

# BACK TO THE FUTURE? GUIDING LIGHT THROUGH AIR

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The concept of channeling light through hollow-core fibers is not a new one — even before Corning’s invention of the first viable, solid-glass telecommunications fiber in 1970, researchers were experimenting with this approach. But these hollow-core waveguides could not compete with the performance seen in their all-glass counterparts, even in the earliest days of commercial fiber-optic development, and these “air fibers” were, in large part, shelved as an area of telecommunications research.

But a quarter of a century later, researchers have turned their attention once again to hollow fibers, sometimes also called “holey fibers,” as a potential telecommunications medium. The allure of atmospheric transmission is powerful: the basic properties of air promise lower attenuation (signal loss) and less non-linearity (signal distortion) compared with transmission through solid media. Of course, in addition to their undeniable potential, air-cored fibers bring their own challenges, which are being addressed in research today. As yet, even the most advanced experimental prototypes remain well behind their glass-cored counterparts in performance, making the latter fiber the technology of choice for communications networks today and for the foreseeable future.

But it is clear that a fiber that combines the advantages of air with the other performance attributes important to conventional fibers — among them bending, splicing and handleability — would be a revolutionary breakthrough in communications technology.

## Reflection, Diffraction, Air and Solids

While hollow-core fibers are often referred to as photonic bandgap fibers (PBGFs), the two concepts are not mutually inclusive.

Hollow-core fibers are just as they sound: fibers that propagate light through air, through a hole or holes within the fiber. This mechanism for propagation can be similar to that of conventional glass-core fibers, via reflection: in basic terms, the light is moved through the core of the fiber — whether glass or air — by bouncing, or reflecting, against the cladding (Figure 1). However, air has a much lower refractive index than a silica cladding. Thus, unlike the case of conventional fiber, in which the higher refractive index of the core leads to complete or total internal reflection, light in hollow-core fibers is typically reflected only partially by the cladding, and thus suffers high losses upon propagation along the fiber.

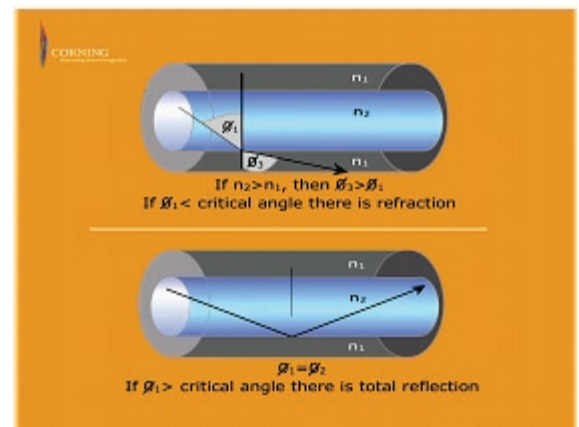


FIGURE 1: Refraction versus reflection, demonstrated within a conventional fiber.

However, the propagation of light via a hollow-core fiber can also occur through diffraction. And that brings us to the concept of photonic bandgap.

Diffraction is, according to Webster's Dictionary, the "deflection and decomposition of light in passing by the edges of opaque bodies or through narrow slits, causing the appearance of parallel bands or fringes of prismatic colors, as by the action of a grating of fine lines or bars." More simply put, light deflects and produces fringes of light and dark bands. The lighter bands can appear to look like "gaps" between the dark bands, thus "photonic bandgap." Like reflection, the phenomenon of diffraction can occur either through air or within solids.

So while photonic bandgap fibers, which use diffraction to propagate light via air or through a solid, are not synonymous with hollow-core fibers, which use either reflection or diffraction to propagate light through air, the two are often used interchangeably. This is primarily because the most promising research in hollow-core fibers is those fibers that use a photonic bandgap structure.

## Imitation: The Sincerest Form of Flattery

While there are numerous patents filed regarding photonic bandgap technology (a basic search on the term at the U.S. Patent and Trademark Office returned more than 500 results), it must be noted that Mother Nature has first claim. Earth, according to one 2003 *Nature* magazine article, has been creating complex photonic bandgap structures since the start of the Cambrian period more than 500 million years ago, to attract mates, frighten prey or enhance sight.

A marine creature called the sea mouse (genus *Aphrodite*), a rather close cousin of the common earthworm, is covered with fine, fur-like hairs; the hairs themselves are lattice-like structures that create a photonic bandgap effect, diffracting light so that the hairs appear an iridescent blue-green.

