Perfect Mirrors Extend Hollow-Core Fiber Applications

Low-loss waveguides based on omnidirectional mirrors can transport light of almost any wavelength. One potential use is fiber optic beam delivery of CO_2 laser light.

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Photonic bandgap fibers have been the subject of active research for several years. One result reaching commercialization is omniguide fiber, a low-loss waveguide that can transport light of almost any wavelength. The fundamental breakthrough enabling development of these fibers is the omnidirectional mirror, which combines the advantages of metallic and dielectric mirrors.

Metallic mirrors reflect light for a wide range of wavelengths and for any angle of incidence, but always absorb some of the incident light. Dielectric mirrors consist of one or more interfaces of high- and low-index materials, and they reflect light with very little absorption. However, a mirror's reflectivity depends on the wavelength, and at any given wavelength, its performance varies with angle of radiation incidence.

In 1998, researchers at Massachusetts Institute of Technology in Cambridge reported developing a "perfect," or omnidirectional, mirror (Figure 1). By creating a dielectric mirror from materials with sufficiently different indices of refraction, they open up a full photonic bandgap.[1] This gives dielectric mirrors omnidirectional reflectivity (efficient reflection for all angles of incidence) for a wide band of wavelengths with very low absorption.

By folding an omnidirectional mirror into a "pipe" that surrounds a hollow core, engineers at OmniGuide Communications Inc. (OGCI) produced a hollow-core fiber with properties that could open up applications such as fiber optic beam delivery of CO_2 laser light (Figure 2). The high reflectivity of the mirror enables the fiber to guide light almost exclusively in its hollow core.

The confinement mechanism in the new fiber design is similar to that of photonic crystal fibers, which rely on a two-dimensional crystal to confine light to a hollow core. One way to think of omniguide fiber is as a one-dimensional photonic crystal fiber. Note that, in both fiber designs, the light is guided in the low-index medium (the hollow core). Conventional silica fibers, however, exploit total internal reflection, with light guided in a high-index core surrounded by a low-index cladding.

Omnidirectional waveguides

In conventional fiber, transmission losses are limited by the bulk losses of the core material. The 1-D photonic bandgap fiber has a hollow core, where 99.9 percent of the light is localized because of the highly effective mirrors. The resulting transmission losses are dramatically lower than the losses of its constituent materials. Recent data show losses of 0.65 dB/m for such fiber, when made of a material with losses of 30,000 dB/m. Thus, its structure suppresses the losses of constituent materials by a factor of more than 45,000.

The range of wavelengths confined by such fiber depends on the range of wavelengths reflected by the omnidirectional mirror surrounding the hollow core. This range can be adjusted by varying mirror layer thickness. Thinner layers confine shorter wavelengths and vice versa. Moreover, because of the hollow core, transmission losses are only weakly sensitive to the wavelength-dependent absorption of the mirror materials. In

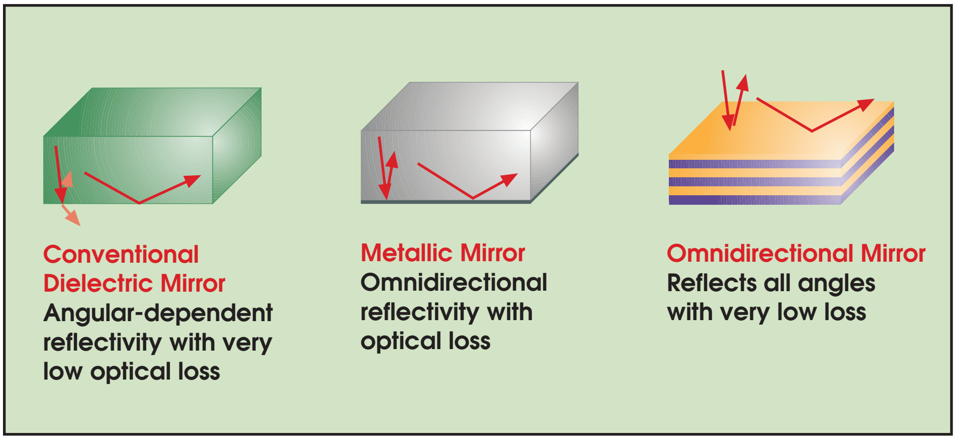

Figure 1. *Using omnidirectional mirror technology developed at MIT, dielectric mirrors can now provide efficient reflectivity for all angles of incidence for a wide band of wavelengths with very low absorption.*

contrast, silica fiber, which has very low material absorption at wavelengths below 2000 nm, is not able to to transmit at longer wavelengths because of the increase in material absorption with wavelength.

