uranium enrichment, for as little as \$25, compared to \$70 to \$80 for gaseous diffusion. The plan called for phasing out gaseous diffusion except for highly enriched uranium, which the Livermore approach was not configured to produce.

Livermore began operating a pilot-sized laser and separator system in 1986 and spent several years refining the technology before they were able to operate full-sized equipment for tens of hours (see Fig. 5). They demonstrated plutonium enrichment first in the early 1990s, with uranium enrichment and scaling to larger scales to follow.

By this point two external developments affected the need for laser isotope enrichment. The end of the Cold War stopped the build-up of the U.S. nuclear arsenal and eliminated the pressure to purify plutonium for new nuclear warheads. It also made surplus highly enriched uranium from the Russian arsenal available for down-blending into reactor fuel at prices well below freshly enriched uranium.

The 1992 transfer of DOE’s enrichment program to the United States Enrichment Corporation put Livermore’s program on standby until July 1994. Livermore completed its uranium-enrichment pilot plant in the fall of 1997, and it processed several thousand kilograms in a series of runs involving 24-hour operation of copper-vapor pumped dye lasers spread over 1.5 years. During that time, they also demonstrated doubled-neodymium pumping of



▲ Fig. 5. One of three units for separation of U-235 in Livermore’s pilot plant for laser isotope separation. (Lawrence Livermore National Laboratory.)

the dye lasers for future pumping in a production facility. But U.S. Enrichment halted those tests in June 1999, citing low prices for enriched uranium and high internal expenses for other work [6]. Those cuts also stopped plutonium enrichment. The motivation for continuing the laser program also was hurt by the continuing successes of the centrifuge programs that had been ongoing worldwide. All told, Livermore's quarter century of laser isotope separation development had cost more than \$2 billion.

By then, molecular laser isotope enrichment had been revived by two Australians, Michael Goldsworthy and Horst Struve, who in 1990 began developing a process they called SILEX for Separation of Isotopes by Laser EXcitation. Like the Los Alamos process, SILEX is based on cooling  $UF_6$  so resonances for molecules containing U-235 and U-238 are clearly separated and the molecules are concentrated in the ground state. Excitation with a 16- $\mu$ m laser source selectively excites molecules containing U-235, producing a product stream enriched in U-235 and a "tails" stream depleted in U-235 but richer in U-238. Details are classified, but the main differences from the old Los Alamos process are thought to be in extraction of the laser-excited U-235 fraction of the material. In the information about this process there has been no hint of the laser-induced chemistry or ionization that initiated the isotope scrambling that plagued the earlier programs.

U.S. Enrichment supported Goldsworthy and Struve's work from 1996 to 2002, and after that funding stopped, they formed a public company called Silex Systems Ltd. in Australia. Silex eventually licensed a joint venture of General Electric and Hitachi called GE Hitachi Nuclear Energy to use the process. After a few years of study, GE Hitachi Nuclear applied for a license to build a pilot plant in North Carolina, which the Nuclear Regulatory Commission approved in 2012. The plan is controversial, and the final outcome remains to be seen, but after a near-death experience, laser uranium enrichment is clinging tenuously to life.

## Acknowledgment

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Thanks to Otis Peterson for assisting with this essay.

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# Lasers for Fusion Research

John Murray

Laser fusion research began [1] at several establishments shortly after the first laser operated in 1960. John Nuckolls of the Lawrence Livermore National Laboratory and others around the world quickly recognized that the laser had the potential to concentrate power to the extreme levels required for small-scale fusion tests. Theoretical analysis showed [1,2] that achieving fusion and significant energy yield with the easiest targets to ignite, a mixture of deuterium and tritium (DT), would require imploding them to extremely high density—perhaps ten thousand times normal liquid density—with nanosecond-scale pulses in the kilojoule to megajoule range. Producing the extreme pressure and fuel implosion velocity required to reach the required density would require irradiance of  $10^{14}$  W/cm<sup>2</sup> with lasers expected to be available in the near term. The challenge was to achieve significant energy yield at a size that looked reasonable for laboratory experiments.

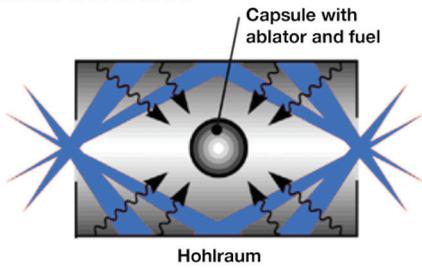
Two basic concepts for laser-driven fusion explosions were quickly developed, as shown in Fig. 1. The direct-drive implosion uses laser energy that impinges directly on a spherical target containing DT fuel within an ablator shell that absorbs laser energy and expands, compressing the remaining ablator and fuel to a small volume in the center of the target and heating it to initiate DT fusion. The indirect-drive implosion absorbs the laser energy on the inside of a heavy metal cavity or hohlraum, producing soft x-rays that illuminate the ablator and implode the fuel capsule as in the direct-drive fusion.

The direct-drive implosion requires extremely uniform irradiance to achieve spherical symmetry. Indirect-drive fusion eases that requirement by converting the laser light to soft x-rays that with proper design uniformly irradiate the central capsule. X-ray absorption in the ablator is also simpler and less subject to nonlinear processes than laser absorption. However, indirect drive couples only 10%–20% of the drive energy to the fuel capsule, so it needs a higher laser drive energy.

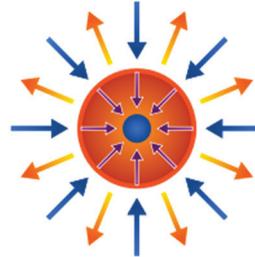
Laser sources for such small targets should store energy from a long pump pulse and deliver a carefully shaped nanosecond pulse. Development of the Q-switch and the neodymium-glass laser were important milestones, providing a nanosecond pulse source and an amplifier that could be made in large sizes and had rather low gain so that it did not break into spontaneous oscillation from stray light before the nanosecond extraction pulse. Those developments encouraged Ray Kidder of Livermore to estimate that a pulse of at least 100 kJ lasting less than 10 ns might be able to ignite a small amount of DT fuel [1].

