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ADVANCES AND APPLICATIONS IN OPTOELECTRONICS

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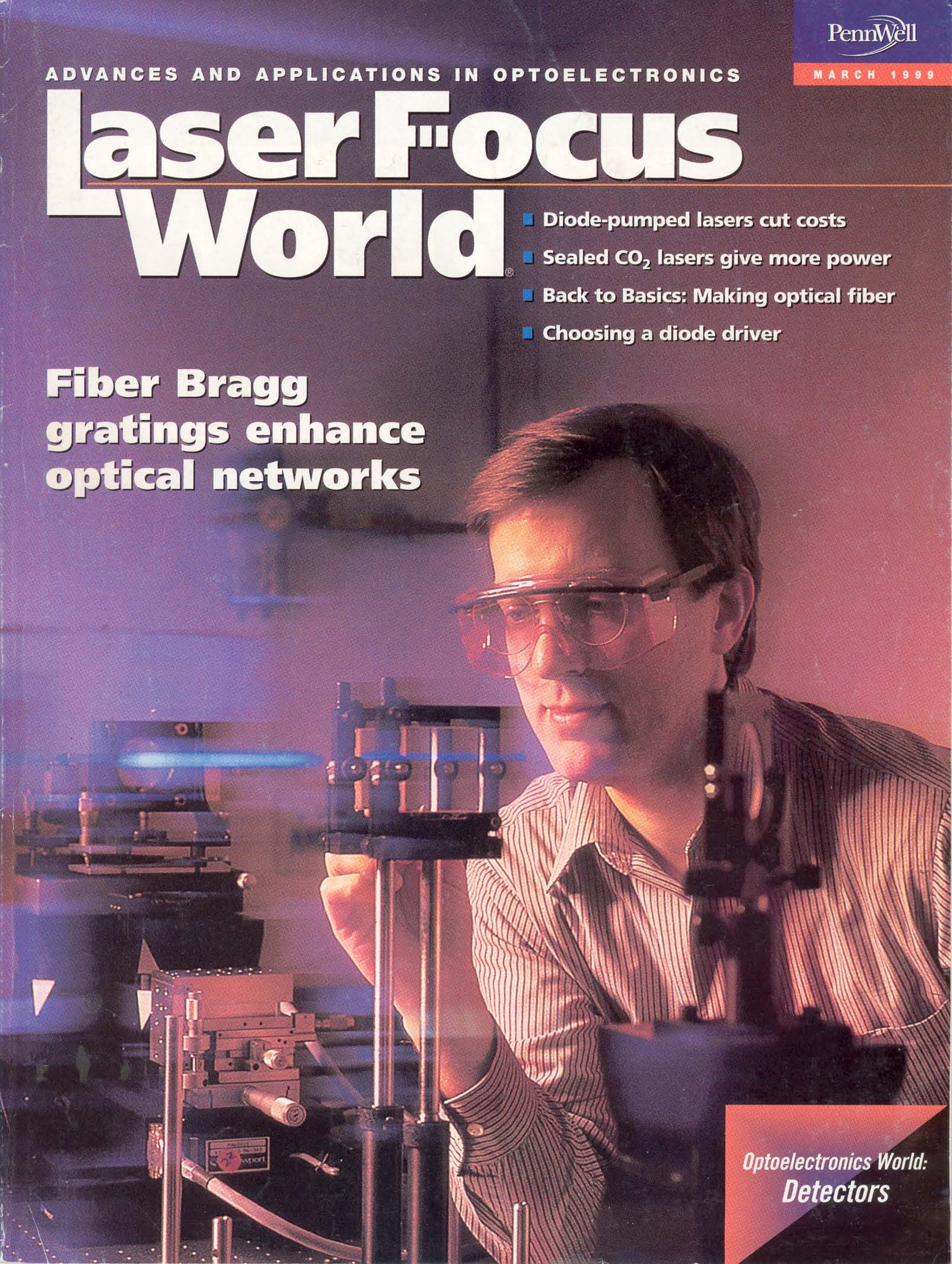


Optoelectronics World:
Detectors

The hard part is finding solid materials transparent at optical wavelengths that can be made into thin, uniform, durable fibers.