Tailoring different structural parameters allows creating a variety of promising product designs based on the 1-D photonic bandgap fiber technology. For instance, including one significantly thicker layer in the mirror achieves dispersion parameters that are 1000 times larger than those of current dispersion-compensating fibers used in telecommunication systems.

Also, by filling the hollow core with material that is optically highly nonlinear and by shrinking the core size, the resulting fiber will have nonlinear coefficients several orders of magnitude larger than those of silica fibers, which may enable all-optical signal processing.

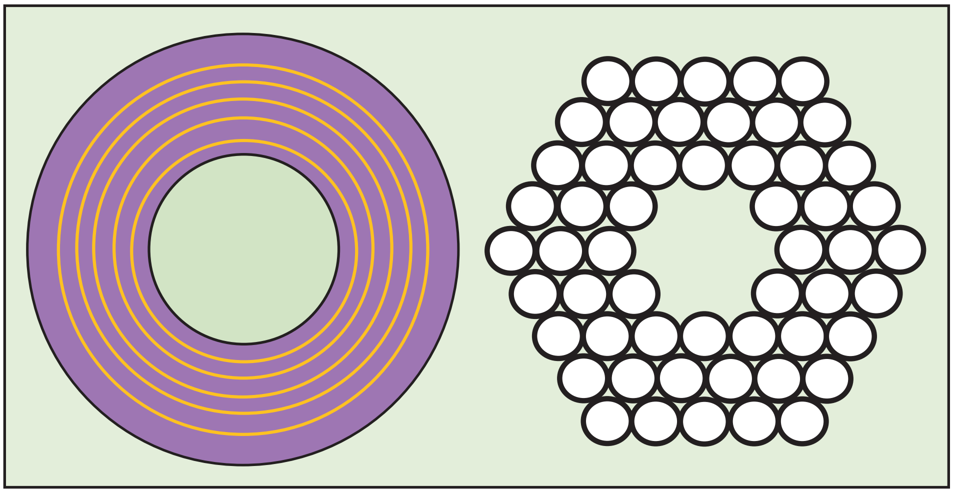

Figure 2. *Hollow-core fiber based on perfect mirror technology could be thought of as 1-D photonic crystal fiber.*

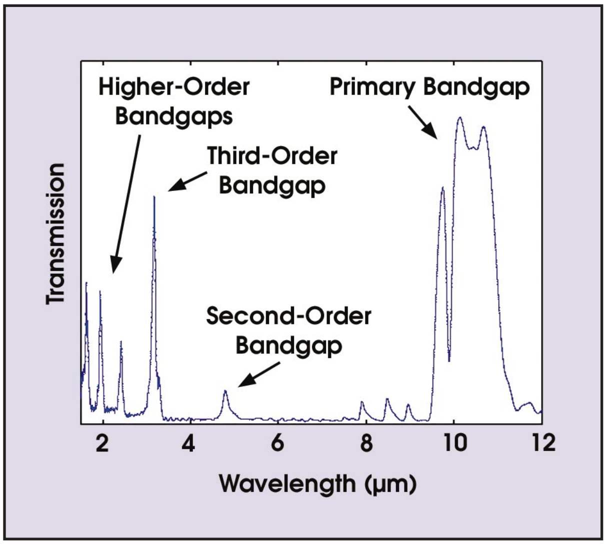

Figure 3. *The omniguide fiber exhibits its best transmission characteristics in the region of the primary bandgap at 10.6 µm. In addition, it transmits other wavelengths in the higher-order bandgap. By scaling the structure properly, engineers can position the primary bandgap anywhere in the IR range.*

Manufacturing

In most cases, fiber manufacturing is a two-step process. First, a large preform is produced, with the same structure as the final fiber, but on a larger scale. Next, this preform is put into a drawing tower, where it is heated and drawn into a fiber. A preform several inches thick and several feet long yields a fiber less than 1 mm thick and several kilometers long while preserving its proportions.

