PennWell

JANUARY 1999

ADVANCES AND APPLICATIONS IN OPTOELECTRONICS

Laser Focus World®

- Photonics West preview
- CMOS sensors offer low-light imaging
- Fiber lasers produce more power
- New design improves laser projectors

ANNUAL MARKET REVIEW AND FORECAST

1998 CTA Awards

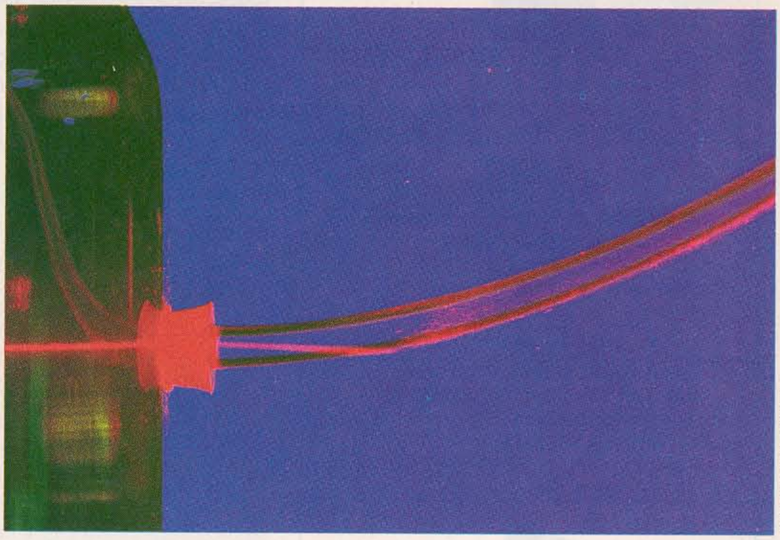
A new Back to Basics series explores key developments in fiberoptics ranging from fiber manufacture to high-speed communications.

Fiberoptic communications: an optoelectronics driver

Jeff Hecht, Contributing Editor

Optical fibers were first developed for imaging and illumination, but the technology has expanded explosively into communications over the past quarter century. Fiber communications has become one of the driving engines of the laser and optoelectronics industry. System requirements pushed the development of whole new families of semiconductor lasers, spawned fiber amplifiers and fiber lasers, and gave birth to sophisticated optics for splitting signals at wavelengths separated by a mere 0.4 nm.

This series of tutorials on fiberoptics, designed to bring readers up to speed in a field that is changing rapidly, begins with a discussion of key concepts. Succeeding articles will cover fibers themselves, associated components, communications of fiberoptics applications, measurements, sensing, beam delivery, and fiber imaging.



KLAUS BIEDERMANN

Water jet guides a red laser beam in the "Laser Grotto" at the Royal Institute of Technology in Stockholm, updating Colladon's experiment.

Key concepts of fiberoptics

Optical fibers guide light from one point to another. Fibers have found a variety of applications where that guiding offers important advantages over transmitting light through the air. The simplest is the flexible light guide, which can deliver light over a convoluted path—or simply around a corner—without complex optics. Single optical fibers can carry laser energy short distances for medical or industrial applications or carry high-speed signals over long distances for communications.

Fibers can be bundled together for illumination or imaging. If the fibers are arranged in the same pattern on each end of a bundle, they transmit an image from end to end, with each fiber appearing as one pixel on the image. Fiberoptic signs can be made by illuminating one end of a bundle and arranging the fibers at the other end to display an image or spell out words.

Fiberoptics also can serve more complex optical functions. Their light-guiding properties concentrate optical power in fiber lasers and optical-fiber amplifiers. Fiber sensors designed to respond to their environment can monitor conditions such as pressure and temperature. Bragg gratings written in optical fibers function as narrow-line optical filters. All these applications depend on the light-guiding properties of fibers.

