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An Effectual Analysis on the Impact of Geometry on Photonic Crystals

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Abstract

Photonic crystals are composed of periodic dielectric, metallo-dielectric—or even superconductor microstructures or nanostructures that affect electromagnetic wave propagation in the same way that the periodic potential in a semiconductor crystal affects electron motion by defining allowed and forbidden electronic energy bands. Photonic crystals contain regularly repeating regions of high and low dielectric constant. Photons (behaving as waves) either propagate through this structure or not, depending on their wavelength. Wavelengths that propagate are called modes, and groups of allowed modes form bands. Disallowed bands of wavelengths are called photonic band gaps. This gives rise to distinct optical phenomena, such as inhibition of spontaneous emission, high-reflecting omni-directional mirrors, and low-loss-waveguiding. Intuitively, the bandgap of photonic crystals can be understood to arise from the destructive interference of multiple reflections of light propagating in the crystal at the interfaces of the high- and low- dielectric constant regions, akin to the bandgaps of electrons in solids. The periodicity of the photonic crystal structure must be around half the wavelength of the electromagnetic waves to be diffracted. This is ~350 nm (blue) to ~650 nm (red) for photonic crystals that operate in the visible part of the spectrum—or even less, depending on average index of refraction. The repeating regions of high and low dielectric constant must, therefore, be fabricated at this scale.

Keywords: Impact of Geometry, Geometry and Photonic Crystal

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Foreword and Introduction

Pioneered by the research group of Philip St. J. Russell in the 1990s, the development of photonic crystal fibers and the exploration of the great variety of possible applications have attracted huge interest. The field, which constitutes a part of the wider field of photonic bandgap structures while incorporating other ideas as well, can be considered as one of the most active fields of current optics research. This is partly because these fibers offer many degrees of freedom in their design to achieve a variety of peculiar properties, which make them interesting for a wide range of applications.

Figure 1: A frequently used solid-core photonic crystal fiber design. There is a triangular pattern of air holes, where the central hole is missing. The gray area indicates glass, and the white circles air holes with typical dimensions of a few micrometers. Only the region around the core is shown.

Photonic Crystal Fiber

A photonic crystal fiber (also called holey fiber, hole-assisted fiber, microstructure fiber, or microstructured fiber) is an optical fiber which obtains its waveguide properties not from a spatially varying glass composition but from an arrangement of very tiny and closely spaced air holes which go through the whole length of fiber. Such air holes can be obtained by using a preform with (larger) holes, made e.g. by stacking capillary tubes (stacked tube technique). Soft glasses and polymers (plastics) also allow the fabrication of preforms for photonic crystal fibers by extrusion. There is a great variety of hole arrangements, leading to PCFs with very different properties.

The simplest (and most often used) type of photonic crystal fiber has a triangular pattern of air holes, with one hole missing, i.e. with a solid core surrounded by an array of air holes. The guiding properties of this type of PCF can be roughly understood with an effective index model: the region with the missing hole has a higher effective refractive index, similar to the core in a conventional fiber.

There are also so-called photonic bandgap fibers (PBG fibers) with a totally different guiding mechanism, based on a photonic bandgap of the cladding region. The latter mechanism even allows guidance in a hollow core (i.e. in a low-index region). Such air-guiding hollow-core photonic crystal fibers (or air core bandgap fibers) can have a very low nonlinearity and a high damage threshold. They typically guide light only in a relatively narrow wavelength region with a width of e.g. 100–200 nm and can be used e.g. for pulse compression with high optical intensities, as most of the power propagates in the hollow core. Most PCFs are made of pure fused silica (→ silica fibers), which is compatible with the above-mentioned fabrication techniques. However, various PCFs made of other materials have been demonstrated, most notably of heavy metal soft glasses and of polymers (plastic optical fibers), sometimes used even for terahertz radiation.

Active Fibers for Amplifiers and Lasers

Laser-active PCFs for fiber lasers and amplifiers can be fabricated, e.g., by using a rare-earth-doped rod as the central element of the preform assembly. Rare earth dopants (e.g. ytterbium or erbium) tend to increase the refractive index, but this can be precisely compensated, e.g. with additional fluorine doping, so that the guiding properties are determined by the photonic microstructure only and not by a conventional-type refractive index difference. With rare-earth-doped PCFs, it is possible to realize, e.g., soliton mode-locked fiber lasers operating in the 1-μm region, where a fiber's chromatic dispersion would usually be in the normal dispersion regime, but can be anomalous for suitable designs.

