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Bjarklev, Anders Overgaard; Riishede, Jesper; Libori, Stig E. Barkou; Broeng, Jes

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Photonic Crystal Fibres - Novel Fibres, New Applications

Anders Bjarklev, Jesper Riishede, Stig E. Barkou Libori, Jes Broeng*

Research Center COM, Technical University of Denmark, DTU-building 345V, DK-2800 Lyngby, Denmark
Tel: (45) 4525 3809, Fax:(45) 4593 6581, e-mail: ab@com.dtu.dk

** Crystal Fibre A/S, Blokken 84, DK-3460 Birkeroed, Denmark*
Phone: + 45 4348 2800,Fax: +45 4348 2801, Web address: http://www.crystal-fibre.com

ABSTRACT

Photonic Crystal Fibres with an air-silica micro-structured cross-section, offer novel fibre designs and new fibre characteristics, compared to standard silica fibres, such as new guiding mechanisms, different group velocity dispersion characteristics and new possibilities when designed as non-linear fibres.

1. INTRODUCTION

Photonic Crystal Fibres (PCF) appear to be of the most mature technologies within the field of Photonic Crystals [1,2]. PCFs have been intensively studied since they were first proposed five years ago [3,4]. PCFs typically consist of a silica background material, and a large number of air holes in the cladding part of the fibre. This offers the possibility of exploiting the large index contrast between silica and air, to obtain fibres with an unusually large numerical aperture. Alternatively one may exploit that light is able to escape the cladding air holes, if the structure scale is sufficiently large, compared to the wavelength of light, thus offering the possibility of fibres with an unusually low numerical aperture. In short PCFs offer a much larger design space than do standard optical fibres. Such PCFs guide light by a mechanism similar to the well-known principle of Total internal reflection (TIR). Such TIR-PCFs were the first PCFs to be demonstrated experimentally [5]. However, by placing the cladding air holes periodically, one may exploit the possibility of Photonic Bandgaps (PBG), and thereby utilize a novel guiding mechanism of light making it possible to e.g. guide light within a hollow core-region. PBG-PCFs were only relatively recently demonstrated experimentally [6]. In this paper both TIR-PCFs and PBG-PCFs will be addressed with special attention to some of the more recent developments within the field of PCFs.

PCFs have matured significantly over the last years, and today focus is increasingly shifting towards applications of the fibres rather than studying the guiding mechanisms of the fibres in detail. Because of the special group velocity dispersion characteristics that may be obtained using PCFs as well as the small mode-field diameters that are possible in PCFs with a large numerical aperture the topics of non-linear effects are receiving considerable attention. Super-continuum generation as an example is intensively studied. In this presentation both the basic properties of PCFs and some of their unique properties will be discussed. Secondly potential applications and some future possibilities will be discussed.

2. Fabrication of Photonic crystal Fibres

A PCF typically consists of a pure silica background material, within which numerous air holes running parallel to the fibre axis are situated. The size, position and number of the air holes determine the specific waveguiding properties of the PCF. The structure of the PCF is created by manually stacking of silica capillaries (tubes) and silica rods. Figure 1 shows a picture of a picture of a PCF perform where the central capillary is substituted by a rod that will later form the core-region of the final PCF. Typically the resulting micro-structured element will be placed within an over-cladding tube, to finalize the preform. The perform is drawn into fibre by placing it in a draw tower, where the outer diameter is reduced to the final size of approximate 125 microns, by heating the preform to approximately 2000 degrees Celcius. The fibre is subsequently coated with polymer and coiled for further handling.

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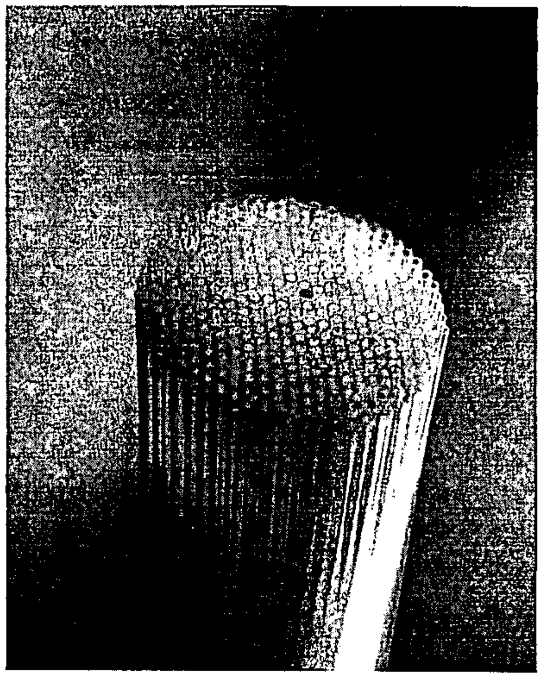