At the simplest level, light guiding in an optical fiber depends on the principle of total internal reflection, which in turn is a consequence of Snell's law of refraction. Snell's law relates the angles of incidence and reflection (θ_i and θ_r) for light passing between two materials with different refractive indexes (n_i and n_r).

$$n_i \sin\theta_i = n_r \sin\theta_r$$

In the familiar case where light from a low-index medium passes through a surface to a higher-index material, the light bends toward the normal, a line perpendicular to the surface. Air-to-glass transmission is one example.

Conversely, light passing from a high-index to a low-index material bends away from the normal. At large-enough angles from the normal, light cannot pass from the higher-index material into the lower-index material. You can find this point if you invert Snell's formula and solve for the angle of refraction θ_r:

$$\theta_r = \arcsin\left(\frac{n_i \sin\theta_i}{n_r}\right)$$

As the angle of incidence increases, the angle of refraction approaches a limit of 90°. The angle of incidence at which θ_r would equal 90° is called the *critical angle.* If you try to calculate the angle of refraction for larger angles of incidence, your computer or pocket calculator will balk because you're trying to calculate the arcsine of a number larger than one.

Physically what happens is that light striking the surface beyond the critical angle from the normal cannot enter the low-index medium. Instead, it is totally reflected back into the high-index medium. Light between the normal and the critical angle undergoes normal refraction; total internal reflection occurs outside that range.

The larger the ratio of the refractive indexes, the smaller the critical angle, and the larger the range over which total internal reflection occurs. For the BK7 glass typically used for laser optics, with refractive index about 1.52, the critical angle in air is about 41° (see Fig. 1). This angle is small enough that light striking a glass–air interface at 45° undergoes total internal reflection—the basis of right-angle prisms. The critical angle is 24.6° for diamond, which has an index 2.4, so light that enters the gem is reflected at a broader range of angles, contributing to its glitter.

Total internal reflection was recognized long before the first recorded light-guiding demonstrations, by Swiss physicist Daniel Colladon in a water jet.[1] French physicist Jacques Babinet pointed out that the same phenomenon occurred in a bent glass rod.[2] (John Tyndall's better-known experiments followed Colladon's.) The principles are the same for water jets and glass rods; light entering one end strikes the sides at a steep angle, so total internal reflection confines light within the medium (see photo on p. 143).

Although the concept is simple, efficient light guiding requires a highly transparent material and a smooth reflective surface that does not contact other objects. Water jets make pretty demonstrations, but light leaks through their turbulent surfaces. Light leaks from bare glass rods where they touch other materials, or where scratches or fingerprints make their surfaces rough. Bare fibers bundled together lose light both where they touch other fibers and from scratches on their surfaces.

The invention that made optical fibers possible was the addition of a low-index cladding layer, proposed by Brian O'Brien and separately by Holger Møller Hansen (see Fig. 2).[3] The cladding protects the crucial surface where total internal reflection takes place, preventing scratches and contact with other materials. The refractive-index difference does not need to be large. A mere 1% difference between core and cladding index gives a critical angle of 82°, which confines light within the fiber core as long as the light strikes the cladding at an angle no more than 8° from the fiber axis.

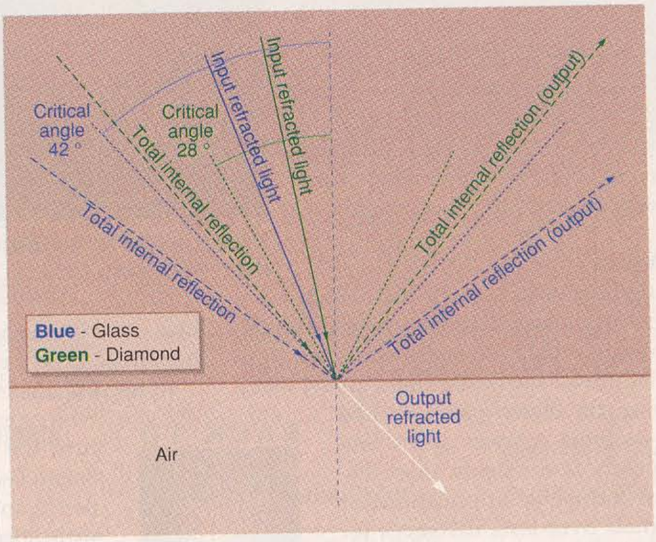


FIGURE 1. The critical angle for total internal reflection depends on refractive index. For high-index diamond, total internal reflection occurs over a broader range of angles than for lower-index glass. (Adapted from Jeff Hecht, *City of Light: The Story of Fiber Optics*, Oxford University Press, New York, 1999).

