

BEYOND DISCOVERY

THE PATH FROM RESEARCH TO HUMAN BENEFIT™

MODERN COMMUNICATION: THE LASER AND FIBER-OPTIC REVOLUTION

*I*t's 11:30 p.m., you're in San Francisco on business, and you want to check for messages at your office in Virginia. First you dial in and get your voice mail. Next you plug your portable computer into the hotel-room telephone jack, hit a few keys, and pick up e-mail from a potential client in South Africa, your sister in Albuquerque, and a business associate in Detroit. Before composing your responses, you do a quick bit of research on the Internet, tracking down the name of the on-line news group you had mentioned to the man in Detroit and the title of a book you wanted to recommend to your sister. A few more keystrokes and in moments your electronic letters have reached Albuquerque and Detroit. Then, knowing that the time difference means the next workday has begun in South Africa, you call there without a second thought.

As recently as 10 years ago, such nearly instantaneous, world-shrinking communication would not have been possible; critical pieces of technology in both computing and communication were just emerging. Then, in 1988, the first transatlantic fiber-optic cable was laid, and the "information superhighway" was on its way to becoming reality.

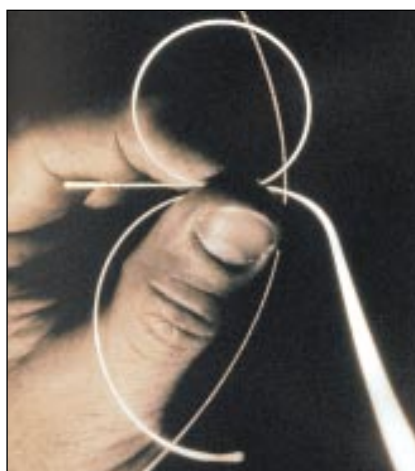
Optical fibers form the backbone of the global telecommunication system. These remarkable strands of glass—each thinner than a human hair, yet stronger, length for length, than steel—were designed to carry the vast amounts of data that can be transmitted via a relatively new form of light—tightly focused laser beams. Together, lasers and optical fibers have dramatically increased the capacity of the international telephone system. With

equally striking improvements in computing, the new communication technology has fueled the exponential growth of the phenomenon known as the Internet.

The following article describes the conception and development of both laser technology and the fibers that allow transmission of a light signal over long distances. It shows how basic research, in this case dating back to Albert Einstein's work in quantum mechanics, can lead to important practical applications. As often happens, the trail took many twists and turns, none of which could have been predicted when the research began.

Help on the Internet

In April 1995, a young Chinese chemistry student at Beijing University lay dying in a Beijing hospital. She was in a coma, and although her doctors had performed numerous tests, they could not discover what was killing her. In desperation, a student friend posted an SOS describing her symptoms to several medical bulletin boards and mailing lists on the Internet, the ever-growing international array of computer linkages through telephone lines. Around the world, doctors who regularly checked these electronic bulletin boards and lists responded immediately.



Loops of hair-thin glass fiber, illuminated by laser light, provide the transmission medium for optical communication systems. A typical fiber-optic cable made up of 100 or more such fibers can carry more than 40,000 voice channels. (Photo courtesy of Lucent Technologies)



In Washington, D.C., Dr. John Aldis, a physician with the U.S. Department of State, saw the message from China. He had recently served in Beijing; he knew the woman's doctors. Using the Internet, he forwarded the message to colleagues in America. Soon an international contingent of doctors joined the e-mail discussion. A consensus emerged—the woman might have been poisoned with thallium, a metal resembling lead. A Beijing laboratory confirmed this diagnosis—the thallium concentration in her body was as much as 1,000 times normal. More e-mail communication ensued, as treatment was suggested and then adjusted. The woman slowly began to recover. Well over a year later, the international medical community was still keeping tabs on her condition through the electronic medium that saved her life.

This story underscores society's increasing reliance on a system of global communication that can link you equally easily with someone in the next town or halfway around the world. People in all walks of life use the telephone system every day to solve a problem or make a date or transfer money or hire an employee. They can do these things by making telephone calls from stationary telephones or from handheld mobile telephones, by sending faxes, or by using computers and dialing into the Internet.

The expanded telephone-line capacity that has allowed the growth of these forms of communication is a recent phenomenon. The United States has enjoyed domestic telephone service for more than a century, but overseas telephone calls were difficult until relatively recently. For a number of years after World War II, calls to Europe or Asia relied on shortwave radio signals that bounced off the ionosphere, the electrically active layer of the atmosphere that lies between 50 and 250 miles above the earth's surface. It sometimes took an operator hours to set up a 3-minute call, and if you got through, the connection was often noisy with static.