***Figure 1:** A picture of a photonic crystal fibre preform formed by manual stacking of silica rods and tubes. The photograph is kindly provided by Crystal Fibre A/S (Blokken 84, DK-3460, Birkerød, Denmark).*

3. Modelling of Photonic Crystal fibres

Originally the theoretical investigations of PCFs were dominated by the search of Photonic Bandgaps. This process was initially hindered by the lack of suitable theoretical models, since the well-known circular symmetric scalar models known from standard fibre theory are clearly insufficient tools for this task. Today a number of vectoria models for the analysis of periodic structures exist [7-10,14,15] and photonic crystals are being extensively studied. One should emphasise that the appearance of photonic bandgaps relies on a strictly periodic dielectric structure. For studying photonic bandgap effects, it will correspondingly often be advantageous to use a model that is optimised for periodic problems (such as the plane wave method, [7,13]).

In order to qualitatively describe the mode-propagation properties in TIR_PCF, the effective index approach was proposed in 1997 [11]. In this method it is assumed that the TIR-PCF may be calculated upon as a circular symmetric standard step-index fibre, however, one employs the effective index of the fundamental cladding mode as the cladding index. The core is introduced as a pure silica core, while the core radius is typically chosen as 0.62 times the typical center- to center cladding hole spacing (assuming that the fibre is formed by a close-packed stacking of silica tubes, with a single silica rod as the core-region). This scalar effective-index method has also been used as a basis for the approximate group velocity dispersion and bending analysis presented in [12]. It is noteworthy that the development of the PCF technology towards larger air holes recently has made it relevant to approximate the fiber by an isolated strand of silica surrounded by air [17].

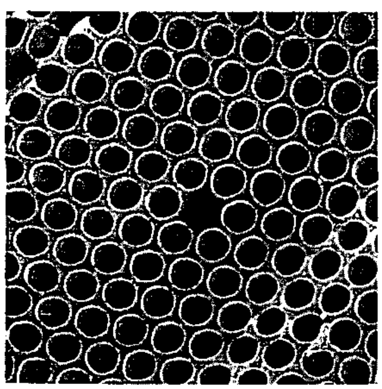
In 1990 the first method for finding PBGs in photonic crystals was described [7]. The method was closely related to methods used for calculating electronic bandgaps in semiconductor crystals, in that it described the magnetic field as a plane wave multiplied by a Bloch function with the two-dimensional periodicity of the photonic crystal. From Maxwell's equations an eigenvalue equation may now be formulated, which is well suited for calculating the PBGs of a periodic dielectric structure, since it describes the field and the structure as a Bloch function [13]. However, to include a core, one has to impose an artificial periodicity, which is handled numerically by creating a supercell with periodically repeated core-defects. This yields correct guided solutions, if the supercell is much larger than the guided mode-area [14]. Such a supercell approach requires a high number of plane waves, which initiated an interest in models capable of handling a large number of basis functions [14].

Based on the fact that silica is an isotropic material, we may choose to solve the waveguiding problem by the well-known vectorial transverse eigenvalue equation as outlined by Monro et al. [15]. In this formulation, the transverse wavevector k is scalar. Therefore, this formulation is suitable for finding guided solutions. Such formulations, therefore, avoid the supercell formulation of the core. One may then describe the cladding by a Fourier formulation (cosines), while the core-defect and the transverse electric field is described by localised functions [15]. The eigenvalue equation may then be recast into a matrix eigenvalue problem, where the matrix elements are found from overlap integrals, which may be calculated analytically. No calculations on photonic bandgap problems have been shown in literature, using this method.

4. Basic operation of index guiding Crystal fibres (TIR-PCFs)

The first crystal fibres studied had a design similar to the one illustrated in Fig.2.a. The operation of such high-index core fibres may be understood from Fig. 2.b., which shows the effective index of the guided modes of a crystal fibre with relatively large air holes in the cladding structure. In addition, the figure shows the effective core and cladding indices and reveals that the high-index core crystal fibres have an operation that may be compared to traditional optical fibres operating by total internal reflection (TIR). This is seen from the fact that the effective indices of the guided modes are positioned between the core and cladding indices.