Cost-effectiveness makes this process attractive. The fiber draw process facilitates both automation and long fiber lengths. The critical element in fiber manufacturing is, therefore, production of a drawable preform.

OGCI produces its fiber preforms by evaporating a chalcogenide glass (As_2Se_3) onto a polymer (polyethersulfone) sheet, wrapping the film around a glass mandrel and consolidating the layers under heat. The glass mandrel is etched out, and the resulting preform is ready to be drawn. Engineers chose these materials for the large contrast in refractive index (~2.7 for As_2Se_3 and ~1.7 for polyethersulfone) and for their ability to be drawn into fibers together because they have compatible thermomechanical properties.

An alternative preform manufacturing process involves chemical vapor deposition, where the preform is built up by successively depositing layers of high- and low-refractive-index material from chemical vapor. This is the dominant approach to preform manufacturing for silica fibers.

The ability to employ established manufacturing techniques is thus a key benefit of omniguide technology. Alternative photonic crystal fiber technologies usually use more exotic manufacturing techniques. For example, the production of hollow-core photonic crystal fibers requires preforms with several hundred holes of precisely controlled location and diameters. This means manual assembly of hundreds of individual silica fiber strands. Other technologies that have been proposed for guiding in the far-IR (such as sapphire or metal-coated hollow fibers) require intricate postprocessing of the drawn fiber, rendering them poorly suited for production in long lengths or large volumes.

Potential applications

The manufacturability of the 1-D photonic bandgap fiber enables a rapid transition from a laboratory demonstration to the marketplace. Potential applications can be found at any IR wavelength of commercial

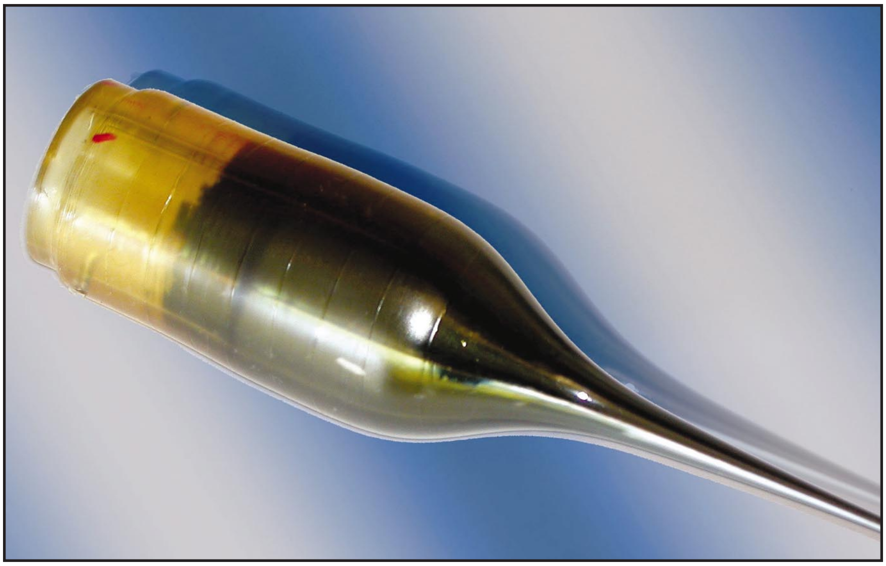

Figure 4. *A fiber preform as it is drawn into a fiber.*

interest. At wavelengths longer than 2000 nm, technical limitations have prevented existing fiber solutions from generating a significant market, despite being available for more than a decade. Those applications include:

Medical. Doctors use lasers of almost any wavelength for a variety of procedures, including ophthalmology, surgery, dermatology, dentistry and veterinary medicine. For surgical applications in particular, the laser light must be delivered from a stationary laser source in the operating room to the surgeon's hand. Fibers add a degree of flexibility by simplifying beam handling in traditional surgery, as well as facilitating endoscopic beam delivery. However, for some of the most useful medical lasers — Er:YAG and CO_2, for example — wavelength precludes the use of the established silica fiber technology, so 1-D photonic bandgap fibers could be an alternative.

Sensing. These fibers also could facilitate remote, noncontact sensing at mid-IR wavelengths in applications such as spectroscopy and thermal sensing.