In 1956, the first transatlantic copper wire cable allowed simultaneous transmission of 36 telephone conversations—a cause for celebration then, a paltry number today. Other cables followed; by the early 1960s, overseas telephone calls had reached 5 million per year. Then came satellite communication in the middle 1960s, and by 1980, the telephone system carried some 200 million overseas calls per year. But as demands on the telecommunication system continued to increase, the limitations of current technology became glaringly apparent. Then, in the late 1980s, came the fruition of a variety of efforts to find the Holy Grail of communication—the harnessing of light itself as a way to communicate.

Using Visible Light?

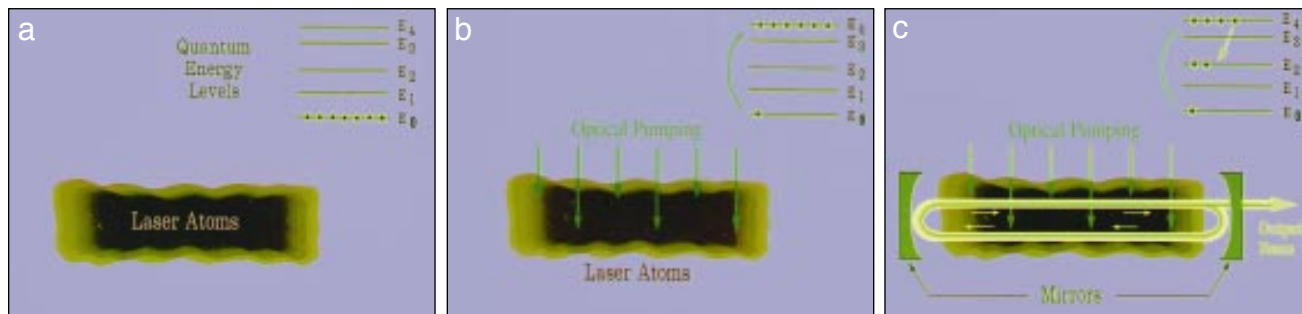
All forms of modern communication—radio and television signals, telephone conversation, computer data—rely on a carrier signal, a wavelike electromagnetic oscillation with a particular frequency. Electromagnetic signals are described in terms of their wavelength (the distance between the peaks of two waves) or their frequency (expressed in hertz, the number of wave cycles per second); the shorter the wavelength, the higher the frequency. By modulating the carrier, we can encode the information to be transmitted; the higher the carrier frequency, the more information a signal can hold.

Copper wire is limited to a frequency of only 1 megahertz, or 1 million cycles per second, enough to carry a few dozen voice channels; at higher frequencies, the wire's electrical resistance increases substantially. Coaxial cables—consisting of a solid conductor placed inside a hollow one to channel the signal between them and shield it from interference—became predominant after World War II and were used for trunk lines between cities; they can carry frequencies of up to 10 gigahertz, or 10 billion cycles per second. Unfortunately these coaxial cables are relatively expensive to lay over long distances, and even satellite and earthbound microwave systems, which operate at frequencies of up to 40 gigahertz, began to reach their practical limit in terms of information-carrying capacity per channel.

The idea of using visible light as a medium for communication had occurred to Alexander Graham Bell back in the late 1870s, but he did not have a way to generate a useful carrier frequency or to transmit the light from point to point. In 1960, an idea first introduced by Albert Einstein more than 40 years earlier bore practical fruit with the invention of the laser. This achievement prompted researchers to find a way to make visible light a communication medium—and a few years later fiber optics arrived.

Physics in the 20th Century

The research that would eventually give rise to the laser had its origins in the branch of physics now known as quantum mechanics. In 1900 Max Planck hypothesized that excited atoms radiate energy in discrete packets, which he called quanta, and not as a continuous range of energies, as the prevailing wave theory of electromagnetic radiation would have it.



