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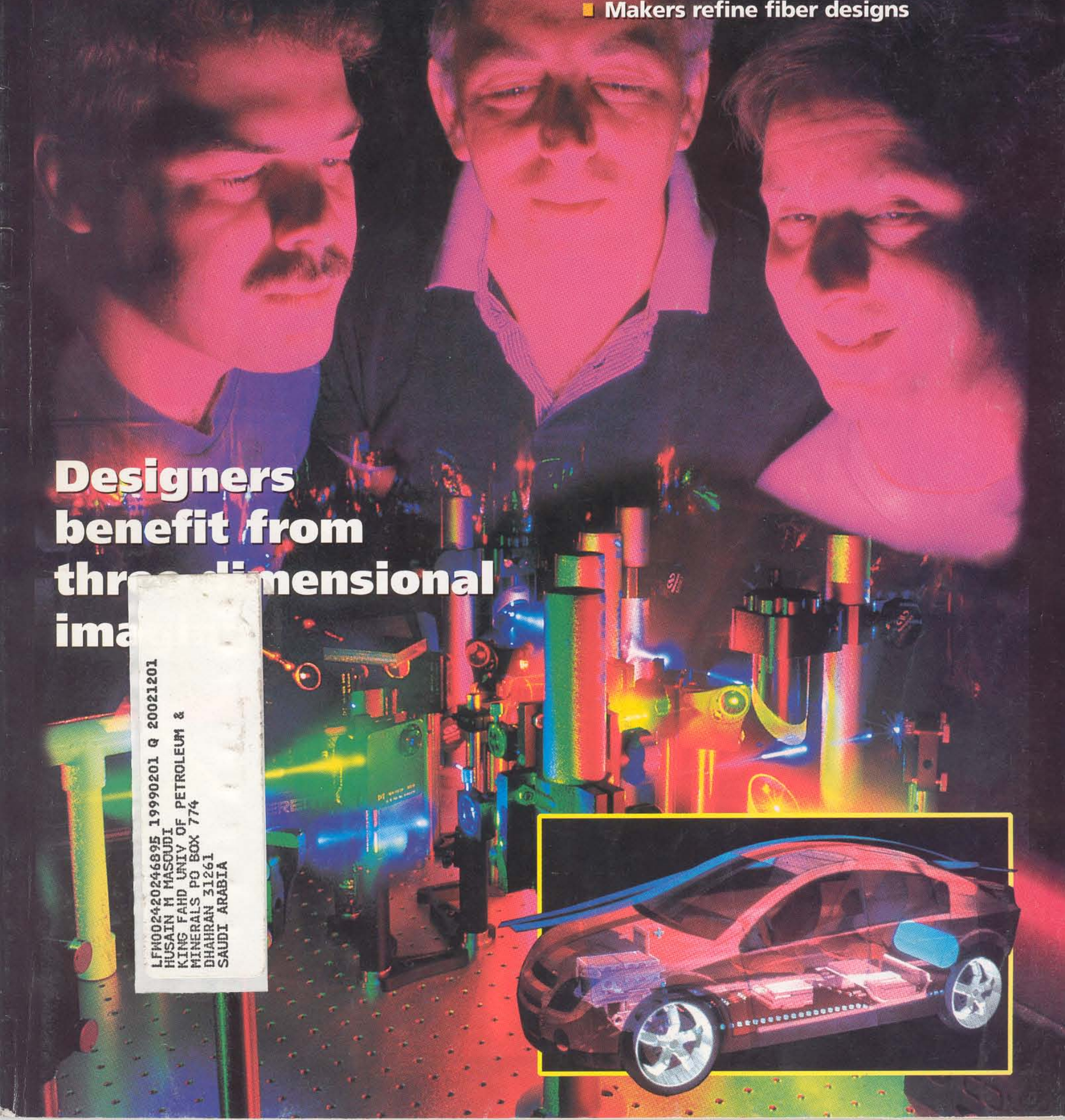

Designers benefit from three-dimensional ima

The refractive-index profile of optical fibers can be tailored to produce waveguiding properties specific to an intended application.