The glass laser is not a perfect solution, however, and in the early years of inertial fusion many other options were explored. The photolytically pumped iodine laser at 1.3  $\mu\text{m}$  was identified as a promising fusion driver as soon as it was demonstrated in the early 1960s. The gas medium makes the laser less limited by nonlinear processes and much less expensive than a solid. The Asterix laser system [3] at the Max Planck Institute for Quantum Optics in Garching, Germany, and the Iskra laser system [4] at the Research Institute of Experimental Physics in Sarov, Russia (formerly Arzamas-16), were used in fusion research. Asterix, now operating in Prague, Czech Republic [5], produces up to 1 kJ in 350 ps, with frequency conversion to 657 and 438 nm. Iskra-5 reached 120 TW in 12 beams in 1991. Pumping a photolytic iodine laser with explosive-driven light sources, looked very appealing as a low-cost (but single-shot) route to megajoule energies [6], but precision control proved too difficult for use in fusion experiments.

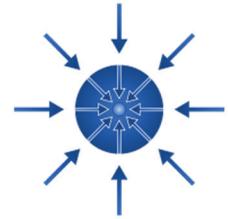
## Indirect Drive



Ablator absorbs x-rays  
Fuel is compressed

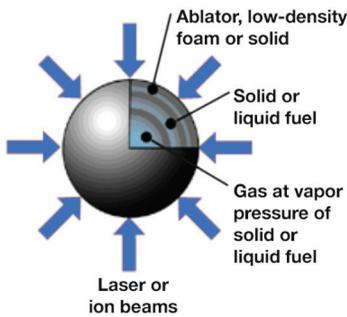


Dense main fuel  
(200-1000 g/cm<sup>2</sup>)



Hot spot in center (10 keV)

## Direct Drive



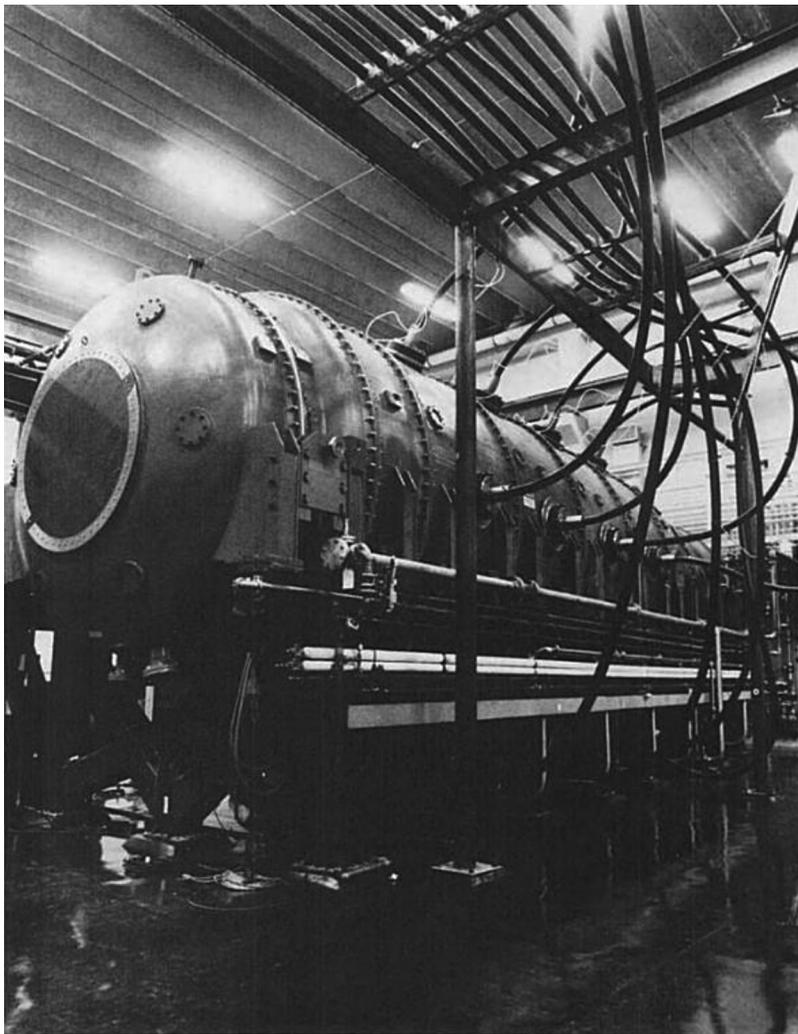
▲ **Fig. 1.** In a direct-drive target, laser beams illuminate a fuel capsule uniformly. In an indirect-drive target, they illuminate the inside of a heavy metal hohlraum surrounding the target and are converted to soft x-rays. The x-rays then implode the fuel capsule.

The 10.6- $\mu\text{m}$  carbon dioxide laser initially seemed an excellent candidate, with high efficiency, the potential for large amplifiers in large sizes, and relatively inexpensive construction. The Antares project (see Fig. 2) [7] at the Los Alamos National Laboratory directed nanosecond  $\text{CO}_2$  pulses of up to 40 kJ on a fusion target from two final amplifiers, each with 12 roughly square 30-cm subapertures. Unfortunately, the long wavelength of the  $\text{CO}_2$  laser proved a severe handicap because laser-plasma instabilities scale with the square of the wavelength, so they are two orders of magnitude larger at 10.6  $\mu\text{m}$  than at 1.06  $\mu\text{m}$ ; therefore  $\text{CO}_2$  laser fusion was abandoned in 1985.