How lasers work. (a) A collection of laser atoms with their quantum energy levels depicted. (b) The optical pumping process, in which a large number of trapped atoms are excited into a higher energy level. (c) Stimulated emission and laser oscillation. Here a light beam tuned to the transmission frequency between the two levels is sent through the collection of atoms, causing those at the

higher energy level to give up their energy to the light beam. Carefully aligned mirrors at either end of the laser cavity form an optical resonator, making the output beam highly monochromatic or highly directional. (Adapted from an illustration provided by Stanford University)

Planck never pursued the implications of this notion, but 5 years later Albert Einstein did, suggesting that light itself was made up not of waves, but of packets of energy (later named photons); the higher the frequency of the light, the more energetic the photon. He then demonstrated how under some conditions, electrons could absorb and emit the energy of photons, and—in a breakthrough that would earn him the Nobel prize—he used this demonstration to explain what was called the photoelectric effect (the discharge of electrons from matter by the impact of radiation, especially visible light).

Meanwhile, not everyone agreed with Einstein's theory of light-as-particle; the debate would continue for a couple of decades. But even before physicists accepted that light was somehow both wave and particle, Einstein discovered yet another phenomenon. According to Niels Bohr's model of the atom, set forth in a series of papers in 1913, electrons occupy specific orbits around the nucleus, determined by the electrons' energy levels. An electron can absorb only the exact amount of energy needed to kick it from one orbit up to a specific higher one, and it emits a specific amount of energy on dropping from an orbit to a lower one. That explained why atoms of a given gas, such as neon, emit a distinctive pattern of wavelengths, and why vapor discharge lamps such as those based on mercury or sodium have a characteristic color.

Atoms that are in an excited state—that is, when their electrons are in higher-energy orbits—will eventually, and spontaneously, fall back to their lowest, or ground state, giving off stored energy in the process. In a given system of atoms, this spontaneous emission occurs at random, with the emitted photons of energy heading off in random directions. Einstein recognized that if atoms in an excited state encounter photons of light with the right amount of energy (namely, an amount equal to the difference between the lower-

energy and higher-energy states), the encounter can trigger a kind of chain reaction of emission that boosts the intensity of the light passing through—as though the electrons, greedy to capture the incoming photons, dropped the ones they already had stored up. Furthermore, the emitted photons all headed in the same direction as the incoming photons. The process is called “stimulated emission.”

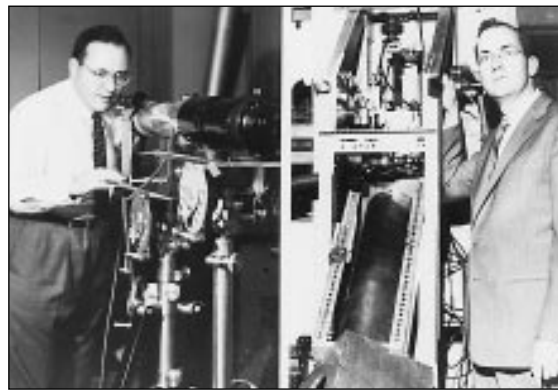
The catch was that amplification by stimulated emission would occur only if more atoms in the population of atoms were in an excited state than in the lower-energy state. That is the opposite of the normal situation, so stimulated emission required what is known as a population inversion—an entire population of atoms had to be artificially boosted into an excited state, usually by exposure to light.

Fast-forward now to 1951. Charles Townes was head of the Columbia University Radiation Laboratory, which was continuing research begun during World War II on microwave physics. Townes was working on microwave spectroscopy and was eager to use short wavelengths in the submillimeter range. But he needed to scale down the mechanical oscillators then being used to generate microwaves in the centimeter range, a problem that seemed insoluble—until he thought of using molecules.

During the next 2 years, Townes worked with James Gordon and Herbert Zeiger to build such a system. Finally, in late 1953, they demonstrated the results of their research. They sent a beam of ammonia through an electric field that deflected molecules that were in a low-energy state and sent high-energy molecules to another electric field; exposure to the second field caused all the high-energy ammonia molecules to drop almost simultaneously to the ground state, emitting microwave photons that were all at the same frequency and traveling in the same direction. Townes called his device a maser, for microwave ampli-



fication by stimulated emission of radiation. As Townes continued to experiment with masers, it became clear that stimulated emission could work with the much shorter wavelengths of infrared and even of visible light. The name “laser” was coined for the device, with the “l” standing for “light.” Seeking to develop a more complete theory of laser action, Townes approached his brother-in-law, Arthur Schawlow, a physicist at Bell Laboratories, one of the nation’s leading centers for research in physics and materials.



