Single–Mode Optical Fiber Allows Almost-Lossless Lightwave Transmission

By Howard Rausch

Almost in the shadow of the Harvard Business School, technology companies are thriving by flouting some of the school's most cherished doctrines.

One day last December an executive of a fiber optics company mentioned that he was busy preparing his budget for 1984. Wasn't he a little late?

"Not at all," he explained patiently. "If we had adopted a budget when we should have, according to the textbooks, we would have made too-large commitments to multi–mode fiber—when the world is going to single mode."

When people talk fiber optics these days, they're usually alluding to a type of fiber that was just beginning to appear commercially a year ago. Last year only about 4 percent of the fiber installed in the United States was single mode; this year single mode will be a large majority.

Continental Telephone of Virginia is a good example. Last year the company operated only multimode systems. This year Contel plans to install 114 lightwave systems, all single mode. Multimode will be used only to upgrade existing facilities.

More recently, Indiana Bell cut more than a 500-kilometer fiber system, of which all but 33 kilometers is single mode.

MCI Telecommunications, Inc., ordered 40,000 kilometers of fiber last year, 95 percent of it single mode.

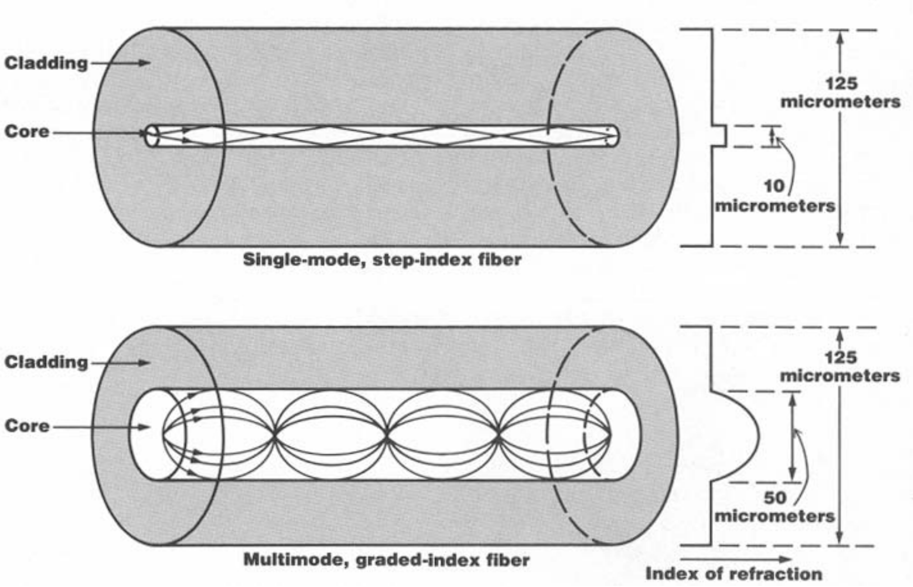
The next transatlantic cable, a $335 million project scheduled to go into service late in 1987, will be optical fiber—single mode in its entirety.

International trend

The shift to single mode is just as pronounced in Europe and in Japan. Early this year, Britain's first single-mode lightwave link went into service over the 28 kilometers between the towns of Luton and Milton Keynes, north of London. The system, without repeaters, operates at 140 megabits per second under an ancient thoroughfare, the Roman road known as Watling Street.

British Telecom, which installed the lightwave system, plans to spend $2.2 billion per year on extensive modernization. "Nearly all our future long-distance cable links will employ single-mode optical fiber," reports Jim Hogdson, vice chairman.

The effort in Japan is, if anything, even more intense. There's considerable but inconclusive evidence that Japan produces as much single-mode fiber as any other country, enough for its extensive domestic needs and for exports around the world, including North America.



Sizes and optical paths differ in single-mode and multimode fiber. Multimode core is larger, although outer cladding is same as for single mode. Optical path is zigzag in multimode, straight line in single mode.

Difficult to fabricate

Like fiber transmission itself, the possibility of ultralarge bandwidth in single mode was easier to conceive than to accomplish. Fabrication requires tight control of both fiber geometry and refractive index profile. The fiber's small core and low numerical aperture make it especially difficult to couple fibers to optical devices without incurring unacceptably high coupling losses.

Historically, multimode fibers were developed first. They were compatible with the light-emitting diodes and short-wavelength lasers that were available. Today, however, single-mode fibers offer so much more capacity that most research and manufacturing efforts have switched to the newer technology.

