Photonic Crystal Fiber in Communication as Waveguide

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Abstract: Photonic crystal fiber finds applications in optical fiber communication and sensors. Depending on solid core & hollow core there are different types of photonic crystal fiber. The properties of power & spectral coverage are compared with different types of sources. Waveguide with different angle is possible by removing few lines of holes. The applications in various areas are discussed.

Keywords: *Photonic crystal fiber, photonic band gap fiber, Index guiding fibers, photonic crystal waveguide.*

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I. INTRODUCTION

Photonic crystal fibers are a new class of optical fibers. Most PCFs are made of pure fused silica , However, various PCFs made of other materials most notably of heavy metal soft glasses and of polymers (plastic optical fibers), sometimes used even for terahertz radiation .

Fiber-optic cables are constructed with a core and a cladding of constant refractive index difference. Light travels through the core as a result of the refraction property of light, which occurs as a result of the difference between the refractive indexes of the core and cladding. This refracted light bears much higher loss during propagation over extended distances, and thus requires repeaters and amplifiers for extended distance communications.

In PCF, on the other hand, light is trapped in the core, providing a much better wave guide to photons than standard fiber optics. The polymers used instead of glass in PCF provide the advantage of a more flexible fiber, which allows for easier and less expensive installation. Various photonic crystals conforming to various photonic lattices are manufactured depending on the required properties of the propagated light.

Their artificial crystal-like microstructure results in a number of unusual properties. They can guide light not only through a well-known total internal reflection mechanism but using also photonic band gap effect.

PCFs are constructed using one of two basic design types, containing either a solid or hollow core. The former is typically made of silica—see Figure 1(left)—which, as for most conventional fibers, relies on total internal reflection. The latter typically contains air: see Figure 1(right). It relies on a photonic band gap to restrict guidance to the core. These basic PCF types encompass a range of fiber designs suited for a variety of applications because they have properties not found elsewhere. For example, unique features of hollow-core fibers include small nonlinearities, low light loss, and the option to fill air cores with gases and liquids. As a result, they are being considered for use in many applications, including sensors, high power-pulse transmission, and medical use.

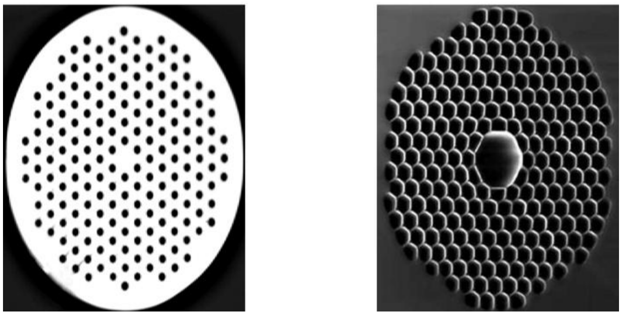

Figure 1. (left) Solid-core and (right) hollow-core fiber

The simplest type of photonic crystal fiber has a triangular pattern of air holes, with one hole missing (see Figure 2), 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 core in a conventional fiber.

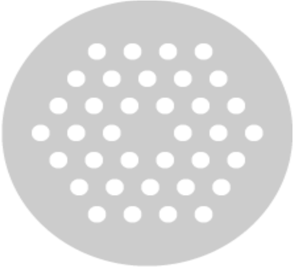

Figure 2. Simple photonic crystal fiber

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.

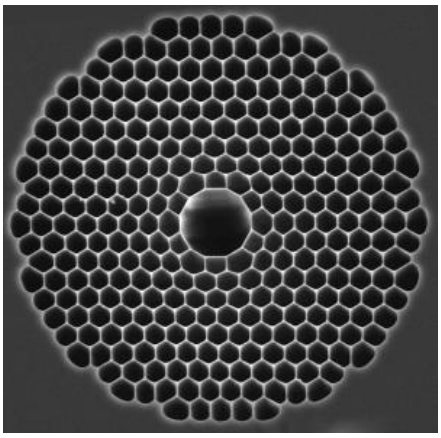

Figure 3: Microscope picture of the end of a hollow-core fiber.