Harnessing the power of light. Arthur Schawlow of Bell Laboratories (left) and Charles Townes of Columbia University published “Infrared and Optical Masers” in 1958—a paper that opened the way to subsequent developments in laser technology and applications. (Lucent Technologies)

In late 1958, the Townes-Schawlow paper, “Infrared and Optical Masers,” appeared in *Physical Review*, a leading physics journal. The paper inspired scientists to try to build a laser device, and in June 1960, physicist Theodore Maiman, at the research laboratory of Hughes Aircraft Company succeeded, using a synthetic ruby.

Lasers, which emit much more highly focused light beams than other light sources, attracted immediate interest. In one experiment performed in 1962, a laser beam 1 foot in diameter was aimed at the moon, 240,000 miles away, where it illuminated a surface area only two miles in diameter. A beam of ordinary light would spread so much in traveling the same distance

that it would illuminate an area 25,000 miles in diameter. Journalists took to the new technology enthusiastically, writing of “light fantastic” and hailing lasers as harbingers of a new age. Film-makers featured lasers as weapons of doom—most notably in the James Bond movie *Goldfinger*. Scientists pointed to the enormous promise of lasers in communication and other fields.

In reality, early lasers had a long way to go to meet those expectations. Creating the population inversion necessary

to generate laser action required so-called optical pumps, such as flash lamps, and these could only produce a pulse of energy rather than continuous laser light and were not efficient in the use of power. Another quite different version, developed later in 1960 by Ali Javan at Bell Laboratories, used a glass tube containing a mixture of the gases helium and neon. This laser had a lower energy threshold and did not overheat, but the glass tube was both bulky and fragile. The first lasers resembled the vacuum tubes that had earlier been used in radios, television sets, and the first computers. By 1960, vacuum tubes had given way to the amazingly small and highly reliable transistor. Could lasers make the same transition?

The Development of Lasers and Fiber-Optics — A Chronology of Selected Events

This timeline shows the chain of basic research that led to fiber-optic communication.

1900

Max Planck initiates a new field of science, quantum physics, by demonstrating mathematically that matter radiates energy in discrete bundles, which he calls quanta.

1913

Niels Bohr formulates a model of the atom in which electrons occupy specific orbits, or energy states, around the nucleus, determined by the electrons’ energy levels.

1951-1953

Charles Townes at Columbia University Radiation Laboratory discovers how to harness stimulated emission to generate a focused microwave beam. He names his invention the maser, for microwave amplification by stimulated emission of radiation. Townes shared the 1964 Nobel prize for this work with two Soviet physicists, N.G. Basov and A.M. Prokhorov, who had come up with a similar idea.

1960

Theodore Maiman of Hughes Aircraft Company builds a laser using synthetic ruby.

1905

Albert Einstein builds on Planck’s theory to explain the photoelectric effect, showing that light is made up of packets, later called photons. In 1921, Einstein earned the Nobel prize for this breakthrough.

1917

Einstein identifies a phenomenon called stimulated emission.

1958

Townes and Arthur Schawlow of Bell Laboratories publish their theory of how stimulated emission would work with much shorter wavelengths, including those of visible light, giving rise to the term laser, for light amplification by stimulated emission of radiation.

1962

Research groups at General Electric, IBM, and the Lincoln Laboratory at MIT report semiconductor laser action using gallium arsenide (GaAs).



Semiconductor Lasers

Transistors make use of the special properties of a class of materials known as semiconductors. Electric current is carried by moving electrons, and ordinary metals, such as copper, are good conductors of electricity because their electrons are not tightly bound to the nucleus of the atom and are freely attracted to a positive charge. Other substances, such as rubber, are insulators—poor conductors of electricity—because their electrons do not move freely. Semiconductors, as their name implies, fall somewhere in between; they ordinarily behave more like insulators, but under some conditions they can be made to conduct electricity.

Early work on semiconductors focused on silicon, but silicon itself cannot emit laser light. The invention of the transistor at Bell Laboratories in 1948 by William Schockley, Walter Brattain, and John Bardeen stimulated research on other semiconductors. It also provided the conceptual framework that would eventually lead to an understanding of light emission in semiconductors.

In 1952, Heinrich Welker, at Siemens in Germany, described semiconductors from elements found in column III and V of the periodic table as potentially useful for electronic devices. One of these, gallium arsenide, or GaAs, was to feature prominently in the search for an efficient communication laser. Necessary precursors to its full exploitation were basic studies of layer-by-layer growth of high-purity crystals, research into defects and dopants (impurities added to a pure substance to change its properties), and analysis of the effects of heat on the stability of compounds. With these advances, research groups at General Electric, IBM, and the Lincoln Laboratory at the Massachusetts Institute of Technology developed working GaAs lasers in 1962.