Meeting the manufacturing challenge of optical fiber

Jeff Hecht, Contributing Editor

The fundamental requirements for making optical fibers sound deceptively simple. All that is needed is a suitable transparent material capable of being drawn into thin, durable fibers, each with a uniform core/cladding structure along its length. However meeting these requirements is a challenge.

Few solids are transparent at optical wavelengths, and some, such as salt, sugar, and ice, fail the durability test. Over the years, silica-based glass and plastics have proven to be the best fiber materials, although only highly purified silica is suitable for low-loss communication fibers. These materials are most transparent at wavelengths between about 0.4 and 2 µm. Silica glass is clearest in the near-infrared, with communication windows at 1.3 and 1.55 µm. Plastic fibers are most transparent in the visible and cannot match the low loss of silica-glass fibers. Transmission at wavelengths longer than about 2 µm requires other materials.

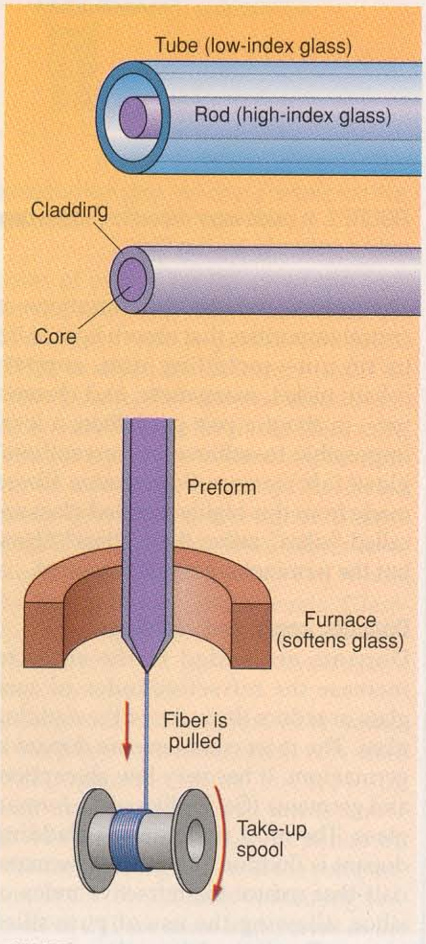


FIGURE 1. A low-index tube is collapsed onto a high-index rod to make a preform, which then is drawn into a clad fiber.

Making the transparent fibers thin and uniform is another problem. The usual approach is to heat one end of a cylinder, or *preform,* of suitable material until it softens, then draw the softened material into a thin filament. Glass is ideal, because thick, viscous molten glass quickly solidifies into a fiber as it is stretched in air. Some plastics also work well, but many materials melt to form thin, watery liquids that won't hold together to form thin filaments even when cooled below their melting point. Water is a good example.

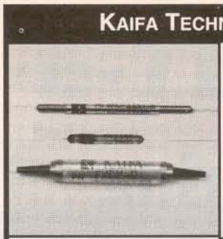
Defining glass

"Glass" is a familiar term with many meanings. From a materials-science standpoint, a glass is a noncrystalline solid with its atoms arranged randomly rather than in a crystalline lattice. A glass resembles a liquid with its atoms frozen in place. Many liquids do not form glasses because they always crystallize when cooled. Even compounds such as silica (SiO_2), which readily forms a glass, may crystallize when cooled slowly.

Most ordinary glasses are based on silica, with other materials added to modify their properties. Calcium oxide (CaO) and sodium oxide (Na_2O) reduce the melting temperature for window glass. Optical glasses contain other compounds to improve their optical uniformity and raise the refractive index above the low value of pure silica, which is 1.45 at 1.0 µm, to values as high as 1.8.

Fabrication of standard optical glasses inevitably leaves traces of impurities such as copper and iron, which absorb some visible light. This absorption raises the attenuation of fibers made from these glasses to about one decibel per meter, which is acceptable for noncommunication applications such as medical endoscopes, but not for communications. Preforms for high-loss step-index multimode fibers can be made simply by inserting a fire-polished rod of high-index core glass inside a tube of lower-index cladding glass and melting the tube so it collapses onto the rod (see Fig. 1).