The 248-nm krypton fluoride laser has also been explored as a fusion driver. The short wavelength is desirable for target interaction, but optics that far in the ultraviolet are difficult to develop. The KrF laser has broad bandwidth, which is desirable for beam smoothing in direct-drive fusion. At the power levels needed for fusion, it generates pulses of 100 ns or longer, which must be optically compressed to the few nanosecond pulses required for fusion. The Nike laser system [8] at the Naval Research Laboratory has explored KrF technology by stacking 56 pulses through an amplifier to give up to 4 kJ on target in 4 ns, and the Ashura laser system [9] at the Electrotechnical Laboratories, Tsukuba, Japan, has operated with up to 2.7 kJ in 20-ns target pulses. Figure 3 shows the 60 $\times$ 60-cm final amplifier of the Nike system.

The neodymium glass laser emerged as the most versatile and successful laser system for fusion research. A major advantage was that its 1.06- $\mu\text{m}$  pulses can be converted efficiently to the second and third harmonics at 532 and 355 nm, which proved less vulnerable to laser-plasma instabilities than longer wavelengths. Xenon flashlamps excite neodymium ions in the glass, which drop to the upper level of the 1.06- $\mu\text{m}$  laser transition. The transition has a lifetime of 300–400 ns and a gain cross-section high enough that energy can be extracted efficiently in short pulses with fluences tolerable for laser optics.

Early glass laser systems used cylindrical rods similar in concept to the first laser, a small cylindrical rod of flashlamp-pumped synthetic ruby crystal. The Del'fin laser system [10] at the Lebedev Institute, Moscow, Russia, used a large array of cylindrical rods serving as subapertures



◀ **Fig. 2.** Final amplifier of the Antares CO<sub>2</sub> laser system. (Courtesy of Los Alamos National Laboratory.)

within a single beamline. Amplifiers that used zig-zag laser beam propagation through large laser glass slabs were also explored [11].

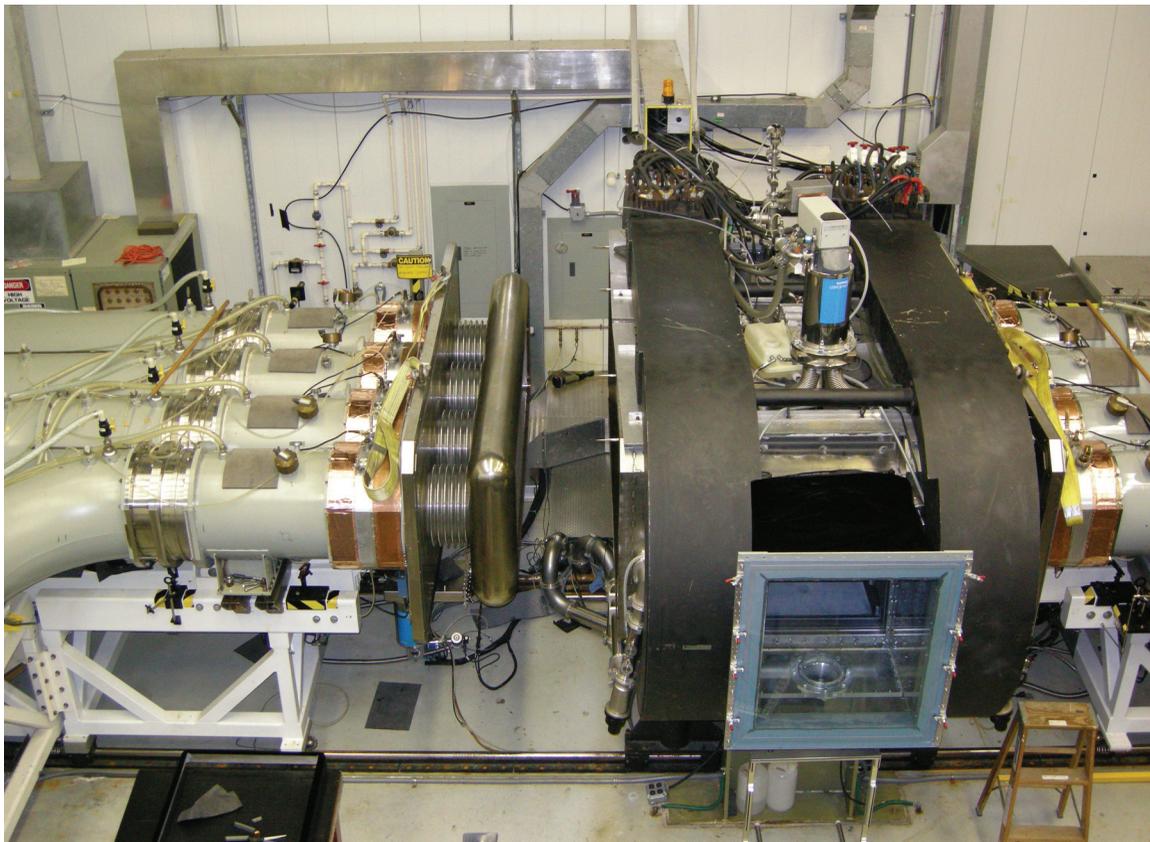
Fusion experiments in the U.S. began in the early 1970s, with three laboratories building a series of neodymium-glass lasers initially operated at 1.06  $\mu\text{m}$ .

Moshe Lubin established the Laboratory for Laser Energetics at the University of Rochester in 1970 and built the four-beam Delta laser in 1972. When the lab's new building was completed in 1978, the six-beam Zeta laser began operation, performing experiments for universities, government agencies, and industry.

The promise of laser fusion also attracted a private company, KMS Fusion, founded by physicist and entrepreneur Keeve M. Siegel in Ann Arbor, Michigan. KMS built its own glass laser, and had some early experimental success, but the company ran short of money. Siegel suffered a fatal stroke while asking Congress for government support in 1975, and KMS Fusion survived for a time on government contracts.