For high-power fiber lasers and amplifiers, double-clad PCFs can be used, where the pump cladding is surrounded by an air cladding region (air-clad fiber). Due to the very large contrast of refractive index, the pump cladding can have a very high numerical aperture (NA), which significantly lowers the requirements on the pump source with respect to beam quality and brightness. Such PCF designs can also have very large mode areas of the fiber core while guiding only a single mode for diffraction-limited output, and are thus suitable for very high output powers with excellent beam quality. Another advantage is that the pump light is kept away from any polymer coating, thus avoiding possible problems with overheating of a coating.

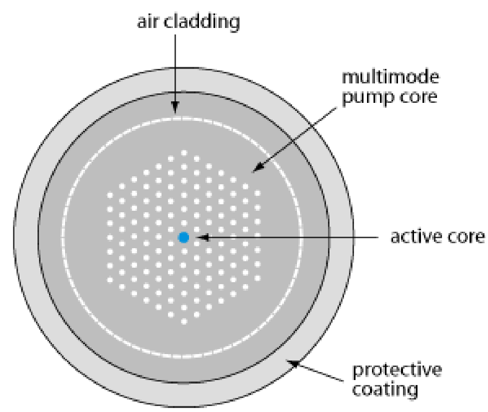

Figure 2: Structure of a photonic crystal fiber with an air cladding.

Doped photonic crystal fibers have favorable properties also for use in fiber-based chirped-pulse amplification systems with very high output peak power.

Properties Achievable by Design

Photonic crystal fibers with different designs of the hole pattern (concerning the basic geometry of the lattice, the relative size of the holes, and possibly small displacements) can have very remarkable properties, strongly depending on the design details:

- It is possible to obtain a very high numerical aperture of e.g. 0.6 or 0.7 of multimode fibers (also for the pump cladding of a double-clad fiber).
- Single-mode guidance over very wide wavelength regions (endlessly single-mode fiber) is obtained for small ratios of hole size and hole spacing.
- Extremely small or extremely large mode areas (possibly with a lower NA than possible with a conventional fiber) are possible. These lead to very strong or very weak optical nonlinearities. PCFs can be made with a low sensitivity to bend losses even for large mode areas.
- Certain hole arrangements result in a photonic bandgap (→ photonic bandgap fibers), where guidance is possible even in a hollow core, as a higher refractive index in the inner part is no longer required. Such air-guiding hollow-core fibers are interesting e.g. for dispersive pulse compression at high pulse energy levels.
- Particularly for larger holes, there is the possibility to fill gases or liquids into the holes. This can be exploited for fiber-optic sensors, or for variable power attenuators.
- Asymmetric hole patterns can lead to extremely strong birefringence for polarization-maintaining fibers. This can also be combined with large mode areas.
- Strongly polarization-dependent attenuation (polarizing fibers) can be obtained in different ways. For example, there can be a polarization-dependent fundamental mode cut-off, so that the fiber guides only light with one polarization in a certain wavelength range.
- Similarly, it is possible to suppress Raman scattering by strongly attenuating longer-wavelength light.
- Very unusual chromatic dispersion properties, e.g. anomalous dispersion in the visible wavelength region, result particularly for PCFs with small mode areas. There is substantial design freedom, allowing for different combinations of desirable parameters.
- Core-less end caps can be fabricated simply by fusing the holes near the fiber end with a heat treatment. The sealed end facets allow for larger mode areas at the fiber surface and thus a higher damage threshold, e.g. for amplifying intense nanosecond pulses.
- Multicore designs are possible, e.g. with a regular pattern of core structures in a single fiber, where there may or may not be some coupling between the cores.

Technical Issues with Fiber Ends

Overall, photonic crystal fibers are handled in similar ways as standard optical fibers. However, special care is required in various respects:

- Ends of PCFs may not be cleaned with liquid solvents, such as ethanol, as capillary forces may pull them into the hole. Of course, the guiding properties can be strongly modified with any liquid in the holes. There is even research on exploiting such effects, e.g. for generating a tunable amount of optical loss by controlling the degree to which a liquid penetrates the holes.