How single mode differs

Multimode and single-mode fibers look identical on casual inspection. The most popular products of each kind have outer diameters of 125 microns. It is the internal optical design of the fiber that is different. In single-mode fiber, as in step-index multimode fiber, light travels in a sharply defined glass core that is surrounded by a glass cladding of slightly lower refractive index. The principal difference is that the diameter of the single–mode fiber's core is only 5 to 10 microns compared with diameters of 50, 100, or even 200 microns for multimode fibers.

In the larger cores, light can propagate in many modes, most of them involving repeated reflections at the core-cladding interface. In the small cores, which are only a few times the wavelength of the light to be transmitted, only one mode can propagate. That mode is called the fundamental mode, and it travels directly down the

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center of the core without multiple reflections at the core-cladding boundary.

The switch to propagation of a single mode occurs at what is termed the "cutoff wavelength." At wavelengths shorter than the cutoff wavelength, the ratio of core diameter to wavelength is larger, allowing more than one mode to travel along the fiber. These modes have different transit times corresponding to the various lengths of the zig-zag optical paths. By contrast, only one path exists in single-mode transmission.

It is the existence of many optical paths that causes bandwidth-limiting dispersion. A pulse launched onto multimode fiber spreads out as it propagates. For binary signals, the '1's smear out into the '0's, and data is irretrievably lost.

Single-mode fibers are free from modal dispersion. There is only one route for the pulse to take, and its spreading in transmission is determined by two smaller effects: bulk dispersion and waveguide dispersion. But these effects have opposite signs. The careful art of fiber design balances these dispersion mechanisms against each other, looking for an opportunity to cancel them completely. Waveguide properties are altered by choosing various values for the core and cladding refractive indices.

Bulk dispersion in the core is fine-tuned by adding precise levels of dopants to the glass; an example is germanium oxide. In single-mode fibers, these two dispersion effects cancel out at 1,300 nm. This wavelength is selected because the other performance-limiting parameter, attenuation, is very low at 1,300 nm, typically about two decibels per kilometer for commercial fiber.

Challenges to designers

So, by exacting design of the single-mode fiber, dispersion is eliminated. That means essentially unlimited fiber bandwidths.

There are still challenges for fiber designers, however. The limitation on 1,300-nm, zero-dispersion fibers is clearly not the bandwidth. Rather, it is attenuation that limits how far a signal can travel before it becomes too weak for detection. But silica fibers have lower attenuation at 1,500 nm than at 1,300.

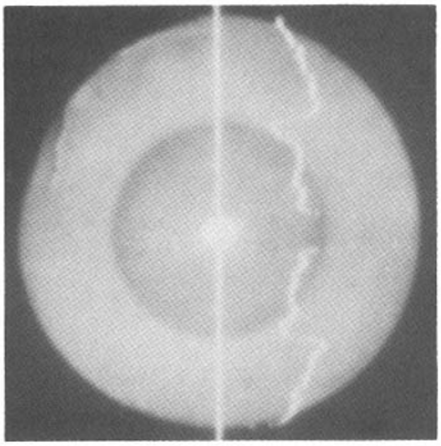
Unfortunately the dispersion effects, which in simple fiber designs can cancel at 1,300 nm, become cumulative at 1,500 nm. So fiber companies are looking for ways to create fibers with multi-layered cladding structures. The goal is for the waveguide properties of the new, complex fiber designs to give zero dispersion at both 1,300 nm and 1,500 nm. Another approach is to use lasers of very narrow spectral width at 1,500 nm and eliminate the effects of bulk and material dispersion by simply having no spectrum to disperse.

Using the so-called third window at 1,500 nm, fibers can transmit vast quantities of information simultaneously at two wavelengths without crosstalk. The promise of this technique is imbedded in lightwave systems being installed today. Although the lasers incorporated in those systems are all 1,300 nm devices, the fibers are carefully scrutinized at 1,500 nm before being buried in trenches and city sewer ducts.

In several years, when the capacity at 1,300 nm is exhausted, the best of modern single-mode systems will be able to supply increased capacity—without new fiber—simply by adding the 1,500 nm devices: lasers, detectors, and optical elements to combine and to separate the two wavelengths. The technique of transmitting separate streams of information at two or more wavelengths is called "wavelength division multiplexing."

Fortunately, the manufacture of single-mode fiber is little or no more expensive than multimode, despite the tighter tolerances. Any increment is more than outweighed by savings in need for costly repeaters. So the buyer receives longer transmission and higher bit rate at approximately the same cost as for multimode fiber.

If these were the only considerations, there would no market for multimode fiber in communications. But they aren't, so multimode manufacturing equipment isn't going onto scrap piles yet.



Single-mode fiber with cleaved end face is tested at Valtec Corp. Trace shows changes in refractive index. Fiber itself is 125 micrometers in diameter; core diameter is 9 micrometers. Photo courtesy AT&T Bell Laboratories.