Even though the basic operating principle of TIR-PCF resemble that of standard optical fibres, Fig.2.b. readily illustrates that a number of novel possibilities exist with TIR-PCF. At low normalized frequencies (i.e., when the cladding inter-hole distance is relatively small compared to the inter-hole distance), one may have a very low effective cladding index. This makes it possible to guide light efficiently in very small cores (even down to 1 μm core diameter), that combined with a strong wave-guide group velocity dispersion, makes it possible to generate white light form approximately 400-1400 nm wavelength. As the normalized frequency is increased, the effective cladding index approaches that of silica (since the light avoids the air-holes). This makes it possible to guide light in a single mode in PCFs with very large core regions (core-diameter up to 20 μm). Furthermore, the cladding index approaches the silica core-index quickly enough to ensure, that PCFs will only guide a finite number of modes, irrespective of the wavelength. Thus, the fibre may be designed to support only one mode at all frequencies (an endlessly single-mode fiber), or two modes as the example fibre from Fig.2.b.



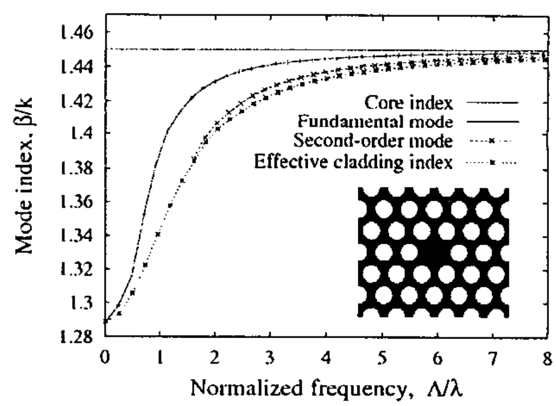


Fig 2.a. Scanning electron micrograph of inner part of an index-guiding crystal fibre. The cladding of the fibre consists of a highly regular, triangular lattice of air holes. The core is formed by the omission of a single air hole. The photograph is kindly provided by Crystal Fibre A/S (Blokken 84, DK-3460, Birkerød, Denmark, http://www.crystal-fibre.com/)

Fig.2.b. Modal index illustration of the operation of a crystal fibre with a triangular air-hole lattice cladding structure and a high-index core formed from a single missing air hole. The figure is calculated [16] for normalized frequencies hence the properties (including the second-order mode cut-off) may be scaled to any wavelength range by scaling the centre-to-centre air hole spacing Λ – provided that the refractive index of silica is equal to 1.45 at the given wavelength range. The fibre supports both a fundamental mode and a second-order mode with a normalized cut-off frequency, Λ/λ, around 1.5. The inset shows a cross-section of the PCF.

5. PHOTONIC BANDGAP GUIDING CRYSTAL FIBRES

If the cladding air holes are placed strictly periodical, photonic bandgaps may appear. These are effective index regions, below the effective cladding index, in which no periodic cladding modes are allowed. By breaking the periodicity of the periodic cladding (by e.g., adding an extra air hole to form a low-index core-region), one may introduce a mode that is only allowed in the low-index core-region, while being forbidden in the cladding region because of the photonic bandgap. This core-mode will, therefore, be guided along the fibre, because of the photonic bandgap of the cladding region. If the core mode has an effective index that is either below or above the effective index range covered by the photonic bandgap at the particular wavelength, the core mode will not be strictly guided (though it may still be a resonant, localized mode).

It has been found that silica-air photonic crystals with air holes arranged in a so-called honeycomb lattice are capable of exhibiting PBG effect for much smaller air holes than triangular (close-packed) photonic crystals [13]. Based on this, the first bandgap guiding crystal fibres (inset to Fig. 3) were designed. The inset shows how an extra air hole is introduced into the center of the fibre to act as a low-index defect region. To understand the waveguiding mechanism, it is valuable to consider the fibre using a modal-index illustration similar to the one used for the index-guiding crystal fibre. Fig.3 shows such an illustration and it is seen, that two forbidden regions open up by photonic bandgap effects below the effective cladding index. No modes are seen to appear above the effective cladding index, in agreement with the fact that the low index core-region should not allow guidance of light by modified total internal reflection. However, the extra air hole causes a single mode to be confined to the core defect and correspondingly be guided through the fibre in the frequency range for which the defect mode falls within the bandgap. Hence, the PBG fiber may only support guided modes within certain transmission windows. Depending on the extent of the PBGs, these transmission windows may be several microns wide and centered at near-infrared wavelengths [16].