Communication fibers are made differently. A process called *flame hydrolysis* burns silicon tetrachloride ($SiCl_4$) vapor in an oxy-hydrogen flame to yield extremely pure *fused silica.* Flame hydrolysis generates extremely pure material because the chlorides of troublesome impurities evaporate at temperatures far above the 58°C boiling point of $SiCl_4$ and thus remain in the liquid.



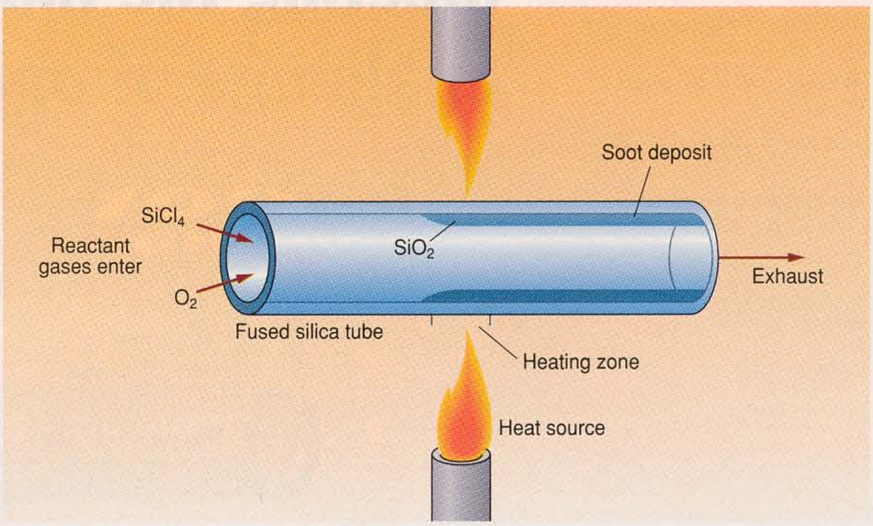


FIGURE 2. In inside vapor deposition, soot is deposited inside a fused silica tube, then collapsed to make a preform for low-loss fiber.

The process reduces concentrations of critical impurities that absorb light at 0.6 to 1.6 µm—including iron, copper, cobalt, nickel, manganese, and chromium—to about a part per billion, a level impossible to achieve in conventional glass fabrication. Sometimes fibers made from this highly purified glass are called "silica" rather than "glass" fibers, but the terminology is not consistent.

Dopants, cores, and claddings

Dopants are added to the silica to increase the refractive index of core glass or reduce the index of the cladding glass. The most common core dopant is germanium. It has very low absorption, and germania (GeO_2), like silica, forms a glass. The most widely used cladding dopant is fluorine, one of the few materials that reduce the refractive index of silica, allowing the use of pure-silica cores. Doping either the core or cladding can make a step-index fiber, as can cladding a pure-silica core with a lower-index plastic. Another variation is the *depressed-clad* fiber, in which the inner part of the cladding is doped with fluorine to reduce its refractive index so the core need not be doped as heavily.

Many communication fibers have more-complex refractive-index profiles. In simple graded-index multimode fibers, glass composition changes gradually from the core to the cladding to provide the desired refractive-index gradient. Single-mode dispersion-shifted fibers typically have four layers—a core, inner cladding, outer core, and outer cladding—and glass compositions often grade from one layer into the other.

Silica preform manufacture

The crucial common feature in silica preforms for low-loss fibers is the formation of fluffy fused-silica "soot" by reacting $SiCl_4$ (and $GeCl_4$ when it is used as a dopant) with oxygen to generate a fine soot of SiO_2 (which includes GeO_2 if the silica is doped). Heating melts the soot, condensing it into a glass preform. The crucial variations are in how the soot is deposited and melted into the final preform.

One approach is to deposit the soot on the inside wall of a fused-silica tube (see Fig. 2). The tube serves as the outer cladding, onto which an inner cladding layer and the core material are deposited. Moving the reaction zone along the tube deposits soot along its length. Variations on the approach are inside vapor deposition, modified chemical-vapor deposition, plasma chemical-vapor deposition, and plasma-enhanced chemical-vapor deposition.

