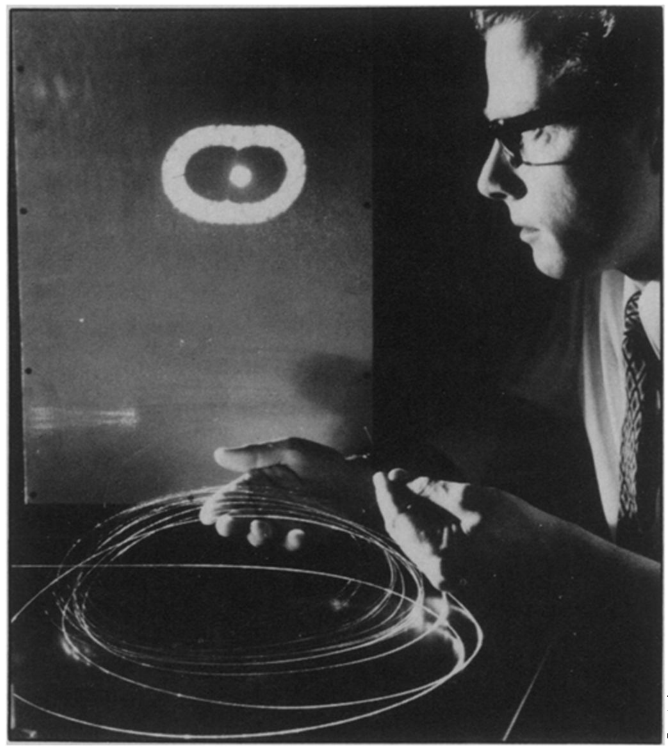
Telephoning by Light, I: The Breakthroughs


Bell Labs

Recent advances in solid state physics and materials research have led to creation of some spectacular devices that make optical communications possible

BY JOHN H. DOUGLAS

A fundamental change in communications—the most revolutionary since development of the telecommunications satellite—is slowly taking shape at Bell Laboratories and a few other research facilities. Born of a pressing need for a compact, high-volume telephone network to replace bulky cables and limited-capacity microwave relays, optical communications is beginning to move from the obscurity of laboratory back benches to the spotlight of the executive conference table. Although widespread application is still probably a decade away for telephoning by light beam, several recent technological breakthroughs have opened new possibilities and buoyed expectations.

Before planners could begin seriously considering an optical communications system, three basic components had to be developed: an accurate, reliable transmitter to change electrical signals into light pulses, a conducting medium with a minimum of loss and distortion over long distances, and a sensitive receiver to reconvert the light pulses into electrical signals. At least a prototype version of each component has now emerged, usually accompanied by some useful new insight into solid-state or materials research.

Most advanced of the components is the conducting medium—a generation of optical fibers that transmit light many orders of magnitude better than the conventional "light pipes" used in photocopiers and medical instruments. At first, researchers tried using the air as a conduction medium, but sending a signal by light between two buildings makes it more susceptible to interference by weather and pollution than existing microwave systems. And transmission through a special atmosphere in a hollow pipe involves too many expensive internal controls. With glass fibers, there was mainly a problem of purity—certain metal ions could not be present in amounts greater than a few parts per *billion*.

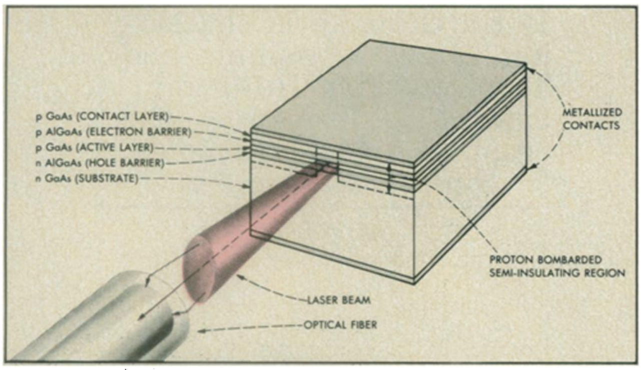
In 1966, a British researcher established the crucial criterion: Communication by fiber-conducted light would be feasible, he said, if losses could be held down to 20 dB (decibels) per kilometer. Since a decibel is defined as 10 times the logarithm of the ratio of initial power divided by transmitted power, a loss of 20dB/km means that only one percent of the original light will emerge from the end of a fiber one kilometer long. Unfortunately, the losses in conventional fibers measure in the thousands of decibels.