It took time to perfect clad fibers because total internal reflection requires a very smooth core-cladding boundary. Early plastic coatings were too inhomogeneous, and mechanical polishing left too many flaws and impurities on the surfaces of glass rods. Larry Curtiss, then a physics undergraduate student at the University of Michigan, made the first good clad fibers by collapsing a hollow glass tube onto a fire-polished rod and drawing the resulting preform into a thin fiber.[4] Today most fibers are still glass-clad, although most preforms are made differently, and there are many different types of fibers.

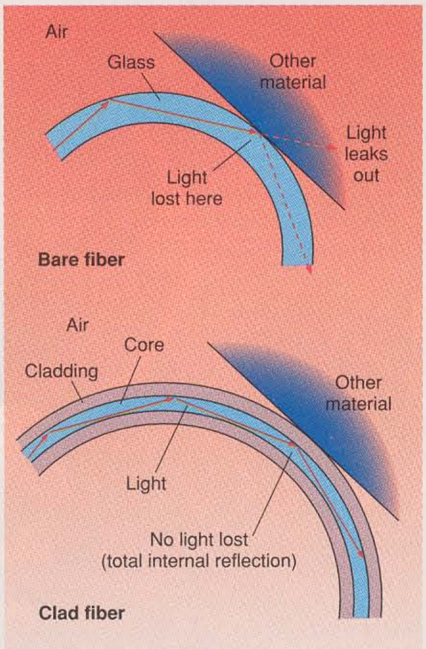


FIGURE 2. Light can leak out of an unclad fiber (top) where it touches other objects. Addition of a cladding (bottom) prevents the core surface from contacting other objects, so total internal reflection is unimpeded.

Fibers as waveguides

Total internal reflection approximates fiber properties, but a precise description of light propagation requires electromagnetic theory. From a physical standpoint, an optical fiber is a dielectric optical waveguide, analogous to solid plastic microwave waveguides. The refractive index corresponds to the dielectric constant in microwave transmission. The major difference is wavelength, which makes optical waveguides much smaller than their microwave counterparts.

Light propagates through an optical fiber in distinct waveguide modes. The modes depend on the geometry of the fiber, the refractive indexes of the core and cladding, and the wavelength of the light. If the fiber dimensions are small enough, it can carry only a single mode. The precise definition of 'small enough' depends on the ratio of core and cladding indexes; the closer the indexes, the larger the core can be and still propagate only a single mode. Standard single-mode fibers have core diameters of about 9 µm and an index difference of about 1%. Larger-core fibers transmit multiple modes; the number increases very quickly with core diameter.

The waveguide view refines our view of light propagation in important ways. Unlike total internal reflection, it does not rigidly confine light within the core–cladding boundary. Some light travels at the core–cladding boundary and within the cladding, depending on details of the fiber structure. This allows effects such as evanescent coupling of light into and out of the waveguide.

Important fiber properties

The most crucial optical-fiber parameters are light coupling into the fiber and attenuation and pulse dispersion within it. Light coupling depends on two factors: focusing light into the fiber core and focusing it within the acceptance angle of the fiber. Both are geometric problems.

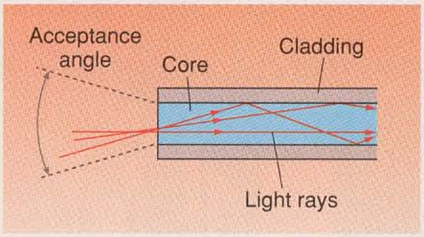


FIGURE 3. Light entering a fiber must fall within the acceptance angle and within the core to be guided along the fiber.