Telecommunications. While still the best available technology for telecom, silica fibers are not loss-free. Also, the nonlinear transmission properties and polarization mode dispersion inherent in any solid-core fiber distort signals on long transmission lines. Cost benefits from the use of hollow-core fiber technology could arise by eliminating some of the need to amplify signals every 50 to 100 km and periodically regenerate them. The advantages could be particularly compelling in submarine networks.

Industrial applications. The highest value segment for laser-based industrial materials processing is that for lasers generating at least 1 kW of optical power. The main application is metal processing — both cutting and welding — in a variety of industries, including automotive and shipbuilding.

Fiber beam delivery

The predominant laser technologies in this market are the CO_2 and Nd:YAG. The former have been reliable low-cost sources for high-power laser systems for many years, but Nd:YAG lasers, which still are about twice as expensive as CO_2 lasers at any given power level, have made inroads in the market, largely because of their capability for fiber optic beam delivery (silica fibers transmit well at 1064 nm). This flexibility means that engineers can mount a fiber guiding an Nd:YAG laser beam on a robot, which can then be integrated into a highly automated steel welding system in an automotive plant.

For CO_2 lasers, there is no similar fiber solution available. Therefore, conventional systems still require hard-optic beam delivery systems, either built into gantry robots or by means of an articulated arm. These solutions are expensive, bulky and prone to frequent repair and maintenance. Fiber optic CO_2 beam delivery could decrease the cost of these machines by simplifying the system design.

Marking and engraving. Most low-power lasers in industrial manufacturing are used for marking and engraving. Marking systems apply product identification, "sell by" dates, charge numbers and similar information on product packages in high-speed, highly automated production lines. The main users of these systems are the pharmaceutical and the food and beverage industries. Engraving systems are used to create appreciation plaques, awards or

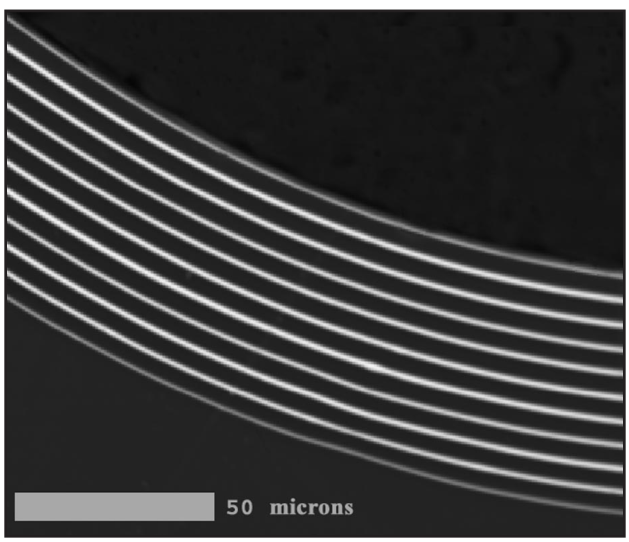

Figure 5. *In this electron microscope image of part of a fiber cross section, white lines represent the high-index material. The periodic layer structure provides robust confinement of the power in the fiber's hollow core.*

signs, which typically require low numbers of units, slower processing speed and highly customized designs.

Here, the choice of laser depends on the material to be processed. CO_2 lasers are used for most soft materials such as cloth, paper or wood, and for glass and most plastics, but not for marking or engraving of most metals. Fiber optic beam delivery also has potential productivity benefits in this area.

Fiber for CO_2 lasers

Recently published research results indicate that 1-D photonic bandgap fibers are viable at CO_2 laser wavelengths and suitable for large-volume production.[2] OGCI, which has obtained an exclusive license from MIT for this technology, is drawing long lengths of fiber on a daily basis. The fibers for guiding CO_2 lasers, which exhibit losses below 0.65 dB/m, can carry 10 W of optical power without cooling. Such performance gives the fiber sufficient power-handling capacity to penetrate segments of the medical and marking markets. The company is in the process of making its first product commercially available.

Work continues to extend fiber delivery to higher power levels. Simulations show that the technology has the potential to deliver multiple kilowatts of CO_2 laser power through thin fibers, while maintaining high beam quality. Such results can be accomplished by means of an improved manufacturing process and introduction of active cooling. Such capability has the potential to revolutionize metal processing in industrial settings. □

Meet the authors

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