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Dispersion properties of photonic bandgap guiding fibers

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We investigate low-index core photonic crystal fibers. Dispersion properties very different from standard fibers are found. Both zero dispersion and very large dispersion is shown possible at 1550 nm wavelength.

A promising new field in optical fiber technology has appeared within the last few years through the realization of so-called photonic crystal fibers (PCF) [1,2]. Such PCFs are characterized by a wavelength-scale periodic arrangement of air holes on a silica background material (a photonic crystal structure) with a central periodicity-breaking region forming the core. The PCFs, recently fabricated, have had a design based on a triangular photonic crystal cladding structure and centrally a single, missing air hole forming the core. Remarkable properties for this type of PCFs have been reported, as for example single-mode operation over an unusually wide wavelength range (from at least 337-1550 nm) [2], and many other properties significantly different to standard optical fibers are expected [3,4]. Despite the periodic arrangement of air holes (generally classified as a photonic crystal structure), it is, however, important to notice that no photonic bandgap effects in these PCFs have yet been observed. The triangular high-index core PCFs do, however, support a fundamental mode that is index-guided [1]. This is because the fundamental mode confined to the high-index core region, experiences the surrounding photonic crystal cladding as a media with an effectively lower index, thereby allowing total internal reflection to take place.

Fundamentally different to index-guiding is localization of light by the photonic bandgap (PBG) effect. Recently we have presented a new PCF design, and theoretically demonstrated how it is possible, by using an improved photonic crystal cladding structure and a low-index core region, to obtain guided modes having an effective index below that of the surrounding cladding structure [5]. This PBG guiding PCF (see Figure 1) does not support a fundamental index-guided mode, as a result of the low-index core, but relies its operation solely on PBG effects. Of crucial importance is the improved cladding structure, based on a so-called honeycomb photonic crystal, which exhibits PBG effects at realizable fiber parameters, a quality not found in the recent triangular-based PCFs. This exhibition of PBG effects at fabricatable parameters represents of course the most basic requirement for realizing fibers operating by the novel waveguiding mechanism.

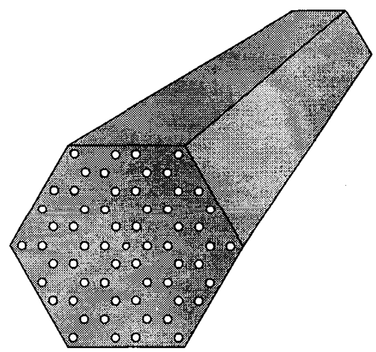

Fig. 1: Schematic of the basic design of a honeycomb-based PBG guiding photonic crystal fiber.

To illustrate the basic characteristics of the PBG guiding PCF, and to serve as a basis for the investigations of its more advanced properties, we have in Figure 2 depicted the modal index, β/k, as a function of the normalized wavelength, λ/Λ, where β is the propagation constant of the mode, k is its free-space wave number, and the normalization factor Λ is the center distance between two nearest air holes. The illustration is for a PCF with cladding hole diameters of 0.55Λ, and a central hole-defect having a diameter of 0.33Λ. For the calculations we employed a super-cell enhanced full-vectorial plane-wave method [6,7] using 1451 basis functions. In the figure, we have also included the envelope of the lowest-order mode, supported by the photonic crystal cladding structure. This envelope defines the effective index of the cladding, and we have used the term radiation line, to emphasize its correspondence with the cladding index of standard fibers. For standard fibers, as well as for the index-guiding

PCFs, the modal index curve is of course appearing above the radiation line, since this is the only region in which localization of light through total internal reflection is possible.

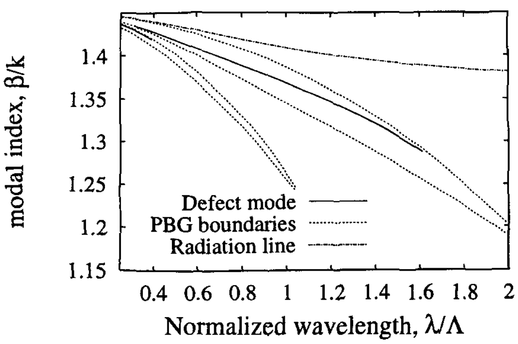

Fig. 2: Modal analysis of the PBG guiding photonic crystal fiber. The material dispersion of silica is not included.