In general, the inner glass is deposited as a series of thin layers. When making graded-index fibers, the doping of input gases can be changed slightly for each deposition step, to produce the desired refractive-index profile. The process also can produce step-index or complex-core fibers. When deposition is completed, a final heating step collapses the tube into a preform.

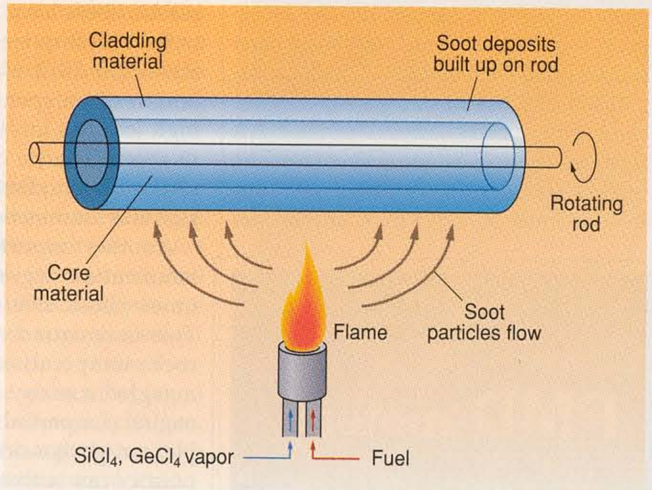


FIGURE 3. Outside vapor deposition lays glass soot onto a ceramic rod that is removed when sintering the preform.

Another important approach is *outside vapor deposition*, which deposits soot on the outside of a rotating ceramic rod (see Fig. 3). The process first deposits core glass, then the cladding layers. The thermal expansion coefficient of the ceramic substrate differs from that of the glass, so it slips out easily when the finished assembly is heated to form a preform. A central hole typically remains in the preform but disappears as fiber is drawn.

The third main approach, *vapor axial deposition*, deposits glass soot onto a rod of pure silica (see Fig. 4). The rod serves as a "seed," with soot deposited on its end becoming the core and soot deposited radially outward becoming the cladding. Nothing must be removed from the center, so vapor axial deposition leaves no central hole.

Finished preforms are mounted vertically in a *draw tower*, where a furnace heats the bottom. Then hot, soft glass is pulled from the bottom, solidifying almost instantly into a fiber as it is exposed to the air. The manufacturer monitors fiber diameter, applies a protective plastic coating, and winds it onto a spool.

Large-core silica fibers

Silica fibers made for laser power transmission are made differently, with large cores of pure silica (to avoid the need for dopants) and only a thin cladding. The oldest type is plastic-clad silica (PCS), in which the cladding is a soft silicone plastic. The silicone cladding is fairly easy to strip from the silica core, which is a problem in some applications but an advantage in others. Hard-clad silica fibers have a tougher plastic cladding. Glass-clad silica fibers have doped-silica claddings; they can handle the highest laser power levels. Glass-clad fibers can have graded-index profiles; plastic-clad versions always have step-index profiles.

Large-core silica fibers have somewhat higher attenuation levels than communication fibers, but typically their attenuation at 0.82 µm is under 20 dB/km. Attenuation depends on both the cladding type and the composition of the core. Fibers containing low levels of OH are more transparent in the near-infrared, but those with high OH levels are more transparent in the ultraviolet. Fibers with thicker cores can han-

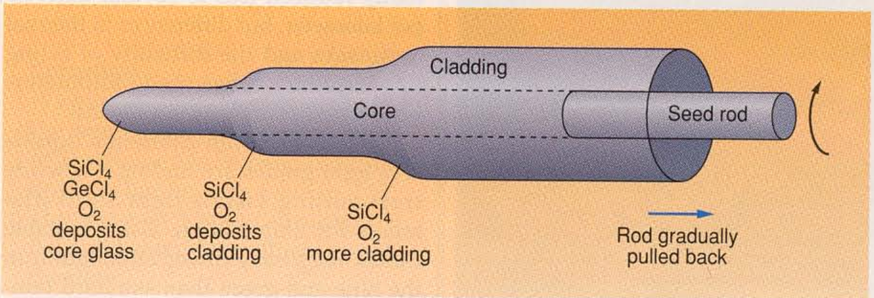


FIGURE 4. Vapor axial deposition grows a fiber preform on the end of a seed rod of fused silica.

dle higher laser powers. For example, rated continuous-wave power capacity in one family of fibers increases from 0.2 kW for 200-µm-core fibers to 1.5 kW for 550-µm-core fibers.

