Pre–1940 1941–1959 1960–1974 1975–1990

1991–Present

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Introduction

Govind Agrawal

This section covers the 25-year period extending from 1990 to 2014. This period is often referred to as the Information Age because of the advent of the Internet during the early 1990s. It is also the period during which computer technology became mature enough that it became difficult to imagine life without a computer. These developments affected quite dramatically both the field of optics and The Optical Society devoted to serving it. The articles in this section make an attempt to document the advances made during this recent period and how they impacted the functioning of The Optical Society.

The most dramatic story of the 1990s is the exponential growth in the capacity of optical communication networks, fueled by the advances such as wavelength division multiplexing and erbium-doped fiber amplifiers. A set of three articles provides the sense of history of this period. In the first one, Jeff Hecht discusses the birth and growth of fiber-optic communication industry starting in 1970 when Corning first announced the invention of the low-loss fiber. In the second of his articles, Jeff Hecht describes how the telecommunication industry grew so rapidly during the 1990s that it led to a “telecom bubble” in the stock market that burst eventually in 2001. In the third article, Rod Alferness, who was at the forefront of this revolution taking place during the 1990s, provides his perspective on the evolution of optical communication networks since 1990.

A set of six articles provides a flavor of how the field of optics is evolving in the twenty-first century. They cover diverse research areas ranging from integrated photonics to biomedical optics to quantum information. The first article by Radha Nagarajan focuses on the recent advances in the area of integrated photonics that are behind the revival of the telecommunication industry after bursting of the “telecom bubble” in 2001. It is followed by Phillip Russell’s article on the new wave of microstructured optical fibers. Russell was the first one to make fibers known as photonic crystal and photonic bandgap fibers. Here is your chance to hear the history from the inventor himself.

The third article in this section, by Wayne Knox, covers the history of ultrafast laser technology. Knox has been involved with ultrafast lasers for a long time and knows their history well. The fourth article is devoted to advances in biomedical optics. Greg Faris describes in this article both the in vivo and in vitro applications made possible by recent advances in the area of biomedical optics. In the next article, David Hagan and Steven Moss focus on novel optical materials that are likely to revolutionize the twenty-first century. The last article by Carlton Caves is devoted to the history of the emerging field of quantum information.

It was difficult to choose among a wide range of topics, and many could not be included because of space limitations, among other things. It is my hope that the reader will gain an appreciation of how the field of optics is evolving during the twenty-first century.

Birth and Growth of the Fiber-Optic Communications Industry

Jeff Hecht

Fiber-optic communications was born at a time when the telecommunications industry had grown cautious and conservative after making telephone service ubiquitous in the United States and widely available in other developed countries. The backbones of the long-distance telephone network were chains of microwave relay towers, which engineers had planned to replace by buried pipelines carrying millimeter waves in the 60-GHz range, starting in the 1970s. Bell Telephone Laboratories were quick to begin research on optical communications after the invention of the laser, but they spent the 1960s studying beam transmission through buried hollow confocal waveguides, expecting laser communications to be the next generation after the millimeter waveguide, on a technology timetable spanning decades.

Corning's invention of the low-loss fiber in 1970 changed all that. Bell abandoned the hollow optical guide in 1972 and never put any millimeter waveguide into commercial service after completing a field test in the mid-1970s. But telephone engineers remained wary of installing fiber without exhaustive tests and field trials. Bell engineers developed and exhaustively tested the first generation of fiber-optic systems, based on multimode graded-index fibers transmitting 45 Mb/s at 850 nm over spans of 10 km, connecting local telephone central offices. Deployment began slowly in the late 1970s, and soon a second fiber window opened at 1300 nm, allowing a doubling of speed and transmission distance. In 1980, AT&T announced plans to extend multimode fiber into its long-haul network, by laying a 144-fiber cable between Boston and Washington with repeaters spaced every 7 km along an existing right of way.

Yet by then change was accelerating in the no-longer stodgy telecommunications industry. Two crucial choices in system design and the breakup of AT&T were about to launch the modern fiber-optic communications industry. In 1980, Bell Labs announced that the next generation of transoceanic telephone cables would use single-mode fiber instead of the copper coaxial cables used since the first transatlantic phone cable in 1956. In 1982, the upstart MCI Communications picked single-mode fiber as the backbone of its new North American long-distance phone network, replacing the microwave towers that gave the company its original name, Microwave Communications Inc. That same year, AT&T agreed to divest its seven regional telephone companies to focus on long-distance service, computing, and communications hardware.

The submarine fiber decision was a bold bet on a new technology based on desperation. Regulators had barred AT&T from operating communication satellites since the mid-1960s. Coax had reached its practical limit for intercontinental cables. Only single-mode fiber transmitting at 1310 nm could transmit 280 Mb/s through 50-km spans stretching more than 6000 km across the Atlantic. AT&T and its partners British Telecom and France Telecom set a target of 1988 for installing TAT-8, the first transatlantic fiber cable. More submarine fiber cables would follow.

In 1982, MCI went looking for new technology to upgrade its long-distance phone network. Visits to British Telecom Research Labs and Japanese equipment makers convinced them that single-mode fiber transmitting 400 Mb/s at 1310 nm was ready for installation. AT&T and Sprint soon followed, with Sprint ads promoting the new fiber technology by claiming that callers could hear a pin drop over it.

Fueled by the breakup of AT&T and intense competition for long-distance telephone service, fiber sales boomed as new long-haul networks were installed, then slumped briefly after their completion.

The switch to single-mode fiber opened the room to further system improvements. By 1987, terrestrial long-distance backbone systems were carrying 800 Mb/s, and systems able to transmit 1.7 Gb/s were in development. Long-distance traffic increased as competition reduced long-distance rates, and developers pushed for the next transmission milestone of 2.5 Gb/s. Telecommunications was becoming an important part of the laser and optics market, pushing development of products including diode lasers, receivers, and optical connectors.

Fiber optics had shifted the telephone industry into overdrive. Two more technological revolutions in their early stages in the late 1980s would soon shift telecommunications to warp speed. One came from the optical world, the fiber amplifier. The other came from telecommunications—the Internet.

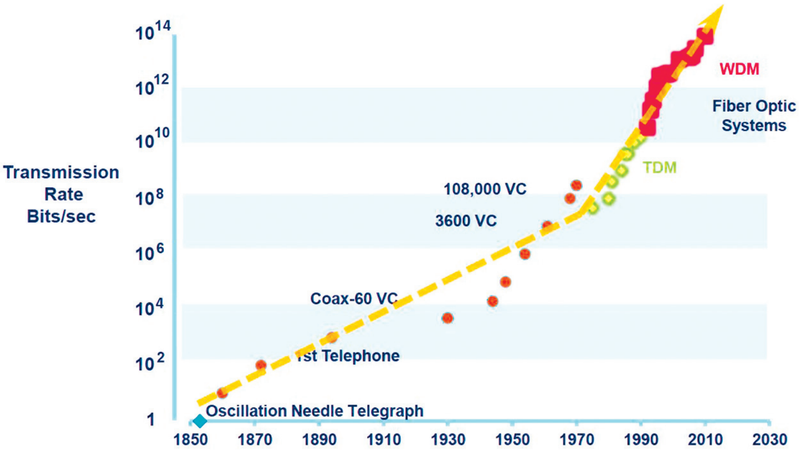
Even in the late 1980s, the bulk of telecommunications traffic consisted of telephone conversations. (Cable television networks carried analog signals and were separate from the usual world of telecommunications.) Telephony was a mature industry, with traffic volume growing about 10% a year. Fiber traffic was increasing faster than that because fiber was displacing older technologies including microwave relays and geosynchronous communication satellites. Telecommunications networks also carried some digital data, but the overall volume was small.

The ideas that laid the groundwork for the Internet date back to the late 1960s. Universities began installing terminals so students and faculty could access mainframe computers, ARPANET began operations to connect universities, and telephone companies envisioned linking home users to mainframes through telephone wiring. Special terminals were hooked to television screens for early home information services called videotex. But those data services attracted few customers, and data traffic remained limited until the spread of personal computers in the 1980s.

The first personal computer modems sent 300 bits/s through phone lines, a number that soon rose to 1200 bits/s. Initially the Internet was limited to academic and government users, so other PC users accessed private networks such as CompuServe and America Online, but private Internet accounts became available by 1990. The World Wide Web was launched in 1991 at the European Center for Nuclear Research (CERN) and initially grew slowly. But in 1994 the number of servers soared from 500 to 10,000, and the data floodgates were loosed. Digital traffic soared.

By good fortune, the global fiber-optic backbone network was already in place as data traffic started to soar. Construction expenses are a major part of network costs, so multi-fiber cables were laid that in the mid-1980s were thought to be adequate to support many years of normal traffic growth. That kept the "Information Superhighway" from becoming a global traffic jam as data traffic took off.

The impact of fiber is evident in Fig. 1, a chart presented by Donald Keck during his 2011 CLEO plenary talk. Diverse new technologies had increased data transmission rates since 1850. Fiber optics became the dominant technology after 1980 and is responsible for the change in slope of the data-rate growth.



▶ Fig. 1. Increase in the data transmission rate from 1850 to 2011 in response to diverse technologies. Fiber optics became the dominant technology after 1980. Note the change in slope around that time. (Courtesy of Corning Incorporated.)

Even more fortunately, Internet traffic was growing in phase with the development of a vital new optical technology, the optical fiber amplifier. Early efforts to develop all-optical amplifiers focused on semiconductor sources, because they could be easily matched to signal wavelengths, but experiments in the middle to late 1980s found high noise levels. Attention turned to fiber amplifiers after David Payne demonstrated the first erbium-doped fiber amplifier in 1987. (See Digonnet's chapter on p. 195.)

Elias Snitzer had demonstrated a neodymium-doped optical amplifier at American Optical in 1964, but it had not caught on because it required flashlamp pumping. Erbium was the right material at the right time. Its gain band fell in the 1550-nm window where optical fibers have minimum attenuation. Within a couple of years, British Telecom Labs had identified a diode-laser pump band at 980 nm and Snitzer, then at Polaroid, had found another at 1480 nm. By 1989, diode-pumped fiber amplifiers looked like good replacements for cumbersome electro-optic repeaters.

What launched the bandwidth revolution was the ability of fiber amplifiers to handle wavelength-division multiplexed signals. The first tests started with only a few wavelengths and a single amplifier; then developers added more wavelengths and additional amplifiers. The good news was that wavelength-division multiplexing (WDM) multiplied capacity by the number of channels that could be squeezed into the transmission band. The bad news was that WDM also multiplied the number of potential complications.

Design of 1310-nm systems was straightforward because it required considering fiber and amplifier performance at only one wavelength. WDM required balancing fiber and amplifier performance across the usable spectrum, as well as dealing with other complications including crosstalk, combining signals at the input, and separating them at the output. All posed optical challenges.

Both erbium-amplifier gain and fiber attenuation vary with wavelength, but communication systems have to deliver the same power at all wavelengths. This meant developing ways to flatten amplifier gain and fiber attenuation along the system.

Chromatic dispersion became a challenge. The 1310-nm window was picked for early single-mode systems because it was the zero-dispersion wavelength. Chromatic dispersion was high enough at 1550 nm to require ways to reduce it. Corning and British Telecom had developed fiber with zero dispersion shifted to 1550 nm in the 1980s, and that technology was used in early optical-amplifier cable systems transmitting at 1550 nm, including the TAT-12/13 transatlantic cable. However, experiments showed a serious problem with WDM in dispersion-shifted fibers. Signals at uniformly spaced wavelengths remain in phase over long distances, causing four-wave mixing and crosstalk exceeding system tolerances.

That problem led Corning to develop non-zero dispersion-shifted fibers, which have enough dispersion at 1550 nm to avoid four-wave mixing. However, the variation in dispersion across the WDM range nonetheless required dispersion management to meet system dispersion tolerances as data rates increased.

WDM also posed optical challenges. Systems required narrow-line lasers spaced evenly across the spectrum, as well as optics to combine and separate the optical signals at the ends of the fiber. That required new types of optical filters with sharp cutoffs to slice the spectrum into the desired bands. Through the 1990s, the bands grew narrower and narrower as designers sought to squeeze as many channels as possible into the limited gain band of erbium-fiber amplifiers.

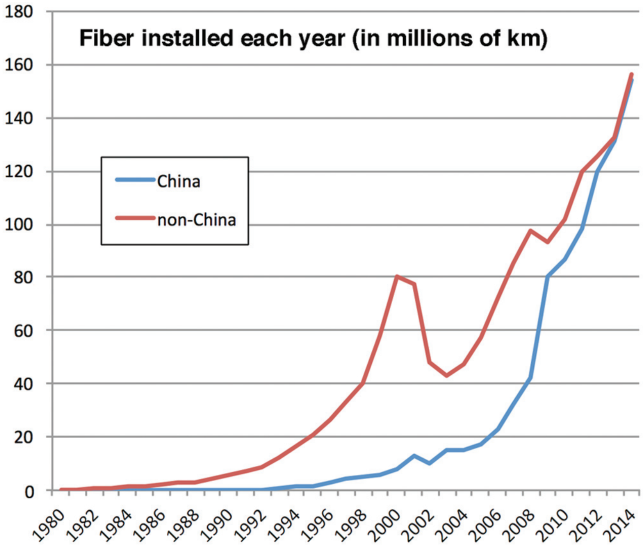
WDM, optical amplifiers, and the Internet combined to give the young fiber optics a big boost. In 1990, when the new technologies were still in the lab, Kessler Marketing Intelligence (now part of CRU International) estimated that sales of cable, transceivers, and connectors in the United States were $948 million, up only 2% from the previous year in a slow economy. Sales overseas were comparable, so the whole market was around $2 billion. Global sales of fiber reached 6.74 million kilometers.

By 1995, when the optical amplifier/WDM revolution was in full swing, the company estimated the global fiber-optic component market at $7.1 billion, with global fiber sales more than tripling to 22.87 million kilometers. The web was in takeoff mode, and as the number of servers soared, Internet traffic may have been doubling every three months, although few reliable numbers are available. Long-distance and international calling had grown with a decline in phone rates. Phone lines were humming with faxes carrying documents that would have been sent by express carrier or mail in 1990.

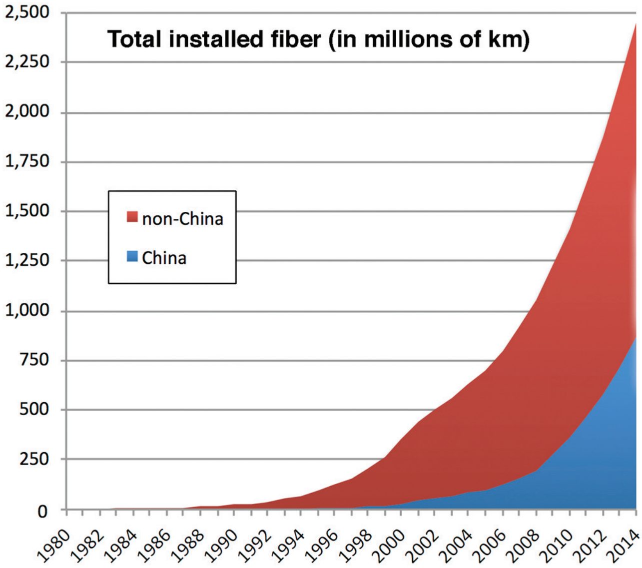
That growth was a welcome boost for optics as a whole. The wind-down of Ronald Reagan's Strategic Defense Initiative had left many optickers out of work in 1990. Telecommunications companies in need of optics specialists hired some of them. Others went to work for fast-growing firms building components or instruments for the fiber market, or started their own companies. Figure 2 shows CRU's data on fiber sales in millions of kilometers, with Chinese sales tracked separately, from 1980 to 2013. The trend in 1995 was clearly upward.

At the postdeadline session of OFC 1996, a team from Fujitsu Laboratories in Japan reported sending a record 1.1 Tb/s through 150 km of fiber, transmitting 20 Gb/s on each of 55 channels, with erbium-fiber amplifiers on both transmitter and receiver ends. Two other teams reported reaching 1 Tb/s over shorter distances by other means, one from AT&T Research and Bell Laboratories and the second from NTT. Fiber had become the key to delivering high bandwidth to a telecommunications industry convinced that you could never have enough bandwidth. The future looked bright.

In fact, as Fig. 2 shows, the light would dim after the bubble burst in 2001. Sales outside of China, little affected by the bubble, dropped from a peak of 80 million kilometers in 2000 to a low of 43 million kilometers in 2003. But then the light brightened. CRU International reports that growth returned outside of China, reaching 128 million kilometers in 2013. China's aggressive modernization program brought its fiber sale to 123 million kilometers in 2013, just short of the rest of the world combined. All told, as shown in Fig. 3, CRU says that cumulative global installation of optical fiber for communications through 2013 exceeds a staggering 2.1 billion kilometers. Optics now connects the world as the backbone of the global telecommunications network.



▲ **Fig. 2.** Total length (in millions of kilometers) of the optical fiber installed each year from 1980 through 2013, divided between China and the rest of the world. (Courtesy of CRU International, http://www.crugroup.com.)



▲ **Fig. 3.** Cumulative installations of communications fiber around the world from 1980 through 2013. (Courtesy of CRU International, http://www.crugroup.com.)

Acknowledgment

Part of this material is adapted, with permission, from Jeff Hecht, *City of Light: The Story of Fiber Optics* (Oxford, 2004).

Telecommunications Bubble Pumps Up the Optical Fiber Communications Conference

Jeff Hecht

Fiber-optic amplifiers and wavelength-division multiplexing (WDM) developed almost perfectly in phase with the explosive growth of the Internet in the 1990s. The new optical technology promised the bandwidth needed to carry fast-growing Internet traffic. Initially the parallel advances of optical and Internet technology seemed an ideal match. Unfortunately, that pairing ignited a speculative bubble that went out of control, creating trillions of dollars of vastly inflated stock valuation that vanished when the bubble collapsed.

An earlier chapter describes how fiber became the backbone of the global telecommunications network. The roots of the Internet go back to the late 1960s, when low-loss fibers were still in development. The Defense Advanced Research Projects Agency (DARPA) (then called ARPA) began funding computer links among university and government laboratories.

A Changing Landscape in Telecommunications

Separately, telecom companies began experimenting with information services connecting home consoles and television screens to mainframe computers through copper telephone lines. In the 1980s, personal computers became the preferred home connections to private services such as CompuServe. Modem speeds carrying these services over phone lines rose from 300 baud in the early 1980s to 56,000 baud in the 1990s.

Public Internet access began about 1989 and took off after the World Wide Web opened the Internet to a wider range of services. In 1994, the Web grew from 500 to 10,000 servers, and data traffic soared. For a brief, heady period in 1995 and 1996, the volume of Internet data may have doubled every three months as hordes of new users explored the Web. Internet traffic then was a small fraction of voice traffic (including faxes), but it was clear that if it continued increasing at that rate it would soon eclipse voice traffic, which was growing about 10% a year.

The emergence of competition and the breakup of the old AT&T monopoly in 1984 had already shaken the telephone industry. Once considered a natural monopoly, telephony had become fragmented. Many competing carriers and the construction of new high-speed, high-capacity fiber networks cut the prices of long-distance and international calls, greatly increasing voice and fax traffic.

Competition also brought more subtle changes that would have a large impact. As a monopoly AT&T published data on its traffic and system capacity to persuade regulators to approve expansion plans. With deregulation and competition, that information became proprietary, and no carrier knew total network traffic or how fast its competitors were growing.

Meanwhile, new technology was expanding capacity of single-mode fiber systems, which had reached 2.5 Gb/s on the busiest routes by the mid-1990s. The first WDM systems reached the market in 1996. The same year saw installation of TAT-12 across the Atlantic, the first submarine cable with optical amplifiers. WDM promised the bandwidth needed to cope with the rapidly growing demand.

Yet in the new competitive environment, nobody knew exactly what that demand was. Traditional phone network managers considered bandwidth a scarce commodity. Market analysts and the press heralded the doubling of Internet traffic every 90 to 100 days. Soon the Federal Communications Commission was citing the same numbers, although the original source—a 1996 Worldcom report—was forgotten.