System developers drive refinements in fiber design

Jeff Hecht, Contributing Editor

Optical fibers normally are classified according to their waveguiding properties. The primary types are defined by the number of modes the fiber carries and the nature of the core–cladding boundary. In recent years, developers have added several subtypes as they have refined fiber properties, particularly to control pulse dispersion and to adapt fibers to transmit multiple-wavelength channels (wavelength-division multiplexing, or WDM).

There are three primary classes of fibers, each of which has its own characteristics and applications (see Fig. 1). *Step-index multimode fibers* have an abrupt transition between core and cladding and a relatively large core that supports many transmission modes. Their main applications are in imaging and illumination. *Graded-index multimode fibers* have a gradual transition between core and cladding, with core refractive index decreasing smoothly to the lower level in the cladding. They also have multimode cores and are used mainly for short-distance communications. *Single-mode fibers* have small light-guiding cores that transmit only a single mode of light. They are used in most fiber communications and come in several variations optimized for particular system applications.

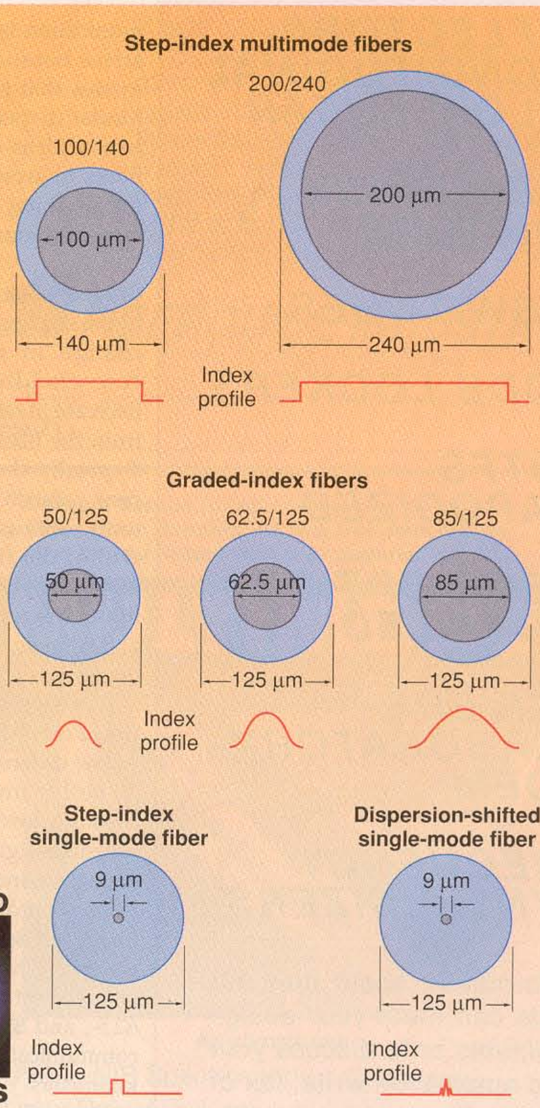

FIGURE 1. Common types of optical fiber, shown here to scale and without the outer plastic coatings that protect the fibers from mechanical damage and simplify handling, exhibit distinctive refractive-index profiles.

Step-index multimode fiber

The top two fibers in Figure 1 are examples of step-index multimode fibers. A low-index cladding covers a large core with higher refractive index. Common varieties include glass-clad glass, plastic-clad plastic, and plastic-clad glass. Typically the cladding is thin relative to the core.

Step-index multimode fibers offer large acceptance angles and large light-collecting and transmitting cores. These are important features for image-transmission and illumination bundles because the input light is spread across the entire receiving surface of the bundle, but only the part that falls on the cores is transmitted. The larger the fraction of the light-collecting area made of fiber cores, and the more efficiently the cores collect light, the better the light transmission. Large core diameters also are critical for carrying high-power laser beams. Spreading the laser energy through a larger volume reduces power density, avoiding material damage, particularly to sensitive fiber ends. Fibers with 400- to 1000-µm cores can transmit high-power beams. Larger cores are better for power transmission, but fiber flexibility decreases with increasing fiber diameter.

