

Photonic-crystal fibers have many uses

Advances in photonic-crystal-fiber technology promise to yield not only better ways to guide light, but more-efficient fiber lasers as well.

With a highly structured cross section of glass and air spaces, photonic-crystal fibers (PCFs), also called microstructured fibers, are the ultimate specialty fiber. Although PCFs have only recently become commercially available, many types are already available to support a rapidly growing range of applications.

PCF operation

A photonic bandgap (PBG) is analogous to the more familiar electronic bandgap in semiconductors, which is a forbidden zone of energies that electrons cannot occupy. A photonic crystal is a microstructured material in which there is a periodic variation in the index of refraction as a function of position. This variation can occur in one, two, or three dimensions, and can be manipulated by controlling the magnitude, shape, and period of the index variation. A commonly used one-dimensional photonic crystal is the thin-film optical coating.

The basic PCF is a fused-silica optical fiber that has a regular pattern of voids, or air holes, that run parallel to its axis (see Fig. 1). Unlike traditional fibers, both the core and cladding are made from the same material. All the waveguiding properties in a PCF thus derive from the presence of the voids.

Two distinct methods, determined by the arrangement pattern of the voids, exist for confining light in a PCF:

photonic-bandgap guiding and index guiding.^{1,2} Photonic-bandgap guiding occurs by surrounding the core of an optical fiber with a photonic-crystal structure. Wavelengths that fall within the photonic crystal's bandgap cannot propagate out and are thus confined to the core. As a result, the core can even have a lower index of refraction than the cladding.

Index guiding is more analogous to the operation of a conventional step-index fiber. A typical index-guided PCF has a solid core and a regular pattern of holes surrounding that core. The holes effectively lower the refractive index of the cladding. Light is therefore guided by modified total internal reflection; however, PCF construction enables much finer and more accurate control of index values.

Important PCF types

For both index- and PBG-guided PCFs, the particular fiber properties can easily be varied by changing parameters such as hole size, arrangement, spacing, and shape. Several important subclasses of PCFs already exist, each optimized for a particular application (see Fig. 2). It's likely that further investigation in the field will yield

many new and useful types.

One PCF type that has been researched in some detail is termed "endlessly single mode." This type typically has a triangular matrix of circular holes with single missing holes in the center. Variations on this design include cores consisting of three, five, or seven missing holes. Mathematical modeling of this structure reveals that, when the ratio of hole size

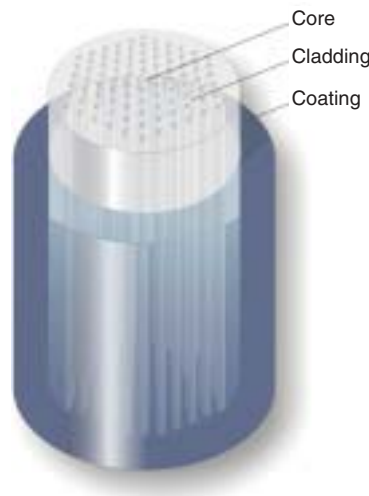


FIGURE 1. Probably the most well-known form of PCF contains a hexagonal array of air holes with one or more missing holes forming a core at the center of the array.

JASON EICHENHOLZ is senior research market and technology manager at Newport, 1791 Deere Avenue, Irvine, CA, 92606; e-mail: jeichenholz@newport.com.

to hole spacing exceeds a certain value, then only single-mode propagation is supported, regardless of wavelength. Furthermore, the core size for such a fiber can range from the very small to the very large and still meet this condition. Thus, it is possible to construct a fiber with a core that is tens of microns in diameter and that supports only single-mode operation over a wide wavelength range. This stands in sharp contrast to step-index fibers, in which small core diameter is required to achieve single-mode operation over a narrow range of wavelengths.

Endlessly single-mode PCFs with a large mode area offer several advantages over traditional fibers. A larger mode area results in a lower power density; thus, these fibers can transmit very high laser powers without damage. Furthermore, the low power density minimizes the occurrence of nonlinear optical effects.

Increasing the volume occupied by the air holes lowers the effective index of the

ratio between core and cladding. This is often accomplished by using a construction consisting of a honeycomb array of large air spaces surrounding a small central core. This extremely small and well-confined mode volume confines a high power density along the fiber length, producing a plethora of nonlinear effects. The large air-filled cladding in this PCF also produces large waveguide dispersion. This waveguide dispersion can be tailored to either enhance or cancel out the inherent dispersion of the fiber material, providing more flexibility in terms of overall dispersion profile than is achievable in step-index fibers. This, in turn, can be used to enhance or reduce various nonlinear processes.

A well-known type of PBG fiber consists of a hollow core surrounded by a close-packed triangular matrix of circular holes. Each particular structure will only guide light in a limited spectral region with a finite spectral bandwidth;

for example, fibers centered around 1550 nm, the bandwidth is typically 100 to 200 nm. Commercial products with transmission centered at 800, 1060, and 1550 nm are available.