But an old problem persisted: overheating. Lasers that used a single semiconductor, usually GaAs, were not very efficient. They still required so much electricity to initiate laser action that, at normal room temperature, they quickly overheated; again, only pulsed operation was possible, which was not practical for communication. Physicists tried various methods for removing the heat—such as placing lasers atop other materials that were good heat conductors, but were unsuccessful. Then, in 1963,



Theodore Maiman with his ruby laser in 1960. The first lasers tended to be bulky and fragile and were prone to overheat. Subsequent work in semiconductors resulted in vastly improved designs. (Hughes Research Laboratories, Inc.)

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1963

Herbert Kroemer at the University of Colorado proposes to reduce energy requirements for lasers and decrease heat production by creating a semiconductor “sandwich” with a thin active layer set between layers of other material.

1970

Morton Panish and Izo Hayashi of Bell Laboratories demonstrate a semiconductor laser that operates continuously at room temperature. Donald Keck, Peter Schultz, and Robert Maurer at Corning Glass Works report the creation of optical fibers that meet the predictions made by Kao and Hockham.

1984

AT&T fiber-optic cable enters service, connecting major cities in the Boston-Washington corridor.

1991

Emmanuel Desurvire at Bell Laboratories along with David Payne and P.J. Mears at England’s University of Southampton, demonstrate optical amplifiers—built into the fiber cable itself.

1966

Charles Kao and George Hockham at Standard Communications Laboratories in England publish a paper demonstrating theoretically that light loss in existing glass fibers could be decreased dramatically.

1976-1977

Fiber-optics trials, based on designs and fiber preparation processes developed at Bell Labs, are initiated in telephone systems in Atlanta and Chicago.

1988

The first transatlantic fiber cable is laid, using glass so transparent that amplifiers are spaced about 40 miles apart.

1996

All-optic fiber cables are laid across the Pacific. Complete round-the-world installation is expected by 1997.



Herbert Kroemer at the University of Colorado proposed a different approach—to build a laser consisting of a semiconductor sandwich, with a thin active layer set between two slabs of different material. Confining the laser action to the thin active layer would require very little current and would keep the heat output at manageable levels.

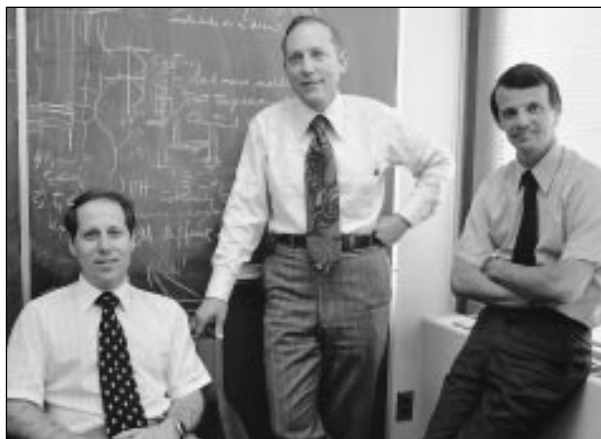
Such a laser could not be built simply by slipping in the active layer, like a piece of cheese between two slices of bread. The atoms in semiconductor crystals are arranged in the form of a lattice, with electrons forming chemical bonds. In order to create a multilayered semiconductor laser with the necessary bonding between atoms, the device had to be grown as a single unit, called a multilayered crystal.

In 1967, Bell Laboratories researchers Morton Panish and Izuo Hayashi suggested the possibility of creating a suitable multilayered crystal by using a modified form of GaAs, in which a few atoms of aluminum would replace some of the gallium, a process called “doping.” The modified compound, AlGaAs, had atomic spacings that would differ from those of GaAs by less than 1 part in a 1,000. When grown on either side of a thin layer of GaAs, the researchers proposed, AlGaAs would restrict all laser action to the GaAs layer. Several years of work lay ahead of them, but the path to “solid-state” lasers—miniature semiconductor devices operating continuously at room temperature—now lay open.

One hurdle remained: how to transmit light signals across long distances. Long-wavelength radio waves travel freely through the air, piercing fog and heavy rain with ease. But short-wavelength laser light bounces off atmospheric water vapor and other particles to such a degree that it is either scattered or blocked. A foggy day could shut down a laser communication link. Light therefore needed a conduit, analogous to telephone lines.