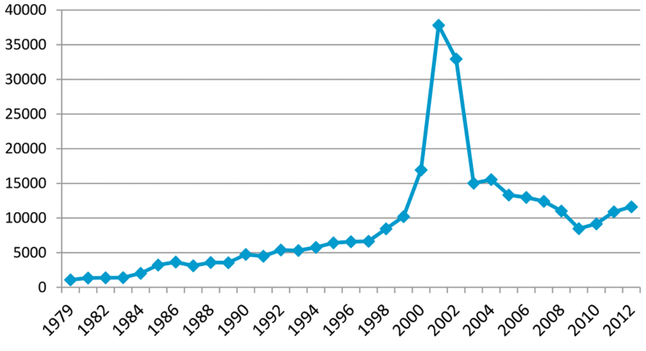
Few in the industry paid much attention in early 1998 when Andrew Odlyzko reported that AT&T's Internet traffic had only doubled during 1997. The dot-com boom was underway, and critical thinking was not in fashion. Writers, business analysts, and stock promoters waxed exuberant about how the Web would revolutionize the economy. With money readily available at low interest, investors poured money into upstart web companies with little more than a handful of employees, a web site, and—perhaps—a warehouse. As the new companies began to go public, their stock prices soared, pumping up the technology-heavy NASDAQ index.

Investors began looking beyond the dot-coms to the telecommunications companies that would provide vital infrastructure for the new economy. Fiber and optics companies were particularly hot commodities because they offered breakthroughs in bandwidth. Investors soon bordered on the euphoric about fiber. Even hard-headed optical engineers decided that if investors were going to throw money at anything optical, they might as well hold out their hats and catch some of it. The boom brought a gold-rush atmosphere to the Optical Fiber Communications Conference (OFC).

The Growth of OFC

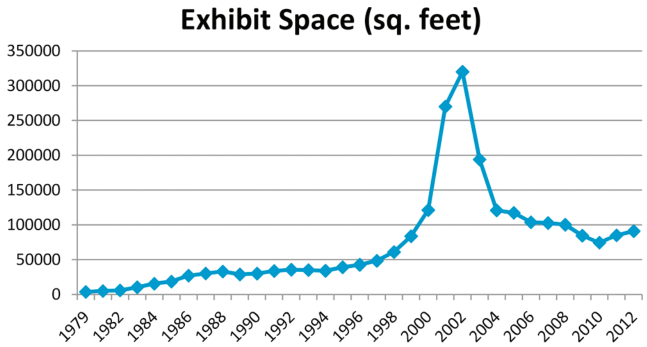
OFC began as a small biennial topical meeting on optical fiber transmission first held in 1975. The first Optical Fiber Communications conference in 1979 had a small trade show and 1082 attendees. It went annual in 1981 and grew along with the fiber industry. In 1986, when fiber had become the backbone of U.S. long-distance traffic, OFC drew 1801 people to Atlanta for the technical sessions, plus 1071 exhibitors and 777 people who only visited the trade show of 150 companies occupying 27,100 square feet. It was the first time more than half of OFC attendees came only for the exhibits. Figure 1 shows how the number of attendees changed over a period extending from 1979 to 2012.

A decade later at San Jose in 1996, only a few more people came for the technical session, but the exhibits had more than doubled, to 2756 exhibit staff and 1990 exhibit-only visitors. Exhibit space had increased over 50%, to 42,700 square feet. Fiber technology had come a long way, and WDM was reaching the market. Ciena squeezed 16 optical channels at 1.6-nm intervals into the erbium-amplifier spectrum. Lucent Technologies and Pirelli also introduced WDM systems. The post-deadline session heard of hero experiments that sent a trillion bits per second through a single optical fiber, although chromatic dispersion and nonuniform amplifier gain limited transmission span to 150 km in the best result, from Fujitsu.



▲ **Fig. 1.** Total attendance over a period extending from 1979 to 2012 showing the sharp peak in the bubble years.

The 1997 OFC, held in Dallas, was only slightly larger than the 1996 event. But the 22–27 February 1998 OFC in San Jose was a big step up. The Optical Society and IEEE had expected total attendance to top 7000, but it jumped 30% to 8446, with technical attendance up 25% to a record 2672. Exhibit space was up 26% to 61,000 square feet, and the number of



▲ **Fig. 2.** Total square footage of the exhibit area over a period extending from 1979 to 2012 showing the sharp peak in the bubble years.

exhibitors rose nearly 16% to 342. Figure 2 shows how the total square footage of the exhibit space changed over a period extending from 1979 to 2012.

Hero experiments reported at the 1998 post-deadline sessions reached a key milestone—the dense-WDM demonstrations that sent a terabit per second hundreds of kilometers through a series of fiber amplifiers. Bell Labs sent a hundred 10-Gb/s channels 400 km, and NTT sent fifty 20 Gb/s channels 600 km. The highest data rate carried commercially at a single wavelength was only 2.5 Gb/s at the time, but Lucent said they would have hardware in service by the end of the year transmitting 10 Gb/s on each of 40 wavelengths. Meanwhile, regional and metropolitan networks were installing WDM systems to increase capacity without costly construction.

Meanwhile, the technology-heavy NASDAQ index was rising about as fast as OFC attendance—closing at 1766 in the middle of OFC, up 29% from a year earlier. Fiber's potential bandwidth was pulling the optics industry along with Internet stocks, and at the end of 1998 the NASDAQ index was up 39% for the year.

The trend continued in 1999, when OFC moved to the larger San Diego Convention Center and drew a record 10,206 people, up 21%, including 3331 technical registrants, a 25% increase. The number of companies rose a comparatively modest 13%, but booth sizes grew faster as big companies pumped up their presence, occupying 83,700 square feet of space, a hefty 37% increase. Stock values were also up, with the NASDAQ at 2339 during the February show, up 32% from during the 1998 OFC.

Wall Street Discovers Optics

As fiber technology improved and the demand for bandwidth soared, sales increased and Wall Street began taking optics seriously.

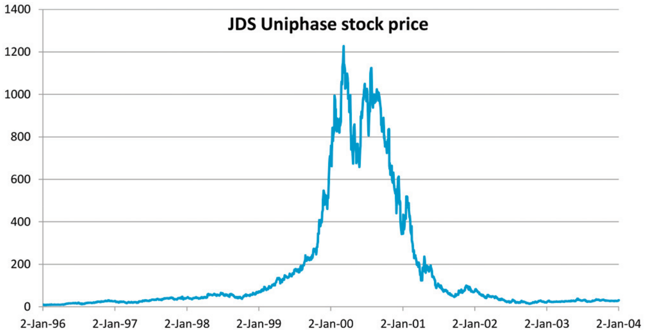
Optics and telecommunication stocks soared during the late 1990s. The stock of JDS-Fitel, formed in 1981, doubled after it went public in 1996, then doubled again in 1997 and in 1998. In early 1999 JDS announced a $6.1 billion merger with another fast-growing optics company, Uniphase.

In May, Enron announced it was forming a bandwidth market to trade capacity on installed fiber systems. It seemed like a good idea at the time. *Fortune* magazine had repeatedly ranked Enron as the most innovative company in the country, and the demand for bandwidth seemed almost unlimited.

JDS Uniphase stock took off, soaring almost a factor of nine in 1999 as it continued a wave of acquisition. In November it announced it would buy Optical Coating Laboratory Inc. for $2.8 billion in stock. Stocks of other optics companies such as Corning and of system makers such as Nortel and Lucent likewise multiplied in price. The whole NASDAQ index nearly doubled during 1999, climbing from 2193 to 4069, but optics stocks rose even faster as investors clamored for optical stocks. Friends and family asked optickers for stock tips. Figure 3 shows how the price of JDSU stock varied over a period extending from 2 January 1996 to 2 January 2004.

January 2000 saw another blockbuster merger, with JDS Uniphase buying E-Tek Dynamics in a deal that would close for $17 billion in June.

OFC recognized the importance of the booming market in selecting technology author and analyst George Gilder as the opening plenary speaker. Gilder had become a fiber enthusiast because he thought the seemingly infinite bandwidth of optics could transform the world. His stock recommendations had lured investors into optical and telecommunication companies, and his presence on the program helped draw throngs of stock analysts, venture capitalists, and investors to join a record crowd of engineers and scientists.



▲ Fig. 3. Price of JDSU stock over a period extending from 2 January 1996 to 2 January 2004 showing the sharp peak in the bubble years.

Lines wound around the Baltimore Convention Center, overwhelming show managers. Technical registration was 6636, almost double the previous year, and total attendance was 16,934, up 65%. Exhibits from 483 companies sprawled over 121,300 square feet.

As if to celebrate Gilder's talk, the NASDAQ index crossed the 5000 mark for the first time on 7 March 2000, the day of his opening talk. The NASDAQ continued upward during the conference, peaking at 5132 on the final day before closing at 5049. As attendees went home to recover from the show, the chief analyst of Prudential Securities said the index could reach 6000 by the end of 2000.

The market had reached dizzying heights. MCI Worldcom's market capitalization reached $168 billion in April 1999. Lucent Technologies reached $285 billion in December 1999. But those were their peak valuations, and other technology stocks were slipping as well. The Monday after OFC the NASDAQ dropped 141 points and did not see 5000 again until July 2015. May saw the first big dot-com failures, and more followed in the summer. The NASDAQ closed the year at 2470, and did not see 3000 again until 2012.

Optical stocks were slower to slip. JDSU's market capitalization peaked at $181 billion during the summer. On 10 July, JDSU announced a mind-boggling plan to buy SDL Inc. for stock then worth $41 billion. That made SDL CEO Donald Scifres a billionaire on paper in August, when *Forbes* ranked him number 218 on its list of the 400 richest Americans. But JDSU stock started sliding downhill in September, and when the deal closed on February 2001, the stock was worth only $13.5 billion.

Aside from stocks slipping to more realistic values, the fiber industry seemed healthy going into 2001. Needing more space, OFC booked the sprawling Anaheim Convention Center for 19–22 March 2001. Booth space sold like hotcakes. A record 970 companies occupied 270,000 square feet at the trade show; both numbers had doubled from 2000. Total attendance more than doubled to 37,806, with technical registration reaching 10,888, a 64% increase.

Industry executives, analysts, and investors packed the OSA Photonics and Telecommunications Executive Forum on the fiber market held across the street at the Disneyland Hotel. Optimism was in the air, but so were hints of trouble. Opening speaker John Dexheimer cited concerns including the first failures in telecommunications, a "massive debt hangover" from some $250 billion in dubious loans to lay new fiber, and many companies trying to do the same thing.

The number of startups in the exhibit hall showed the massive investment in cutting-edge optical technology. The technical sessions included such impressive feats as Alcatel's transmission of 3 Tb/s through 7380 km of fiber, enough to span the Atlantic. But that capacity was far beyond what anyone needed in April 2001, too many companies on the show floor offered nearly identical products, and some booths displayed no identifiable product but stock.

Within sight of Disneyland, the optics industry had slipped into a cartoon world. Like Wile E. Coyote, the industry had run off clear off the cliff, but in cartoon physics the law of gravity lets you hang in mid-air with your legs churning until you look down. Only then does gravity take hold and bring the inevitable "splat."

The bubble was collapsing and sales were slumping. In April JDSU laid off 5000 people, about a fifth of its employees. In a 9 May plenary talk at CLEO, JDSU CEO Josef Straus said he had learned "the laws of gravity apply up and down." The telecomm industry was learning that it is hard to make money selling cheap bandwidth, especially when projected Internet traffic growth rates turned out to be as exaggerated as Worldcom's profit statements.

Enron's bandwidth market never took off, and by the summer of 2001 the whole company was looking wobbly. By year's end, Enron became the biggest bankruptcy in U.S. history.

By September, Nortel stock worth $1000 a year earlier was worth only $72. A grim joke noted that investing the same amount in Budweiser—the beer, not the stock—would have left empty bottles worth $76 in a state with a deposit law. JDS wrote off nearly $50 billion in "goodwill" and slashed its staff to less than half its peak level. In January 2002, Global Crossing, which had built a global fiber network, filed for bankruptcy with $12 billion in debt, the fifth largest in U.S. history.

The magic was gone when OFC returned to Anaheim in March 2002, but the industry's legs were still churning furiously in mid-air. OFC sold 320,000 square feet of booth space to 1204 exhibitors, over 20% more companies than in 2011. But some exhibitors never showed, having run out of money. With 32,944 attendees, the show was busy, but many were job-hunting.

At the OSA Executive Forum, market analyst John Ryan looked back at 1999 to 2001 as "the drunken sailor years" when network operators spent tens of billions of dollars on equipment they did not need. But he held out hope, declaring "Unlike the concept of selling dog food on the Internet, telecom isn't going away." The audience laughed, a bit uneasily. Four months later, MCI Worldcom eclipsed Enron's record to become the largest bankruptcy in American history, toppled by some $11 billion in accounting fraud that earned CEO Bernie Ebbers a 25-year jail sentence.

That was the last giant OFC. Attendance dropped by more than half in 2003, as 15,023 people spread thinly through the sprawling Atlanta Convention Center. Exhibitor count and booth space shrank less precipitously, perhaps because the space was sold in advance, and as in 2002 some companies never showed up.

Plots of OFC attendance and exhibits show the bubble years as aberrant spikes, not quite as dramatic as peaks in company stock prices. The most recent OFC, shown in Figs. 1 and 2, in 2012 in Los Angeles, drew 11,617 attendees, with 560 exhibitors occupying 91,000 square feet—putting the 2012 OFC midway between the 1999 and 2000 gatherings. Growth has resumed, at a more rational level.

Looking back, Gilder was right in calling fiber a disruptive technology. But he failed to understand that such a disruption could cause a destructive bubble in stock prices. The bubble's inevitable collapse vaporized illusory gains many times the $65 billion fraud of Bernard Madoff's Ponzi scheme. The market capitalization of JDSU alone shrank from a peak of $181 billion to a current few billion dollars, a loss of 2.5 Madoffs.

The industry survived the bubble, although scars remain. Someday your brother-in-law may forgive you for saying JDSU stock was a good investment in 2000.

Further Readings

1. L. Endlich, *Optical Illusions: Lucent and the Crash of Telecom* (Simon & Schuster, 2004).
2. J. Hecht, *City of Light: The Story of Fiber Optics, Revised and Expanded Edition* (Oxford University Press, 2004).
3. O. Malik, *Broadbandits: Inside the $750 Billion Telecom Heist* (Wiley, 2003).
4. B. McLean and P. Elkind, *The Smartest Guys in The Room: The Amazing Rise and Scandalous Fall of Enron* (Portfolio-Penguin, 2004).
5. A. Odlyzko, "Internet growth, myth and reality, use and abuse," http://www.dtc.umn.edu/~odlyzko/doc/internet.growth.myth.pdf.

The Evolution of Optical Communications Networks since 1990

Rod C. Alferness

Introduction

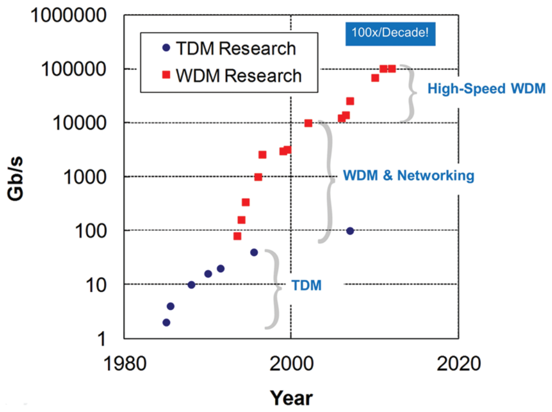
Optical communication networks have played a critical role in the information/communication revolution and in turn have fundamentally changed the world and daily life for billions around the globe. Without cost-effective, high-capacity optical networks that span continents and connect them via undersea routes, the worldwide Internet would not be possible. Optical access systems, both fiber/cable and fiber-to-the home, are also essential to bring broadband access to that global Internet to homes and businesses. Increasingly important, ubiquitous broadband optical networks provide the high-bandwidth backhaul essential for wireless access networks that enable today's smartphone users. These networks also provide the always available broadband access that will make cost-effective and energy-efficient cloud services available to all in the future.

All this has been made possible because, as capacity demand has grown exponentially following the advent of the Internet, optical technology has made possible a dramatic reduction in the cost per bit carried over an optical fiber, allowing cost-effective capacity scaling. On average, transmission capacity over a single fiber has increased at a rate of ~100-fold every ten years over the last thirty years. As a result, as traffic has grown and is aggregated at the ingress and disaggregated at egress nodes, new higher-capacity generations of long-haul and metro optical systems have been deployed at a total cost that has grown sub-linearly relative to capacity.

Of course, the advantage of the optical frequencies for communication is the inherent ability to serve as a carrier for very-high-bandwidth information. Fiber provides an extremely attractive transmission medium that offers both ultra-low loss and low chromatic dispersion. The latter results in minimal pulse spreading, resulting in low inter-pulse (bit) interference after transmission over large distances. At its most basic implementation, an optical transmission system requires an optical source whose generated dc optical signal can be modulated with information at the information bandwidth of interest, a fiber, and an optical detector and supporting electronics.

Figure 1 captures the progress of the "hero" research transmission experiments [1]. Shown is the maximum information capacity carried on a single fiber versus the year the research results were achieved. For this review, it is convenient to describe the research progress in fiber optic transmission capacity in three waves or eras. In what follows, we use those generations, each enabled by a set of critically important optical component technology innovations, to provide an overview of the advances in optical communications since 1990.

At the start of the 1990s, commercially deployed systems provided per fiber capacities of about 1 Gb/s. They were used primarily in long-haul intercity applications to carry highly aggregated voice service. At that time, increase in capacity demand was still driven mostly by population growth as well as some increase in new services such as fax. The wavelength window utilized was the minimum chromatic dispersion 1.3-μm window. To increase time division multiplexed bit rates (TDM) for fixed distance between electrical regenerations, both signal strength relative to noise and quality of the detected signal with respect to pulse-to-pulse



▲ Fig. 1. Reported research transmission systems experiments showing maximum transmission capacity over a single fiber vs. the year of the research results.

interference are important. To mitigate the reduced receiver power at higher bit rates, research focused on moving to the lowest-loss wavelength window around 1.55 μm. Unfortunately, for the standard single-mode fiber then available, chromatic dispersion at 1.55 μm was significant. For systems that employed directly modulated lasers that exhibit wavelength "chirp" during the change from the "on" to "off" state, that dispersion caused problematic pulse spreading interference.

Three technology advances were instrumental in strongly mitigating these limitations to enable increased TDM rates. To avoid chromatic dispersion, it was essential that the semiconductor laser operating at 1.5 μm be truly single frequency. That capability was provided by the distributed feedback (DFB) laser, which could also be directly modulated to provide information encoding. In addition, as TDM rates increased, external optical waveguide modulators that provided high-speed optical information encoding without the "chirping" effects proved to be essential for data rates above several gigabits per second.

Finally, high-gain, high-bandwidth avalanche photodiodes (APDs) to provide reasonable optical to electrical conversion efficiency were also needed for high-speed TDM systems. The combination of single-frequency lasers operating at 1.5 μm, signal encoding with external interferometer waveguide modulators, and detection with APDs resulted in record transmission experiments (2–16 Gb/s over 100-km spans) in the early 1990s that led to commercially deployed 10 Gb/s systems in the late 1990s.

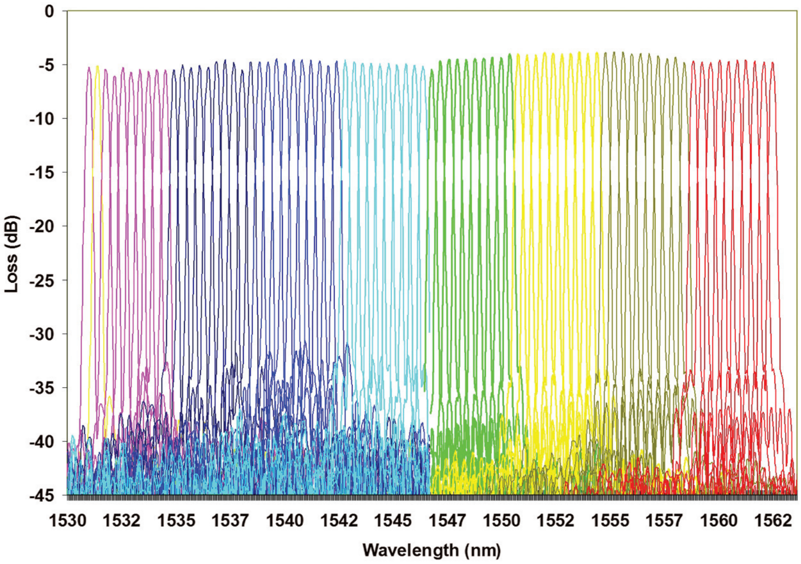
Wavelength division multiplexed (WDM) transmission systems employ multiple wavelengths, each separately encoded with information that is passively multiplexed together onto a single single-mode fiber, transmitted over some distance, and then wavelength demultiplexed into separate channels whose information is detected and received. While such systems had been proposed earlier, they had not initially gained popularity because of the need for a regenerator for each wavelength at repeater sites. Compared with increasing capacity via TDM, the approach did not scale capacity as cost effectively as TDM.