John Emmett and Carl Haussmann led development of a series of glass lasers for fusion experiments at Livermore. The one-beam, 10-J Janus laser conducted the first fusion shots in 1974. The one-beam Cyclops laser followed, a prototype of one beam in the 20-beam Shiva laser. The two-beam Argus laser came on line in 1976, followed in 1977 by Shiva, which reached 10 kJ.

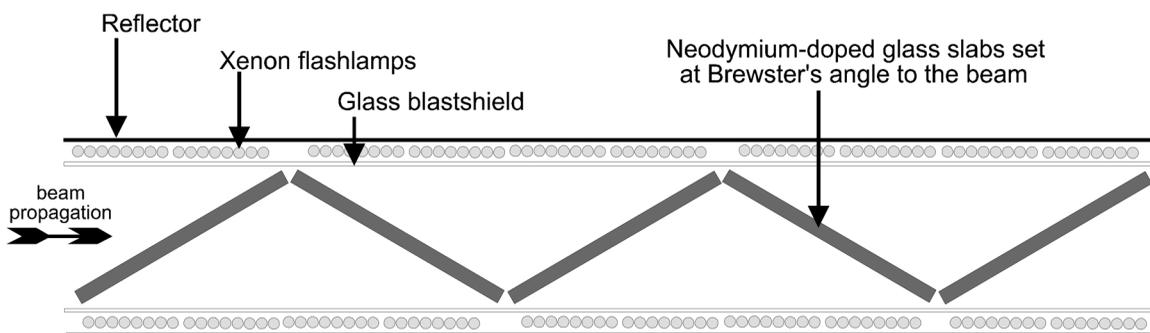
The most popular design for modern neodymium glass lasers with apertures larger than 10-cm is the Brewster's-angle slab amplifier shown in Fig. 4. A laser beam polarized in the plane of the figure



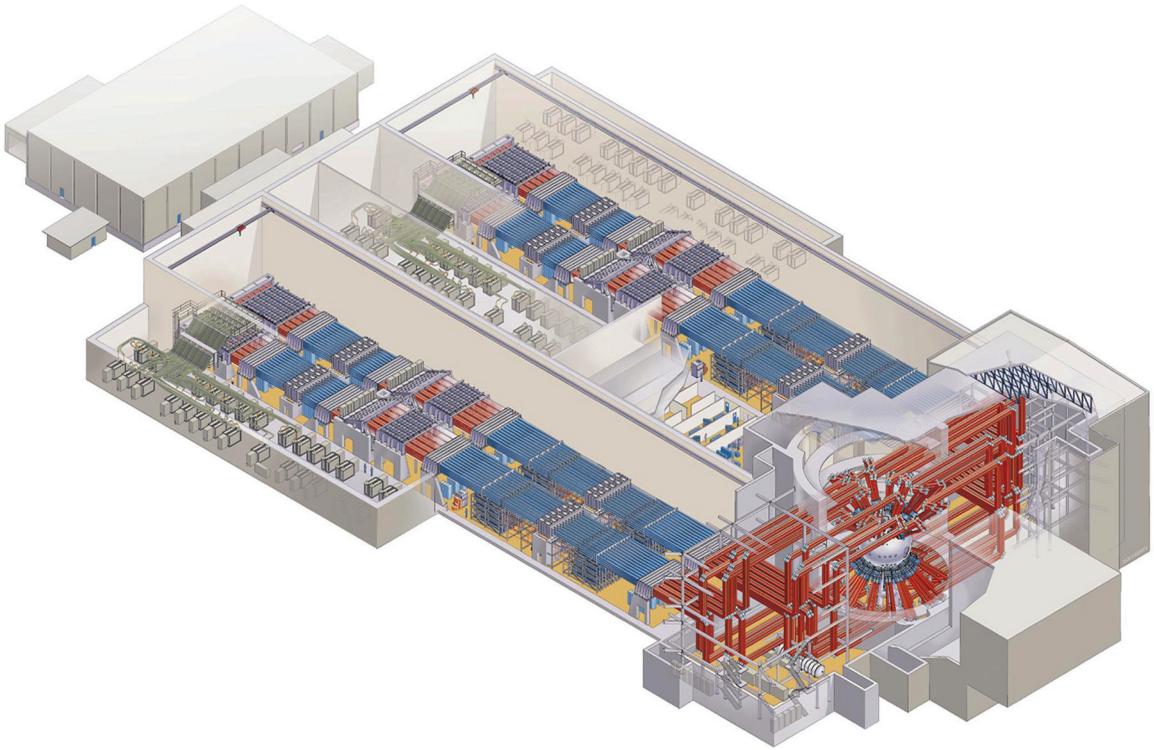
▲ Fig. 3. The 60-cm aperture final amplifier of the Nike KrF laser. The amplifier is pumped from two sides by electron beams generated by the cylindrical pulse-forming lines. (Courtesy of Naval Research Laboratory.)

sees no loss when it strikes the slab surfaces at Brewster's angle, and the slab faces are also easily accessible for flashlamp pumping. Early examples [12] used circular disks of glass, forcing elliptical beam profiles. More modern designs use elliptical or rectangular slabs so that the laser beam can be circular or square.

Many large glass fusion lasers have been built with those amplifiers, such as Gekko [13] at Osaka University, Japan; Vulcan [14] at the Rutherford-Appleton Laboratory, Didcot, UK; Omega [15] at the University of Rochester; Phebus at the Commissariat a l'Energie Atomique, Limeil-Valenton, France; and the sequence of lasers [16] leading to the Nova laser at Livermore completed in 1984. There



▲ Fig. 4. A Brewster's angle slab amplifier using neodymium glass. The laser beam sees no loss if it propagates through this series of slabs with polarization in the plane of the figure. (Courtesy of Lawrence Livermore National Laboratory.)