Optical Fibers Emerge

Optical fibers offered one approach, although in the mid-1960s it was by no means certain that the answer lay in this direction and other possibilities were seriously considered. Light is channeled in glass fibers by a property known as total internal reflection. The equations governing the trapping of light inside a flat glass plate were known to Augustine-Jean Fresnel as early as 1820, and their extension to what were then known as glass wires was achieved by D. Hondros and Peter Debye in 1910. It was not until 1964, however,



In 1970 Corning Glass Works scientists Donald Keck, Robert Maurer, and Peter Schultz successfully prepared the first batch of optical fiber with sufficient transparency to make fiber-optic communication a reality. (Corning Inc.)

that Stewart Miller at Bell Laboratories deduced detailed ways to probe the potential of glass as an efficient long-distance transmission medium.

Although hair-thin strands of glass were already known to carry light over short distances and were already being used in industry and medicine to take light to otherwise inaccessible places, the light typically lost up to 99% of its strength when passing along as little as 30 feet of fiber.

In 1966, Charles Kao and George Hockham at Standard Telecommunications Laboratories in England asserted that fibers of much greater transparency lay within reach. In a landmark theoretical paper, they showed that the high losses characteristic of existing fibers theoretically resulted from minute impurities in the glass—primarily water and metals—rather than from intrinsic limits of the glass itself. They forecasted that light loss in fibers could be decreased dramatically from 1,000 decibels to less than 20 decibels per kilometer. Given that improvement, amplifiers to boost the light signal could be spaced at intervals of miles rather than yards—comparable with the spacing of repeaters that amplified weak signals along conventional telephone lines.

Like the work of Townes and Schawlow a decade earlier, the Kao-Hockham paper spurred a number of researchers to produce such low-loss fibers. The breakthrough came in 1970 at Corning Glass Works when Donald Keck, Peter Schultz, and Robert Maurer successfully prepared an optical fiber hundreds of yards long with the crystal clarity that Kao and Hockham had proposed. Shortly thereafter, Panish and Hayashi at Bell Laboratories demonstrated a semiconductor laser that could operate continuously at room temperature, and John MacChesney and coworkers, also at Bell



Laboratories, independently developed fiber preparation methods.

These activities marked a turning point. The means now existed to take fiber-optic communication out of the physics laboratory and into the realm of mainstream engineering. In the course of the next decade, as research continued, optical fibers gained increasingly in transparency. By 1980, the best fibers were so transparent that a signal might pass through 150 miles of fiber before becoming too weak to detect. If the seas of the world were that clear, one could sail across the deepest parts of the Pacific and see the ocean floor as easily as the bottom of a swimming pool.

But optical fibers with this degree of transparency could not be prepared using traditional methods. The breakthrough came with the realization that pure silica glass, free of all light-absorbing metal impurities, could only be prepared directly from vapor components—thereby avoiding the contamination that inevitably accrued from the conventional use of melt-containing crucibles. Progress now centered on selecting the right balance of vapor components and on optimizing their reactions. The developing technology rested heavily on a knowledge of chemical thermodynamics, a science refined by three generations of chemists from its original espousal by Willard Gibbs in the 19th century.

Practical Systems Take Shape

Still, it would take more than good fiber to build commercial-grade communication systems. Lasers—which would require lifetimes of up to 1,000,000 hours—were still coming up short in reliability, failing after no more than a few hours of operation. Moreover, there was as yet no economical method of producing reliable lasers in the quantities that would be needed.

It proved possible to get around these demands, at least to some degree, by sidestepping the use of lasers. A simpler type of device was the light-emitting diode, or LED, which resembles the red and green indicator lights in a cassette player or VCR. LEDs proved adequate for transmitting limited numbers of telephone calls over modest distances, but they lacked the efficiency and capacity needed for long-distance and transoceanic service.

Again, it was necessary to draw on work from the research laboratory. At about the same time that Panish and Hayashi were doing their breakthrough work on multilayered crystals, two colleagues at Bell Laboratories, J. R. Arthur and A. Y. Cho, were coming up with a dif-

ferent crystal-growth method—called molecular-beam epitaxy, or MBE. “Epitaxy” is the growth of crystals of one mineral on the face of crystals of another mineral, and MBE was so precise that it could put down a layer of semiconductor material with a thickness measured in atoms. By confining electrons and their emitted light, this extremely thin layer proved highly efficient at generating laser action while using less electric current. Even better, the new MBE devices achieved the desired 1,000,000-hour lifetimes.