The fiber amplifier totally changed the value proposition of WDM systems. While not a pulse regenerator, the optical amplifier provides relatively low-noise 20–30-dB amplification—sufficient to compensate for transmission loss over 50–100 km of low loss fiber. Most importantly, the optical amplifier can simultaneously amplify multiple wavelengths, each carrying a high-capacity TDM signal. Notably, there is no mixing of signals, and amplification can be achieved for signals with arbitrarily high information rates. Both erbium-doped and Raman-based fiber amplifiers have been developed, with the former being the commercial workhorse. The erbium-doped fiber amplifier gain peaks at about 1.55 μm—well aligned to the fiber loss minimum.

Besides the fiber amplifier, the other key enabling technologies for WDM transmission systems are the wavelength multiplexing and demultiplexing devices and single-mode lasers whose wavelength can be precisely matched to the mux/demux wavelength response. For large wavelength counts, waveguide grating routers based on silica waveguide technology are typically employed. Figure 2 shows the 80-wavelength output from an early silica-based arrayed waveguide router. High-power (~100-mW output power) semiconductor pump lasers are required. Fiber amplified transmission systems are essentially analog systems where amplifier noise from each repeater accumulates, as does dispersive and nonlinear pulse spreading. Careful dispersion management is very important. Zero-chirp optical modulators are especially important for signal encoding to leverage the cost effectiveness of the amplifier over longer distances without electrical regenerators.

The first WDM commercial systems, deployed in terrestrial long-haul applications in the mid-1990s, employed eight wavelengths at 2.5 Gb/s, a tenfold improvement over the single-channel systems

Fig. 2. Measured wavelength response of a silica waveguide based grating router 80-wavelength channel multiplexer/demultiplexer with 50 GHz channel spacing.



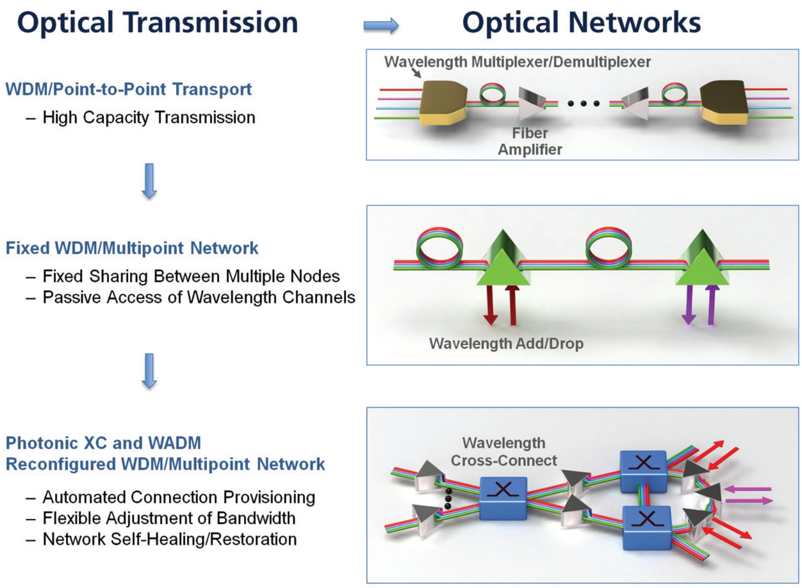
previously available. As multiplexing devices and amplifier performance was improved, the number of wavelengths was soon doubled and then quadrupled. In the research lab, work focused on WDM for higher TDM rates, 10 Gb/s and beyond.

The first WDM systems were deployed over existing "standard" single-mode fiber. However, to reduce the phase-matched nonlinear mixing effect of fiber at its zero-dispersion wavelength, so called "non-zero-dispersion shifted" fibers were developed. Such fibers could be used as the transmission fiber or in the repeater site as a "dispersion compensating fiber" to undo dispersion accumulation. In this case the transmission fiber has sufficient dispersion over the transmission distance to avoid four-wave mixing but produces pulse spreading that is undone by the compensating fiber.

Undersea lightwave systems were an important driver and early adopter of fiber amplified WDM transmission systems that were especially attractive because they avoid undersea high-speed electronics, which reduced the lead time for reliability testing. In addition, properly designed WDM transmission systems offered the potential for future capacity growth by increasing the wavelength bit rate or the number of wavelengths. The first such system, a transatlantic system, included 16 wavelengths at 2.5 Gb/s each with repeater spacing of 100 km.

In research labs around the world, as multiplexing devices and amplifier performance were improved and techniques to mitigate dispersive and nonlinear transmission impairments developed, single-fiber transmission capacity results were improved, sometimes quite dramatically, every year. These extraordinary "hero" transmission systems experiments became the highlight of the post-deadline session of The Optical Society (OSA, and IEEE Photonics and Communications) sponsored Optical Fiber Conference (OFC) each year. Increased capacity in transmission systems experimental results over the years (Fig. 1) were achieved by increasing the per wavelength bit rate from 2.5 Gb/s to 10 Gb/s to 40 Gb/s to 100 Gb/s. Key issues that needed to be addressed included demonstrating high-speed electronics, modulators, and receivers at the higher rates; mitigating nonlinear fiber; and managing dispersive effects. Total capacity was also increased by increasing the number of wavelengths. This was achieved either by increasing the bandwidth of the amplifier or by finding ways to reduce the wavelength spacing without reducing the information rate/wavelength, resulting in improved spectral efficiency.

The adoption of WDM transmission led to wavelength-based reconfigurable optical networks that provide wavelength-level, cost-effective network bandwidth management. That evolution is shown schematically in Fig. 3. Initially WDM was employed over linear links where all wavelengths were aggregated onto the fiber at one node and carried with periodic amplification to an end node. However, in real networks, especially as the distance achievable without electronic regeneration has been increased, the sources and destinations of traffic require off and on ramps for traffic entering between



◀ **Fig. 3.** Evolution of reconfigurable, wavelength routed optical networks employing reconfigurable optical add/drops (ROADMs) and optical cross-connects.

large metropolitan areas. Optical wavelength add/drop multiplexers provide those high-capacity on/off ramps with a full wavelength of capacity and allow all other wavelengths to pass through the node benefiting from the amplification. While initially these were fixed in number and which wavelengths were added/dropped, these modules are now fully remotely reconfigurable with respect to both the number of channels and which wavelengths are added/dropped.

Networks are not linear but are meshed to enhance resilience to equipment failures and fiber cuts. They require branching points where several fiber routes coming into a major metropolitan area connect to several exiting routes and also drop/add wavelengths at the node. In this case optical switch modules, referred to as optical cross-connects, which, in a wavelength-selective manner connect wavelength channels from one input fiber route to a particular output route, are employed.

Automated, reconfigurable optical switch cross-connects have become essential elements in today's WDM optical networks to effectively manage bandwidth capacity as demands increase and change. The enabling technologies for reconfigurable wavelength add/drop multiplexers and cross-connects are electrically controlled optical switches, either broadband or wavelength selective, together with components known as wavelength multiplexers/demultiplexers. A variety of technologies have been used for optical switch fabrics, including micro-mechanical (MEM), liquid crystal, and thermo-optical waveguide switches. Integrated modules that include wavelength demultiplex/demultiplex (demux/mux) together with optical space switches are also commercially available. Commercial wavelength reconfigurable optical networks have been widely deployed at both national and metropolitan levels. Integration, both monolithic and hybrid, has been important to cost effectively achieve the functional complexity required for modern optical networks.

An important advantage of optical networks is the potential to upgrade the bit rate per wavelength without the need to deploy new optical networking elements. The inherent bit rate independence of optical amplifiers (other than the possible need for higher pump power), optical switch fabrics, and mux/demux elements has allowed carriers to upgrade properly designed reconfigurable optical networks, initially operating at 10 Gb/s, to 40 Gb/s and 100 Gb/s by changing out only the ingress transmitters and egress receivers—a significant advantage of optical networks. Express wavelengths can now be carried cross continent without going through costly electronic regenerators, while along the way traffic can be optically dropped and added to fully utilize the high-bandwidth-fiber pipe.

At the time of this writing, commercial reconfigurable optical networks available and deployed for national and metro applications have capacities of ~10 Tb/s (100 wavelengths at 100 Gb/s) with fully reconfigurable wavelength add/drop capability. Transoceanic commercial systems are operating at capacities of ~4 Tb/s.

The ubiquitous deployment of broadband wireless systems together with massive sharing of consumer produced video and growing demand to access “cloud” based computational services continues to drive bandwidth demand at 25%–40% per year. There is every indication that demand will continue to grow at ~10× over the next ten years. Given the state of current commercial systems, this suggests the need for 1 Pb/s systems in the next 8–10 years. Commercially, the next targeted bit rate is likely to be 400 Gb/s followed by 1 Tb/s. To achieve higher speeds requires continued advancement in high-speed electronics, photo detectors, modulators, and integration. It also requires the ability to launch higher optical power while mitigating nonlinear effects. The number of wavelength channels is limited by the required bandwidth per channel and the total transmission bandwidth limited by the amplifier. Optimizing system spectral efficiency is essential. Achieving long-distance transmission without regeneration is also important for cost-effective networks.

To achieve higher effective per wavelength channel capacity while limiting speed requirement, research has focused on advanced coding techniques that use both amplitude and phase information as offered by coherent detection. By employing coherent techniques it is also possible to apply polarization multiplexing to effectively double channel capacity. Coherent techniques also allow the use of electronics to mitigate deleterious transmission impairments. These modulation formats, including quadrature phase-shifted keying (QPSK) and quadrature amplitude modulation (QAM), require the use of high-speed digital signal processors to convert the input signal information into the coded amplitude and phase-modulation signals to drive complex nested optical amplitude and phase modulators to encode the optical signal. As an example, with polarization multiplexing and 64-QAM (64 symbols per bit), one can transmit at an effective rate of 320 Gb/s with electronics, modulator, and receiver operating at only 80 Gbaud/s. The benefits come with transmission trade-offs as well as the complexity of high-speed digital signal processors. There has been substantial research progress in this area over the last five years as reflected in the systems results of Fig. 1.

Within the past several years, concern has been growing that keeping up with bandwidth demand will require another major technological leap—an additional dimension of multiplexing. The proposed dimension is to use space division as implemented either via multiple cores in a fiber or multi-modes of a single-core fiber. For the system to be cost effective compared to simply building parallel fiber optic systems, it likely will be necessary to also demonstrate optical amplifiers, at least, to act upon multiple spatial modes simultaneously. Integration is likely to be essential.

Because of limited space we have focused here on long-haul and metro optical communication networks. However, leveraging the technologies outlined here, there has been tremendous progress in optical access systems as well. Fiber optic technology has been used to feed coaxial cable systems, allowing increased reach and per user capacity. There is also increasing deployment of fiber-to-the-home systems, especially using TDM-based passive optical network (PON) technology. Recently, combined WDM and TDM PON technologies have been deployed to provide per home/business capacities of 1 Gb/s.

In addition, optical technology to provide intrabuilding interconnection in data centers is a growing application that will become even more critical as cloud services evolve. Distances are relatively short, and low cost is especially important. Optical and opto-electronic integration, either hybrid or monolithic, will be essential. The role of optical switching in data centers is being explored.

Throughout this history of incredible progress, OSA has played a critically important role in fostering and nurturing the continuous discovery, invention, and demonstration of optical components and systems that have been key to the dramatic progress of this field. OFC, a premier global conference on optical communications, was first held (as the Topical Meeting on Optical Fiber Transmission) in 1975 in Williamsburg, Virginia. OFC/NFOEC 2013 had more than 12,000 attendees from all over the world. The OFC post-deadline sessions are standing-room only events where researchers around the globe present their latest breakthrough results.

OSA has also nurtured newly emerging technologies in their formative stages, including fiber amplifiers, reconfigurable optical networks, and fiber to the home through highly focused topical meetings that offer ample opportunity for discussion and debate. The *Journal of Lightwave Technology*, co-sponsored by OSA and IEEE, has been a key journal for sharing and archiving advances in the field. Many of the members of the optical communication field have played leadership roles in OSA as well.

Acknowledgements

In this short historic overview, scope and space have not allowed proper citations [2]. My thanks to the large global community—many of whom are members of OSA—who have contributed to the extraordinary progress in optical networks described here.

References

1. Adapted from R. W. Tkach, "Scaling optical communications for the next decade and beyond," Bell Labs Tech. J. **14**, 3–9 (2010).
2. Suggested further reading for recent overview and update: Special issue on the Evolution of Optical Networks, Proc. IEEE **100**(5) (2012).

Integrated Photonics

Radhakrishnan Nagarajan

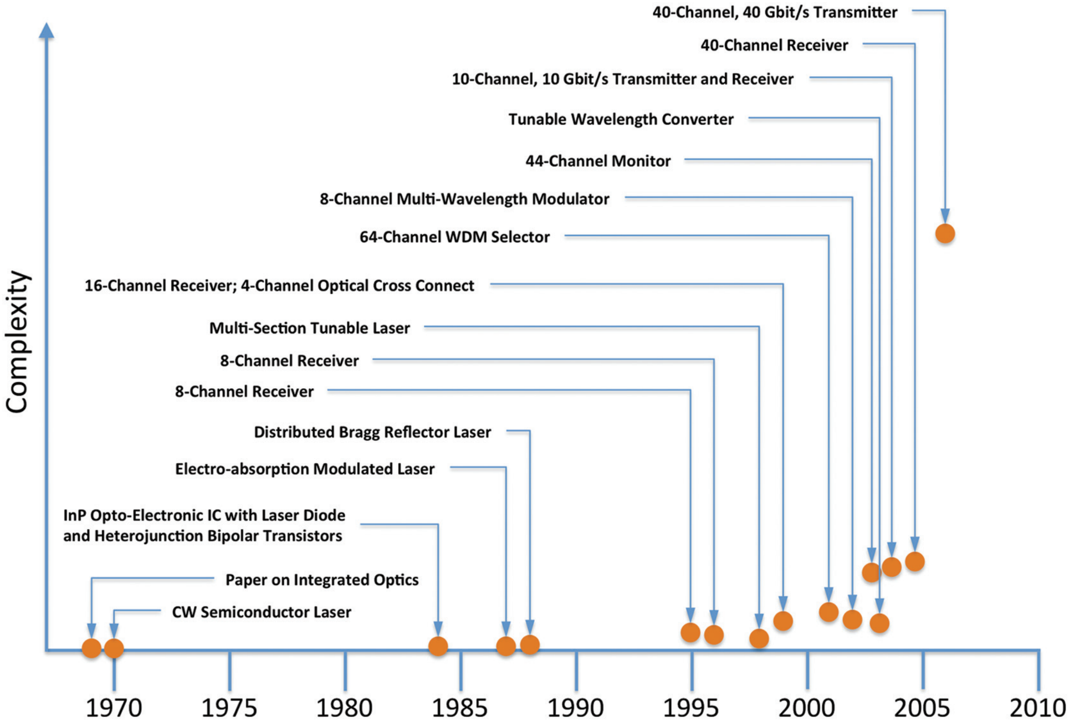
An essay on the history of integrated photonics invariably starts with the seminal paper by Miller [1]. In 1969 the idea was way ahead of its time, and many of the components needed to make such an integrated circuit a reality had yet to be invented. Hayashi and Panish's demonstration of the continuous wave (CW) room temperature operation of a semiconductor laser, a critical device for the photonic integrated circuit (PIC), was still a year away [2]. Optical transport, where PICs find their applications, got its somewhat fortuitous start in 1970 as well with the report of a low-loss optical fiber by the group at Corning [3].

There is always some personal bias in presenting the historical evolution of any technology. Figure 1 graphically shows one such historical progression of PIC complexity, as measured in the number of integrated components on a single InP substrate, with time. The details of the devices and references presented in Fig. 1 are in [4]. InP and its alloys are the material of choice in fabricating light emitters for optical transport applications. This is due to the low-loss window at 1550 nm and the low-dispersion point at 1300 nm in the standard silica optical fiber.

For the first decade or so after the demonstration of the CW laser in the GaAs system, InP lasers started to mature. In the mid-1980s there was active work in the area of opto-electronic integrated circuits (OEICs), where the integration of electronic devices such as HBT (heterojunction bipolar transistor) and FET (field effect transistor) with laser diodes and photodetectors was pursued. In the late 1980s three-section tunable DBR (distributed Bragg reflector) lasers were introduced. This was also when electro-absorption modulators (EAMs) integrated with distributed feedback (DFB) lasers were demonstrated. The trend continued with more complicated (four and five section) tunable laser sources that were also integrated with an EAM or a semiconductor optical amplifier (SOA). The next step was the demonstration of the arrayed waveguide grating (AWG) or PHASAR (phased array) router integrated with photodetectors for multi-channel receivers or with gain regions and EAM for multi-frequency lasers and multi-channel modulated sources. One of the most complex PICs reported in the last century was a four-channel optical cross-connect integrating 2 AWGs with 16 MZI (Mach–Zehnder interferometer) switches. At this stage the most sophisticated laboratory devices still had component counts below 20 while those in the field had component counts of about 4.

The trend in low-level photonic integration continued into the 2000s with one of the larger chips reported being a 32-channel WDM channel selector. In 2003, ThreeFive Photonics reported a 40-channel WDM monitor chip, integrating 9 AWGs with 40 detectors. MetroPhotonics reported a 44-channel power monitor based with an echelle grating demultiplexer. The commercial development of both chips was subsequently discontinued. The first successful attempt at a commercial large-scale photonic integrated chip (LS-PIC) was made in 2004 when Infinera introduced a 10-channel transmitter, with each channel operating at 10 Gbit/s. This device with an integration count in excess of 50 individual components was the first LS-PIC device deployed in the field to carry live network traffic. This was quickly followed in 2006 by a 40-channel monolithic InP transmitter, each channel operating at 40 Gbit/s, with a total component count larger than 240, and aggregate data rate of 1.6 Tbit/s. The complementary 40-channel receiver PIC also had an integrated, polarization independent, multi-channel SOA at the input.

2004, the year when the first commercial large-scale photonic integrated circuit was deployed, proved to be a watershed year for silicon photonics as well when Intel demonstrated

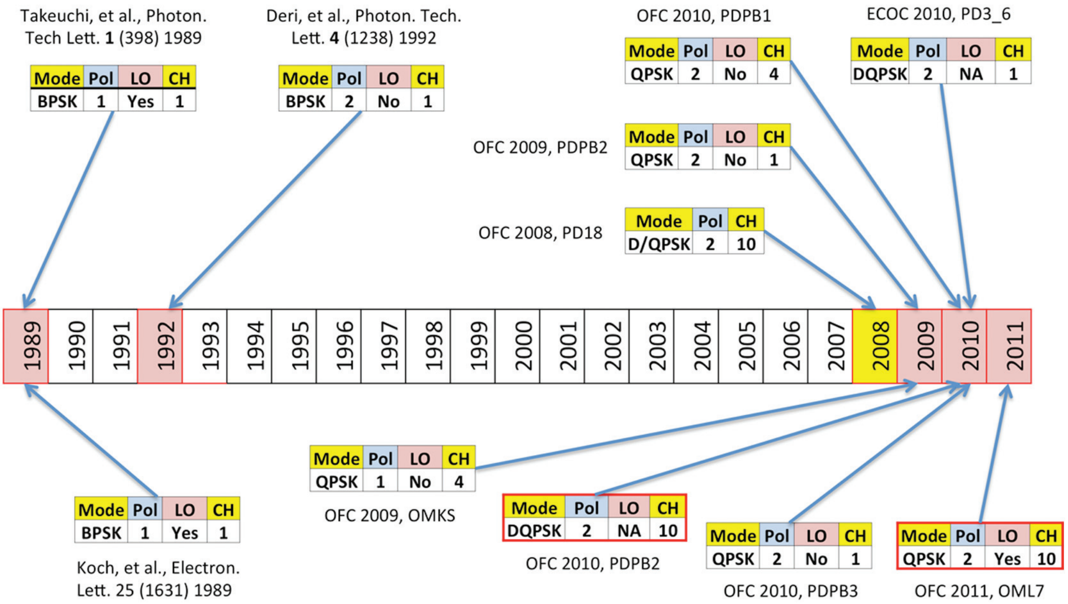


▲ **Fig. 1.** Historical trend and timeline for monolithic, photonic integration on InP (without including vertical cavity InP devices). The vertical scale is linear, and the red filled circles start at 1 and go to 240. The trend shows an exponential growth in PIC complexity in recent years. Unlike silicon ICs where the transistor count is a universal metric, there is no unique benchmark for complexity in photonic integration. For this exercise, we have counted a functional unit (which may be a combination of other optical elements) as a device. For example, an MZI is counted as 1 and not as 3. Likewise an AWG is counted as 1 irrespective of the fraction of the PIC real estate it occupies.

the first gigabit per second optical silicon (Si)-on-insulator (SOI) modulator [5]. Si as a platform for optical integration dates back to the 1980s [6,7]. In [6] can be found an excellent review of the early years of Si photonics. Unlike InP, Si has a centro-symmetric crystalline structure and does not exhibit the linear electro-optic effect that is commonly used for modulating light in InP. Most Si modulators are based on the carrier plasma effect, change of refractive index with carrier accumulation, or depletion. Although this is a weak material effect, the capacitor structure, which allows for a large effective charge transfer, improves the efficiency considerably [6]. Although there are reports of integrated Ge lasers on Si substrates [8], for the most part the light sources for Si photonics are made of InP and are integrated using hybrid techniques [9].