There are also so-called photonic band gap fibers (PBG fibers) with a totally different guiding mechanism, based on a photonic band gap of the cladding region. The latter mechanism even allows guidance in a hollow core (that is in a low-index region), such that most of the power propagates in the central hole. Such air-guiding hollow-core photonic crystal 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 for example 100–200 nm and can be used for pulse compression with high optical intensities, as most of the power propagates in the hollow core. Photonic crystal fibers are generally divided into two main categories:

Index-Guiding Fibers: Have a solid core like conventional fibers. Light is confined in this core by exploiting the modified total internal reflection mechanism.

Photonic Band gap (Air Guiding) Fibers: Have periodic micro structured elements and a core of low-index material (hollow core). The core region has a lower refractive index than the surrounding photonic crystal cladding. The light is guided by a mechanism that differs from total internal reflection in that it exploits the presence of the photonic bandgap (PBG).

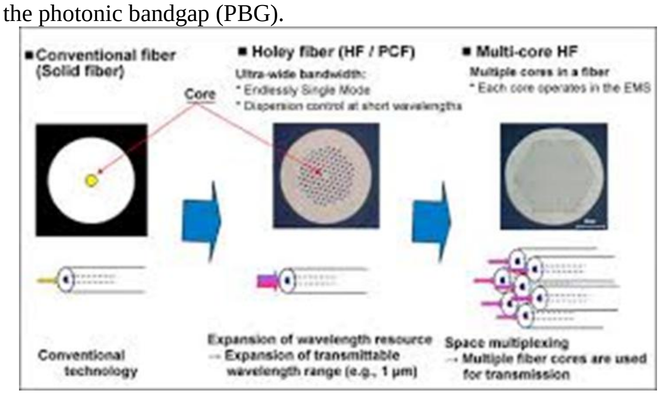

Figure 4 Diagrammatic comparison for conventional ,PCF & multi core PCF

PCF can be used in broadband super continuum devices in metrology, optical-coherence tomography, and spectroscopy. Passive highly nonlinear PCFs can be pumped with short pulses to produce a super continuum of power distributed over a wide bandwidth, exhibiting the high brightness characteristics of fiber lasers and the broad spectral coverage of white-light sources. This is a combination not offered by other technologies (see Figure 5). Highly nonlinear PCFs can be tailored to support various pump wavelengths with flexible design of small core, high numerical aperture and dispersion to achieve superior super continuum generation.

II. PHOTONIC CRYSTAL WAVEGUARD

There is large variety of waveguides based on photonic crystals. In the case of holes grating the simplest way to create a waveguide consists of removing one or more lines of holes. Light guiding in these structures can be based on refraction and the existence of a photonic band gap as well. Generally the waveguide is designed at the time of the grating writing. For this reason, several guiding structures of different geometries can be introduced simultaneously. These guides are noted Wn for n removed lines of holes figure below presents the case of a W1 guide containing a triangular network.

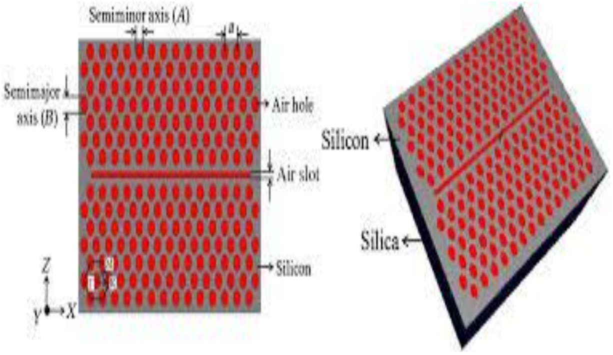

Figure 5. Superior power and spectral coverage of a PCF-based super continuum (SC) source. ASE: amplified spontaneous emission, SLED: super luminescent LED.

The nature of light guiding in these structures makes it possible to produce curved guides. Figure below reports a curved waveguide created by etching a thin layer of the GaAs semiconductor.