A major drawback of step-index multimode fibers for com-

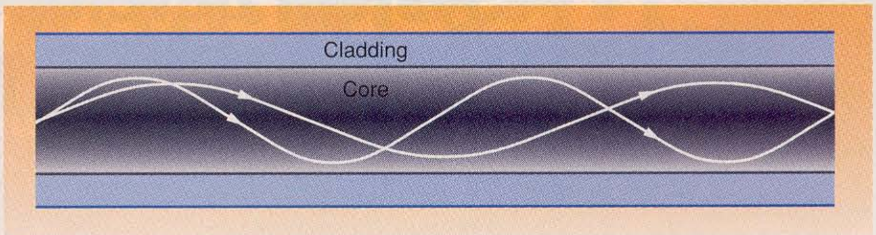

FIGURE 2. In a graded-index fiber, refraction by the lower-index glass away from the fiber axis bends light rays back toward the center of the fiber.

munication is modal dispersion, which arises because the fibers carry many modes that travel at different speeds. Modal dispersion limits transmission bandwidths of step-index multimode fibers to around 20 MHz/km, too low for anything but low-speed, short-distance communications.

Graded-index multimode fiber

Light guiding does not require a sharp change in refractive index at the core–cladding boundary. A graded decrease in refractive index with distance from the fiber axis also can guide light. Typically the index decreases from a peak value in the center of the core to the same value as the cladding. As light rays within the fiber's confinement angle move away from the fiber axis, they pass through layers of lower and lower index, and refraction bends them back toward the fiber axis (see Fig. 2).

Like step-index fibers, graded-index fibers carry many modes, so light rays follow different paths. However, as rays go farther from the fiber axis, they pass through lower-index material, which transmits light faster. Careful choice of refractive-index gradient balances the increase in distance traveled against the increased speed through lower-index material. This reduces modal dispersion enough that graded-index fibers with 50, 62.5-, and 85-µm cores can be used for communications over distances to a few kilometers.

These fibers can collect light from larger sources and over a larger range of angles than single-mode fibers, but they cannot match the performance of fibers transmitting a pure single mode. A crucial limitation comes from modal noise, which arises from random shifts in the relative phases of different modes transmitted by the fiber. This is the equivalent of the speckle pattern visible when laser light is projected onto a screen, but because the fiber core is small, it manifests itself as a change in signal intensity rather than a spatial pattern.

Single-mode fibers

The smaller the core diameter, the fewer modes a fiber transmits. Shrink the core enough, and it is limited to only a single mode. Single-mode waveguides avoid problems of modal dispersion and modal noise, making them ideal for high-performance communication systems.

Because a single-mode optical fiber is actually a dielectric waveguide, the simple ray model of total internal reflection does not accurately portray light transmission. The single mode actually extends a short distance into the cladding, which is measured as the "mode-field diameter" and is cited in fiber specifications. Typically the difference between mode-field diameter and core diameter is about 10% to 15% in step-index single-mode fiber, and typical mode-field diameters are 9.3 µm at 1.31 µm and 10.5 µm at 1.55 µm. Light transmission also extends slightly beyond the core-cladding boundary in multimode fibers, but this difference is small enough to be ignored.

Dispersion and single-mode fiber

Single-mode transmission does not completely eliminate the pulse dispersion that limits the speed of fiberoptic communication systems. Transmission of light over even a small range of wavelengths causes *chromatic dispersion*, which is measured in picoseconds of pulse spreading per kilometer of fiber length and nanometer of light-source spectral width. Controlling chromatic dispersion can greatly enhance fiber capacity.

Chromatic dispersion is the sum of

two components—*material dispersion* and *waveguide dispersion*. Material dispersion arises from the variation in the refractive index of glass with wavelength, which causes pulses to spread out as they travel along a fiber, with the fastest wavelengths leading. Waveguide dispersion arises from the dependence of waveguide properties on transmission wavelength.

The two dispersions can have different signs, so they can cancel each other out at certain wavelengths (see Fig. 3). This zero-dispersion wavelength is 1.31 µm in *standard* or *step-index single-mode,* fiber, the simplest type on the market, which has a sharp refractive-index step between a simple cylindrical core and the surrounding cladding.

Standard single-mode fiber is widely deployed, and many fiber systems transmit at 1.31 µm to take advantage of its low dispersion at that wavelength. However, the longer 1.55-µm transmission window offers two important advantages—it includes the minimum of fiber attenuation and is in the operating range of erbium-doped fiber amplifiers. In turn, these advantages make 1.55 µm the preferred window for high-performance systems and wavelength-division multiplexing (WDM) with up to dozens of channels in the erbium amplifier band.