In Fig. 1 we saw the progression of PIC complexity thru the 2005 timeframe. Although some of the PICs, such as the switches and CW sources, were modulation format agnostic, for the most part these operated using OOK (on–off keying). Figure 2 shows the progression of PICs used for advanced modulation formats such as QPSK (quadrature phase shift keying) used in optical coherent communication. The details of the devices and references presented in Fig. 2 can be found in [10].

Coherent optical communication development started in the mid-1980s. After a gap of more than ten years, in the mid-2000s the field went through a revival with the availability of high-speed Si ASICs and advanced digital signal processing algorithms that eliminated the need for ultra-stable optical sources and analog phase/frequency/polarization tracking of the optical carrier at the receiver. Early coherent receiver PICs were all single channel. They were designed for binary phase shift keying (BPSK) modulation format. BPSK is similar to QPSK except that there are no data in the quadrature



▲ **Fig. 2.** A timeline for the development of coherent PICs. There is a gap between the early 1990s, when EDFAs were first introduced, and late 2000s when coherent communication systems saw deployment. Key: Mode = BPSK, QPSK; Pol = number of polarizations detected; LO = whether a LO was integrated into the PIC; CH = number of channels integrated onto a PIC. Most of these PIC's are receivers, with exception in 2008 when a 10 channel transmitter PIC was reported which included an I /Q modulator integrated with an optical source, for each channel, on the same substrate.

component of the signal. A simple, single-stage MZ modulator (MZM) may be used to generate a BPSK signal. BPSK signals have lower spectral efficiency but better noise margin for longer transmission distances. There were early attempts to integrate a LO (local oscillator) on the receiver PIC as well. A multi-channel PIC with I/Q MZM integrated with an optical source was reported in 2008. There have been a number of variants on the DQPSK and QPSK (with external LO) receiver PICs reported since then. The DQPSK PICs also have the polarization components integrated onto the same substrate. The first multichannel, dual polarization, QPSK receiver PIC with an integrated LO per wavelength was reported in 2011. Unlike the first phase of the history of integrated photonics discussed in Fig. 1, the evolution of coherent PICs shown in Fig. 2 has devices on both the InP and Si platforms.

References

1. S. Miller, "Integrated optics: an introduction," Bell Syst. Tech J. **48**, 2059–2069 (1969).
2. I. Hayashi, M. Panish, P. Foy, and S. Sumski, "Junction lasers which operate continuously at room temperature," Appl. Phys. Lett. **17**, 109–111 (1970).
3. I. Kapron, D. Keck, and R. Maurer, "Radiation losses in glass optical waveguides," Appl. Phys. Lett. **17**, 423–425 (1970).
4. R. Nagarajan, M. Kato, J. Pleumeekers, P. Evans, S. Corzine, S. Hurtt, A. Dentai, S. Murthy, M. Missey, R. Muthiah, R. Salvatore, C. Joyner, R. Schneider, M. Ziari, F. Kish, and D. Welch, "InP photonic integrated circuits," J. Sel. Top. Quantum Electron. **16**, 1113–1125 (2010).
5. D. Samara-Rubio, L. Liao, A. Liu, R. Jones, M. Paniccia, O. Cohen, and D. Rubin, "A gigahertz silicon-on-insulator Mach-Zehnder modulator," in *Optical Fiber Communication Conference* (Optical Society of America, 2004), post-deadline paper 15.
6. G. Reed, W. Headley, and C. Png, "Silicon photonics: the early years," Proc. SPIE **5730**, 596921 (2005).

7. R. Soref, “The past, present, and future of silicon photonics,” IEEE J. Sel. Top. Quantum Electron. **12**, 1678–1687 (2006).
8. R. Camacho-Aguilera, Y. Cai, N. Patel, J. Bessette, M. Romagnoli, L. Kimerling, and J. Michel, “An electrically pumped germanium laser,” Opt. Express **20**, 11316–11320 (2012).
9. M. Heck and J. Bowers, “Hybrid and heterogeneous photonic integration,” in *Handbook of Silicon Photonics*, L. Vivien and L. Pavesi, eds. (CRC Press, 2013), Chap. 11.
10. R. Nagarajan, C. Doerr, and F. Kish, “Semiconductor photonic integrated circuit transmitters and receivers,” in *Optical Fiber Telecommunications, Vol. VI A: Components and Subsystems*, I. Kaminow, T. Li, and A. Willner, eds. (Elsevier, 2013), Chap. 2.

New Wave Microstructured Optical Fibers

Philip Russell

Background

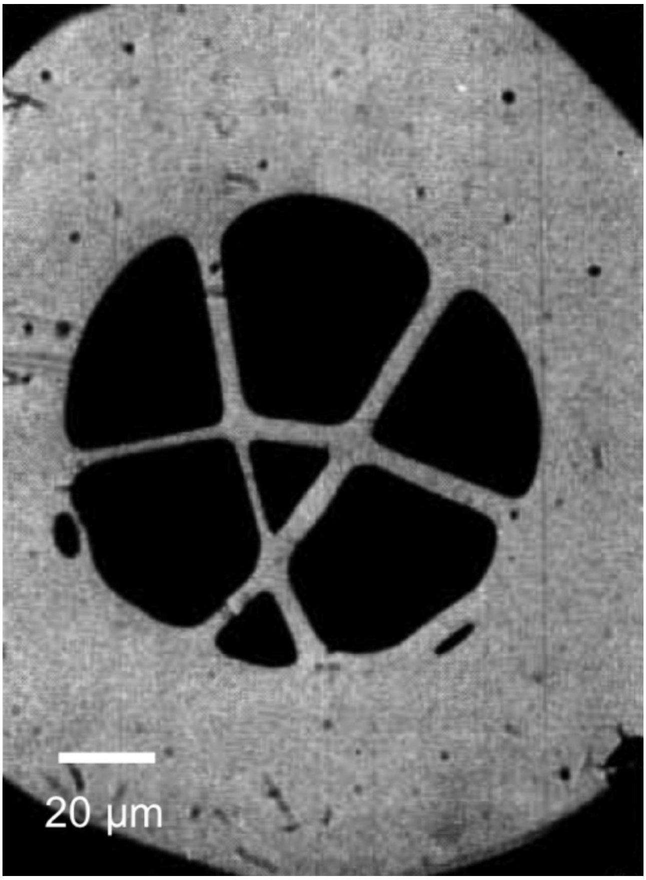
In the early 1990s there was a good deal of excitement about three-dimensional periodic structures in which light cannot exist at frequencies within a photonic bandgap (PBG) [1]. Henry van Driel (Optical Society Fellow, University of Toronto) even compared the atmosphere at a packed-out Quantum Electronics and Laser Science (QELS) session on PBGs (on the afternoon of the last day of the conference) to 1969 Woodstock! At that time it occurred to the author that, if one could create a two-dimensional PBG crystal of microscopic hollow channels in the cladding of an optical fiber, low-loss guidance of light in a hollow core might be possible [2,3]. The challenge would be to design a suitable structure and not least work out a way of making it (in pioneering work at Bell Laboratories in the early 1970s, primitive structures with a small number of large hollow channels had been made, the aim being air-clad glass fiber cores [4]). (See Fig. 1.)

Actually, the first hints that total internal reflection—the workhorse of conventional fiber optics—might not be the only way to guide light had emerged in 1968 with the little known theoretical work of Melekhin and Manenkov in the Soviet Union [5], followed by a more detailed study—again purely theoretical—by Yariv and Yeh at Caltech in 1976 [6]. Their idea was to create a cylindrical Bragg stack from concentric tubular layers of alternating high and low refractive index. Rays of light traveling within a certain range of conical angles would be Bragg reflected back into the core for all azimuthal directions. The trick then was to choose a core diameter that supports a Mie-like resonance at conical angles where the cylindrical Bragg stack has a radial stop-band, resulting in a low-loss guided mode (note that such "Bragg fibers" do not possess a PBG since light is free to propagate azimuthally).

The operating principle of both of these proposals is closely linked to anti-resonant reflecting optical waveguiding (ARROW), in which light is partially confined by a structure of one or more pairs of anti-resonant layers. Originally proposed by Duguay (AT&T Bell Laboratories) in 1986, these are essentially Fabry–Perot cavities operating off resonance so that they reflect light strongly back into the core [7,8]. When the number of such layers becomes large the ARROW structure begins to resemble a Bragg waveguide; i.e., the anti-resonance condition coincides with the presence of a radial stop-band [9].

Although solid-core versions of Bragg fibers have been produced using modified chemical vapor deposition (MCVD) (at IRCOM in Limoges, France) [10], for guidance in a *hollow* core one is up against the need for the radial stop-band to appear at values of axial refractive index less than 1. This means that individual layers must be very thin (~0.69 λ, where λ is the vacuum wavelength), enhancing the effects of dopant diffusion during fiber drawing and further reducing the already weak index contrast. Small index contrast also has the drawback that, for good confinement, a large number of periods is needed and the structure must be highly perfect to avoid leakage through defect states in the cladding layers.

The ideal structure would consist of a series of concentric glass layers with air between them, but of course this would not hold together mechanically. A possible compromise is to fabricate a structure of rings held together with thin glass membranes, but the losses so far reported are quite high [11]. One could think of increasing the index contrast using two solid



▲ **Fig. 1.** Three-core fiber made by Kaiser and colleagues at Bell Labs in the early 1970s. (Reprinted with permission of Alcatel-Lucent USA Inc.)

materials, but here the problems are extreme for another reason. Pairs of drawable glasses with compatible melting and mechanical properties, a large refractive index difference and high optical transparency are hard to found. More exotic combinations of chalcogenide and polymer overcome the mechanical problems, offering moderately low losses even though the absorption is extremely high in the polymer layers. Nevertheless, the company Omniguide has achieved 1 dB/m at 10 μm in such Bragg fibers [12], which are now used in laser surgery [13].

Making the First Photonic Crystal Fiber (PCF)

When the author proposed what he first called "holey fiber," defusing any anxious looks by adding that the word needed an "e," he was met with a good deal of skepticism. Would this new thing, the "photonic bandgap," really work—wasn't the refractive index of silica glass too small? The literature suggested that two-dimensional PBGs appear only if the refractive index ratio is very large, say 2.2:1 for a two-dimensional dielectric–air structure [1] (actually this turns out to be true only for purely in-plane propagation [14]). Even if it did work, would the bend losses not be huge? And then there were the practicalities of making it. The author remembers Clive Day, who had been at the Post Office Research Laboratories in Martlesham (UK) in the 1970s, recalling how difficult the "single-material" fibers had been to make (in 1997 British Telecom donated Day's three-legged drawing tower to the author's then group at the University of Bath, allowing them to make many of the first discoveries about photonic crystal fibers (PCFs)). (See Fig. 2.)

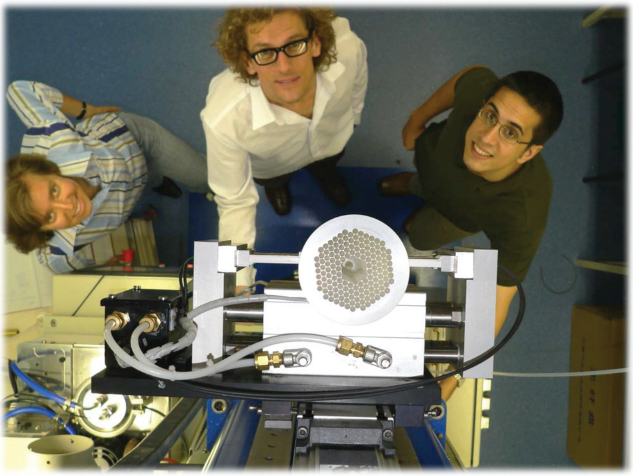
Although conventional lithography worked well for very thin photonic crystal structures, it was hard to see how it could be adapted to produce even millimeter lengths of PCF. More promising was work at Naval Research Laboratories in Washington, where Tonucci had shown that multi-channel glass plates with hole diameters as small as 33 nm, in a tightly packed array, could be produced using draw-down and selective etching techniques [15]. The maximum channel length was limited by the etching chemistry to ~1 mm, and though the structures were impressively perfect, they were not fibers. The earliest attempt, in 1991, involved drilling a pattern of holes into a stub of silica glass, the hope being that it could be drawn into fiber. Machining an array of 1 mm holes in a stub of silica ~2.5 cm in diameter (the largest the drawing furnace would accommodate) proved beyond the capabilities of the ultrasonic drill, so this approach was abandoned. Since then it has been shown that drilling works well for softer materials such as compound glasses or polymers. Another versatile technique is extrusion, in which a molten glassy material is forced through a die containing a suitably designed pattern of holes. Although not yet successfully used for fused silica (existing die materials contaminate the glass at the high temperatures needed [16]), extrusion works well for both polymers [17,18] and soft glasses [19]. (See Fig. 3.)

After various different approaches had been tried, the first successful silica–air PCF structure emerged from the drawing tower in late 1995, the result of the efforts of Tim Birks and Jonathan Knight—postdocs in the author's group at the Optoelectronics Research Center (ORC) in Southampton. The preform was constructed by stacking 217 silica capillaries (eight layers outside the central capillary) into a tight-packed hexagonal array. The diameter-to-pitch ratio of the holes in the final fiber was too small for PBG guidance in a hollow core, so we decided to make a PCF with a solid central core surrounded by 216 air channels [16]. The result was a working PCF, which guided by a kind of modified total internal reflection. The results were reported in 1996 in a post-deadline paper at OSA's Conference on Optical Fiber Communications and subsequently published in *Optics Letters* [20,21]. (See Fig. 4.)

Breakthroughs and Applications

This work led to the discovery of "endlessly single-mode" (ESM) PCF, which, if it guides at all, supports only the fundamental guided mode [14]. There is a story behind the publication of this result. Submitted to *Optics Letters*, the manuscript received lukewarm or negative reviews and was initially rejected. Feeling that justice was on their side, the group appealed to the editor, Anthony Campillo, who took a look at it and decided to accept it. Currently (October 2015), with more than 1700 citations, it is one of the most frequently cited in the field. ESM behavior is also a feature of ridge waveguides formed by etching a thin film of dielectric material so as to produce a raised strip, and in fact Kaiser points this out in his 1974 paper [4]. The reason is simple: thinner structures support modes with lower refractive indices, which means that the fundamental mode of the thicker ridge will be trapped by the equivalent total internal reflection. Compared to planar ridge waveguides, however, ESM-PCF is

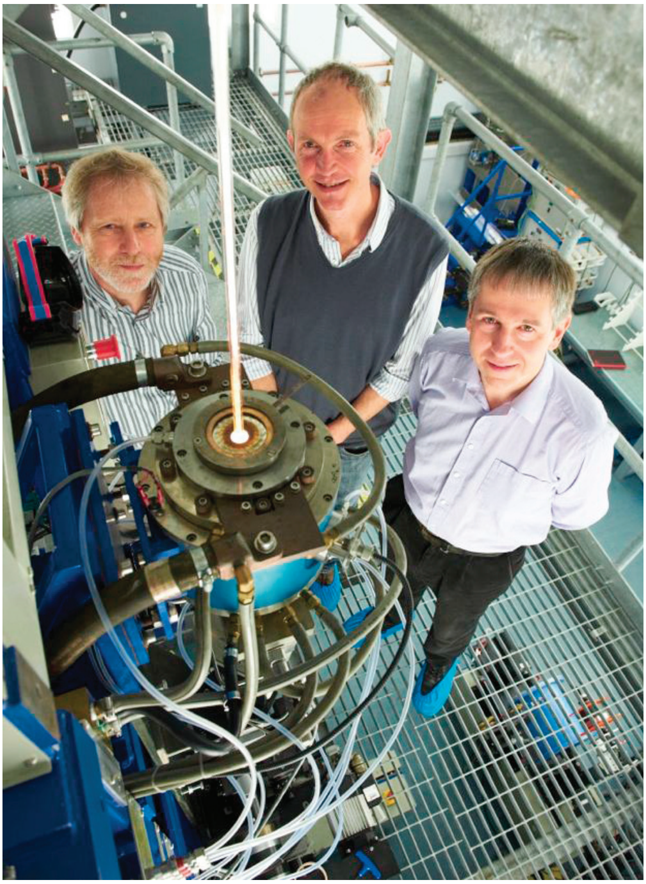
▲ **Fig. 2.** Clive Day working with his three-legged drawing tower at the Post Office Research Laboratories in Martlesham (UK) in the 1970s. (Courtesy Dr. Clive Day and the Post Office Research Centre, Martlesham Health, UK.)



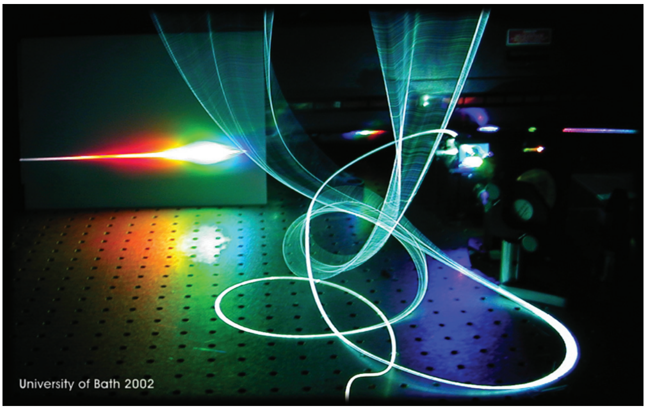
▲ **Fig. 3.** Maryanne Large, Martijn van Eijkelenborg and Alex Argyros drawing polymer PCF at the University of Sydney. (Photograph by Justin Digweed.)

free of birefringence, provided its structure has perfect sixfold symmetry [22].

Armed with a technique suitable for routine manufacture of microstructured fibers, they set off to explore what could be done—the fun had begun. A string of results followed, the first being an ESM-PCF with an ultra-large mode area [23]. This arose from the realization that ESM behavior allowed one to operate in regimes where a conventional fiber would be multimode. At the other extreme, it was pointed out in 1999 that cores of diameter ~1 μm, surrounded by large hollow channels, would have very high anomalous dispersion at 1550 nm, which it was later realized would push the zero dispersion to wavelengths much shorter than the canonical 1.29 μm associated with conventional silica single-mode fiber [24]. This was to lead to perhaps the biggest breakthrough so far in applications of PCF: the demonstration by a team at Bell Laboratories that an octave-spanning frequency comb could be produced using ~100 fs pulses of few nanoJoule energies from a mode-locked Ti:sapphire oscillator [25,26]. This created huge excitement when it was presented as a post-deadline paper at OSA's Conference on Lasers and Electro-Optics in 1999, and contributed materially to the award of the 2005 Nobel Prize for Physics to Jan Hall of NIST in Boulder, Colorado, and Ted Hänsch of the Max-Planck Institute for Quantum Optics in Munich [27,28]. (See Fig. 5.)