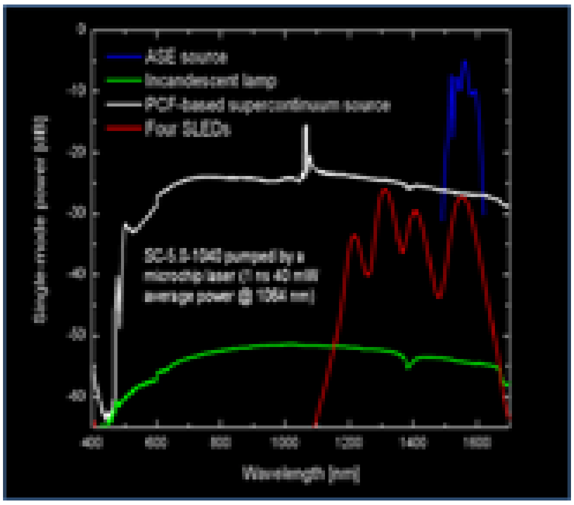

Figure 6: PCF waveguides

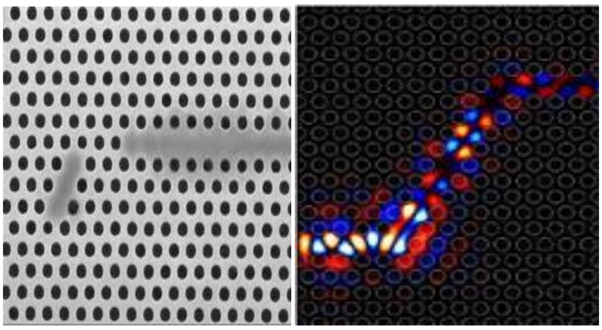

Figure 7: Waveguides with different angle.

The turn is obtained by omission of two lines of holes in the direction. This consists of two arms forming an elbow of 120 degree. Note that such a configuration is not allowed in the case of conventional waveguides. However, this type of component is not yet completely optimized and studies still continuing in this direction. The creation of this type of waveguide should certainly allow development of high density photonic circuits similar to the integrated circuits of microelectronics.

III. ACTIVE FIBERS FOR AMPLIFIERS AND LASERS

Laser-active PCFs for fiber lasers and amplifiers can be fabricated, for example by using a rare-earth-doped rod as the central element of the preform assembly. Rare earth dopants (for example ytterbium or erbium) tend to increase the refractive index, but this can be precisely compensated, 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, solution mode-locked fiber lasers operating in the 1-μm region, where a fiber's chromatic dispersion would usually be in the normal dispersion regime.

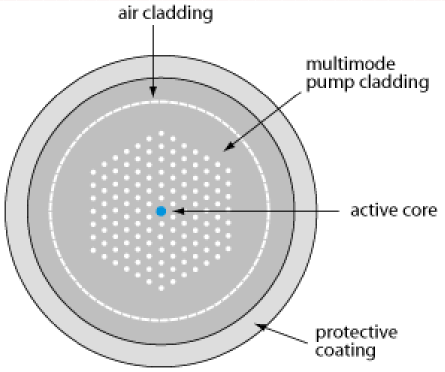

Figure 8: Structure of a photonic crystal fiber with an air cladding.

For high-power fiber lasers and amplifiers, double-clad PCFs (Figure 8) 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, 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 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. Doped photonic crystal fibers have favorable properties also for use in fiber-based chirped-pulse amplification systems with very high output peak power.

3.1 Properties 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 0.6 or 0.7 of multimode fibers for the pump cladding of a double-clad fiber.
- Single-mode guidance over very wide wavelength regions 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
- Band gap (photonic band gap 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 example for dispersive pulse at high pulse energy levels.
- Particularly for larger holes, there is the possibility to fill gases or liquids into the holes. Gas-filled PCFs can be exploited for fiber-optic sensors, for nonlinear spectral broadening at very high power levels, 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 for example 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, for amplifying intense nanosecond pulses.
- Multicore designs are possible, with a regular pattern of core structures in a single fiber, where there may or may not be some coupling between the cores.

IV. 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, 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 possible, but can be 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, example, 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.

V. 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 super continuum generation (frequency combs), Raman conversion, parametric amplification, or pulse
- Telecom components, e.g. for dispersion control, filtering or switching
- Fiber-optic sensors of various kinds
- Quantum optics in which 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 application

VI. CONCLUSION

The Photonic crystal fiber is a revolutionary optical fiber that not only redefines trustworthy communication; it also paves the way for sensors and amplifiers.

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