New components needed

Single-mode systems require new families of laser emitters, of receivers, connectors, couplers, even new measuring instruments.

The first laser diodes were based on GaAlAs for the wavelength range 700 to 900 nanometers. This range corresponds to the first "transmission window" in fiber, the region of low attenuation. These thoroughly engineered lasers have stable operating characteristics at temperatures as high as 100 degrees centigrade, with extrapolated lifetimes well above 100,000 hours at 25 degrees.

For long wavelengths, 1,300 to 1,500 nanometers, where dispersion can be made to disappear almost completely in single-mode fiber, laser diodes were developed more recently.

For the system near London, Standard Telephones & Cables supplies lasers with high output power at 1,300 nanometers. The laser's output is coupled to a single-mode fiber "tail." Launch efficiency is increased by a coupling lens. The entire assembly is hermetically sealed in a rugged package for mounting onto a printed circuit board.

For shorter wavelengths, highly developed silicon technology has produced sensitive avalanche diodes that detect signals efficiently. Above 1,000 nanometers, however, their response falls rapidly. For use at 1,300 nm, the best results are obtained with receivers from the InGaAsP system or with P-I-N photodetectors.

Lasers and receivers optimized for single-mode systems are in production in several places. Competition is not yet intense because demand continues to exceed supply. This situation could change as early as this year as more manufacturing capability comes online, mostly in the United States, at American and Japanese-owned companies.

Specialized connectors

In single-mode connectors, demand out strips supply by an even greater margin. The first commercial devices appeared only in mid-1983. By the end of this year, some of the biggest companies in connector-making will have moved into single-mode production. But their attraction to single-mode fiber goes beyond the telecommunications application.

Because of their low loss over long distances, fibers in telecommunications are generally connected in the field by splicing, where losses can be as low as 0.1 decibel, lower than are possible with commercial connectors.

Where then do connectors appear prominently in lightwave telecommunications? One place is at repeaters, although fewer of these are needed with the widespread deployment of single-mode fibers with low signal degradation. Another site for connectors is near each laser and receiver; these are commonly "pigtailed" to fibers that have connectors. With such an arrangement, a new transmitter can be introduced onto an existing fiber without having to splice in the small, crowded environment of the rear panel of a telephone exchange's terminal bay, where such additions usually take place. In such an environment, splicing is difficult and often dangerous.

These are not huge markets. There's probably not enough potential business in telecommunications to attract such companies as Nippon Electric and ITT Cannon, nor even smaller newcomers such as Dorran Photonics.

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But single-mode's appeal isn't confined to telecommunications. It's also beginning to attract interest for shorter-haul applications, where lower bit rates are required and where losses introduced by connectors are less significant.

Several telephone companies, for example, plan to extend single-mode fiber from existing trunks all the way to the premises of major subscribers. And computer makers are considering single mode for user sites. At computer sites, as at telephone sites, it's far simpler to interconnect through standardized connectors than through splicing. The customer can often connect his own device without specialized training in splicing.

Small connectors attract giant firms

The intricacies of the fiber connector have lured another corporate giant into the lightwave industry: Polaroid. In the course of refining its camera design, the company had developed techniques for fabricating lenses and mirrors to tolerances within two microns, or one millionth of an inch. For this precision in optics, and for the prospect of economies that could be achieved in molding, Polaroid found a customer in GTE Laboratories, a corporate neighbor in Waltham, Massachusetts. GTE was looking for lenses for fiber-optic connectors—and found them. Today, GTE's new line of expanded-beam connectors uses precision-molded acrylic lenses fabricated by Polaroid.

Perhaps as a result of its experience with GTE, Polaroid began to assemble an impressive staff with expertise in fiber optics. In early March there were 20 professional people involved in both technology and marketing. There was also elaborate equipment, including a fiber draw tower for making single-mode fiber.

Intense speculation about this secret project centers on the prospect of a family of components to enhance coupling of light from lasers and incoherent light-emitting diodes into the cores of optical fibers. A related product could be the coupler, traditionally made by fusing fiber bundles together. Polaroid may have the technology to replace such fused coupler with molded parts.

The commercial attractiveness of single-mode lightwave technology appears clearly in the pace of product development. Specialized lasers, receivers, and connectors were introduced only months after the announcements of the first single-mode fibers.

As with all new technologies, rapid improvements in basic products—in this case the fiber itself—dictate changes in requirements for components. That's one reason for the slow emergence of standards and for manufacturers' inability to adopt mass production methods. Improvement on both fronts could considerably strengthen lightwave's already formidable competitive position.