▲ **Fig. 4.** Right to left: Tim Birks, Jonathan Knight, and the author at the University of Bath in 2011. (Courtesy University of Bath.)



▲ **Fig. 5.** Iconic photograph of white-light supercontinuum taken in 2002 by Ph.D. student Will Reeves. (Courtesy University of Bath.)

The year 1999 also saw the first report of a hollow-core PCF, indicating that one could indeed guide light using the new physics of PBGs [29]. Fred Leonberger, the program chair of CLEO 2002 in Long Beach, California, was kind enough to invite the author to give one of the plenary talks—a sure sign that PCF had, within only a few years, attracted considerable attention. The next technological steps focused mostly on improving the performance, mainly the loss, of these new fibers. Following intensive development at Corning and BlazePhotonics (a post-deadline paper at OFC in 2004 reported 1.7 dB/km [30]), the lowest published loss of hollow core PCF stands at 1.2 dB/km at 1550 nm [31]. Just before BlazePhotonics closed down, the R&D team actually had reduced the value still further to 0.8 dB/km.

It was rapidly realized that thermal post-processing, together with pressure control, twisting, and stretching, could be used to make radical changes in the local fiber characteristics post-fabrication.

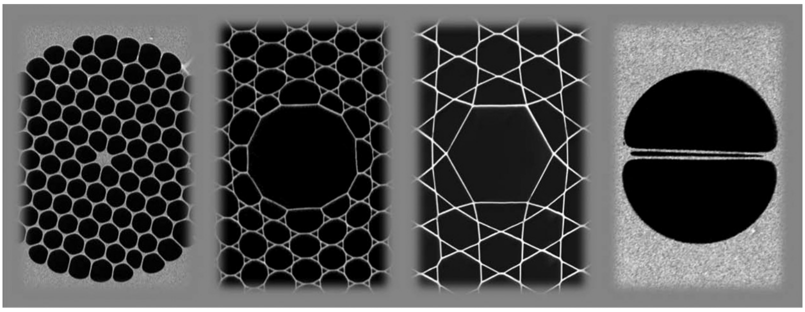


Fig. 6. Scanning electron micrographs of a selection of different photonic crystal and microstructured fibers. (Courtesy Max-Planck Institute for the Science of Light.)

These techniques have thrown up a large number of useful devices, including long-period gratings, rocking filters, helical fibers, and the remarkable "photonic lanterns" now used to filter out atmospheric emission lines in fiber-based astronomy [32,33]. Based on all-solid multi-core fibers, these devices perform the astonishing feat of adiabatically channeling each mode of a multi-mode fiber into separate single-mode fibers.

Applications of the new fiber structures continue to emerge, an obvious highlight being broadband light sources millions of time brighter than incandescent lamps and extending into the UV, pumped by Q-switched Nd:YAG microchip lasers or Yb-doped fiber lasers at 1-μm wavelength. These are now to be found in many laboratory instruments, including commercial microscopes. New types of sensing, fiber have emerged, some of them reminiscent of the original single-material fibers of Kaiser (e.g., the so-called "Mercedes" fiber [34]). Hollow core PCF has perhaps opened up the greatest number of new opportunities. For example, it is being employed as a microfluidic system for monitoring chemical reactions, in which guided light is used both to photo-excite and to measure changes in the absorption spectrum [35]. (See Fig. 6.) Compared to conventional microfluidic circuits, the quantity of liquid required is very small, the long path-length means that very small absorption changes can be detected, and the high intensity achievable in the narrow core for moderate optical power means that reactions can be rapidly initiated. PCF is also being used in many other optical sensors, with applications in environmental detection, biomedical sensing, and structural monitoring.

The unique ability of hollow-core PCF to keep light tightly focused in a single mode in a gas is creating a revolution in nonlinear optics. For the first time it is possible to explore ultrafast nonlinear optics in gases in a system where the dispersion can be tuned by changing the gas pressure and composition [36]. Raman frequency combs spanning huge ranges of frequency, from the UV to the mid-IR, can be generated at quite modest power levels [37,38]. Atomic vapors of, e.g., Rb and Cs can be incorporated into the hollow core, permitting experiments on EIT and few-photon switching [39]. Hollow core also adds a new dimension to the important field of optical tweezers: the absence of diffraction means that radiation forces can be employed to transversely trap and continuously propel dielectric particles over curved paths many meters in length [40].

In Conclusion

The Optical Society, through its conferences and publications (especially *Optics Letters* and *Optics Express*), has played and continues to play a major role in promoting a disruptive technology that, through delivering orders of magnitude improvement over prior art, seems likely over the next decades to have an increasing impact in both commercial and scientific research.

References

1. E. Yablonovitch, "Photonic band-gap structures," J. Opt. Soc. Am. B **10**, 283–295 (1993).
2. P. St.J. Russell, "Photonic-crystal fibers," J. Lightwave Tech. **24**, 4729–4749 (2006).
3. P. St.J. Russell, "New age fiber crystals," IEEE Lasers Electro-Opt. Soc. Newsletter **21**, 11 (2007). http://2photonicssociety.org/newsletters/oct7/21leos05.pdf.

4. P. V. Kaiser and H. W. Astle, "Low-loss single-material fibers made from pure fused silica," Bell Syst. Tech. J. **53**, 1021–1939 (1974).
5. V. N. Melekhin and A. B. Manenkov, "Dielectric tube as a low-loss waveguide," Sov. Phys. Tech. Phys. USSR **13**, 1698–1699 (1969).
6. P. Yeh and A. Yariv, "Bragg reflection waveguides," Opt. Commun. **19**, 427–430 (1976).
7. M. A. Duguay, Y. Kokubun, T. L. Koch, and L. Pfeiffer, "Antiresonant reflecting optical wave-guides in SiO_2-Si multilayer structures," Appl. Phys. Lett. **49**, 13–15 (1986).
8. J. L. Archambault, R. J. Black, S. Lacroix, and J. Bures, "Loss calculations for antiresonant waveguides," J. Lightwave Technol. **11**, 416 (1993).
9. N. M. Litchinitser, S. C. Dunn, B. Usner, B. J. Eggleton, T. P. White, R. C. McPhedran, and C. M. de Sterke, "Resonances in microstructured wavetuides," Opt. Express **11**, 1243–1251 (2003).
10. F. Brechet, P. Roy, J. Marcou, and D. Pagnoux, "Single mode propagation in depressed-core-index photonic-bandgap fiber designed for zero-dispersion propagation at short wavelengths," Electron. Lett. **36**, 514–515 (2000).
11. A. Argyros, M. A. van Eijkelenborg, M. C. J. Large, and I. M. Bassett, "Hollow-core microstructured polymer optical fiber," Opt. Lett. **31**, 172–174 (2006).
12. B. Temelkuran, S. D. Hart, G. Benoit, J. D. Joannopoulos, and Y. Fink, "Wavelength-scalable hollow optical fibres with large photonic bandgaps for CO_2 laser transmission," Nature **420**, 650–653 (2002).
13. F. C. Holsinger, C. N. Prichard, G. Shapira, O. Weisberg, D. S. Torres, C. Anastassiou, E. Harel, Y. Fink, and R. S. Weber, " Use of the photonic bandgap fiber assembly CO_2 laser system in head and neck surgical oncology," Laryngoscope **116**, 1288–1290 (2006).
14. T. A. Birks, J. C. Knight, and P. St.J. Russell "Endlessly single-mode photonic crystal fiber," Opt. Lett. **22**, 961–963 (1997).
15. R. J. Tonucci, B. L. Justus, A. J. Campillo, and C. E. Ford, "Nanochannel array glass," Science **258**, 783–785 (1992).
16. D. C. Allan, J. A. West, J. C. Fajardo, M. T. Gallagher, K. W. Koch, and N. F. Borrelli, "Photonic crystal fibers: effective index and bandgap guidance," in *Photonic Crystals and Light Localisation in the 21st Century*, C. M. Soukoulis, ed. (Kluwer, 2001), pp. 305–320.
17. H. Ebendorff-Heidepriem, T. M. Monro, M. A. van Eijkelenborg, and M. C. J. Large, "Extruded high-NA microstructured polymer optical fiber," Opt. Commun. **273**, 133–137 (2007).
18. M. A. van Eijkelenborg, M. C. J. Large, A. Argyros, J. Zagari, S. Manos, N. A. Issa, I. M. Bassett, S. Fleming, R. C. McPhedran, C. M. de Sterke, and N. A. P. Nicorovici, "Microstructured polymer optical fibre," Opt. Express **9**, 319–327 (2001).
19. H. Ebendorff-Heidepriem, K. Kuan, M. R. Oermann, K. Knight, and T. M. Monro, "Extruded tellurite glass and fibers with low OH content for mid-infrared applications," Opt. Mater. Express **2**, 432–442 (2012).
20. J. C. Knight, T. A. Birks, P. St.J. Russell, and D. M. Atkin, "Pure silica single-mode fiber with hexagonal photonic crystal cladding," in *Conference on Optical Fiber Communications* (Optical Society of America, 1996).
21. J. C. Knight, T. A. Birks, P. St.J. Russell, and D. M. Atkin, "All-silica single-mode fiber with photonic crystal cladding," Opt. Lett. **21**, 1547–1549 (1996).
22. M. J. Steel, T. P. White, C. M. de Sterke, R. C. McPhedran, and L. C. Botten, "Symmetry and degeneracy in microstructured optical fibers," Opt. Lett. **26**, 488–490 (2001).
23. J. C. Knight, T. A. Birks, R. F. Cregan, P. St.J. Russell, and J. P. De Sandro, "Large mode area photonic crystal fibre," Electron. Lett. **34**, 1347–1348 (1998).
24. T. A. Birks, D. Mogilevtsev, J. C. Knight, and P. St.J. Russell, "Dispersion compensation using single-material fibers," IEEE Photon. Technol. Lett. **11**, 674–676 (1999).
25. J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," Opt. Lett. **25**, 25–27 (2000).
26. J. K. Ranka and R. S. Windeler, "Nonlinear interactions in air-silica microstructure optical fibers," Opt. Photon. News **20**(8), 21–25 (2000).
27. T. W. Hänsch, "Nobel Lecture: Passion for precision," Rev. Mod. Phys. **78**, 1297–1309 (2006).
28. J. L. Hall, "Nobel Lecture: Defining and measuring optical frequencies," Rev. Mod. Phys. **78**, 1279 (2006).
29. R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St.J. Russell, P. J. Roberts, and D. C. Allan, "Single-mode photonic band gap guidance of light in air," Science **285**, 1537–1539 (1999).

30. B. J. Mangan, L. Farr, A. Langford, P. J. Roberts, D. P. Williams, F. Couny, M. Lawman, M. Mason, S. Coupland, R. Flea, H. Sabert, T. A. Birks, J. C. Knight, and P. St.J. Russell, "Low-loss (1 dB/km) hollow core photonic bandgap fiber," in *Optical Fiber Communications Conference* (OSA Technical Digest), post-deadline paper PDP24 (2004).
31. P. J. Roberts, F. Couny, H. Sabert, B. J. Mangan, D. P. Williams, L. Farr, M. W. Mason, A. Tomlinson, T. A. Birks, J. C. Knight, and P. St.J. Russell, "Ultimate low loss of hollow-core photonic crystal fibres," Opt. Express **13**, 236–244 (2005).
32. S. G. Leon-Saval, T. A. Birks, J. Bland-Hawthorn, and M. Englund, "Multimode fiber devices with single-mode performance," Opt. Lett. **30**, 2545–2547 (2005).
33. T. A. Birks, B. J. Mangan, A. Diez, J. L. Cruz, and D. F. Murphy, "'Photonic lantern' spectral filters in mullti-core fiber," Opt. Express **20**, 13996–14008 (2012).
34. C. M. B. Cordeiro, M. A. R. Franco, C. J. S. Matos, F. Sircilli, V. A. Serrao, and C. H. B. Cruz, "Single-design-parameter microstructured optical fiber for chromatic dispersion tailoring and evanescent field enhancement," Opt. Lett. **32**, 3324–3326 (2007).
35. J. S. Y. Chen, T. G. Euser, N. J. Farrer, P. J. Sadler, M. Scharrer, and P. St.J. Russell, "Photochemistry in photonic crystal fiber nanoreactors," Eur. J. **16**, 5607–5612 (2010).
36. J. C. Travers, W. Chang, J. Nold, N. Y. Joly, and P. St.J. Russell, "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers [Invited]," J. Opt. Soc. Am. B **28**, A11–A26 (2011).
37. F. Couny, F. Benabid, P. J. Roberts, P. S. Light, and M. G. Raymer, "Generation and photonic guidance of multi-octave optical-frequency combs," Science **318**, 1118–1121 (2007).
38. A. Abdolvand, A. M. Walser, M. Ziemienczuk, T. Nguyen, and P. St.J. Russell, "Generation of a phase-locked Raman frequency comb in gas-filled hollow-core photonic crystal fiber," Opt. Lett. **37**, 4362–4364 (2012).
39. M. Bajcsy, S. Hofferberth, V. Balic, T. Peyronel, M. Hafezi, A. S. Zibrov, V. Vuletic, and M. D. Lukin, "Efficient all-optical switching using slow light within a hollow fiber," Phys. Rev. Lett. **102**, 203902 (2009).
40. O. A. Schmidt, M. K. Garbos, T. G. Euser, and P. St.J. Russell, "Reconfigurable optothermal microparticle trap in air-filled hollow-core photonic crystal fiber," Phys. Rev. Lett. **109**, 024502 (2012).

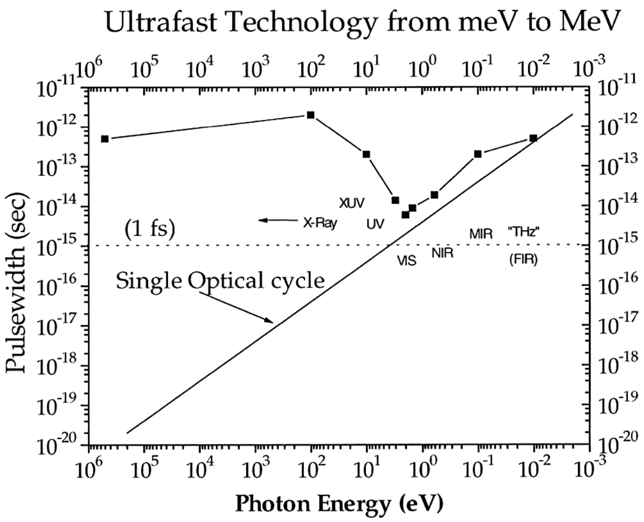
Ultrafast-Laser Technology from the 1990s to Present

Wayne H. Knox

The field of femtosecond lasers was in a difficult state in January 1984. Lasers that generated pulses of 100 fs or less in duration were few and far between, but there were a growing number of research applications they could be applied to. For example, at Bell Laboratories in Holmdel, New Jersey, David A. B. Miller and Daniel S. Chemla were very interested in studying the excitonic nonlinear optical response and electro-optic properties of GaAs-based quantum wells, which were rather new back then. The author was a post-doc with that group and was able to take advantage of the magnificent femtosecond laser labs that had been developed by Richard L. Fork and Charles V. Shank to work on the generation of infrared femtosecond pulses, which were perfect to use to study the dynamics of GaAs-based quantum wells. A few years before, Chuck Shank's group had developed the first colliding pulse mode-locked laser that reliably gave pulses of great stability and always shorter than 100 fs around 625 nm wavelength [1]. They had built a multi-stage dye-cell amplifier system pumped by a frequency-doubled Q-switched Nd:YAG laser at 10 Hz rate, producing millijoule pulse energies that were more than intense enough to generate a beautiful white-light continuum. Pumped by an argon laser with a few watts of green light, the dye laser produced average powers of a few tens of milliwatts in a train of femtosecond pulses as long as the dye jets were behaving well. Bad behavior included clogging, popping hoses squirting dye all over the lab. And, of course, the dye would eventually turn bad and have to be changed. So, given that the laser was generating only one color of light in the visible at low power and was running on 40 kW of electrical line power, while using five gallons per minute of chilled water, it was very difficult to imagine how such a laser technology could be useful in the world someday.

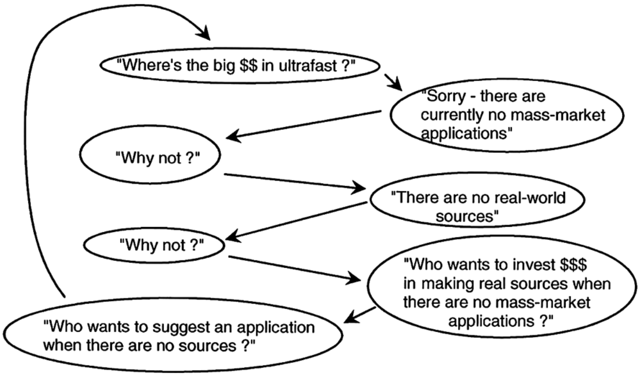
The development of Ti:sapphire lasers by Peter Moulton while at MIT Lincoln Labs and subsequent demonstration of Kerr-lens mode locking by Wilson Sibbett's group [2, 3] were a tremendous advance for the field, offering much higher powers and near-infrared tunability as well. Chirped-pulse amplification, by Gerard Mourou's group at the University of Rochester in 1985 [4], led to widely scalable oscillator-amplifier systems of great variety and complexity. Simultaneously, development of erbium and then later ytterbium fiber gain media together with the development of cheap high-power laser diode pump sources were driven strongly by demand during the telecommunications bubble that peaked in March 2000 with the NASDAQ briefly hitting 5000. Combining these advances in solid-state as well as fiber technologies now has made possible a new generation of practical ultrafast compact laser sources that are offered by more than 30 commercial suppliers, many of which are still in search of their "killer application." Figure 1 shows the state of the ultrafast-laser field in 1995, plotting shortest pulse width as a function of photon energy. We can see that the attosecond short-wavelength frontier had been identified, but not explored yet, and note the tremendous advances in that field have been driven by science and technology developments in many fields since then.

The Optical Society (OSA) has been at the forefront in promoting ultrafast laser technology through its various journals and conferences. In 1995 a CLEO (Conference on Lasers and Electro-Optics) tutorial entitled "Ultrafast Optical Power Supplies" was given by the author [5], which reviewed the progress of the field and laid out some of the challenges for laser developers. Figure 2 shows an “Ultrafast Catch-22” that seemed to exist then and still seems to be true today. With the rapid developments in source technologies and materials in the late 1990s, it appeared that it would be possible to develop compact reliable sources of femtosecond pulses covering a variety of parameter ranges; however, few commercial applications had been developed, and therefore there were few incentives to invest in those technologies. Figure 3 shows that a wide range of applications require a wide range of versatile sources, and no single laser can satisfy all of them; therefore, individual unit volumes remain low. In 1996 a plenary talk was given by the author at CLEO titled “Ultrafast Epiphany: The Rise of Ultrafast Science and Technology in the Real World” [6]. *The Epiphany was that ultrafast lasers could actually be useful for things beyond the obvious ones in high-speed measurements.* This is indeed the most important consideration about the use of ultrafast laser technology. In some cases, there may be absolute value in the use of ultrafast laser technology. In such a case, there is simply no other way to carry out a certain application without the use of femtosecond lasers. Those cases may not be very numerous. But in most of the other cases, there is competing technology, and then femtosecond laser technology has to offer enhanced value but at a price that is commensurate with the increased value that it offers. Most ultrafast laser oscillators still cost \$50–\$150K today, so they need to add a lot of value to justify that expense.

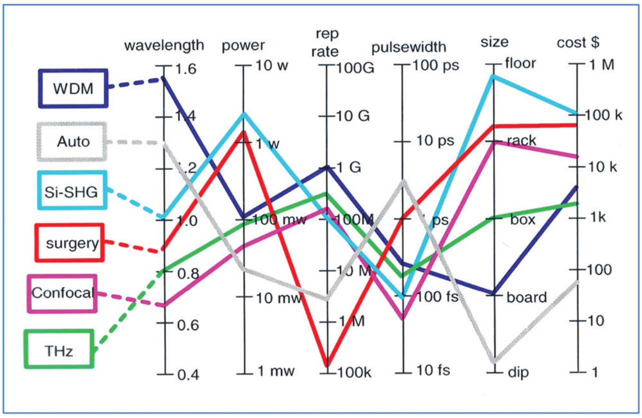


▲Fig. 1. Survey of the ultrafast laser field in 1994. The short-wavelength attosecond frontier had been identified, but not explored.