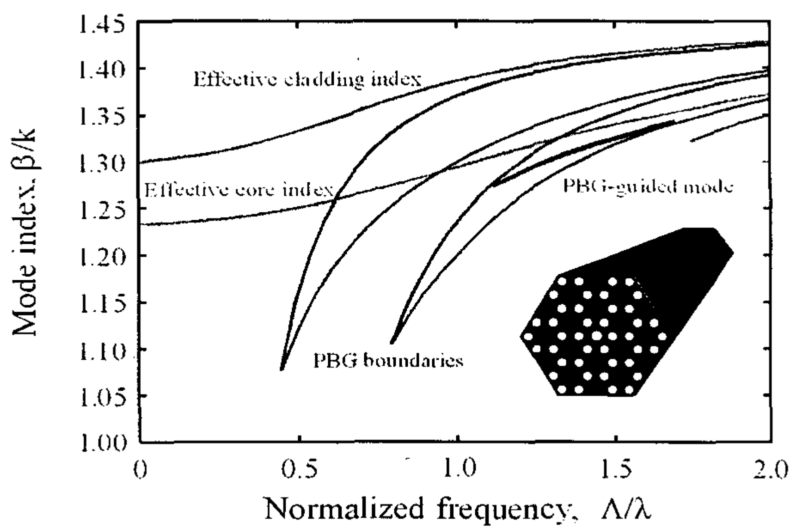


Fig.3. Illustration of the two lowest-frequency PBGs of a honeycomb crystal fibre with a cladding air filling fraction of 30% and a defect hole with same size as the cladding holes. Within the primary PBG, a single degenerate mode is found. This defect mode may not propagate in the cladding structure (due to the photonic bandgap effect) and the mode is strongly localized to the region that breaks the periodicity of the photonic crystal, i.e., the region containing the extra air hole forms the core of the PBG-fibre. The inset shows schematically the design of a honeycomb crystal fibre with the core region formed as a deliberately introduced spatial defect through the use of an extra air hole.

As with TIR-PCFs one can have both confinement in very small core-regions (when employing wide bandgaps), or alternatively single-mode guidance of light in large core-regions. This last possibility was shown in the first practical demonstration of light guided in a hollow core-region [18]. Typically PBG guided modes exhibit positive group velocity dispersion, however, as the guided mode approaches the photonic bandgap edges, the waveguide group velocity dispersion may become either more positive (at the bandgap edge approached at long wavelengths) or negative (at the bandgap edge approached at short wavelengths). For hollow core fibres, this effect may be quite profound, allowing both very strong positive and negative group velocity dispersion, as the guided light spreads out from the hollow core to the surrounding silica [19]. PBG fibres appear to have novel possibilities as non-linear devices, because of the very positive waveguide group velocity dispersion that they allow (even stronger than the non-linear TIR-PCF), and the tight mode confinement that PBG-PCF allow.

Also the hollow core fibres appear to have novel possibilities as a non-linear component. These fibres can be designed to have very low group velocity dispersion, which combined with the possibility of introducing nonlinear gasses into the core-region promises novel non-linear possibilities.

6. LARGE-MODE-AREA PHOTONIC CRYSTAL FIBRES

The most widely addressed class of PCFs contain the index-guiding PCF - or the high-index core PCF. These fibres operate as discussed by the principle of Modified Total Internal Reflection (M-TIR), and they are as such quite similar to standard optical fibres, since they guide light confined to a high-index core surrounded by a cladding with a relatively lower refractive index. In standard optical fibres, the refractive index difference between core and cladding is typically obtained by doping the core region with index-raising materials such as germanium. In PCFs, however, the index difference is obtained by lowering the effective refractive index of the cladding through introduction of air-holes. This allows the fabrication of optical fibres in un-doped silica, but - even more important – the cladding consisting of pure silica and air-holes provides an effective refractive index with unique spectral properties compared to those of solid materials. In other words, the effective refractive index of the cladding may vary in a prescribed manner with wavelength, and we are able to design fibres with spectrally unique properties compared to those of standard optical fibres.
Examples of these new properties include fibres with very large mode field diameters or fibres with very small mode field diameters. In Figure 4, an example of Scanning Electron Microscope (SEM) picture of a Large-Mode-Area (LMA) photonic crystal fibre is shown. This fibre is interesting not only because it has a very large mode field diameter (MFD around 20 microns at a wavelength of 1550 nm), but also because it is single mode for any wavelength at which the silica base material is transparent. This is in contrast to standard optical fibres, which typically have a cut-off wavelength below which the standard fibre becomes multi-moded.

