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

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Photonic Bandgap Fibers: Theory and Experiments

by

A.Bjarklev, J.Broeng, and S.E.Barkou

Research Center COM, Technical University of Denmark, DTU, Building 345v, DK-2800, Kgs. Lyngby, Denmark, Phone: + 45 45 25 38 09, Fax: + 45 45 93 65 81, E-mail: ab@com.dtu.dk

Introduction: In 1987, it was suggested [1,2] that the electronic bandgaps in semiconductors could have an optical analogy –the so-called photonic bandgaps (PBGs), which could be found in periodic dielectric structures. This suggestion initiated research activities, which over the past few years have lead to a new class of optical fibers, in which the cladding structure consist of a periodic system of air holes in a matrix of dielectric material –typically silica. These fibers have been given several names ranging from holey fibers [3], microstructure fibers [4], photonic crystal fibers [5], to photonic bandgap (PBG) fibers [6], and it will be a first aim of the presentation to clarify the use of these terms. Originally, it was suggested to place the cladding air holes on a triangular-lattice [7], but recent research has lead to alternative suggestions, such as fibers with air holes situated on a honeycomb lattice [8], or on a Kagomé lattice [9]. We will in the presentation address, how the fiber cladding structure influences the resulting waveguiding properties.

The core may be introduced by breaking the periodicity of the air holes at the center of the fiber. It has been demonstrated experimentally that this makes it possible to localize modes in the core region by the PBG effect. The photonic crystal fibers (PCFs) were first proposed for a high-index-core region, surrounded by a periodic dielectric structure consisting of a matrix of microscopic holes placed in a silica-glass-base material. These early PCFs operated by a total-internal reflection (TIR) like principle. However, the application of the PBG effect makes it possible for the central part of the fiber to be a low-index region (e.g., the fiber core itself contains an air filled micro-channel). Such true-bandgap fibers were first theoretically suggested, and, later experimentally demonstrated. In the presentation, we will provide illustrative examples on the differences between these physical effects, and the most recent research results will be discussed.

PCFs offer the possibility of making all-silica fibers, which may guide light in air. This property may become very useful in combination with sensor technology, where the new waveguides may prove an interesting alternative to evanescent-field waveguides, which for instance have been applied for highly sensitive detection of refractive-index changes. Also, it becomes possible to have fibers with group-velocity dispersion, and bending-loss performance that is quite different from those of standard optical fibers. In the presentation, different PCFs will be compared with respect to fundamental waveguiding properties, and evaluated along the lines of classical optical fibers.

Air guiding crystal fibers: PBG guiding fibers have the highly interesting potential of localizing a high fraction (and in principle all) of the PBG-guided mode(s) in air/vacuum regions. One of the requirements for obtaining such waveguidance in air is that the cladding structure is able to exhibit at least one PBG that covers β/k-values equal to or less than one (where β is the propagation constant of the guided mode and k is the wave number). From a modal index illustration this may be observed as PBGs extending below the air-line (i.e., the line defined by $\beta/k=1$). It is not trivial to determine how to design periodic structures exhibiting PBGs at low β/k-values. However, using a heuristic argument, the ability of a periodic structure to exhibit PBGs extending below the air-line is related to the total air-filling fraction of the structure. Close packing of elongated, circular elements results in a highly air-filled structure, and, therefore, makes the optimum basis-structure for high filling fraction 2D photonic crystals.

In Fig. 1, we have used a modal index illustration to analyze a triangular photonic crystal with very large air holes ($d/\Lambda=0.9$, where Λ is the pitch between holes in the cladding structure). As seen from the figure, several PBGs appear - but only within narrow intervals do they fall below the air-line. However, within each of these intervals, the PBGs allow for the cladding structure to reflect light incident from air. From a practical point of view, the easier PBGs to access are those appearing for the higher normalized frequencies, as this results in the largest structure dimensions with respect to wavelength. Using this knowledge and simple considerations on the core design, Cregan *et al.* have experimentally demonstrated air-guiding crystal fibers having a large hollow core [10]. The first theoretical analysis (see Fig.2) of such air-guiding crystal fibers [11] found that the leakage-free operational windows of the fibers are limited to a few tens of nanometers at visible and near-infrared wavelengths, even for ideal triangular photonic crystals. Considering first applications within the area of telecommunication, then the use of an optical fiber that allows waveguidance in air or vacuum, in principle, holds the potential of breaking fundamental loss-limitations of optical transmission systems. The narrow transmission windows may not necessarily be a limiting factor, even for WDM applications, since a very close