Standard single-mode fiber is usable at 1.55 µm as long as the transmitter linewidth is extremely narrow. However, dispersion becomes a problem at high transmission speeds or in dense-WDM systems with closely spaced channels. Other types of single-mode fibers offer ways to reduce the effects of dispersion on high-performance systems.

Dispersion-shifted single-mode fiber

Material dispersion is inherent to silica, and little can be done to change it. However, novel core–cladding structures can alter waveguide dispersion and thereby change overall chromatic dispersion, which is what matters in a transmission system. *Dispersion shifting* uses this effect to shift the zero-dispersion wavelength.

In *zero-dispersion-shifted* fibers, the zero-dispersion wavelength is at 1.55 µm, to match the minimum absorption wavelength (see Fig. 4). These fibers have a dual-core structure with a central inner core surrounded by an inner cladding of pure silica—this, in turn, is surrounded by an outer core. This structure increases waveguide dispersion, as required to shift zero dispersion to longer wavelengths. Unfortunately, having the zero-dispersion wavelength in the middle of many wavelength channels increases the interchannel crosstalk caused by four-wave mixing, so zero-dispersion-shifted fibers are not desirable in WDM systems.

An alternative is to move the zero-dispersion wavelength outside the wavelength range of erbium-fiber amplifiers

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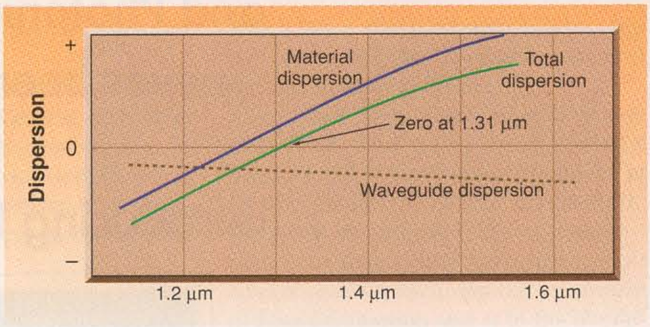


FIGURE 3. Waveguide dispersion offsets material dispersion to produce zero chromatic dispersion at 1.31 µm in standard step-index single-mode fiber.

in *non-zero-dispersion-shifted* fibers. This avoids four-wave mixing and requires only a modest change in fiber design.

Dispersion-compensating fiber

The principle of dispersion-tailoring can easily be extended to make *dispersion-compensating fibers*. These special-purpose fibers are designed to have chromatic dispersion equal in magnitude but opposite in sign to the chromatic dispersion of other fibers in the system. If chromatic dispersion is nearly canceled, performance of systems using standard single-mode fiber can be upgraded without the cost of installing new cable along the entire route. Typically, single-mode fiber systems are designed with high dispersion so that short lengths can compensate for longer lengths of standard fiber. For example, one kilometer of compensating fiber with dispersion of –85 ps/km-nm could offset the +17 ps/km-nm dispersion of 5 km of standard single-mode fiber. Although a complete new system could give higher performance, this approach can be much cheaper.

Special fibers for DWDM

The rapid growth of interest in dense WDM (DWDM) transmission at dozens of wavelengths has led to development of special fibers optimized for that application. Adding more wavelength channels inevitably increases the total power transmitted through the tiny core of a single-mode fiber. Where the power per channel also is high, near transmitters or optical amplifiers, the total power density in a small-core fiber could lead to nonlinear effects that degrade transmission. Complex core designs can lower the power density by expand-