Light that falls outside of the fiber core is not guided within the fiber. If it enters the cladding, it leaks out after a short distance. The larger the core, the easier it is to direct light into it. When fibers are assembled into bundles, the claddings are kept as thin as possible, so as much light as possible enters the light-carrying cores. The *packing fraction* defines the fraction of core surface per unit area.

The *acceptance angle* is the largest angle to the fiber axis at which light can enter the fiber core and still be guided along it. Figure 3 shows what this means for light entering a fiber with core index 1% higher than the cladding. The critical angle for total internal reflection inside the fiber is 82°, so the *confinement angle* within the fiber θ_c is 8°, the complement of the critical angle. Refraction of light entering the fiber core from air increases the acceptance angle in air θ_a, multiplying it by the core refractive index, yielding an acceptance angle of 12° in this case.

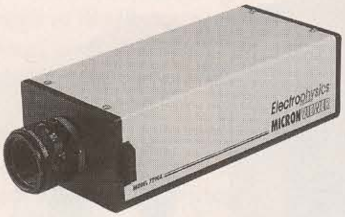
In practice, the acceptance angle normally is measured as the numerical aperture or NA, defined (for light entering the fiber from air) as

$$\mathrm{NA} = \sqrt{\left(n^2_{\mathrm{core}} - n^2_{\mathrm{cladding}}\right)}$$

For the example in Fig. 3, with core index 1.5 and cladding 1.485, NA = 0.21. Note that numerical aperture does not depend on core diameter.

Attenuation in fiber

The *attenuation* of an optical fiber is the



sum of light lost by *scattering* in the fiber, *absorption* by fiber materials, leakage of light out of the core caused by environmental factors such as microbending, and end losses. Like loss in other materials, it depends strongly on wavelength (see Fig. 4). Normally scattering and absorption dominate.

Rayleigh scattering dominates at short wavelengths, setting the floor for total attenuation at wavelengths shorter than 1.5 µm. It is proportional to the inverse fourth power of the wavelength, λ^{-4}. Residual impurities absorb light at some wavelengths shorter than 1.5 µm; absorption by silica increases for wavelengths longer than about 1.6 µm.