Drawing on the basic understanding of crystal growth developed a decade or so earlier by scientists at Bristol University and Bell Laboratories, research into different methods of production and different semiconductor compounds continued through the 1970s and into the 1980s. By 1975, laser technology was sufficiently well developed to permit operational trials in major cities. From origins in the theoretical quantum physics of Albert Einstein, fiber-optic communication was now focused on the practical concerns of production, installation, and repair. Engineers were particularly concerned about repair—splicing broken optical fibers would be a challenge akin to cutting a hair from your head and then putting it back into place.

The first test came at AT&T in Atlanta in 1976. Work crews installed two fiber-optic cables—each 2,100 feet long and containing 144 fibers—by pulling them through standard underground ducts, which required the cables to negotiate sharp bends. To everyone’s immense relief, installation did not break any of the fibers, nor did the tight bends degrade their performance. Commercial service began the next year in Chicago, where a fiber-optic system carried voice, data, and video signals over 1.5 miles of underground cable that connected two switching offices of the Illinois Bell Telephone Company.

Fiber Optics to the Fore

The prospect of widespread installation of fiber-optics systems was exhilarating. In the United States, railroad rights-of-way offered convenient paths for long-distance fiber cables, which were so robust that even the strong vibrations of heavy trains did not disturb them. Work proceeded slowly at first. In 1978, the total of all fiber-optic installations in the world came to only 600 miles. In 1980, AT&T filed plans with the Federal Communications Commission for a 611-mile system that would connect major cities in the Boston-Washington corridor. Four years later, when the system



Remote learning is just one of the innovations enhanced by developments in fiber-optic communication. (Corning Inc.)

entered service, its cable, less than 1 inch across, provided 80,000 voice channels for simultaneous telephone conversations. By then, the total length of fiber cables in the United States alone approached 250,000 miles—enough to stretch to the moon.

Similar cables soon spanned the world's oceans. The first transatlantic cable entered service in 1988, using glass so transparent that its amplifiers for regenerating weak signals could be spaced more than 40 miles apart. Three years later, another transatlantic cable doubled the capacity of the first one. Transpacific cables have also come into use, offering easy telephone service for the burgeoning United States trade with Asia.

Basic Research Remains Vital

Amid those fast-paced developments, basic research continued to yield important improvements. In early fiber-optic systems, the amplifiers for regenerating a weak signal constituted a bottleneck. Although optical devices could be used to detect an incoming laser signal, some sort of electronic circuitry was needed to convert it to electric current, amplify the current, and then drive a new laser to recreate the optical signal. This limited the system to the capacity of the electronic amplifiers, which was considerably less than the potential capacity of the lasers and optical fibers.

But in 1985, at England's University of Southampton, physicist S. B. Poole discovered a solution. Adding a small quantity of the element erbium to the glass used in optical fibers would make it possible to build an all-optic amplifier. A short strand of erbium-doped glass,

spliced into the main fiber, would receive energy from an external source and act as a laser in its own right, amplifying a weak optical signal without using electronics.

Poole's colleagues at Southampton, David Payne and P. J. Mears, and Emmanuel Desurvire at Bell Laboratories, proceeded to turn the discovery into practical and effective fiber-optic amplifiers. In 1991, investigators at Bell Laboratories demonstrated that an all-optic system would have a carrying capacity about 100 times that then achievable with electronic amplifiers. In short order, both European and American communication firms installed all-optic cables across the Atlantic, and a Pacific cable entered service in 1996.

Clearly, progress has been remarkable and rapid. Impressive as these accomplishments are, even more dramatic advances are on the horizon. Although today's fiber-optic systems serve as trunk lines, carrying large numbers of voice and data channels between central telephone stations, industry specialists speak wistfully of the "last mile"—from the central station to your home. Today's telephone system spans that last mile with conventional copper-wire equipment, which provides good voice connections but is still inadequate for carrying large quantities of high-speed data.

High-speed data lines for that last mile are available, and many businesses have them, but they are generally more expensive than is practical for home use today. Whatever new technology turns out to provide the last crucial link from individuals to the rest of the world, the research that gives rise to it will have come from scientists who probe beneath the immediate needs of any given industry, investigating seemingly unrelated processes to understand the fundamental nature of the world.

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