An air-core fiber has several potential advantages over solid-core fibers. For example, air-core fibers can transmit high powers without damage or the introduction of nonlinear

effects. Also, there are no Fresnel reflections at the fiber ends. In addition, the core can be filled with particles, gases, or liquids to alter its properties in a variety of ways. Such an arrangement can form the basis for several types of fiber sensors.

Photonic-crystal fiber lasers

One of the most promising applications for PCFs is in high-power fiber lasers. Traditionally, these are constructed using dual-clad, step-index fibers with a polymer outer cladding and a core doped with rare-earth ions, most commonly ytterbium and erbium. Unfortunately, it is difficult to extend this design to produce single-mode output at higher pump and output powers. This is because the small core size required for single-mode

operation produces high power densities, which lead to detrimental nonlinear effects. Various techniques have been developed to increase core size in step-index fiber lasers while still maintaining single-mode output. These techniques include careful control of index profile and initial excitation profile and the intentional introduction of microbending losses, which preferentially inhibit propagation of higher-order modes. These approaches have practical limitations in terms of thermal and mechanical stability, however.

An alternative dual-clad fiber-laser architecture based on PCF technology exploits the best aspects of large-mode-area fibers and high-NA air-clad fibers to scale the optical output to higher powers. This structure confers several distinct advantages for achieving high-power output.

A ring of air holes effectively confines the pump light to a silica multimode pump core, commonly referred to as the inner cladding (see Fig. 3). This type of PCF construction allows for a higher NA of the inner cladding than is possible using step-index construction. The higher NA permits efficient pumping with relatively inexpensive high-power large-emitting-area pump diodes. The microstructured edges of the inner cladding serves to scramble the pump modes, leading to efficient coupling of the pump power into the active core; this is even the case

PASSIVELY COOLED PCF LASERS OPERATING AT AN OUTPUT OF GREATER THAN 100 W/M HAVE BEEN DEMONSTRATED.

for circular inner-cladding shapes. Moreover, the absence of a polymer outer cladding eliminates the danger of damage to the exposed fiber end by high pump powers.

Within the inner cladding, another microstructured rare-earth-doped core defines the laser-beam output parameters. The single-mode core can be expanded to a large mode area to facilitate high power levels in a single mode while avoiding nonlinearities and pro-

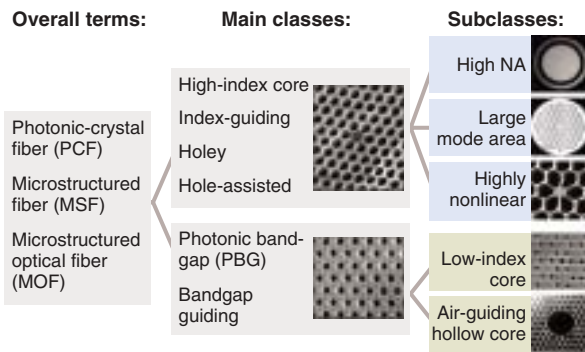


FIGURE 2. Many subclasses of PCFs are available that support a wide variety of applications.

cladding. A common way of implementing this in practice is to use a circular array of long, thin-walled air gaps. The result is a fiber with a very high numerical aperture (NA). Commercially available fibers with this design typically offer large-core multimode operation with an NA of up to 0.7. This combination of large core and high NA is particularly useful because it enables highly efficient coupling of light from an extended source such as a high-power laser diode.

Highly nonlinear fibers—useful for applications like supercontinuum generation, four-wave mixing, Raman amplification, and optical parametric amplification—are constructed by producing a very small core diameter (down to 1 μm), in combination with a high index



FIGURE 3. A ytterbium-doped dual-clad PCF (seen in cross section) serves as a fiber laser. With an NA of 0.62, its multi-mode pump core accepts laser-diode light; the laser emits single-mode light in the 1000- to 1100-nm range with a beam quality M^2 of approximately 1.2.

viding a good overlap between the pump

mode and the laser mode.

Recently, PCFs have been developed in which the cores have also been co-doped with photorefractive materials, enabling fiber-Bragg gratings to be inscribed right into the core using UV laser light, thus further simplifying the architecture.

In the past, there have been questions as to whether the large air gap in the inner cladding of a PCF laser would act as a thermal insulator, causing problems with heat dissipation at higher powers. However, recently developed thermal models have shown that there is no significant difference in the heat-dissipation capabilities of standard dual-clad fiber lasers and properly designed dual-clad PCF lasers.³ Passively cooled PCF lasers operating at an output of greater than 100 W/m have already been

demonstrated. This value can be doubled using forced air or passive water-cooling, without the occurrence of significant nonlinear or thermo-optical effects.

At this time, the most promising use for PCFs is in the construction of higher-power next-generation fiber lasers and supercontinuum generation. As research on PCFs continues, it is likely that many more uses will be discovered and their impact will spread to numerous applications in research, biomedicine, sensing, and materials processing. □

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