- Cleaving and fusion splicing PCFs is in principle possible, but tentatively more difficult, particularly for fibers with large air content. During fusion splicing, the air may expand and distort the fiber structure. Connections between fibers are also possible with a variety of mechanical splices, fiber connectors, protected patch cables, beam expansion units, etc.
- Even when the splicing process works well, there may be a substantial coupling loss due to a mismatch of mode areas, e.g. when a small-core PCF is coupled to a standard single-mode fiber. There are special tapered single-mode fibers and tapered PCFs for enhancing the coupling efficiency, but these may not be easily available.

One-dimensional photonic crystals

In a one-dimensional photonic crystal, layers of different dielectric constant may be deposited or adhered together to form a band gap in a single direction. A Bragg grating is an example of this type of photonic crystal. One-dimensional photonic crystals can be either isotropic or anisotropic, with the latter having potential use as an optical switch. One-dimensional photonic crystal can form as an infinite number of parallel alternating layers filled with a metamaterial and vacuum. This produces identical PBG structures for TE and TM modes.

Recently, researchers fabricated a graphene-based Bragg grating (one-dimensional photonic crystal) and demonstrated that it supports excitation of surface electromagnetic waves in the periodic structure by using 633 nm He-Ne laser as the light source. Besides, a novel type of one-dimensional graphene-dielectric photonic crystal has also been proposed. This structure can act as a far-IR filter and can support low-loss surface plasmons for waveguide and sensing applications.

Two-dimensional photonic crystals

In two dimensions, holes may be drilled in a substrate that is transparent to the wavelength of radiation that the bandgap is designed to block. Triangular and square lattices of holes have been successfully employed.

The **Holey fiber** or photonic crystal fiber can be made by taking cylindrical rods of glass in hexagonal lattice, and then heating and stretching them, the triangle-like airgaps between the glass rods become the holes that confine the modes.

Three-dimensional photonic crystals

There are several structure types that have been constructed:

- Spheres in a diamond lattice
- Yablonovite
- The woodpile structure – "rods" are repeatedly etched with beam lithography, filled in, and covered with a layer of new material. As the process repeats, the channels etched in each layer are perpendicular to the layer below, and parallel to and out of phase with the channels two layers below. The process repeats until the structure is of the desired height. The fill-in material is then dissolved using an agent that dissolves the fill-in material but not the deposition material. It is generally hard to introduce defects into this structure.
- Inverse opals or Inverse Colloidal Crystals-Spheres (such as polystyrene or silicon dioxide) can be allowed to deposit into a cubic close packed lattice suspended in a solvent. Then a hardener is introduced that makes a transparent solid out of the volume occupied by the solvent. The spheres are then dissolved with an acid such as Hydrochloric acid. The colloids can be either spherical or nonspherical.
- A stack of two-dimensional crystals – This is a more general class of photonic crystals than Yablonovite, but the original implementation of Yablonovite was created using this method.
- "The photonic crystal beam splitter that we made is a fundamental optical component used to control polarized light," explains Dr Mark Turner from Swinburne University. "Specifically what makes our device unique is its ability to directly work with circular polarization at a microscopic scale."
- Circular polarization uses 3D laser nanotechnology to exploit circular polarization to build a microscopic prism that contains in excess of 750,000 polymer nanorods. holes is 4 µm.

Applications

Their special properties make photonic crystal fibers very attractive for a very wide range of applications. Some examples are:

- fiber lasers and amplifiers, including high-power devices, mode-locked fiber lasers, etc.
- nonlinear devices e.g. for supercontinuum generation (→ frequency combs), Raman conversion, parametric amplification, or pulse compression
- telecom components, e.g. for dispersion control, filtering or switching
- fiber-optic sensors of various kinds
- quantum optics, e.g. generation of correlated photon pairs, electromagnetically induced transparency, or guidance of cold atoms.

Even though PCFs have been around for several years, the huge range of possible applications is far from being fully explored. It is to be expected that this field will stay very lively for many years and many opportunities for further creative work, concerning both fiber designs and applications.

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