



The photonic crystal fibers, a revolutionary spectrum in imminent telecommunication diligence: A gentle overview

Amit Kumar, NK Singh, Hema Gera

Applied Science Department, Institute of Engineering & Technology, MIA, Alwar, Rajasthan, India

Abstract

The current explosion in information technology has been derived from our ability to control the flow of electrons in a semiconductor in the most intricate ways. Photonic crystals promise to give us similar control over photons - with even greater flexibility because we have far more control over the properties of photonic crystals than we do over the electronic properties of semiconductors. Given the impact that semiconductor materials have had on every sector of society, photonic crystals could play an even greater role in the 21st century, particularly in the optical-communications industry. In this paper we present the some of the advantages of using photonic crystal fibers (PCFs) for telecommunications over conventional glass or plastic fibers.

Keywords: information technology, electrons, photonic crystals, semiconductors

Introduction

The focus of telecommunications is transmitting pulses of light at high signaling rates and in an efficient manner. Fiber optics technology has undergone a number of revolutionary changes since the initial breakthroughs that saw the introduction of the conventional step index fibers ^[1, 2] and later that of the single material fibers wherein propagation was defined by an effective air cladding structure ^[3]. However, no matter how exquisite the method of propagation, and irrespective of the material system, the sole driver for most of that time has been the transportation of light from one point to another, whether by step-index confinement determined by simple Fresnel reflections or by coherent Fresnel reflections in bandgap fibers such as Bragg fibers ^[4]. Optical fibers and most micro structured optical fibers have relied on the transparency of silica till now to provide low transmission losses. The losses in the electromagnetic energy propagating in fibers are basically due to material absorption, material scattering, waveguide scattering due to form-inhomogeneities, mode losses due to fiber bending and cladding losses. All these necessarily led to fiber designs centered on controlling the near field of an optical mode along this distance in order to control its propagation and attempt to, in most cases, retain its properties after travel.

Photonic Crystal Fibers

Photonic-crystal fibers can be defined as a class of optical fibers whose properties are based on photonic crystals. Photonic crystals are made up of periodic dielectric or metallo-dielectric nanostructures that affect the propagation of electromagnetic waves in the same way as the periodic potential in a semiconductor crystal affects the electron motion by defining allowed and forbidden electronic energy bands. Basically, photonic crystals contain regularly repeating internal regions of high and low dielectric constant. Photons (behaving as waves) propagate through this structure - or not -

depending on their wavelength. Wavelengths of light that are allowed to travel are known as modes, and groups of allowed modes form bands. Disallowed bands of wavelengths are called photonic band gaps. A commonly used one-dimensional photonic crystal is the thin-film optical coating. PCFs are typically silica optical fibers in which two-dimensional periodic structures with a regular array of tiny air holes are introduced in the cladding region and extend in the axial direction of the fiber ^[5].

There are two particular ways, determined by the arrangement of the void spaces, by means of which light can be confined in a PCF: photonic-bandgap guiding and index guiding. Photonic-bandgap guiding is brought about by surrounding the core of an optical fiber with a photonic-crystal structure ^[6, 7]. 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. The typical index-guided PCF has a solid core and a regular pattern of holes surrounding that core. The holes effectively reduce 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. For both index- and Photonic Band Gap -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. Some of these are endlessly single mode solid-core PCF, all-solid glass PCF with raised - index doped glass strands (colored gray) in the cladding, solid-core PCF with high air-filling fraction and small core, Dual-core PCF, Kagomé hollow core PCF, Seven-cell hollow-core PCF, Birefringent PCF, Carbon-ring structure for PBG guidance, Double-clad PCF with offset doped lasing core and high numerical aperture inner cladding for pumping

etc. It's likely that further investigation in the field will yield many new and useful types (see Fig. 1). One PCF type that has been researched in some detail is the endlessly single mode PCF. This type typically has a triangular matrix of circular holes with single missing holes in the center. Variations in 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 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

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 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.

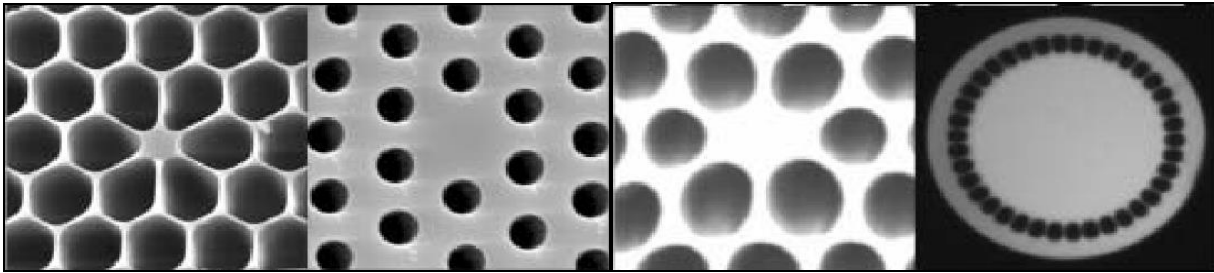


Fig 1: The microstructure of photonic crystal fibers allow for an almost endless variety of designs, each optimized for different applications. Shown here are examples of a highly nonlinear fiber (top left), a large-mode-area fiber (top right), a polarization-maintaining fiber (bottom left), and a fiber with ultra-high numerical aperture (bottom right).