A number of applications for femtosecond technology were predicted by the author in 1995 and 1996; it might be interesting to see how those predictions have come out. The first known commercial application of femtosecond technology was coherent phonon generation and detection for multilayer thin film metrology, by Rudolph Instruments in New Jersey. For this, an OEM laser source was developed by Coherent, Inc. In 1995, the author predicted that a high-power chirp-pulse amplified femtosecond laser would be mounted on a truck and used by the military forces. Today, indeed such a truck has been developed and sold by Applied Energetics for detection and detonation of IEDs (improvised explosive devices). The TeraMobile project has taken atmospheric propagation of femtosecond pulses truly throughout the globe in search of applications. In 1995, the author predicted that ultrafast electro-optic sampling systems would be commercially available, and indeed such systems are available from Ando and others. In 1996, the author predicted that ultrafast sources would power new generations of two-photon microscopes, and several companies now offer these, including Zeiss/IMRA and BioRad/Spectra-Physics, but they are not yet widely used in clinical practice. In 1995, the author predicted that someday there would be commercial terahertz radiation spectrometers. Indeed, this area has advanced tremendously, with commercial systems available from seventeen companies [7]. Applications for



▲Fig. 2. The incentive to invest in development of practical “real-world” femtosecond lasers comes from the applications. Lasers and applications must be developed in parallel.



▲**Fig. 3.** The various needs for ultrafast optical laser systems identified in 1995. A wide range of applications requires a wide range of laser technology options.

terahertz measurements have exploded, including at least the following: insulating foam analysis, chemical analysis, explosive detection, concealed weapons detection, moisture content, coating thickness, basis weight measurement, product uniformity, and structural integrity. In 1996, however, the author certainly did not predict that ultrashort lasers spanning greater than one octave range would produce a revolution in high-precision frequency measurements, yet that has emerged as an important new area, and there are now at least three companies supplying femtosecond lasers with 6-fs or shorter pulses. In 1985, such an experiment was worthy of the *Guinness Book of World Records*, but now it is commercially available. Micromachining in many materials using femtosecond pulses has developed into a significant commercial area. In 1996, although there was research in that area, the author did not predict that it would become commercially significant. Several companies, including Clark-MXR, now offer commercial versions of ultrafast manufacturing systems. It should be pointed out that terahertz systems that are based on femtosecond lasers are currently offered by four companies; however, thirteen other companies offer terahertz systems based on continuous-wave sources [7]. Similarly, ultrafast manufacturing systems have to compete with excimer lasers and other conventional types of advanced manufacturing approaches. Both of these examples illustrate that while ultrafast laser technology may offer enhanced value to certain applications, the extra cost involved puts it on a par with competing technologies.

And this leads us to the most important application of femtosecond laser technology to date. One outgrowth of femtosecond material-damage studies occurred at the University of Michigan in the 1990s [8]. A very well-developed technology for excimer laser ablation of the human cornea (LASIK) had been developed, but it required the creation of a corneal flap. A technique was developed using a rapidly vibrating razor blade to create a corneal incision and horizontal flap that could be lifted off to expose the middle part of the stroma, which is the tough structural part of the cornea. Ophthalmologists got used to using the razor blade system, which cost them about $30,000. But it turns out that a new approach developed involving the use of focused femtosecond light pulses could create a dense array of microbubbles that, once interconnected, could be lifted like a “flap.” With this new approach, patients would not have to worry about their corneas being cut with a razor blade. This technique gained excellent market acceptance, and with additional benefits in enhanced precision of the corneal flap thickness and positioning, it was found that patients greatly preferred this technology. Over time, during 2000 and up to the present, it has been firmly established that femtosecond-laser flap cutting is the one preferred by patients. Ophthalmologists have been able to work out successful business plans involving the new systems (which cost over $500,000 and have expensive annual maintenance plans). So, it is clear that one application has risen far above all others in economic value and market acceptance, and this was unpredictable back in 1996.

Looking to the future of vision correction, a new approach is being developed that does not involve cutting of the cornea. This technology creates a controlled index of refraction change [9–11] using high-repetition-rate femtosecond lasers. It is hoped that this approach will replace much if not all of currently used refractive correction technologies; however, much work to do remains to be done.

It is expected that many new areas of application will continue to emerge for femtosecond lasers in the future. In each case, there will be a definitive test of the value of the new technology, and each one will be an interesting story. Will we be writing about applications of attosecond technology some day? Surely we will!

References

1. R. L. Fork, B. I. Greene, and C. V. Shank, "Generation of optical pulses shorter than 0.1 psec by colliding pulse mode locking," Appl. Phys. Lett. **38**, 671–673 (1981).
2. D. E. Spence, P. N. Kean, and W. Sibbett, "Sub-100 fs pulse generation from a self-mode-locked titanium-sapphire laser," in *Conference on Lasers and Electro-Optics*, Vol. **7** of 1990 OSA Technical Digest Series (Optical Society of America, 1990), p. 619.
3. D. E. Spence, P. N. Kean, and W. Sibbett, "60-fsec pulse generation from a self-mode-locked Ti:sapphire laser," Opt. Lett. **16**, 42–44 (1991).
4. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**, 219 (1985).
5. W. H. Knox, "Ultrafast optical power supplies," tutorial presented at Conference on Lasers and Electro-Optics (CLEO) (Optical Society of America, 1995).
6. W. H. Knox, "Ultrafast epiphany: the rise of ultrafast science and technology in the real world," in *Conference on Lasers and Electro-Optics (CLEO)* (plenary presentation), OSA Technical Digest (Optical Society of America, 1996), paper JMC2.
7. Private communication, X.-C. Zhang and A. Redo-Sanchez, 2012.
8. R. R. Krueger, T. Juhasz, A. Gualano, and V. Marchi, "The picosecond laser for nonmechanical laser in situ keratomileusis," J. Refract. Surg. **14**, 467–469 (1998), and references therein.
9. L. Ding, R. Blackwell, J. F. Kunzler, and W. H. Knox, "Large refractive index change in silicone-based and non-silicone-based hydrogel polymers induced by femtosecond laser micro-machining," Opt. Express, **14**, 11901–11909 (2006).
10. L. S. Xu and W. H. Knox, "Lateral gradient index microlenses written in ophthalmic hydrogel polymers by femtosecond laser micromachining," Opt. Mater. Express **1**, 1416–1424 (2011).
11. L. S. Xu, W. H. Knox, M. DeMagistris, N. D. Wang, and K. R. Huxlin, "Noninvasive intratissue refractive index shaping (IRIS) of the cornea with blue femtosecond laser light," Investig. Ophthalmol. Vis. Sci. **52**, 8148–8155 (2011).

Biomedical Optics: In Vivo and In Vitro Applications

Gregory Faris

Call it what you will: biomedical optics, biophotonics, optics in the life sciences, or lasers in medicine; light, lasers, and optics have played a tremendous role in biology and medicine over the last few decades, and this role is growing. This chapter covers activities on biomedical optics for in vivo and in vitro applications. Additional material on biomedical optics can be found in the chapter by Jim Wynne on LASIK.

Optical methods are used in medicine and biology for both diagnostics and therapeutics. Important aspects of optical methods for these applications include the ability to use multiple wavelengths to perform spectroscopy (i.e., detect or stimulate specific transitions to provide molecular information) or to perform multiplexing with multi-color probes, the ability to penetrate tissue (particularly in the near infrared), the ability to produce changes in molecules, and the potential to produce low-cost and portable instrumentation.

Clinical use of optical methods has a long history. Early methods relied on the observer's eye for imaging through human tissue, with reports of detection of hydrocephalus (accumulation of cerebrospinal fluid within the cranium, 1831) [1], hydrocele (accumulation of fluid around the testis, 1843) [2], and breast cancer (1929) [3]. The advent of the laser and microelectronics enabled applications such as retinal surgery using argon lasers in the 1960s [4] and pulse oximetry in the 1970s [5]. However, the largest growth in biomedical optics methods began in the 1990s, where advances in lasers, image sensors, and genetic modification led to the advent of many new biomedical optics methods, among them optical coherence tomography (OCT) [6], in vivo diffuse optical imaging, multi-photon microscopy [7], revival of coherent anti-Stokes Raman spectroscopy (CARS) microscopy [8], photoacoustic imaging, bioluminescence imaging [9], green fluorescence protein as a marker for gene expression [10], and bioimaging using quantum dots [11,12].

In Vivo Imaging and Spectroscopy

Optical imaging in tissue generally falls into two classes: those based on unscattered light ("ballistic" photons), which can provide very high spatial resolution (on the order of micrometers, i.e., the cellular level) but with limited tissue penetration (on the order of 1–2 mm), and those based on scattered light (diffuse imaging), which can provide good tissue penetration (many centimeters) at the expense of resolution (limited to on the order of 1 cm). Examples of high-resolution in vivo imaging include OCT, confocal imaging, and nonlinear microscopy. Examples of diffuse methods include diffuse optical tomography, tissue oximetry, and pulse oximetry.

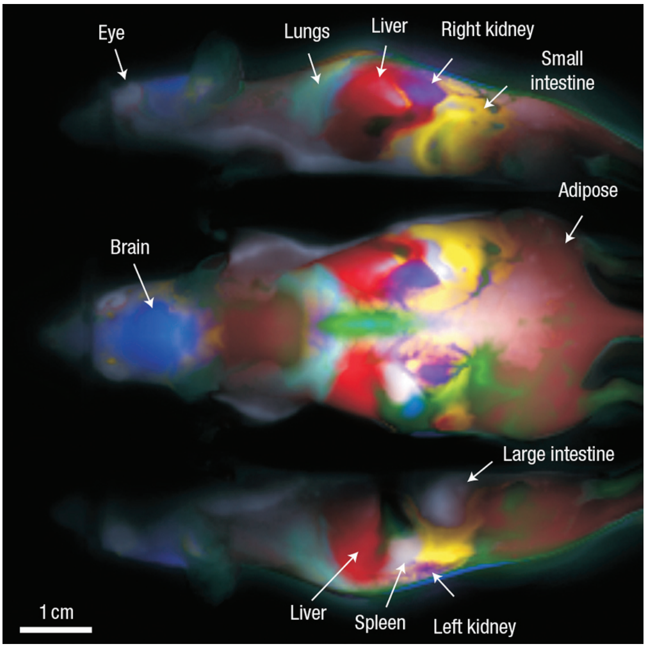
In Vivo Molecular Probes and Image Contrast. The ability to perform molecular imaging or spectral multiplexing is one of the primary advantages of optical methods. For in vivo imaging, a range of targets is available with endogenous contrast. For absorption measurements, these include most notably oxyhemoglobin and deoxyhemoglobin (the basis for pulse oximetry, tissue oxygenation monitoring, optical brain monitoring and imaging, and diffuse optical tomography), as well as spectral variation of scattering, melanin, bilirubin, and cytochrome oxidase. Endogenous fluorophores in vivo include nicotinamide adenine dinucleotide (NADPH), flavins, collagen, and elastin. Exogenous chromophores and fluorophores in clinical use include fluorescein for retinal angiography and corneal abnormalities, indocyanine green (ICG) for monitoring vasculature and perfusion, isosulfan blue for tracing the lymph system, and sensitizers for photodynamic therapy. More advanced chromophores and fluorophores are under development, including molecular beacons and nanoparticles. The latter can potentially combine diagnostic and therapeutic capabilities. A significant hurdle in the use of advanced chromophores in humans is regulatory approval, though the various advanced contrast agents are currently used in animal studies. There are several commercial systems available today for optical molecular imaging of small animals.

Diffuse optical imaging in vivo has been pioneered by Britton Chance (Fig. 1) and others. Significant application areas of diffuse optical imaging include small-animal imaging, brain monitoring and imaging, and cancer detection. In diffuse optical tomography, image reconstruction is used to produce two- or three-dimensional images from a set of absorption or fluorescence images. Dynamic or differential imaging can be used to enhance contrast from diffuse optical imaging. An example is shown in Fig. 2, which displays an image of internal organs in a mouse derived from the dynamics of dye uptake following injection.

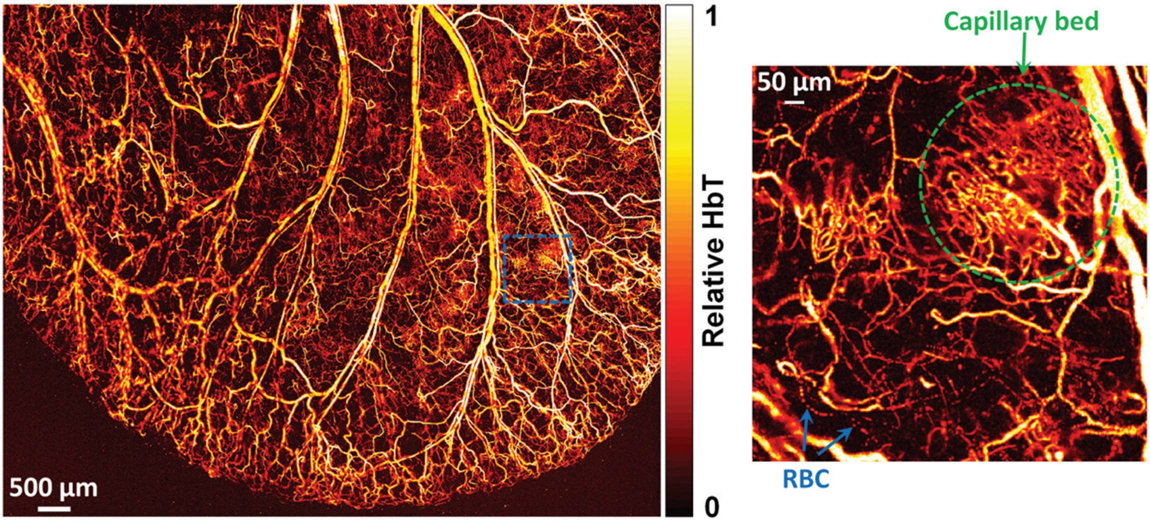
Photoacoustic imaging and spectroscopy combine the relative advantages of optical and acoustic methods. Absorption of a laser pulse produces an acoustic wave that is detected by an acoustic transducer. This method provides the molecular specificity of optical methods (e.g., localizing blood vessels through optical absorption of blood) with the spatial resolution of acoustic methods, which is superior to that of diffuse optics. An example of photoacoustic imaging of blood vessels with optical resolution in a mouse ear is shown in Fig. 3.

Optical coherence tomography (OCT). OCT, pioneered by James Fujimoto (Fig. 4) and others, is an interferometric method for reflectance in vivo microscopy providing high resolution (approximately a micron) at depths of approximately a millimeter in biological tissue. Early work on OCT was primarily performed in the time domain using very-short-coherence light sources [6]. More recently, spectral domain or Fourier domain

▲ **Fig. 1.** Britton Chance (The Optical Society [OSA]). (AIP Emilio Segre Visual Archives, Physics Today Collection.)



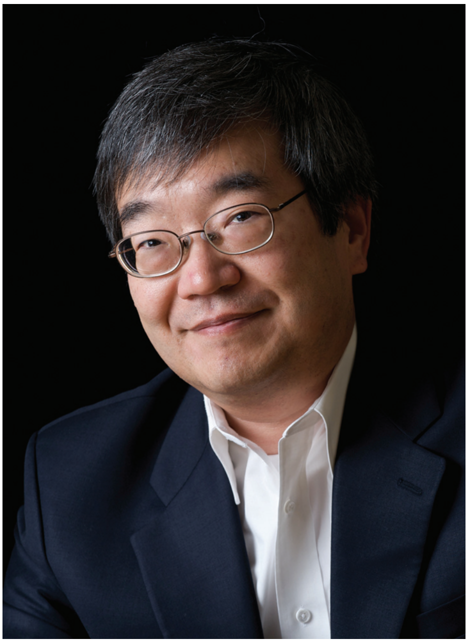
▲ **Fig. 2.** In vivo, non-invasive anatomical mapping of internal organs in a mouse derived from temporal response of ICG uptake following injection. Nine organ-specific regions are found from the different circulatory, uptake, and metabolic responses. (Copyright © 2007, Nature Publishing Group.)



▲ **Fig. 3.** Optical-resolution photoacoustic microscopy image of relative total hemoglobin in living mouse ear. Images show detailed vascular anatomy, including densely packed capillary bed and individual red blood cells traveling along a capillary in the inset at right [26].

OCT [13] methods using tunable lasers or spectrometers have been widely adopted because these provide a better signal-to-noise ratio and faster scanning. OCT is widely used clinically in ophthalmology, with other applications to endoscopy for gastrointestinal or cardiovascular applications being evaluated.

Endoscopy and miniature imaging systems. As image sensors are produced in smaller sizes for applications such as smart phones, miniature imaging systems are being developed. This trend and the use of micro-electro-mechanical systems (MEMS) has allowed production of endoscopes with smaller sizes or with greater functionality such as higher resolution, better depth penetration, or molecular imaging capabilities. Miniaturization has enabled other applications such as swallowable pill cameras that can image the gastrointestinal system and miniaturized imaging systems for imaging brain activity in active animals [14].



▲ **Fig. 4.** James Fujimoto (OSA) (Photo by Greg Hren, courtesy of RLE at MIT.)

In Vitro Methods

Microscopy. Although microscopy has been a well established method in the life sciences for hundreds of years, the development of lasers and low-noise image sensors has enabled several advances in microscopy in the last few decades. With ultrafast lasers, it has been possible to perform nonlinear microscopy with little or no damage to cells. A variety of nonlinear methods have been applied to microscopy including second and third harmonic generation microscopy, multiphoton excited fluorescence microscopy (pioneered by Watt Webb, Fig. 5, and others) [7], and nonlinear Raman spectroscopy (including CARS and stimulated Raman spectroscopy) [8,15]. Examples of images acquired using coherent Raman microscopy are shown in Fig. 6. Nonlinear microscopies have been performed in vivo with excitation wavelengths as long as 1700 nm, allowing imaging depths of over 1 mm [16].

A variety of methods have been applied to improve the resolution of microscopy beyond the diffraction limit. Superresolution (the subject of the 2014 Nobel Prize in Chemistry) has been achieved based on finding the centroid of intermittent dye emission [photoactivated localization microscopy (PALM) [17] and stochastic optical reconstruction microscopy (STORM) [18]] or through nonlinearities such as for stimulated emission (STED) [19] or saturated structured illumination microscopy [20]. Subwavelength information can also be obtained using light to monitor the proximity between fluorophores using Förster resonance energy transfer (FRET) or metal nanoparticles (molecular ruler) [21]. Lateral diffusion can be monitored using fluorescence recovery after photobleaching (FRAP). Digital holographic microscopy provides both amplitude and phase images and allows computational reconstruction at different imaging planes.

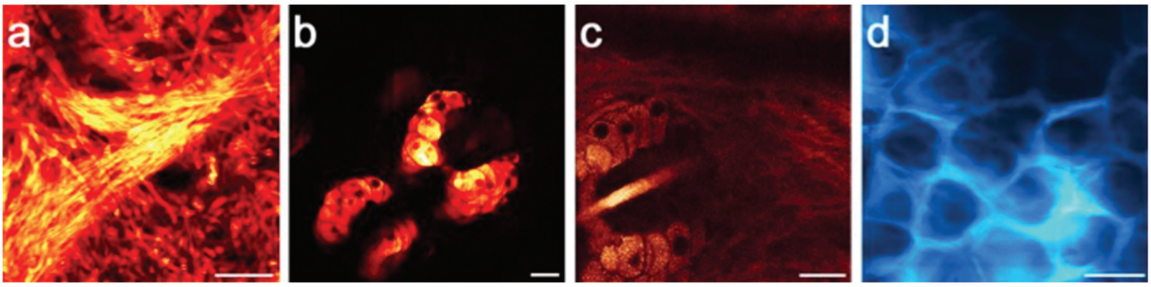
▲ **Fig. 5.** Watt Webb (OSA). (Photograph by Charles Harrington. Copyright Cornell University.)

Genetic modification and control. The DNA of cells or animals may be modified to produce optical signatures. For example, the green fluorescent protein (subject of the 2008 Nobel Prize in Chemistry) may be spliced into an organism to provide a fluorescent marker for gene expression. Bioluminescence such as that from the firefly can also be used to monitor gene expression. For example, insertion of the gene for luciferase into an animal allows imaging of gene expression by imaging yellow bioluminescence once the luciferin substrate is administered. For improved penetration in tissue, longer-wavelength versions of fluorescent proteins and bioluminescent substrates are being developed.