The purity required was so great that preparing the glass in the best platinum crucibles would not suffice—too many platinum ions would find their way into the finished fiber. Finally, materials experts at Bell Labs tried a different tack, creating an exquisitely pure core of fused quartz, doped with just the right amount of germanium, by vapor deposition inside a hollow glass tube, whose composition was not so critical. The tube and core together may then be heated and drawn into a fiber the diameter of a human hair. Using this technique, Bell scientists have succeeded in reducing losses to levels far below the critical level; using an optimum wavelength of light, one fiber now shows a loss of only 1.2 dB/km.

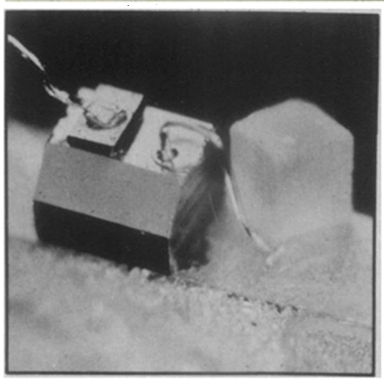
Given a pure material to work with, the continuing search for an optimum fiber design was begun. When a sharply defined pulse of light starts to travel down a fiber, various parts of it travel at different velocities, so that by the time the pulse reaches a receiver some kilometers down the line, it has spread out and may even be indistinguishable from the next pulse just behind. The easiest way to picture this "dispersion" phenomenon is to imagine that parts of a pulse enter a fiber at slightly different angles and travel down its length as separate rays, bouncing back and forth. Since the distance travelled by each ray is slightly different, after a while the rays begin to spread out. (Actually the light doesn't travel in rays but in quantized "modes" or patterns that travel at different velocities.)

To minimize pulse dispersion, several design alternatives are possible for the fibers. If the fiber core is extremely small, only one centrally directed ray or mode can pass. Surrounding a larger core with a cladding of lower refractive index traps the rays inside the core by reflection. An air gap around the small core of a single-material fiber also causes internal reflection. One of the most immediately promising designs is a fiber whose refractive index gradually decreases from the center out to the edge. This causes the various rays to be focused back toward the center so that they all travel along the fiber at the same speed.

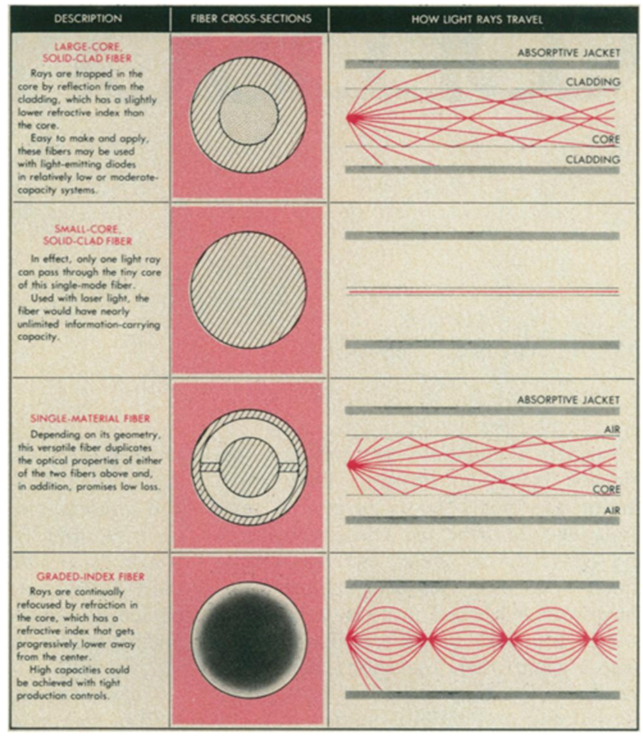
The small core designs would have the least dispersion, but they can only be used with powerful, coherent laser light and are much harder to handle physically. Splicing two small core fibers is literally like trying to join two human hairs end to end so that their centers exactly coincide. Large core designs do not necessitate laser light and can be handled more easily, but many practical problems like splicing and cabling still remain to be developed for use in field conditions. Because of their extreme fineness, all the fibers are very flexible, and an exterior coating of organic



Illustrations: Bell Labs



Designs of various fibers, right. Diagram of miniature laser, above. Photo of laser, beside grain of salt, left. Light from single material fiber, far left.



polymer makes them quite strong and resistant to damage. The inherent imperviousness of glass fibers to water and corrosion was one of the attractive features that led to their consideration in the first place.