Plastic fibers

Plastic optical fibers are light, inexpensive, flexible, and easy to handle. However, these advantages have long been outweighed—especially for communications—by attenuation much higher than that of silica. Years of research have reduced plastic loss considerably, but the best laboratory fibers still have loss around 50 dB/km. Commercial plastic fibers have loss as low as 70 dB in the visible range, but loss increases to about 150 dB/km at the 650-nm wavelength of inexpensive red LEDs. This high loss has limited their applications to short-distance communications and to flexible bundles for image transmission and illumination.

Another important concern is high-temperature degradation that typically limits plastic fibers to use below 85°C. This may sound safely above normal room temperature, but it leaves little margin in many environments. The engine compartment of cars, for example, can get considerably hotter. Newer plastics can withstand temperatures to 125°C, but their attenuation is higher.

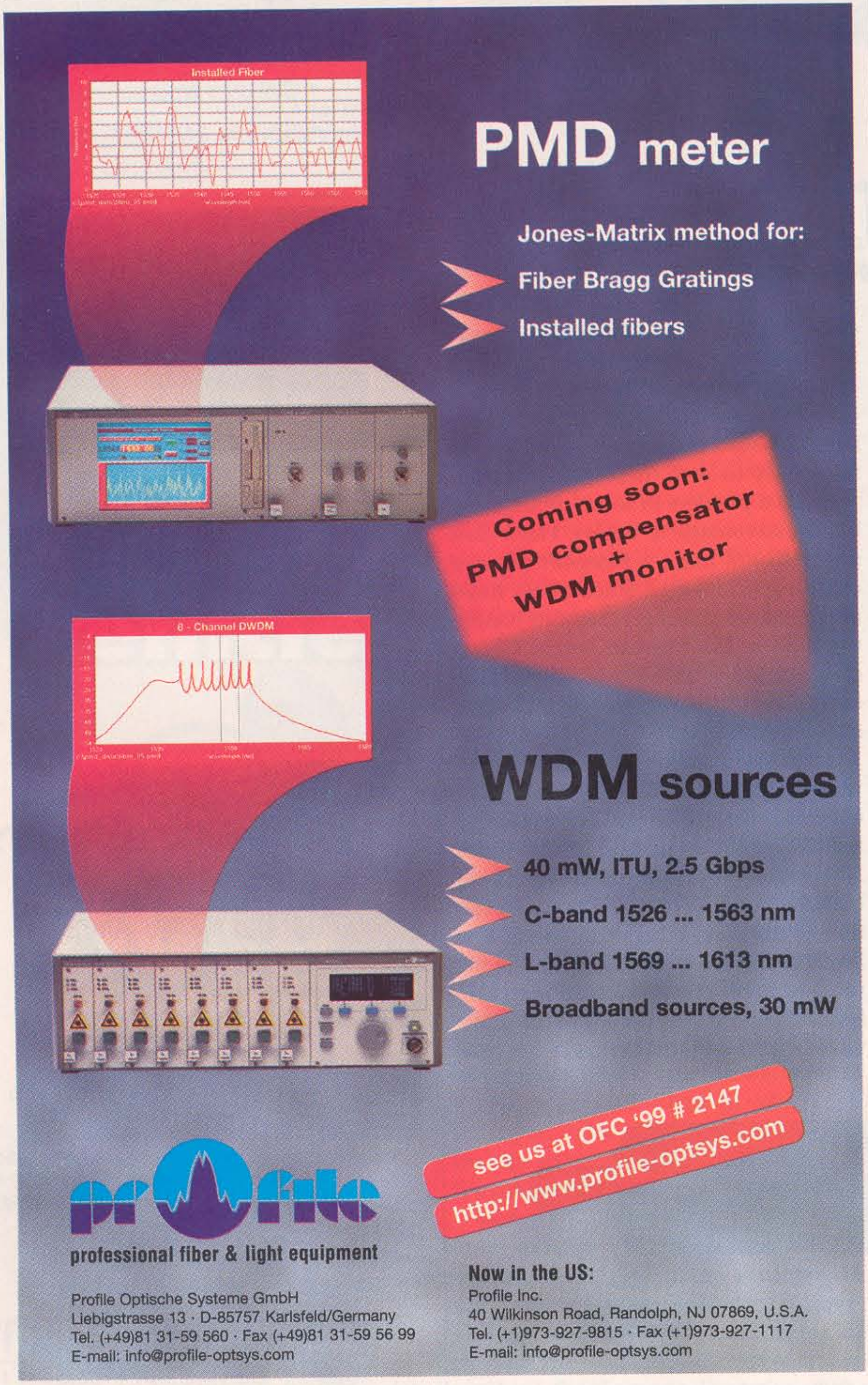
Standard step-index plastic fibers have a core of polymethyl methacrylate (PMMA) and a cladding of a lower-index polymer, which usually contains fluorine. The core–cladding index difference is larger than in glass fibers, so their numerical aperture is larger. Typical core diameters range upwards from 85 µm to more than 3 mm. Thicker light-guiding rods made of flexible plastic sometimes are called fibers, but it's hard to think of something as thick as a pencil as a "fiber."