▲ **Fig. 5.** The NIF laser fusion facility. NIF has 192 laser beams of 40-cm aperture and a 10-m diameter target chamber seen at the right end of the picture. (Courtesy of Lawrence Livermore National Laboratory.)

have been many others [17]. Nova was the largest of its generation, with ten 46-cm beamlines able deliver up to 30 kJ at 351 nm in shaped pulses of a few nanoseconds duration for indirect-drive experiments.

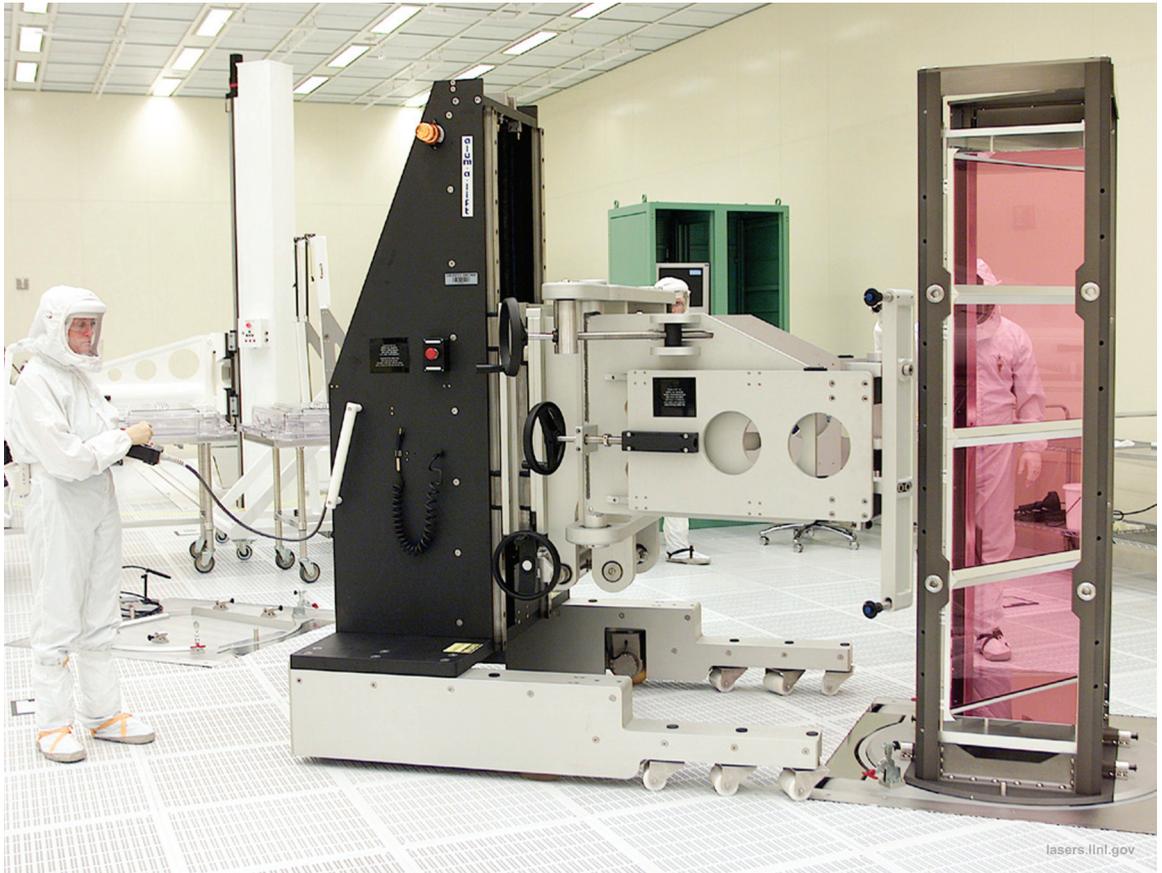
The Omega Upgrade laser at Rochester [15] began experiments in 1995. It delivers 30 kJ in 20-cm diameter beams at 351 nm in a 64-beam geometry optimized for direct-drive targets. The beams use a technique [18] called “smoothing by spectral dispersion” (SSD) to smooth the irradiance to give a very uniform profile on the target.

The largest fusion laser system now operating [19] is the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL). Figure 5 is an artist’s sketch of the facility. It contains 192 laser beamlines of 40-cm square aperture and was designed to irradiate targets with pulses to 1.8 MJ at the third harmonic (351 nm), and to have very flexible output pulses for a wide variety of target experiments [20].

NIF irradiates indirect-drive targets with conical arrays of beams that illuminate three rings of 64 beam spots each on the inside of a cylindrical hohlraum. This allows experimenters to tune the x-ray distribution within the hohlraum to optimize target implosions. The NIF beam arrangement can also be used to drive some direct-drive targets [21–23]. SSD smoothing is available if required.

Each beamline includes sixteen slabs, with the beam making four passes through the final amplifier (see Fig. 6) before exiting and being directed into the target chamber. Such multipass amplifiers reduce the number of intermediate amplifiers and reduce cost of the facility, though they are harder to design and control than the single-pass amplifier chains used for most fusion laser systems in the past. Each preamplifier module in NIF injects about 1 J into each of four adjacent beamlines. The oscillator that drives the preamplifiers is a fiber laser that uses modulators and other hardware derived from those developed for fiber-optic communications systems.

The Laser Megajoule (LMJ) project under construction [23] by the Commissariat à l’Energie Atomique at Le Barp near Bordeaux, France, will have amplifiers similar to NIF, but will have 240



▲ **Fig. 6.** A stack of four NIF slabs ready for insertion into the final amplifier. (Courtesy of Lawrence Livermore National Laboratory.)

beamlines with 18 slabs each, and somewhat higher energy output capability. An eight-beam prototype called Ligne d'Intégration Laser (LIL) is currently operating.

