1960–1974

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 (Al_2O_3) doped with trivalent chromium ions, which he knew from his earlier work on microwave masers.

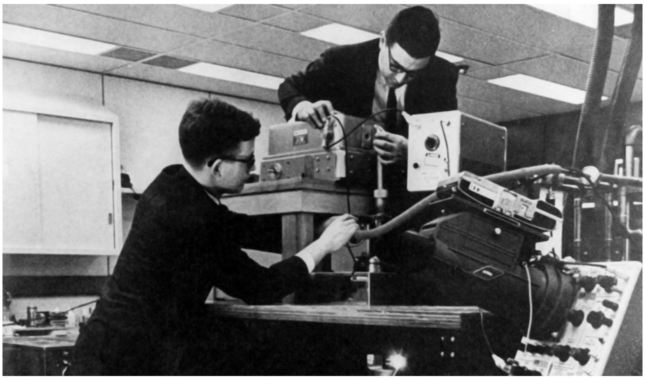
Maiman resolved doubts about ruby's quantum efficiency, but producing a population inversion was a problem because the laser transition terminated in the ground state. When he calculated requirements for laser operation based on gain per pass and mirror reflectivity, Smith wrote, "He concluded that the 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 (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 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 CaF_2: trivalent uranium and divalent samarium. He and Stevenson ordered custom-grown crystals of uranium- and samarium-doped 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 $CaF_2{:}U^{3+}$ and $CaF_2{:}Sm^{2+}$ 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 $CaF_2{:}U^{3+}$ and $CaF_2{:}\,Sm^{2+}$ 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, 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+}: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.

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