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.

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.

One of the most promising aspects of the use of PCFs will be the ability to couple and integrate efficiently with photonic crystal based switches, detectors, filters and interconnects – devices that could increase efficiency in telecommunications systems and cut down the size of the components. Photonic crystal transmitters, waveguides and receivers can all be realized by means of PCFs as recent technological

breakthroughs show.

For transmitters, high power fiber lasers can be developed using PCFs. 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. Here the switching capability, and time periods are highly desirable.

The Photonic crystal waveguides can be realized by PCFs with their bandgaps tuned to transmit highly specific band of waves. With bending losses reduced to a minimum and the development of proper dispersion compensation models the

high group velocity dispersion characteristic of PCFs could be an advantage since it tends to suppress nonlinear interaction between channels in multi-wavelength transmission systems. As far as receiving systems are concerned PCF based radiation sensors along with interferometers complete the picture. The PCFs impregnated with nanoparticles are said to be excellent autonomous radiation sensing systems^[8]. The nanoparticles are introduced into the voids of the PCF. This leads to a coupling of light emitted from the nanoparticles to the core and the corresponding change can be read optically or electrically. The interferometers function basically as accessories for coupling different modes and realizing different states and also in some cases as strain sensors etc. While, the practical implementation of the so called Photonic networks will take substantial time to be realized, mathematical models paint a hopeful picture.

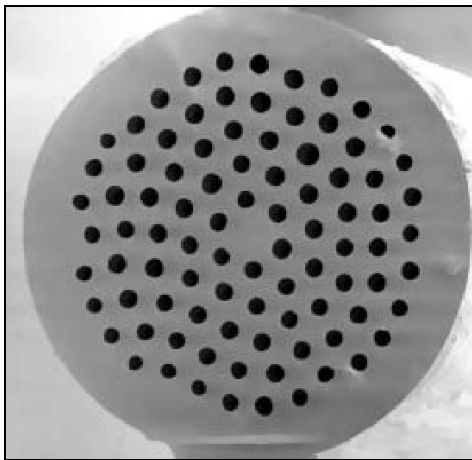


Fig 2: Cross section of a large-mode-area photonic crystal fiber designed for high power delivery. The fiber guides in a single spatial mode, despite a core diameter of 15 μm .

Conclusion

Photonic crystal fibers are innovative technology based on the specific behavior of light in periodic dielectric structures. Basic properties of light guidance in PCFs can be understood through simple 1D example, but for deeper insight, advanced numerical simulations must be performed. Due to bandgaps, light guidance in media with lower refractive index or even in the hollow core is possible. PCFs have interesting features which can be tailored only by geometry of transverse microstructure. These features are being intensively investigated and numerous applications of PCFs are emerging. In telecommunications, PCFs can be used for auxiliary devices, whilst for usual waveguides, the attenuation at telecom frequencies must still be reduced and the cost effectiveness on the market must be achieved. The recent advances in the reduction of the attenuation level of index-guiding PCFs have left little doubt that these fibers, from an attenuation point of view, will be able to compete with conventional solid fibers for data transmission applications. One can even speculate that the ultimate attenuation level of the PCF might be even lower than that of conventional fibers since the PCF is a single material fiber with no boundary between two types of glass with different thermal expansion coefficients.

Acknowledgment

The Authors take this opportunity to express gratitude to Mr. Robin Kumar for his invaluable guidance and co-operation throughout the project. He provided constant encouragement and unceasing enthusiasm at every stage of the project work. He has been the principal motivating force behind this work and provided all kind of possible help.

References

1. Kapron F, Keck DB, Maurer RD. *Appl. Phys. Lett.* 1970; 17:423.
2. Keck DB, Maurer RD, Schultz PC. *Appl. Phys. Lett.* 1973; 22(7):307-309.
3. Kaiser PV, Astle HW. *Bell Syst. Tech. J.* 1974; 53:1021-1039.
4. Yeh P, Yariv A, Marom E. *J. Opt. Soc. Am.* 1978; 68:1196.
5. Knight JC, Birks TA, Russell St PJ, Atkin DM. All-silica single-mode optical fiber with photonic crystal cladding, *Opt. Lett.* 1996; 21:1547-1549.
6. Bjarklev A, Broeng J, Bjarklev AS. *Photonics Crystal Fibres*, Kluwer Academic Publishers, 2003.
7. Russell P. *Science*, 2003, 299-358.
8. Xie Z, Lu Y, Wei H, Yan J, Wang P, Ming H. *Applied physics. B, Lasers and optics*, 2009, ISSN 0946-2171.