Omega Upgrade, NIF, and LMJ also will have the capability to deliver kilojoule-class, petawatt-power picosecond beams to target from beamlines that use grating compression of frequency-chirped pulses [24]. This capability allows them to explore an advanced target design [25] called the “fast ignition” target that uses the main laser output to compress a target, and a separate petawatt picosecond beam to heat the central spot of the target sufficiently for ignition. Target implosion simulations suggest that such targets will offer higher net gain (fusion energy out divided by laser energy in) than conventional targets, highly desirable for future applications of laser fusion to energy production. Other laser facilities also have experimental programs investigating fast ignition. Petawatt beams are also useful for other experiments such as x-ray backlighting of imploding targets.

The National Ignition Facility succeeded in delivering pulses of more than 1.8 mJ to targets in 2012. However, that design energy proved insufficient to ignite fusion targets. Further experiments have increased yield, and Livermore researchers are focusing on improving target compression and reconciling theory with experimental results.

Researchers have long hoped to use laser fusion for electric power generation. The HiPER project [26] in the European Community, FIREX [27] in Japan, and LIFE [28,29] in the U.S. are all exploring energy applications of advanced laser fusion concepts. These projects are developing concepts for high-average-power facilities to follow NIF and LMJ, either with advances from NIF/LMJ-like technologies or with advanced diode-pumped solid-state lasers that offer higher efficiency and better thermal properties. Large slabs of laser-grade transparent ceramics [30,31], if developed in time, would be very valuable for advanced laser fusion projects since they offer the laser and thermal properties of

laser crystals without the difficulty of growing large crystals. There are numerous other studies of conceptual designs for laser fusion power plants using solid-state [32] or KrF [33,34] lasers.

Fifty years after its origins, fusion research with lasers is a vibrant research area that has sparked many developments in both fusion and laser technology, and continues to do so.

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# History of Laser Remote Sensing, Laser Radar, and Lidar

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Lidar and remote sensing grew from developments in optical spectroscopy, optical instrumentation, and electronics in the 1930s to 1950s. Starting in 1930, searchlights were directed upward and atmospheric scattering was measured with a separately located telescope. Starting in 1938, pulsed electric sparks and flashlamps were used in searchlights to measure cloud base heights. Middleton and Spilhaus introduced the term LIDAR (for Light Detection and Ranging) in 1953.

The laser revolutionized lidar and launched laser remote sensing. In 1962 Louis Smullen of MIT and visiting scientist Giorgio Fiocco (who had worked on radar at Marconi) detected backreflection from the Moon using 50-J, 0.5-ms pulses from a Raytheon ruby laser transmitted through a 12-inch telescope together with a 48-inch receiving telescope and a liquid-nitrogen cooled photomultiplier at MIT Lincoln Laboratory. (See Fig. 1.) The signal that returned after 2.5 s was very weak, including only about 12 photons, and had to be recorded by photographing a double-beam oscilloscope trace using “vast amounts of Polaroid film and time.” The project was called “Luna-See,” probably reflecting its difficulty. The following year a newly invented rotating mirror Q-switch shortened a 0.5-J ruby pulse to 50 ns for a series of lidar studies of the upper atmosphere. The first use of the term lidar referring to such a laser radar system was used by Goyer and Watson in 1963 and by Ligda in 1964.

During the next decade advances in laser technology drove improvements in laser remote sensing. Richard Schotland in 1964 detected the concentration of a gas in the atmosphere for the first time by temperature-tuning the wavelength of a ruby laser across a water vapor absorption line. This was the first Differential-Absorption Lidar (DIAL) system.

Other groups went on to detect other species. After a detailed theoretical analysis of lidar techniques by Byer and Kildal in 1971, Hinkley and Kelley showed experimental detection of air pollutants using tunable diode lasers in 1971, and Byer and Garbuny detailed DIAL requirements for pollution detection in 1973. Karl Rothe and Herbert Walther’s group in Germany used DIAL with tunable dye lasers to detect NO<sub>2</sub> and in 1974–1976 Ed Murray, Bill Grant, and colleagues at SRI detected the gas with a tunable CO<sub>2</sub> laser. Menzies and Hinkley in 1978 measured atmospheric gases with a laser absorption spectrometer (LAS), two waveguide CO<sub>2</sub> lasers, and stripchart recorders mounted in a plane (see Fig. 2). In 1979, they measured atmospheric gases with the balloon-borne Laser Heterodyne Radiometer shown in Fig. 3. Sune Svanberg’s group at the Lund Institute mapped the mercury emission from coal-fired power plants in a seminal DIAL study in the 1980s, Jack Bufton at NASA Goddard measured atmospheric CO<sub>2</sub> in 1983, Ed Browell at NASA Langley measured water vapor and ozone in the atmosphere and the flow of Sahara Desert dust from Africa to the Southeast United States, and Nobuo Sugimoto and Kazuhiro Asai’s group measured similar Asian dust flow.

DIAL also performed landmark environmental observations. In 1993, Bill Heaps’ group at NASA Goddard and Stuart McDermid’s group at JPL tracked variations of stratospheric ozone levels in time and space for the first time, validating data suggesting an “ozone hole” collected by solar occultation instruments on NASA satellites in the 1980s. The satellite sensors had detected the hole years earlier but had not transmitted the data to the ground because the software considered the measured ozone levels too low to be accurate. The problem was



▲ **Fig. 1.** Photo of “Luna-See,” the first laser radar measurement of a laser beam backscattered from the Moon (white speck at the upper left) in May 1962 at Lincoln Laboratory by MIT Prof. Louise Smullen (left), Raytheon laser scientist Dr. Stanley Kass (middle), and visiting radar scientist Dr. Giorgio Fiocco (right). (Courtesy MIT Museum.)