For enough light to enter a fiber to give a strong signal a long distance away, the light source must be about the same size as the fiber. Fortunately, a reliable miniature source already exists—the light-emitting diode (LED), invented at Bell Labs—commonly used in display panels, such as those in pocket calculators. The active elements of the device are simply two dissimilar layers of semiconductor material—one an *n*-type (electron conducting) and the other a *p*-type (hole conducting). When voltage is applied across the junction between the two layers, electrons and holes recombine, emitting light. By carefully mounting the thin active layers on a sturdier substrate, into which is joined an optical fiber, a practical transmitter is created.

Because of their proven reliability and ease of control, LED's will probably be used in the first practical optical communications systems, but they have distinct disadvantages. The light they emit is spread over a spectrum of frequencies, and since each frequency travels down the fiber at a slightly different velocity, a short initial pulse again begins to spread out (a phenomenon called "frequency dispersion" as opposed to the "mode dispersion" discussed earlier). The surplus frequencies could, of course, be filtered out, but the signal would be weak.

A better solution was to create a miniature laser, which radiates in a spectrum some 40 times narrower than a LED, and can supply more useful power to a signal pulse. Bell scientists reasoned that if the radiating region of a LED could be made just the right size, with partially reflecting ends, it would act as a resonating chamber in which photons would bounce back and forth amplifying one particular frequency of the light—that is, to "lase." The result was creation of the world's smallest laser: an assembly the size of a grain of salt, with a radiating region less than 20 microns wide.

These new "injection lasers" can be flashed at almost a half billion times a second, opening the way for sending vast quantities of data much faster than any other system. By adding a tiny lens, they can be coupled to the low-loss, narrow-core fibers, while LED's must be joined to the less efficient, wide-core fibers. However, the lasers are not yet as reliable as the LED's, having only a few months of useful life, while lifetimes of several years will be required for use in practical telephone systems.

The final basic component of a simple optical communications line is a detector that is small enough to be attached to the hair-like fibers, sensitive enough to detect a distance-weakened signal, and precise enough to distinguish among smeared-out pulses coming at it millions of times a second. Only a miniature solid-state device would begin to fill the bill, and the most likely candidates are the so-called "*pin*-photodiode" and the closely related "avalanche photodiode."

In each, the detection process is just the reverse of the light-emitting process of the LED. A photon enters a neutral region between an *n* and a *p* semiconducting layer, where it is absorbed, creating an electron-hole pair. By applying a voltage across the device with the positive pole at the *n* layer (reversed from the usual voltage bias) the electron migrates in that direction and is absorbed, creating a tiny current. So sensitive is the resulting detector that nearly 80 percent of the individual light quanta entering the device are converted to electron-hole pairs. The current produced is less than a billionth of an ampere and takes only a billionth of a second to generate.

For very high pulse rates, the "noise" inherent in electronic circuits that must amplify the tiny signal current becomes too great, so a way to incorporate some amplification into the detector itself had to be found. This was accomplished by adding an additional *p* layer between the original *n* layer and the neutral region, and then applying a higher voltage. Now when electrons begin to move toward the positive pole, they accelerate so fast that they knock additional electrons out of position, creating an avalanche of charge—hence the name "avalanche photodiode." This detector is so sensitive that it approaches the theoretical limit of detecting individual light quanta.

While the technical breakthroughs involved in the development of each of these devices are gathering much attention because of their applicability to optical communications, numerous "spin-offs" can also be anticipated. Lasers the size of salt grains, light detectors that approach the theoretical limits of sensitivity, and optical fibers millions of times more brilliant than those available just a few years ago will certainly find new applications in medicine, industry and research. Meanwhile, efforts are accelerating to bring these devices together to create a reliable communications system with a transmission capacity beyond anything possible today: to be discussed next week. □