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channel spacing with negligible cross-talk should, in principle, be possible as dispersion and non-linear effect may practically be eliminated. Due to the scalability of the electromagnetic properties of photonic crystals, these air guiding PBG-fibers may, furthermore, be found to be very suitable for providing high-power deliverance at mid-infrared wavelengths over a relatively broad wavelength range - the wavelength ranges around 3.0 and 10.6 microns being especially interesting for medical applications such as laser surgery [12]. The localization of light inside a hollow core has the further potential that a strong light-matter interaction becomes feasible, if the core is filled with e.g., a gas or a liquid, which is very attractive for sensor applications.

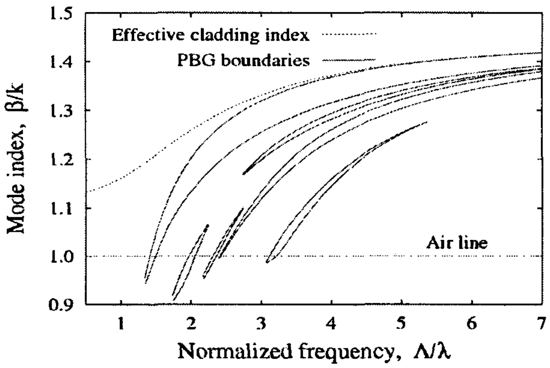

Figure 1: PBGs exhibited by a triangular photonic crystal structure with a relatively high air-filling fraction of 73%. The photonic crystal may reflect light incident from air at the (β/Λ, k/Λ)-intervals, where the air-line falls within one of the PBGs.

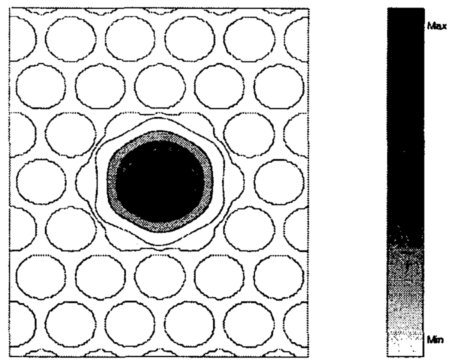

Figure 2: Field distribution of the fundamental, air-guided mode. The dashed lines indicate the air holes in the fiber.

Future work: An important point that must be addressed for the practical development of crystal fibers in the future is their tolerances towards minor fluctuation in the core-cladding region. Previous results have indicated that the degree of structural fluctuations, which may occur during fabrication, can prove crucial for the use of PBG-fibers in applications, where negligible polarization mode dispersion is required (e.g. for long-distance, high-speed telecommunication links) [6]. On the other hand, research also indicates that by deliberately enhancing asymmetries in crystal fibers, birefringence-degrees that are beyond what can be obtained using conventional fibers are feasible –pointing towards the use of crystal fibers for polarization maintaining applications. Another potential applicational area of crystal fibers concerns the introduction of multiple cores within the fibers. These are difficult to realize in conventional fibers, but cause no extra efforts for crystal fibers [13]. Multi-core crystal fibers may be used for various types of sensors (as e.g. bend and strain sensors) or multi-channel telecommunication systems.

Conclusion: While crystal fibers are very much in their infancy, it is clear that they must undergo a long maturity process in order to fulfill some of the attractive prospects that we have addressed. However, due to their unique ability of providing novel cut-off, spot-size, and dispersion properties, as well as allowing leakage-free waveguidance in a low-index core region, the list of potential future applications is so long that further research should be well stimulated.

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