▲ **Fig. 2.** Photo of 1978 JPL laser absorption spectrometer (LAS) lidar system mounted in a Beechcraft Queen Air aircraft. (Courtesy of R. Menzies, JPL.)

corrected by programing the satellite to transmit raw data for observations on and off the absorption line instead of just the ratio of the two.

The advent of tunable quantum cascade lasers, tunable optical parametric oscillators, and tunable solid-state and semiconductor lasers now have made DIAL measurements of atmospheric gases almost routine. DIAL instruments regularly monitor methane and CO<sub>2</sub> emissions to the atmosphere and measure ammonia and other gases for industrial process control. That’s a big advance from the 1960s, when ozone and smog levels in Los Angeles were monitored by timing the deterioration of a rubber band placed outside a window and stretched by a small weight.

John Reagan’s group at the University of Arizona began lidar mapping of atmospheric aerosols in the late 1960s, and others built on their effort. Pat McCormick and David Winker of NASA Langley flew

one of the first lidars in space, the Laser In space Technology Experiment (LITE) in 1994 on Space Shuttle mission STS-64, which mapped cloud-top heights and range-resolved distributions on a global scale. Lidar also proved valuable in observing particulates injected into the stratosphere by volcanic eruptions, which take about six months to mix with the atmosphere and remain airborne for about five years.

Hard-target lidar trackers and range finders were developed especially for military applications, with significant progress made by Al Jelalian's group at Raytheon, and Ingmar Renhorn and Ove Steinvall at the Sweden NDRI. Al Gschwendtner's group at MIT Lincoln Lab developed a high-speed imaging heterodyne Doppler lidar that could take full-view Doppler range-resolved images at a 30-Hz frame rate. Those heterodyne systems led to lidars with much higher pulse rates for scanning and mapping hard targets and terrain. Alan Carswell of the University of

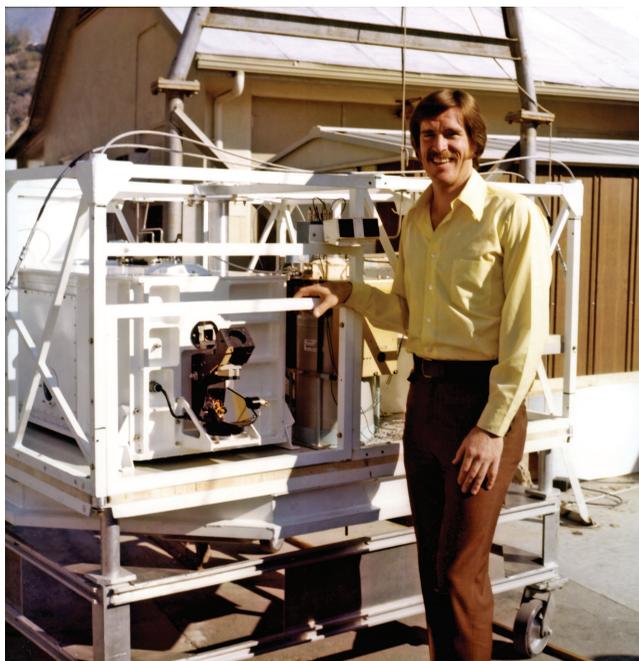
Toronto founded the Optech Corp., which developed suitcase-sized imaging lidar scanners that fire 200,000 pulses per second. Linked to a precision GPS network, these systems have compiled detailed 3D maps of urban buildings and discovered and mapped Mayan ruins hidden under jungle canopies using a foliage-penetrating lidar. Such precision mapping lidars have been so successful that they now perform most detailed geographical coordinate measurements. Another sign of their importance is that NIST has established a standards group for lidar mapping.

Laser-induced fluorescence (LIF) also can detect important species in the atmosphere. Doug Davis and Bill Heaps at Georgia Tech, Charlie Wang's group at the Ford Scientific Research Center, and the author in 1975 were the first to detect the OH free radical under ambient conditions at a concentration of 0.01 parts per trillion. OH is important as the major rate controller for chemical reactions that deplete ozone in the upper atmosphere.

Large flashlamp-pumped dye lasers often were used to produce frequency-doubled pulses near 282.5 nm, and operating them could be interesting. The large dye lasers quickly photobleached the dye, so 55-gallon drums of pure ethanol were used to extend the lifetime of the circulating solvent. Federal tax had to be paid on the pure drinking alcohol—about \$2000 a barrel—which was returned after dye was added and the liquid disposed of to show it had not been drunk. Recirculating the dye-alcohol solution stabilized fluid temperature, but the coaxial flashlamps had limited lifetimes and would explode after a few hundred hours. The Ford group had put the dye-alcohol pump downside of the flashlamp, so when the lamp exploded the pump just sucked in air. Unfortunately, Bell Labs had placed the dye-alcohol pump in front of the flashlamp, so it sprayed alcohol into the exploding flashlamp, causing a major fire. The arrangement was reversed in later laser designs.

In 1980, Jim Anderson of Harvard conducted a series of high-altitude balloon-borne laser measurements that confirmed the key roles of stratospheric OH and Freon in ozone depletion. Bill Heaps' group at NASA Goddard conducted similar measurements with a balloon-borne laser spectrometer, but in one case the parachute failed to deploy upon descent, creating what Heaps called the world's first "Lidar Pancake."

LIF lidar also studied the tenuous sodium layer that surrounds the Earth at an elevation near 90 km. Early lidar studies in 1972 by Gibson and Sandford, and in 1978 by Marie Chanin's group in



▲ Fig. 3. Photo of Bob Menzies and JPL laser heterodyne radiometer balloon instrument sitting in its gondola frame in 1979. (Courtesy of R. Menzies, JPL.)

France, measured sodium levels with a tunable yellow dye laser. They also observed gravity or breathing waves of the upper atmosphere, dynamic waves that travel around the world. Separate studies by L. Thomas' group in 1979, Chet Gardner's group at the University of Illinois in 1990, and C. Y. She's group in 1992 at Colorado State University showed that LIF excitation of the sodium layer could provide a beacon or "guide star" for adaptive optics compensation of atmospheric turbulence in ground telescopes. Most large ground-based telescopes now use laser-produced guide stars together with compensating optics to remove turbulence effects in milliseconds.