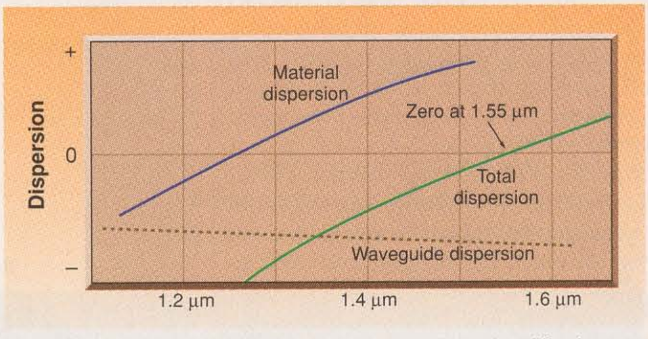
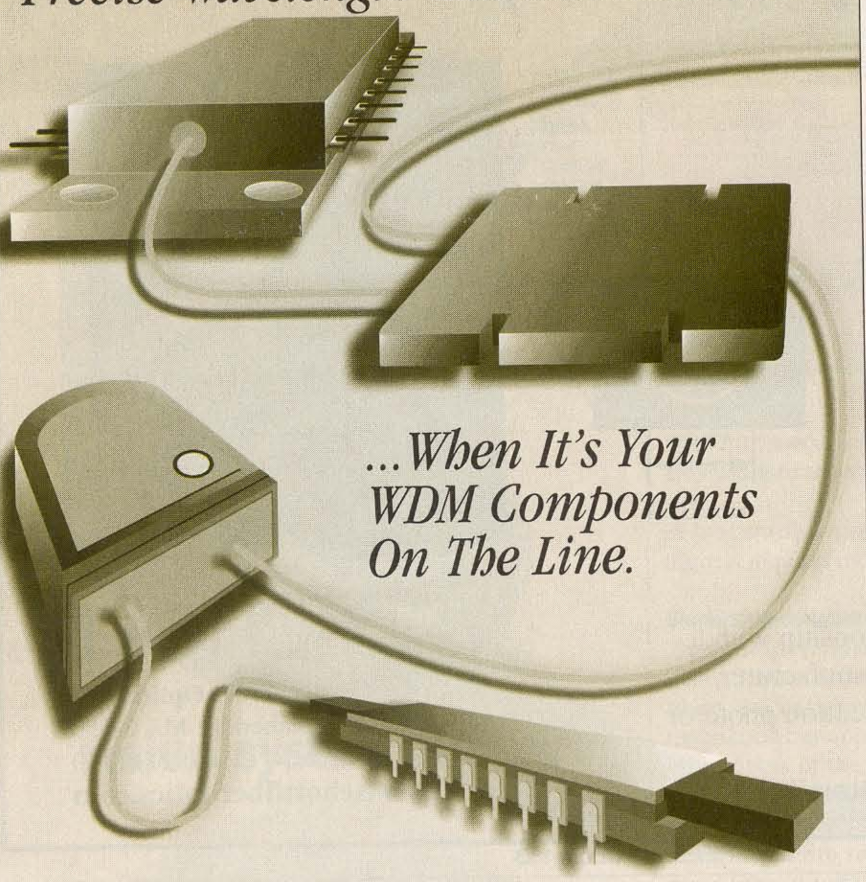


FIGURE 4. Increasing the magnitude of waveguide dispersion shifts the zero-dispersion wavelength to 1.55 µm.



ing the effective area of the single mode in *large-effective-area fibers*. For example, surrounding the core with a ring of high-index material can spread light over a larger volume in the fiber. Commercial versions have core areas more than 30% higher than non-zero-dispersion-shifted fibers; even larger cores have been reported in the laboratory.

Another concern is the variation in chromatic dispersion across the range of wavelengths in DWDM systems. The problem becomes more important the wider the range of wavelengths, and it could become serious with development of new fiber amplifiers operating in the long-wave band at 1565 to 1620 nm. This has led to development of *reduced-slope fibers*, non-zero-dispersion-shifted fibers in which the core is designed to reduce the variation in chromatic dispersion by about a third.

A final new type of fiber addresses an emerging concern—expanding transmission to cover the entire range from about 1280 to 1625 nm. This requires removing virtually all of the water, which normally causes absorption between about 1340 and 1440 nm. *Dry fibers* with low loss through the entire range are now available commercially. With optical amplifiers not readily available across most of that range, the main interest in these fibers is for "metro" systems operating over tens of kilometers or less, distances that do not require amplifiers.

All three of these new fiber types have been introduced within the past year, and their acceptance remains to be determined. Continuing refinements in fiber design are likely to meet the evolving needs of system developers. ❑

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

Next month, Back to Basics will discuss fiber materials.

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