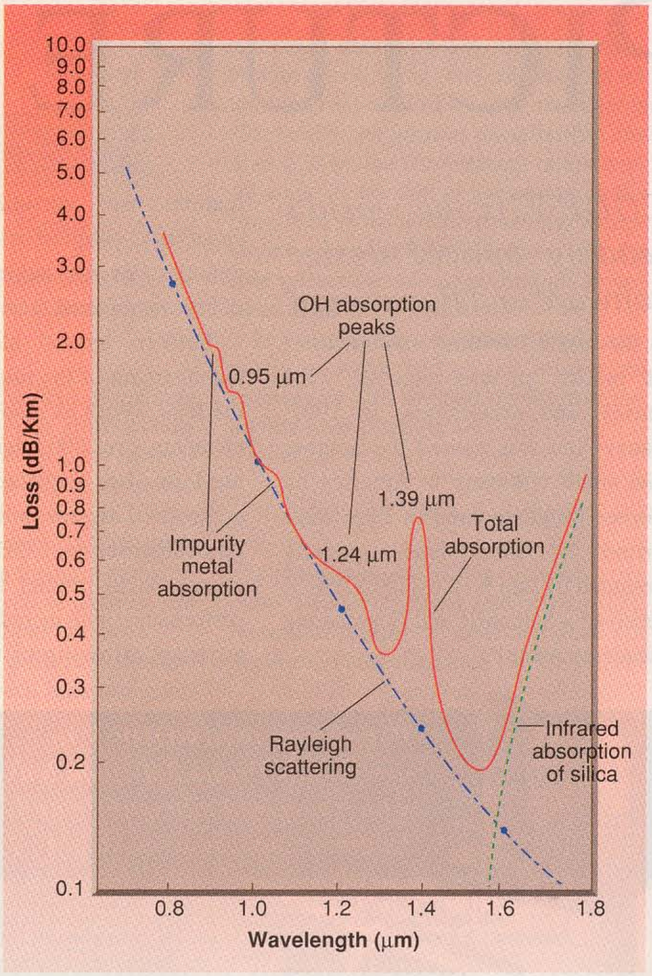


FIGURE 4. Impurities such as OH-TK, Rayleigh scattering, and infrared absorption by silica all contribute to loss in silica fibers. This is an illustrative curve; the loss of individual products will differ.

Total attenuation is measured in the relative units of decibels

$$\text{db loss} = -10 \times \log_{10}\left(\frac{\text{power out}}{\text{power in}}\right)$$

The minus sign avoids negative numbers in attenuation measurements. Decibels can be converted to absolute units by referencing them to a specific power level, such as dBm (decibels relative to one milliwatt), with the sign indicating if power is above or below the reference level. The use of decibels simplifies loss calculations: the sum of component losses equals total loss, and loss per unit distance multiplied by total distance equals total attenuation.

Bandwidth and dispersion

The transmission bandwidth or data rate of a fiberoptic system is limited by the spreading or *dispersion* of signals. The effect is simplest to explain for digital pulses, but the same principles apply to analog systems. Dispersion occurs because all light in the pulse does not travel at the same speed. There are four distinct types, modal, material, waveguide, and chromatic.

Modal dispersion occurs in fibers that transmit multiple modes, because each mode has a characteristic velocity. The differences build up with distance and are measured in nanoseconds per kilometer of fiber. The effect is large in multimode step-index fibers, smaller in graded-index fibers, and not present in single-mode fibers.

The range of wavelengths in the signal affects two of the four kinds of dispersion. *Material dispersion* arises from the variation of refractive index with wavelength; it is inherent in the glass used in the fiber. *Waveguide dispersion* occurs because the properties of a waveguide depend on its dimensions measured in units of wavelength. This means that a waveguide looks 'smaller' as the wavelength increases. These two kinds of dispersion can have either positive or negative signs; added together, they produce *chromatic dispersion*. Fibers have a characteristic chromatic dispersion measured in picoseconds per nanometer-kilometer; system dispersion is that number multiplied by source bandwidth (in nanometers) and fiber length (in kilometers). Fiber designers can do little to change material dispersion, but they can adjust waveguide dispersion by changing the core–cladding structure. This makes it possible to produce single-mode fibers with nominally zero dispersion at one wavelength between about 1.3 and 1.65 μm. Chromatic dispersion is of prime importance for single-mode fibers but also affects graded-index multimode fiber. It dictates the use of narrow-line laser sources for high-speed transmission.

Polarization-mode dispersion is the smallest effect, arising from slight differences in refractive index (and thus the speed of light) for light of different polarizations passing through single-mode fiber. Because these modes are strongly coupled to each other, polarization-mode dispersion increases only with the square root of transmission distance. The effect is small, but becomes significant at transmission speeds of several gigabits per second. ❑

Next month, Back to Basics will discuss types of optical fibers.

ACKNOWLEDGMENT

This article is adapted from Jeff Hecht, *Understanding Fiber Optics, 3rd ed.*, Prentice Hall, Upper Saddle River, NJ, 1999.

REFERENCES

1. Daniel Colladon, "On the reflections of a ray of light inside a parabolic liquid stream," *Comptes Rendus*, 1842
2. Babinet, "Note on the transmission of light by sinuous canals," *Comptes Rendus*, 1842
3. Brian O'Brien, U.S. Patent 2,825,260, "Optical Image Forming Devices," issued Mar. 1958; Holger Møller Hansen, Danish patent application, 1951.
4. Lawrence E. Curtiss, Glass fiber ptical devices, US patent 3,589,793, issued June 29, 1971.