Lidar observations of the small Doppler shift in backscattered light arising from target velocity are challenging but can yield valuable results. In 1970, Milt Huffaker used a laser-Doppler system to detect aircraft trailing vortices. In the early 1980s, Freeman Hall and Mike Hardesty's group at NOAA and Christian Werner's group at DFVLR/Germany developed a coherent CO<sub>2</sub> laser system that mapped range-resolved wind-speed profiles near airports and within boundary flow geometries. Later, Sammy Henderson and Huffaker's group at Coherent Technologies Inc. developed coherent lidars based on solid-state laser systems near 2 μm. Direct-detection lidars developed during the past decade can also measure Doppler-shifted returns in ways that complement the coherent measurements. Now fiber-laser-based coherent Doppler lidars are mapping wind fields around wind turbines to increase efficiency of the blade pitch and direction.

Laser-induced-breakdown spectroscopy (LIBS) has also shown promise in the past decade for detecting chemicals at ranges from less than a meter out to a few hundred meters. Focusing a 0.1-J, 5-ns pulse through a telescope can produce dielectric breakdown in the air, yielding identifiable lines of atomic and ionized species in the plasma. It is a long way from the 3500-J, 1-μs CO<sub>2</sub> pulses Vladimir Zuev of the Tomsk Laser Institute in Siberia used to produce a plasma spark 2 km from the laser—earning him a semi-serious prize at the 1986 International Laser Radar Conference in Toronto for having made the world's longest cigarette lighter.

Conferences and workshops have played a vital role in the development of lidar and laser remote sensing. Much early and fundamental research was reported at Optical Society (OSA) Annual Meetings and March American Physical Society meetings in the 1960s, and at early CLEA/CLEO/CLEOS conferences in the 1970s. The International Symposium on Remote Sensing of Environment, first held in Ann Arbor in 1962, continues through today with an emphasis on passive satellite sensing.

One of the earliest conferences devoted to lidar was the 1968 Conference on Laser Radar Studies of the Atmosphere in Boulder, Colorado, chaired by Vernon Derr. It continues today as the International Laser Radar Conference (ILRC), run by the International Coordination Group on Laser Atmospheric Studies (ICLAS). One of the first conferences to look at the wide range of lidar techniques for species detection was the Workshop on Optical and Laser Remote Sensing, sponsored by the Army Research Office (ARO) in Monterey, California, in 1982 and chaired by Aram Mooradian and the author; Fig. 4 shows some attendees. An outgrowth of this was OSA's Topical Meeting on Optical Techniques for Remote Probing of the Atmosphere, first held in Incline Village/Lake Tahoe in 1983 and held biannually for the next several decades, sometimes changing emphasis and name. The Coherent Laser Radar Conference held first in 1980 in Aspen, Colorado, by Milt Huffaker is still going strong today with the most recent meetings in Barcelona, Spain, in 2013 and Boulder in 2015.

For the past five decades, laser remote sensing and lidar has been an outstanding and rewarding research career, often following the growth and expansion of the laser industry. It has seen the development of many worldwide collaborations among lidar colleagues and friends. Figures 5 and 6 shows a "lidar banquet dinner" at the 1994 17th International Laser Radar Conference in Sendai, Japan, with all participants obviously enjoying themselves.

Laser remote sensing has benefitted from the development of new lasers and improvements in their ease of use, compactness, cost, and reliability. Lidar systems in the 1970s occupied one or two optical tables, had laser lifetimes of hours, and relied on computer data acquisition systems operating at megahertz speeds. Over the past decade, lidar systems have started to use \$10 tunable LEDs, 10 GHz computers on a chip, and mini-spectrometers—shrinking systems so that portable suitcase systems are now routine.

Further reductions in size and cost are expected in the future. (Can we dream of tunable quantum cascade lasers for \$100?) Metamaterials and quantum-confined photonics will impact lasers and



▲ Fig. 4. Some attendees at the 1982 ARO Workshop on Optical and Laser Remote Sensing in Monterey, Calif. L-R: Dennis Killinger, Charles C. Wang, Gil Davidson, Paul Kelley, Norman Menyuk, and Phil Russell.



▲ Fig. 5. Good lidar friends attending a banquet dinner at the 17th International Laser Radar Conference in Sendai, Japan in 1994. (Left to right) bottom: Takao Kobayashi, Pat McCormick, Chet Gardner, Dennis Killinger, Jack Bufton; top: Akio Nomura, Osamu Uchino, Hiromasa Ito, Yasuhiro Sasano, Kazuhiro Asai, Toshikazu Itabe.



▲ Fig. 6. Humio Inaba, Rod Freulich, Jack Bufton, Kin Pui Chan, Mike Hardesty, and Dennis Killinger at 17th ILRC in Sendai, Japan, 1994.

detection techniques such as femtosecond absorption spectroscopy. It is hard to predict the future, but it is certain that major technical improvements will occur...they always have. As the technology continues to improve and laser remote sensing and lidar techniques become more widely accepted, we will find uses for lidar in applications not yet imagined.

It is sobering to recall that 40 years ago we thought that the main use of lidar and laser remote sensing was going to be akin to *Star Trek* where Spock scans the distant planet surface with a “laser” beam and tells the Captain that there are two humanoids on the planet’s surface and one has a bad kidney. Who would have guessed back then that one of the huge commercial successes for lidar today would be mapping of urban buildings and geological features, finding buried Mayan ruins, mapping wind fields for wind farms, detecting and mapping global climate change gases and pollutants in the atmosphere, and laser sensing of pharmaceuticals and chemicals at close ranges.