Graded-index fibers with losses below 50 dB/km have been made in the laboratory by heat treating to diffuse high-index materials from a fluorinated plastic preform core into the lower-index cladding material. The preform then is drawn into a fiber, as with glass fibers.

Liquid-core fibers

In the early days of fiberoptic communication, developers desperate for low-loss fibers filled thin silica tubes with tetrachloroethylene, an extremely transparent dry-cleaning fluid with a refractive index higher than silica. They eventually reduced loss to several decibels per kilometer, but differences in thermal expansion and the difficulty of filling tiny capillary tubes made kilometer-scale liquid-core fibers impractical.

Now 2- to 8-mm-diameter liquid-core light guides are finding a new life transmitting visible light short distances for illumination. Using suitable fluids, they have lower attenuation in the blue and green than standard bundled fibers. Use of plastic tubes makes



the liquid waveguide flexible, and use of modest lengths—typically only a few meters—avoids problems with thermal expansion.

Mid-infrared fibers

Because scattering losses drop with the inverse fourth power of wavelength ($1/\lambda^4$), communications researchers made a major search for mid-infrared fiber materials in the 1980s. Silica absorption rises rapidly at wavelengths longer than 1.6 µm, so materials researchers investigated nonoxide glasses, hoping to achieve losses well below 0.1 dB/km. They encountered serious problems both in purifying infrared-transparent materials and in drawing strong, durable fibers from them. However, mid-infrared fibers meet the requirements of specialized applications such as infrared instrumentation or fiber amplifiers

Fluorozirconate fibers transmit light between 0.4 and 5 µm. They are made primarily of zirconium fluoride (ZrF_4) and barium fluoride (BaF_2), with some other components added to form a glass. The lowest losses for commercial fluorozirconate fibers are about 25 dB/km at 2.6 µm, but loss as low as about 1 dB/km has been reported in the laboratory.

Fibers made from sulfur and selenium compounds, called chalcogenide glasses, transmit at 3.3 to 11 µm, but their overall loss is much higher. Attenuation is greater than 1 dB/m for most of their range, with a minimum of 0.7 dB/m at 5.5 µm. The compounds resist water but are attacked by strong bases. ❑

Next month, Back to Basics will discuss special-purpose fibers.

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

Correction

We inadvertently ran the photo of the water jet at the Royal Institute of Technology in Stockholm upside down in our January issue (p. 143). The water jet is not in an antigravity field and should be falling toward the floor.