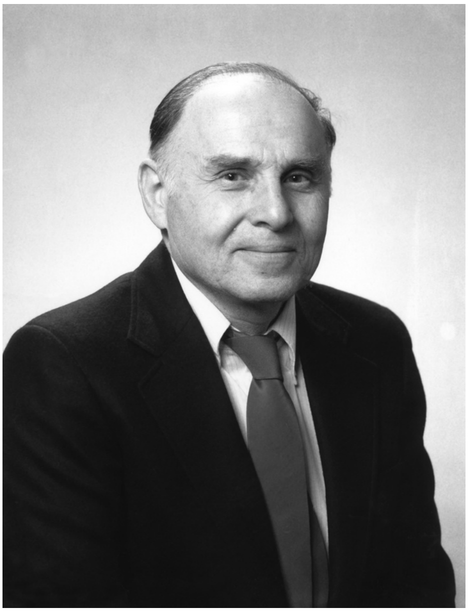
Single molecular detection. With the very small illumination volumes available with lasers and low-noise detectors it has been possible to image single molecules [11]. This allows probing variation in behavior of individual molecules rather than simply measuring ensemble averages of many molecules.

Optical tweezers or optical trapping (pioneered by Arthur Ashkin, Fig. 7, and others) [23] has allowed manipulation of cells or measurement of small forces for the study of molecular motors. Optical traps have enabled very precise studies of various molecular motors in cells. Recent developments include multiple optical traps produced using computer-generated holograms and cell stretching.

Microfluidics. Optics forms a natural pairing with microfluidics (optofluidics) because of the ability to remotely monitor conditions in microscopic volumes and the ability to use light to produce changes in the droplet contents or to manipulate or control microfluidic transport.



▲ **Fig. 6.** Label-free coherent Raman scattering microscopy showing (a) myelinated neurons in mouse brain, (b) sebaceous glands in mouse skin, (c), single frame of coherent anti-Stokes Raman movie acquired at 30 Hz, and (d) image of penetration trans-retinol in the stratum corneum. All scale bars are 25 μm [27].



▲ **Fig. 7.** Arthur Ashkin. (AIP Emilio Segre Visual Archives, Physics Today Collection.)

Other Applications. Optical methods have found other widespread uses in biomedicine. Examples include immunohistochemistry and fluorescence immunohistochemistry to label specific molecules on tissue sections in pathology, photolithography and fluorescence microscopy to map gene expression or genotype on DNA microarrays (gene chips), and matrix-assisted laser desorption/ionization (MALDI) for soft ionization of samples for mass spectroscopy.

Quantum dots are semiconductor nanoparticles for which quantum confinement leads to different colors based on the nanoparticle size and provides advantages for bioimaging [11,12]. Important qualities for quantum dots are the lack of photobleaching and wide range of colors that can be produced. Quantum dots are used for research including both in vitro and in vivo applications in animal studies.

Surface plasmon resonance. Surface plasmon resonance, particularly in noble metals, can be used in sensing and imaging. The resonance of the light field with the natural frequency of surface electrons at a gold layer is a powerful method for probing molecular interactions because of the high sensitivity, and no probe molecule is required. This method, commercialized notably by Biacore, is very widely used in biology laboratories. Surface plasmon resonance of single noble metal nanoparticles also allows detection of multiple colors using dark field microscopy.

Correlation methods and particle tracking. A number of other optical methods are well developed and commonly used in biomedical studies, such as dynamic light scattering and fluorescence correlation spectroscopy for monitoring the size and interactions of small particles such as proteins or micelles. For particles with stronger scattering, microscopic imaging can provide information on the cell's physical properties or intracellular interactions based on single particle tracking.

Therapeutics and Photomodification

One of the earliest applications of lasers in medicine was the use of argon ion lasers for retinal surgery. Other ophthalmic therapeutic applications include corrective surgeries such as LASIK and now ultrafast lasers for assistance in cataract surgery. Photodynamic therapy is used for treatment of certain cancers. Lasers are widely used for various cosmetic skin therapies including skin resurfacing, hair removal, vein treatment, acne scar treatment, tattoo removal, and treatment of port wine stain.

Cellular control and modification. Light may also be used to trigger changes in cells. For example, light may be used to turn on or off ion channels in vivo based on the proteins such as channelrhodopsin [24]. In this way light carried by optical fibers can activate different portions of the brain in awake animals. Ultrafast lasers are being used to perform nanosurgery and nanoporation on cells.

OSA's Role in Biomedical Optics

Throughout its history, OSA has played an active role in biomedical optics. The first issue of the *Journal of The Optical Society of America* in 1917 included articles titled "The nature of the visual receptor process" and "A photochemical theory of vision and photographic action," and this journal has been a significant publication for vision research since. As new journals were offered (*Applied Optics*, *Optics Letters*, and *Optics Express*) these, too, became important journals for instrumentation and techniques in biomedical optics. In 2006, the Society created the *Virtual Journal for Biomedical Optics* to collect biomedical optics papers in a single place (Greg Faris, founding editor). In 2010, OSA initiated a journal dedicated to the field, *Biomedical Optics Express* (founding editor, Joe Izatt). This journal follows the open access, online format of *Optics Express*. OSA meetings, including the Annual Meeting (later Frontiers in Optics) and the Conference on Lasers and Electro-Optics (CLEO) have regularly had significant content in biomedical optics and vision. A topical meeting "Topics in Biomedical Optics" (BIOMED) with heavy emphasis on in vivo methods was launched in 1994, and OSA is the cosponsor of the European Conferences on Biomedical Optics (ECBO) together with SPIE. A second meeting, Optics in the Life Sciences, with particular focus on microscopy, optical trapping, and contrast methods was begun in 2009, occurring in alternate years with BIOMED.

References

1. R. Bright, "Diseases of the brain and nervous system," in *Reports of Medical Cases Selected with a View of Illustrating the Symptoms and Cure of Diseases by a Reference to Morbid Anatomy* (Longman, Rees, Orms, Brown and Green, 1831), Vol. II, Case CCV, p. 431.
2. T. B. Curling, "Simple hydrocele of the testis," in *A Practical Treatise on the Diseases of the Testis and of the Spermatic Cord and Scrotum* (Samuel Highley, 1843), pp. 125–181.
3. M. Cutler, "Transillumination as an aid in the diagnosis of breast lesions," Surg. Gynecol. Obstet. **48**, 721–729 (1929).
4. F. A. L'Esperance, Jr., "An opthalmic argon laser photocoagulation system: design, construction, and laboratory investigations," Trans. Am. Ophthalmol. Soc. **66**, 827–904 (1968).
5. J. W. Severinghaus and Y. Honda, "History of blood gas analysis. VII. Pulse oximetry," J. Clin. Monit. **3**, 135–138 (1987).
6. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical coherence tomography," Science **254**, 1178–1181 (1991).
7. W. Denk, J. H. Strickler, and W. W. Webb, "Two-photon laser scanning fluorescence microscopy," Science **248**, 73–76 (1990).
8. A. Zumbusch, G. R. Holtom, and X. S. Xie, "Three-dimensional vibrational imaging by coherent anti-Stokes Raman scattering," Phys. Rev. Lett. **82**, 4142–4145 (1999).
9. C. H. Contag, P. R. Contag, J. I. Mullins, S. D. Spilman, D. K. Stevenson, and D. A. Benaron, "Photonic detection of bacterial pathogens in living hosts," Mol. Microbiol. **18**, 593–603 (1995).
10. M. Chalfie, Y. Tu, G. Euskirchen, W. W. Ward, and D. C. Prasher, "Green fluorescent protein as a marker for gene expression," Science **263**, 802–805 (1994).
11. W. C. W. Chan and S. Nie, "Quantum dot bioconjugates for ultrasensitive nonisotopic detection," Science **281**, 2016–2018 (1998).
12. M. Bruches, Jr., M. Moronne, P. Gin, S. Weiss, and A. P. Alivisatos, "Semiconductor nanocrystals as fluorescent biological labels," Science **281**, 2013–2016 (1998).
13. A. F. Fercher, C. K. Hitzenberger, G. Kamp, and S. Y. Elzaiat, "Measurement of intraocular distances by backscattering spectral interferometry," Opt. Commun. **117**, 43–48 (1995).
14. K. K. Ghosh, L. D. Burns, E. D. Cocker, A. Nimmerjahn, Y. Ziv, A. E. Gamal, and M. J. Schnitzer, "Miniaturized integration of a fluorescence microscope," Nat. Methods **8**, 871–878 (2011).
15. M. D. Duncan, J. Reintjes, and T. J. Manuccia, "Scanning coherent anti-Stokes Raman microscope," Opt. Lett. **7**, 350–352 (1982).
16. N. G. Horton, K. Wang, D. Kobat, F. Wise, and C. Xu, "In vivo three-photon microscopy of subcortical structures within an intact mouse brain," in 2012 Conference on Lasers and Electro-Optics (CLEO), OSA Techincal Digest (Optical Society of America, 2012).
17. E. Betzig, G. H. Patterson, R. Sougrat, O. W. Lindwasser, S. Olenych, J. S. Bonifacino, M. W. Davidson, J. Lippincott-Schwartz, and H. F. Hess, "Imaging intracellular fluorescent proteins at nanometer resolution," Science **313**, 1642–1645 (2006).
18. M. J. Rust, M. Bates, and X. Zhuang, "Sub-diffraction-limit imaging by stochastic optical reconstruction microscopy (STORM)," Nat. Methods **3**, 793–795 (2006).

19. S. W. Hell and J. Wichmann, "Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy," Opt. Lett. **19**, 780–782 (1994).
20. M. G. Gustafsson, "Nonlinear structured-illumination microscopy: wide-field fluorescence imaging with theoretically unlimited resolution," Proc. Natl. Acad. Sci. U.S.A. **102**, 13081–13086 (2005).
21. C. Sonnichsen, B. M. Reinhard, J. Liphardt, and A. P. Alivisatos, "A molecular ruler based on plasmon coupling of single gold and silver nanoparticles," Nat. Biotechnol. **23**, 741–745 (2005).
22. W. E. Moerner and L. Kador, "Optical detection and spectroscopy of single molecules in a solid," Phys. Rev. Lett. **62**, 2535–2538 (1989).
23. A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," Opt. Lett. **11**, 288–290 (1986).
24. E. S. Boyden, F. Zhang, E. Bamberg, G. Nagel, and K. Deisseroth, "Millisecond-timescale, genetically targeted optical control of neural activity," Nat. Neurosci. **8**, 1263–1268 (2005).
25. E. M. C. Hillman and A. Moore, "All-optical anatomical co-registration for molecular imaging of small animals using dynamic contrast," Nature Photon. **1**, 526–530 (2007).
26. S. Hu, K. Maslov, and L. V. Wang, "Second-generation optical-resolution photoacoustic microscopy with improved sensitivity and speed," Opt. Lett. **36**, 1134–1136 (2011).
27. K. Wang, C. W. Freudiger, J. H. Lee, B. G. Saar, X. S. Xie, and C. Xu, "Synchronized time-lens source for coherent Raman scattering microscopy," Opt. Express **18**, 24019–24024 (2010).

Novel Optical Materials in the Twenty-First Century

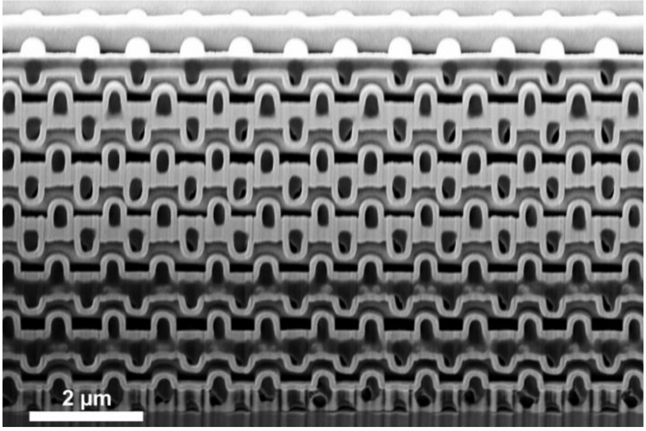
David J. Hagan and Steven C. Moss

It is a somewhat daunting task to speculate on optical materials for the next century. Before proceeding, it is perhaps useful to imagine how someone may have tried to write such an essay 100 years ago. Looking back at volume 1 of the *Journal of The Optical Society of America*, discussion of materials was limited to photographic emulsions, metallic films, and color filters. Of course, an optical scientist of that time could have had no inkling of the revolutions that were to follow (lasers, semiconductor electronics, fiber optics, to name but a few) that would transform our concept of optics, give birth to the field of "photonics," and in many ways redefine what we mean by an "optical material." Although it is hard to imagine that the twenty-first century could be as revolutionary as the twentieth century was for the field of optics and photonics, it certain that things will change in ways that we cannot imagine. With that in mind, this essay focuses on some recent advances in materials that in our opinion are promising. Whether they will significantly impact our field well into the twenty-first century, time will tell.

Even in the last few decades, the face of photonic materials research has changed markedly. Thirty years ago, the field was dominated by the development of new bulk materials, such as new IR glasses, nonlinear crystals, or doped laser crystals, while today research in new photonic materials has more emphasis on advances at the nano or micro scale that can result in materials with new or enhanced properties. There is also a great deal of research in integration of different photonic materials for enhanced functionality, resulting in flexible photonic platforms, infrared photonics devices, semiconductor-core fibers and integration of III-Vs, organics, or carbon electronics into silicon electronic platforms. The tremendous growth in the breadth and depth of the field of optical materials resulted in The Optical Society's decision to launch a new journal devoted to the subject, *Optical Materials Express,* in 2011.

New Optical Materials

Some of the most interesting work in the development of new materials for optics and photonics is in cases where the "newness" is related to the physical structure of the material at the nanoscale, rather than to its chemical structure. One may categorize these into three main types. In the first types nanostructuring modifies the electronic structure directly producing new material properties that are quite unlike the bulk, as observed, for example, in plasmonic nanoparticles; semiconductor quantum dots; or two-dimensional monolayer structures such as graphene, silicene, germanene, molybdenum disulfide, or boron nitride. Graphene is one of six different basic forms of nanocarbon: graphene, graphite, fullerenes, nanodiamond, nanotubes, and nanocones. These forms of nanocarbon provide an attractive set of building blocks for future nanoelectronic and nano-optic devices [1]. Both graphene and carbon nanotubes are particularly interesting since their optical absorption extends smoothly across an extremely wide wavelength range, allowing for diverse applications such as infrared detectors and solar cells. Quantum-confined semiconductors, i.e., quantum wells, wires, and



▲ **Fig. 1.** Oblique-view electron micrograph of a woodpile photonic-crystal polymer template (black to dark gray) coated with Al:ZnO (bright gray.) (Frölich and Wegener, Opt. Mater. Express **1**(5), 883–889 [2011].)

dots, also fall into this category, although in this case the partial confinement results in relatively small modifications to the electronic properties. Nevertheless, quantum-well materials have already become the materials of choice for semiconductor lasers and are the basis of the important quantum-well infrared photodetector (QWIP) devices. Quantum wires and quantum dots offer the possibility of improved laser and detector materials, while quantum dots also offer significant efficiency improvements for solar cells and for displays. Improvements in mid-infrared detector materials based upon advances in strained-layer superlattice structures and nBn-type structures are also likely.

Nanoscopic metal particles exhibit properties markedly different from those of bulk metals. These nanoplasmonic materials [2] have gained a great deal of attention since the discovery of surface-enhanced Raman scattering (SERS) in the 1970s. Benefiting from recent advances in nanofabrication techniques, research in nanoplasmonics has recently been very successful in using noble metal (especially silver and gold) nanostructures to control light fields well beyond the limit of diffraction. Such control has already contributed to enhancing light interaction with tiny amounts of matter down to the single-molecular level. This enhancement, where the plasmonic particles effectively act as nanoscopic antennas that collect and redirect electromagnetic fields may find applications in diverse fields, including infrared detection, solar cells, and nonlinear optics. Recent work has focused on materials for plasmonics other than silver and gold, including oxides and nitrides, particularly TiN. Other compounds, alloys, and nanostructured materials are likely to prove useful for plasmonic applications.

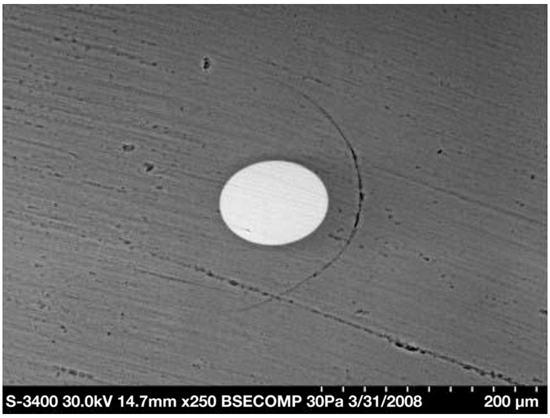
A second category encompasses cases where micro or nano structure provides enhanced functionality of known photonic materials, for example, ceramics and advanced polymer composites. Ceramic fabrication processes provide the properties of crystals with the functionality of amorphous materials, enabling large parts to be formed that are relatively strain free and have homogenous doping relative to single crystals in applications where high thermo-mechanical performance and large apertures are needed. This is leading to improved laser gain media with superior optical quality, with engineered index and doping profiles that make possible diode-pumped solid-state lasers in the 100-kW range. Similarly, optical ceramics are now offering advantages in applications such as efficient lighting, solar-energy harvesting, and radiological and nuclear detection. Optical polymer nanocomposites (OPNs), composites of nanoscopic inorganic particles in a polymer host, have emerged as a promising field thanks to advances in optical polymer materials, nanoparticle synthesis, and nanoparticle functionalization and dispersion techniques. OPNs have the potential to fulfill a broad range of photonic functions including highly scattering materials for backlighting of liquid crystal displays, narrowband filters, integrated magneto-optic and electro-optic devices, and optical amplification and lasing.

Third, metamaterials [2] are periodic composite materials of the type shown in Fig. 1 that may have bulk properties that are very different from the component materials, for example, negative-index metamaterials. The origins of this field can be traced back to research in the 1950s on microwave engineering for antenna beam shaping; artificial materials have recently regained a huge interest triggered by attractive theoretical concepts such as superlensing and invisibility at optical frequencies. Metamaterials often employ plasmonic nanostructures, providing a close connection between the two fields. The strong local fields that occur in these materials can be used to strongly modify the nonlinear properties of the component materials. For example, second and third harmonic generation (SHG and THG) may be strongly enhanced and nonlinear optical refraction and absorption may be strongly modified in these metamaterials, since the nonlinearity scales with the electric-field enhancement to a higher power.

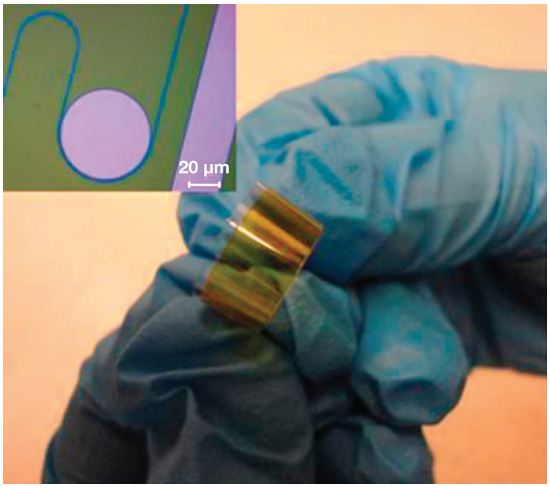
Advances in Optical Materials Integration and Processing

Just as interesting and groundbreaking as the advances in new materials is the research in integration of different photonic materials for enhanced functionality, resulting in flexible photonic platforms; infrared photonics systems; semiconductor-core fibers; and integration of SiGe, SiC, SiGeC, and III-Vs and of organics or nanocarbons into silicon electronic platforms. Additionally, new processing methods such as direct laser writing are resulting in new photonic platforms that were not previously possible.