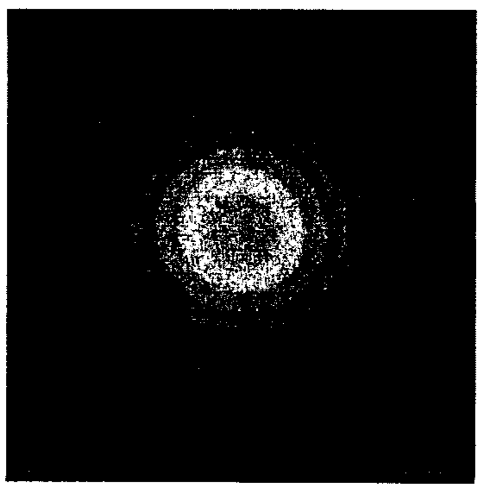


Fig.4: Cross section of a large-mode-area PCF having a mode field diameter of 20 microns at a wavelength of 1550 nm. The near-field picture (recorded at the output end of the fibre) of the guided mode is superimposed. The photograph is kindly provided by Crystal Fibre A/S (Blokken 84, DK-3460, Birkerød, Denmark, http://www.crystal-fibre.com/).

7. HIGHLY NON-LINEAR PHOTONIC CRYSTAL FIBRES

From focussing on the basic photonic crystal fibre itself and its special way of guiding light, research is presently turning towards applications of the fibres. Some of the new applications that are receiving a significant amount of attention is based on non-linear effects in the fibres. Most interest has been directed towards super-continuum generation in PCFs and applications of this in metrology, optical coherence tomography and spectroscopy. The unique property of the highly non-linear (HNL) PCF appears as a combination of very strong mode confinement and altered dispersion properties. A particularly interesting example is the polarization maintaining (PM) HNL-PCF illustrated in Figure 5, with a small mode field area (~3 μm^2) and different mode-dispersion properties of the two orthogonal modes guided by the fibre. Future applications of these non-linear fibres within the telecommunications area comprises advanced all-optical network components such as wavelength converters and signal regenerators.

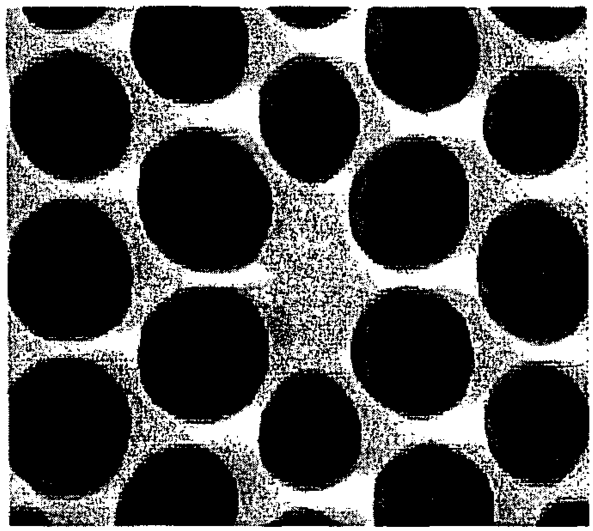


Fig.5: Scanning Electron Microscope (SEM) picture of a highly non-linear polarization maintaining PCF. The photograph is kindly provided by Crystal Fibre A/S (Blokken 84, DK-3460, Birkerød, Denmark, http://www.crystal-fibre.com/).

8. CONCLUSION

Due to the unique ability of photonic crystal fibres to provide novel cut-off, spot-size, and dispersion properties, as well as allowing leakage-free waveguidance in a low-index core region, the potential future applications are numerous. We have emphasized some of the fundamental properties of these new fibers, as well as pointed out their differences compared to conventional fibres and indicated some of their potential future applications.
Photonic crystal fibres offer great design flexibility. The numerical aperture interval that is attainable with silica fibres has been greatly increased from arbitrarily low to a numerical aperture above 0.5. PCFs may, therefore, be superior to standard fibres both as linear and nonlinear fibres. Further PCFs offer completely new possibilities such as positive waveguide dispersion in single-mode fibres and the possibility of guiding light e.g., in hollow cores - by the photonic bandgap effect.

Important issues, such as low losses, low polarization mode dispersion, good control of the properties in the communication windows still need to be addressed for photonic crystal fibres to exhibit their full potential. For specific applications, however, photonic crystal fibres have already proven their worth and more areas will follow as better control of the key parameters is attained.

ACKNOWLEDGMENTS

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