Some butterflies also have shimmering wings — sometimes shockingly so — created by a complex layering of scales and air that diffracts light. Depending on how these naturally occurring photonic bandgap structures are organized, a butterfly's wing might flash brilliantly blue only when still, or only when moving, or perhaps even appear differently colored depending on the angle at which the insect is being viewed (Figure 2).

The lesson here is that photonic bandgap structures allow for a virtually limitless variety of designs, each of which will dramatically affect the outcome: which wavelengths of light are absorbed and which are propagated.

This has obvious practical applications for optical communications, and has been the focus of much of the latest hollow-core fiber research. Photonic bandgap fibers can be designed for diverse purposes. A photonic bandgap fiber could be developed to diffract and propagate light at a specific wavelength or across several wavelengths, or to create high or low dispersion at certain wavelengths. As in nature, the diversity of photonic bandgap structures in fiber could be limitless.



**FIGURE 2:** The iridescence of the wings in some species of butterflies is caused by a complex layering of air with tiny reflective and non-reflective scales, a naturally occurring photonic bandgap structure. At left is a photograph (not an illustration) of a male *Morpho rhetenor*, with its brilliant blue iridescent wings. The second photograph is a close-up of both reflecting and non-reflecting scales on the wing of a *Morpho rhetenor*; the reflecting scales are the finer structures on the right. Information and photograph courtesy of [Butterflies: On the Wings of Freedom](#).

# Photonic Bandgap and Photonic Crystal Fibers

Photonic bandgap fibers (PBGFs) typically consist of air channels embedded in silica glass, though it should be noted that, as stated previously, this photonic bandgap effect can be created within solids. PBGFs are also sometimes called photonic crystal fibers (PCFs) because the periodic arrangement of air holes, or voids, within the fiber appear crystalline to the photons propagating in the material. Of course, this is not always true of all PBGF profiles, and photonic crystal fibers can use internal reflection to guide light through air rather than diffraction, as mentioned earlier. For the purposes of this article, PBGF will be used to describe hollow-core fibers that use diffraction to guide light, while PCF will be used to describe solid-core fibers with “holey” claddings that guide via reflection.

Photonic Crystal/Bandgap Fibers: Geometries

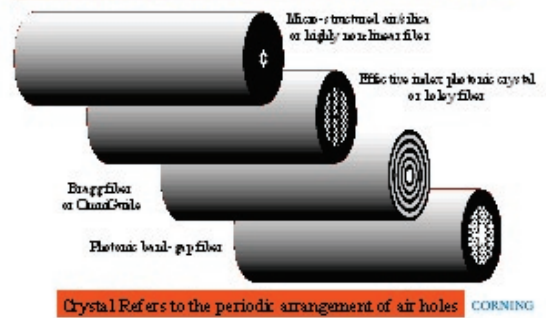


FIGURE 3: Photonic crystal/bandgap fiber geometry types.

PBGFs and PCFs currently being researched have widely varying geometries, their one commonality being the voids in the cladding structure. The examples in Figure 3 are just a sampling of the possibilities. The Bragg fiber is the notable exception to the “crystal” air hole placement of the others, as it is actually a photonic bandgap structure created through a thin-film stack rolled into a hollow tube of fiber. (Thin films are designed to modify light propagation, such as by reducing reflection or blocking certain wavelengths.)

There are a number of ways to develop these complex honeycomb-like structures, including an extrusion of silica glass powder, non-oxide glasses and polymers. The most common method, however, is the “stack and draw” approach, in which capillaries are bundled to create the fiber preform in the desired photonic bandgap formation. The optical fiber is then drawn and coated similarly to conventional glass-core fibers.

Why silica? Silica, the basis of conventional glass fiber manufacturing, is a mature and truly trusted fiber material, preferred for its intrinsically low loss in optical transmission and offering a moderately high index contrast. Silica also allows for “single material processing” (the fiber becomes a structure formed entirely of silica and air), simplifying overall design and manufacturing complexity and, like conventional fibers, can be used to create both single-mode and multimode fibers.

## The Possibilities: From Endlessly Single-Mode to High-Power

An intriguing property that helped ignite the fledgling field of photonic crystal fibers was the endlessly single-mode effect observed in solid-core PCFs. Unlike conventional fibers, which become multimode below a certain cutoff wavelength, PCFs can be designed to always support only a single-mode. While in practice this effect is limited by bend loss, its application potential includes coarse wavelength-division multiplexing (CWDM), high-power transmission and single-polarization fibers. These solid-core PCF fibers can exhibit a host of other extreme properties, including very high birefringence, extremely small core sizes and very high dispersion.