Infrared materials are notoriously difficult to process, causing integrated mid-infrared devices to be extremely challenging to fabricate. Progress in development of materials for such applications has slowly evolved to the point where interesting integrated devices based on chalcogenides are now being produced [5]. Chalcogenides, being composed of weakly covalently bonded heavy elements, have bandgaps that are in the visible or near-infrared region of the spectrum, and low vibrational energies make them transparent in the mid-infrared. They can also act as hosts for rare-earth dopants. Advances in processing using CHF_3 gas chemistry etching have now resulted in As_2S_3 rib waveguides with losses as small as 0.35 dB cm^{-1}. Chalcogenide fibers, although studied since the 1980s, still have not shown improvement over heavy-metal oxides for mid-infrared transmission, but as fiber draw capabilities improve, many other materials are becoming possibilities for fibers in this wavelength range, for example, the demonstration of a fiber with a crystalline silicon core, shown in Fig. 2. Additionally, developments in photonic-crystal fibers, where in some cases most of the optical mode does not overlap with the material, provides yet more avenues for optical fibers for new wavelength ranges using materials for which implementation in traditional fibers would be impossible. As photonics becomes more pervasive in practical systems, researchers are finding materials platforms for devices and interconnects to meet industry needs. For example, patterning of photonic devices on mechanically flexible polymer substrates has produced high-quality flexible photonic structures, an example of which is shown in Fig. 3.



▲ **Fig. 2.** Crystalline-silicon-core optical fiber with silica cladding. (Ballato *et al*., Opt. Express **16**(23), 18675–18683 [2008].)



▲ **Fig. 3.** A flexible microdisc resonator on polymer substrate. (Copyright © 2012, Rights Managed by Nature Publishing Group.)

Laser processing of traditional materials provides yet another avenue for new platforms for devices and interconnects, even though the materials themselves are not new. For example, femtosecond direct laser writing [7] relies on nonequilibrium synthesis and processing of transparent dielectrics with short-pulse lasers, which open up new ways to create materials and devices that are not currently possible with established techniques. The main advantage remains in the potential to realize three-dimensional (3D) multifunctional photonic devices, fabricated in a wide range of transparent materials. This technique offers enormous potential in the development of a new generation of 3D components for micro-optics, telecommunications, optical data storage, imaging, astrophotonics, microfluidics, and biophotonics at the micro and nano scale. Another related advance in laser-written photonics components is photo-thermo-refractive (PTR) glass, which requires heat treatment to develop laser-written index changes, usually in the form of gratings. This produces very-high-quality Bragg diffractive gratings with absolute diffraction efficiency in excess of 95%, allowing highly stable volume holographic elements to be fabricated.

In this century, full 3D design at the nanoscale will play an important role in the architectural design of optoelectronic components. At present, fabrication processing is mostly limited to stacks of two-dimensional (2D) layers with some coarse modifications in the plane. Laser direct writing, hierarchical self-assembly, and other advances in lithography will allow placement of structures of pre-determined size and topology at will anywhere within a 3D solid architecture. This will involve manipulation of single atoms for applications such as quantum computing (e.g., N-V complex in diamond, P in silicon, SiC, and other materials with defects) as well as structures involving anywhere from a few atoms to a few dozen atoms for other applications, such as optical modulators, laser diodes (quantum cascade lasers, QCLs), and nonlinear optical materials [improved SHG, THG, optical parametric oscillators, and optical parametric amplifiers (OPOs and OPAs)].

Summary

Advances in optical materials over the last thirty years have resulted in both evolutionary and revolutionary advancements of optics, optoelectronics, and photonics. However, this short article cannot begin to cover the areas that we expect to be impacted by optical materials. Advances in optical materials have begun to impact biophotonics and biomedicine with promise for improvements in human health and the treatment of disease [8]. The impact of advanced optical materials on solar cells is briefly discussed above but is not discussed in detail. Advances in manufacturing for inexpensive solar cell materials including amorphous silicon, materials containing organic dyes, and nanopatterning may speed their integration into power infrastructure. Work on developing quarternary and quinternary materials including dilute nitride materials may enhance efficiencies in high-efficiency multi-junction solar cells. Advances in optical materials will have a broader impact on energy consumption and sustainability through development of new, more efficient devices and applications such as photochromic and electrochromic materials for climate control in buildings and vehicles. Optical materials, including LCDs and organic light-emitting diodes (OLEDs) have led to a revolution in display technology. This will likely continue, resulting in even better displays, monitors, and TVs with brighter colors, blacker blacks, better contrast, better resolution, and wider field of view using new OLEDs or organic/inorganic composite LEDs incorporating rare earth and other materials. Polymer and organic/inorganic systems that enable wearable electronics and optoelectronics, including materials for neuroprosthetics incuding retinal imaging, are likely to become important. In short, we expect advances in optical materials to pervade almost every aspect of human life. The future of optical materials is bright.

References

1. Feature issue on Nanocarbon for Photonics and Optoelectronics, Opt. Mater. Express **2**(6) (2012).
2. Focus issue on Nanoplasmonics and Metamaterials, Opt. Mater. Express **1**(6) (2011).
3. A. Frölich and M. Wegener, “Spectroscopic characterization of highly doped ZnO films grown by atomic-layer deposition for three-dimensional infrared metamaterials,” Opt. Mater. Express **1**(5), 883–889 (2011).
4. J. Ballato, T. Hawkins, P. Foy, R. Stolen, B. Kokuoz, M. Ellison, C. McMillen, J. Reppert, A. M. Rao, M. Daw, S. Sharma, R. Shori, O. Stafsudd, R. R. Rice, and D. R. Powers, “Silicon optical fibre,” Opt. Express **16**(23), 18675–18683 (2008).

5. Focus issue on chalcogenide glass, Opt. Express **18**(25) (2010).
6. Y. Chen, H. Li, and M. Li, “Flexible and tunable silicon photonic circuits on plastic substrates,” Sci. Rep. **2**, 622 (2012).
7. Virtual feature issue on femtosecond laser direct writing and structuring of materials, Opt. Mater. Express **1**(5) (2011).
8. N. J. Halas, “The photonic nanomedicine revolution: let the human side of nanotechnology emerge,” Nanomedicine (London) **4**, 369–371 (2009).

Quantum Information Science: Emerging No More

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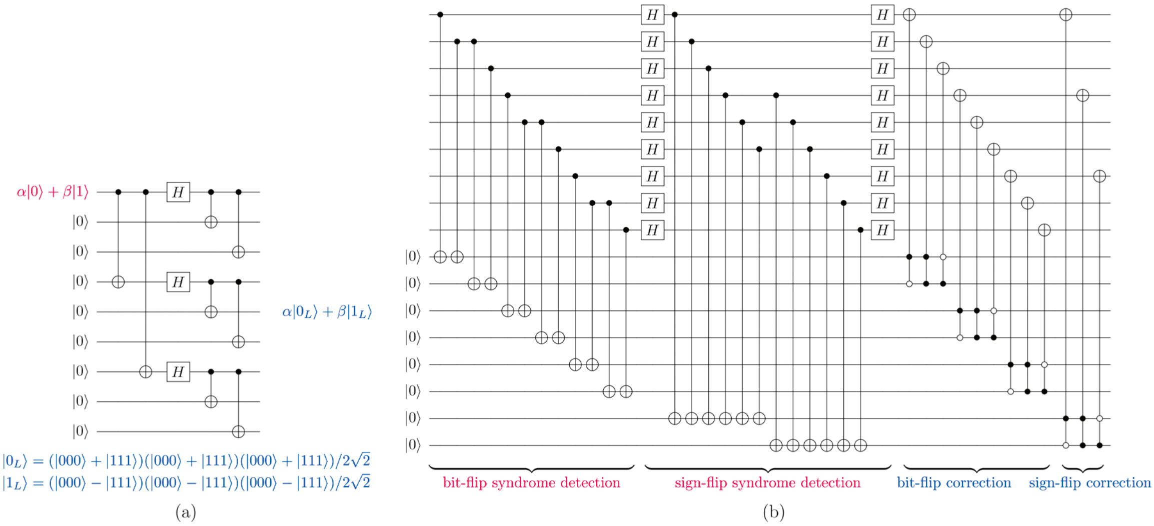
Quantum information science (QIS) is a new field of inquiry, nascent in the 1980s, founded firmly in the 1990s, exploding in the 2010s, now established as a discipline for the twenty-first century.

Born in obscurity, then known as the foundations of quantum mechanics, the field began in the 1960s and 1970s with studies of Bell inequalities. These showed that the predictions of quantum mechanics cannot be squared with the belief, called local realism, that physical systems have realistic properties whose pre-existing values are revealed by measurements. The predictions of quantum mechanics for separate systems, correlated in the quantum way that we now call entanglement, are at odds with any version of local realism. Experiments in the early 1980s demonstrated convincingly that the world comes down on the side of quantum mechanics. With local realism tossed out the window, it was natural to dream that quantum correlations could be used for faster-than-light communication, but this speculation was quickly shot down, and the shooting established the principle that quantum states cannot be copied.

A group consisting of quantum opticians, electrical engineers, and mathematical physicists spent the 1960s and 1970s studying quantum measurements, getting serious about what can be measured and how well, going well beyond the description of observables that was (and often still is) taught in quantum-mechanics courses. This was not an empty exercise: communications engineers needed a more general description of quantum measurements to describe communications channels and to assess their performance. These developments led, by the early 1980s, to a general formulation of quantum dynamics, capable of describing all the state changes permitted by quantum mechanics, including the dynamics of open quantum systems and the state transformations associated with the most general measurements. An important advance was a quantitative understanding of the inability to determine reliably the quantum state of a single system from measurements.

The 1980s spawned several key ideas. A major discovery was quantum-key distribution, the ability to distribute secret keys to distant parties. The keys can be used to encode messages for secure communication between the parties, conventionally called Alice and Bob, with the security guaranteed by quantum mechanics. In addition, early in the decade, physicists and computer scientists began musing that the dynamics of quantum systems might be a form of information processing. Powerful processing it would be, since quantum dynamics is difficult to simulate, difficult because when many quantum systems interact, the number of probability amplitudes grows exponentially with the number of systems. Unlike probabilities, one cannot simulate the evolution of the amplitudes by tracking underlying local realistic properties that undergo probabilistic transitions: the interference of probability amplitudes forbids; there are no underlying properties. If quantum systems are naturally doing information processing that cannot be easily simulated, then perhaps they can be turned to doing information-processing jobs for us. So David Deutsch suggested in the mid-1980s, and thus was born the quantum computer.

As the 1990s dawned, two new capabilities emerged. The first, entanglement-based quantum-key distribution, relies for security on the failure of local realism, which says that there is no shared key until Alice and Bob observe it. This turns quantum entanglement and the



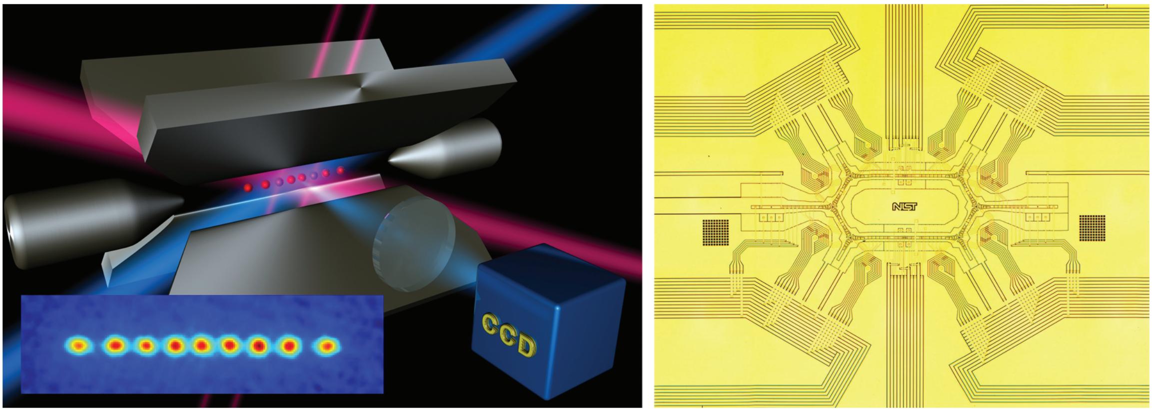
▲ **Fig. 1.** (a) Coding circuit for Shor nine-qubit quantum code. An arbitrary superposition of the 0 and 1 (physical) states of the top qubit is encoded into an identical superposition of the 0 and 1 (logical) states of nine qubits. (b) Error (syndrome) detection and error-correction circuit for Shor nine-qubit code. Six ancilla qubits are used to detect a bit flip (exchange of 0 and 1) in any of the nine encoded qubits, and two ancilla qubits are used to detect a relative sign change between 0 and 1 in any of the nine encoded qubits. Correction operations repair the errors. The code detects and corrects all single-qubit errors on the encoded qubits and some multi-qubit errors.

associated failure of local realism from curiosities into a tool. The second capability, teleportation, lets the ubiquitous Alice and Bob, who share prior entanglement, transfer an arbitrary quantum state of a system at Alice's end to a system at Bob's end, at the cost of Alice's communicating a small amount of classical information to Bob. Surprising this is, because the state must be transferred without identifying it or copying it, both of which are forbidden. Sure enough, the classical bits that Alice sends to Bob bear no evidence of the state's identity, nor is any remnant of the state left at Alice's end. The correlations of pre-shared entanglement provide the magic that makes teleportation work.

These two protocols fed a growing belief that quantum mechanics is a framework describing information processing in quantum systems. The basic unit of this quantum information, called a qubit, is any two-level system. The general formulation of quantum dynamics provides the rules for preparing quantum systems, controlling and manipulating their evolution to perform information-processing tasks, and reading out the results as classical information.

The mid-1990s brought a revolution, sparked by discoveries of what can be done in principle, combining with laboratory advances in atomic physics and quantum optics that expanded what can be done in practice. The first discovery, from Peter Shor, was an efficient quantum algorithm for factoring integers, a task for which there is believed to be no efficient classical algorithm. The second was a proposal from Ignacio Cirac and Peter Zoller for a realistic quantum computer using trapped ions. This proposal drew on a steady stream of advances that promised the ability to control and manipulate individual neutral atoms or ions, all the while maintaining quantum coherence, and applied these to the design of the one- and two-qubit gates necessary for quantum computation. The third discovery, quantum error correction, was perhaps the most surprising and important finding about the nature of quantum mechanics since its formulation in the 1920s. Discovered independently by Peter Shor and Andrew Steane, quantum error correction (Fig. 1) allows a quantum computer to compute indefinitely without error, provided that the occurrence of errors is reduced below a threshold rate.

Definitely a field by 2000, QIS galloped into the new millennium, an amalgam of researchers investigating the foundations of quantum mechanics, quantum opticians and atomic physicists building on a legacy of quantum coherence in atomic and optical systems, condensed-matter physicists working on implementing quantum logic in condensed systems, and a leavening of computer scientists bringing an information-theoretic perspective to all of quantum physics.



(a) (b)

▲ Fig. 2. (a) Linear ion trap. Ions (red) are trapped by a combination of DC and RF voltages. Two internal states of each ion, labeled 0 and 1, act as qubits. Laser beams (blue) drive quantum gate operations; two-qubit gates are mediated by the Coulomb repulsion between ions. Readout is by resonance fluorescence recorded by a CCD camera: absence or presence of fluorescence signals a qubit's 0 or 1 state. The inset shows detection of nine ions. (b) NIST Racetrack surface ion trap. Made of a quartz wafer coated with gold in an oval shape roughly two by four millimeters, this trap features 150 work zones, which are located just above the surface of the center ring structure and the six channels radiating out from its edge. Qubits are shuttled between zones, where they can be stored or manipulated for quantum information processing. The trap could be scaled up to a much larger number of zones. (Fig. 2(a) courtesy of R. Blatt, Quantum Optics and Spectroscopy Group, University of Innsbruck. Fig. 2(b) courtesy of J. Amini, Ion Storage Group, NIST.)

QIS researchers are implementing the fundamental processing elements for constructing a quantum computer in a variety of systems: ions trapped in electromagnetic fields, controlled by laser pulses and herded to interaction sites by electric fields (Fig. 2); circuit-QED, in which superconducting qubits are controlled by microwaves in cavities and transmission lines; neutral atoms cooled and trapped, interacting via cold collisions or by excitation to Rydberg levels; impurity atoms, vacancies, and quantum dots in semiconductor or other substrates, controlled electronically or photonically; and photonic qubits processed through complicated linear-optical interferometers, capable of implementing efficient quantum computation provided that they are powered by single-photon sources and the photons can be counted efficiently. As experimenters develop these basic elements for quantum information processing, theorists integrate them into architectures for full-scale quantum computers, including quantum error correction to suppress the deleterious effects of noise and of unwanted couplings to the external world that destroy quantum coherence. An active research effort explores the space of quantum error-correcting codes to find optimal codes for fault-tolerant quantum computation.

Other researchers investigate exotic architectures for quantum computation, such as topological quantum computation, which encodes quantum information in many-body systems in a way that is naturally resistant to error, obviating or reducing the need for active quantum error correction. A prime candidate uses as qubits the quasi-particle excitations known as non-Abelian anyons, neither bosons nor fermions, but occurring naturally in fractional quantum-Hall states. Braiding of the anyons is used to realize quantum gates.

Experimenters verify the performance of quantum-information-processing devices using quantum-state and quantum-process tomography, techniques invented by quantum opticians to identify a quantum state when one can generate the same state over and over again. The inefficiency of these tomographic techniques drives a search for more efficient ways to benchmark the performance of such devices.

Computer scientists explore the space of quantum algorithms, searching for algorithms that perform useful tasks more efficiently than can be done on a classical computer and seeking to understand generally the class of problems for which quantum computers provide an efficiency advantage. One class of problems, present from the beginning of thinking about quantum computers, is the simulation of complex quantum systems, including complex materials, molecular structure, and the field theories of high-energy physics.

Quantum communications, the home of much early QIS thinking, now hosts the field's premier practical application, quantum-key distribution. Secret keys, distributed to distant parties over optical fiber and through free space, are used to encode messages for secure communication. Fundamental research continues on ensuring security in practical situations; using properties of the data exchanged in key distribution to guarantee security, instead of relying on an assumption that quantum mechanics is correct; the design of quantum repeaters, which, by using pre-shared entanglement, can extend the reach of key distribution beyond the usual limit set by losses in optical fiber; and the communication complexity of distributed information-processing tasks.

The theory of entanglement is used in condensed-matter physics to characterize the ground and thermal states of many-body quantum systems with local interactions. The degree and locality of entanglement become important variables for such systems, useful, for example, in characterizing when the low-energy states of the system can be efficiently described and simulated.

From its beginning, QIS has been a productive mixture of quantum weirdness and applications. The field has advanced by interplay between experiment and theory: experimental breakthroughs inspire theorists to dream of what might be, and the dreams of theorists inspire experimentalists to reduce the dreams to quantum reality. Physicists were forced to quantum mechanics, the highly successful framework for all of physical law, because the causal, deterministic, realistic narrative of classical physics fails for microscopic systems. Within the quantum framework, it is not surprising that one can do things that cannot be encompassed within a classical narrative; QIS is the discipline that does those things. In a broad sense, QIS is a sort of quantum engineering: though still rooted in fundamental science, QIS seeks ways to control the behavior of quantum systems and turn them to performing tasks we want done, instead of their doing what comes naturally.

QIS has burst well outside the bounds of what can be summarized in a brief history. To provide an illustration of what this means, the author searched the website of *Reviews of Modern Physics*, the premier journal for physics review articles, for all articles that have the phrase "quantum information" in the title or abstract. The search turned up 26 articles, the first of which appeared in 1999. These 26 articles collectively have 7,370 citations, 283 per article, and an h-index of 23. Promote the field to a full discipline.

There is more. Searching titles and abstracts misses many RMP articles associated with quantum information, so the author searched the tables of contents of all issues of RMP from 2000 to the end of 2012, adding to the previous list all those articles on quantum information that somehow neglected to include quantum information in the title or abstract, articles on the foundations of quantum mechanics, and articles on open quantum systems. This gives 44 review articles since 2000. In the period from 2000 to 2006, there were 16 articles, a rate of 2.6 per year. Since 2007, the pace has accelerated: there have been 28 review articles in RMP, a rate of 4.7 per year, more than one article per quarterly issue. And mind you, these are review articles, each of which cites dozens to hundreds of primary research papers.

It is time to stop talking about quantum information science as an "emerging field." A discipline represented in every issue of RMP is no longer emerging. It has arrived.