However, more interesting than the PCFs are the PBGFs, whose promise is tantalizing, if still early in the development stage. First, air has intrinsically lower attenuation, scattering and non-linearity compared with virtually any solid material, attributes that are obviously important to telecommunication fiber optics.

Second, the dispersion control possibilities of hollow-core PBGFs are promising. In single-mode fibers, dispersion — or pulse broadening — is primarily due to a combination of material dispersion, contributed by the composition of the core itself, and waveguide dispersion, contributed by the design of the fiber’s profile. Conventional glass-core fibers have a moderate amount of design elasticity to create specific dispersion profiles, and a fairly limited impact on material dispersion, primarily via dopants. Hollow-core PBGFs can combine the

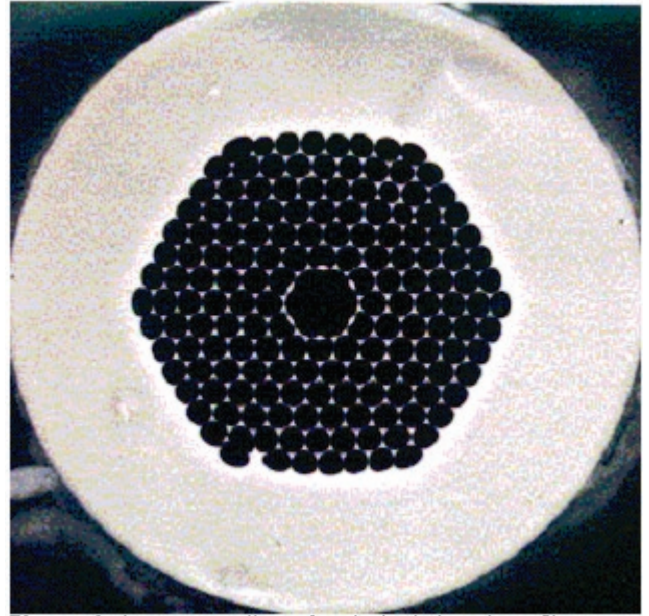
virtually limitless design possibilities of photonic bandgap structures with the inherent low material dispersion of air (orders of magnitude lower than any solid material), creating the potential for fibers with highly controllable dispersion.

Clearly, a fiber with ultra low attenuation, low non-linearity and almost limitless dispersion flexibility is the “holy grail” of transmission fibers and, like the “holy grail,” an as-yet-undiscovered find. However, the first applications of these hollow-core PBGFs are likely to come in the form of specialty optical fibers that will take advantage of the low non-linearity of PBGFs to guide high power pulses at a variety of wavelengths. In a collaboration with Cornell University, Corning’s PBGF was used to demonstrate a 100X increase in the power delivery of femtosecond pulses in optical fiber. (A link to the full story, as reported in the September 2003 issue of *Science* magazine, can be found at the end of this article.)

Corning research in photonic crystal fibers has lately focused on the type of silica-based PBGF fiber seen in Figure 4. This design employs a truly two-dimensional photonic crystal structure made up of air columns that run the length of the fiber. This design has several advantages: the 10-micron core can provide single-mode operation and compatibility with conventional optical fibers, while the silica allows for single material fabrication and low material losses.

This fiber type recently achieved 13 dB/km attenuation in Corning tests, light years ahead of most laboratories’ work and recognized with a publication in the prestigious journal *Nature*. Clearly, this is not performance on par with today’s conventional optical fibers. A typical standard single-mode fiber might have attenuation of about .35 dB/km at 1310 nm, for example. And PBGF research prototypes are still demonstrating limitations in polarization properties and modal properties, and they are not being produced in lengths or quantities that make them viable for telecommunications today.

But considering that more than 30 years ago, Corning scientists were the first to achieve a “low-loss” attenuation of about 17 dB/km with a glass-core fiber (the attenuation of the incumbent copper technologies of the time), it is an exciting step for a potential “game changer” in fiber-optic technology.



**FIGURE 4:** A cross-section of a photonic bandgap fiber, stacked and drawn at Corning’s state-of-the-art research facility, Sullivan Park. Note the central air core and air/silica honeycomb-like photonic bandgap structure, surrounded by cladding.