The fundamentally different operation of the PBG guiding PCF is realized, by the opening up of forbidden regions below the radiation line. Within these photonic bandgap regions, the locally broken periodicity around the core region will allow for confinement of light that is being expelled from the (full-periodic) cladding structure. Indeed, a single doubly-degenerate mode is seen to traverse the first bandgap region from approximately $\lambda/\Lambda = 0.3$ to 1.6. Another mode enters the second, lower PBG region at approximately $\lambda/\Lambda = 0.4$ and is extending to $\lambda/\Lambda \approx 0.1$. For the specific parameters presented here, the honeycomb PCF will, thus, be single-moded in the normalized wavelengths range from 0.4 to 1.6. For a PCF with the realistic hole separation, Λ, of 2.0 μm this range corresponds to $\lambda = 0.8$ to 3.2 μm. These so-called defect-modes are strongly confined to the core (despite this being a low-index region), and may thus be guided over long lengths without coupling to the surrounding cladding structure. The PBG effect, hereby, provide us with a completely new type of optical fiber. This is of course of large fundamental interest in the field of optical fiber technology, and due to the different operation compared to today's fibers, we expect them to have a great potential for improving and adding upon the wide range of applications of optical fibers. One of the key aspects is of course the dispersion properties, and in particular we in this work illustrate the new possibilities within dispersion management offered by the PBG guiding fibers.

Qualitative information about the dispersion in the PBG guiding fibers may be obtained by regarding the curvature of the mode-curve in Figure 2. In this context, a strong downwards bending indicate a large positive dispersion, and vice versa, according to the expression

$$D = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2} \qquad (1)$$

where n is the mode index β/k. From Figure 2, we, therefore, realize that the PBG guiding PCF offers the potential of a large positive dispersion in a wavelength range where the fiber is single-moded. This feature is not seen in index-guiding fibers, and is our first indication of the unique dispersion properties of the PBG guiding fibers.

In order to accurately determine the dispersion properties of the honeycomb PCF, we again employed the full-vectorial plane-wave method, but to include also the material dispersion of silica, we used an iterative scheme incorporating the generally used Sellmeier dispersion relation [8]. The result of such a dispersion calculation for a series of honeycomb PCFs with Λ-values ranging from 1.4 μm to 2.9 μm (and hole sizes similar to that of the previously studied PCF) is illustrated in Figure 3. For applications within the area of telecommunication, we have chosen to focus on the wavelength range from 1.2 to 1.7 μm. We notice how a very large positive dispersion may be achieved in this range, in agreement with that expected from the relatively strongly downwards bending mode-curve in Figure 2 (for $\Lambda = 1.4$ μm, this 1.2 to 1.7 μm range corresponds to $\lambda/\Lambda = 0.9$ to 1.2). Especially, dispersion values as large as 250 ps/km/nm km at 1550 nm wavelength is seen to be realizable for the single-mode PBG guiding PCF with $\Lambda = 1.4$ μm.

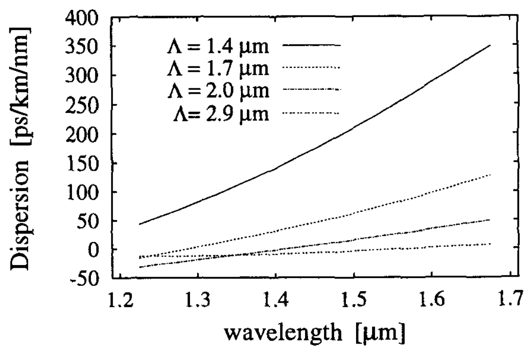

Fig. 3: Dispersion of the PBG guiding photonic crystal fiber. The material dispersion of silica is included through the Sellmeier dispersion relation.

From a more application oriented point of view, it is probably even more relevant to minimize the dispersion variation across a very wide wavelength window, but still keep a certain non-zero value for improved four-wave mixing performance. As described for standard fibers in [9], fibers with dispersion slopes of 0.045 ps/km/nm^2 and dispersion values in the range of 2-8 ps/km/nm have been fabricated. We will, therefore, direct our attention to some of the possibilities of the new PCFs in this respect, and this is indicated by some of the lower curves in Figure 3. Again, in agreement with a corresponding almost linear mode-curve section in Figure 2, we find for $\Lambda = 2.9$ μm the important result of a very flat dispersion curve, having nearly zero dispersion at 1550 nm.

This early study of dispersion in PBG-guiding PCFs, where no optimizations of the PCFs have been performed, leads us to conclude that these new fibers have dispersion characteristics very different from standard optical fibers. Noticeably, the fibers may be designed for flat, near-zero dispersion over a wide wavelength range, or they may exhibit dispersion significantly above the material dispersion. Therefore, new dispersion management schemes appear to be opened up by the emergence of these fibers. At the conference we will be addressing the dispersion properties of realistic PCFs further, and aim at revealing some of their ultimate performance limits.

To conclude, we wish to emphasize that the area of PBG guiding fibers is completely new, and we are here only providing the very first insight into their dispersive properties. We expect much future work to explore their full potential, and this is of course far from limited to dispersion managing purposes only. Finally, the new means of light-matter interaction, only offered by the PBG guiding PCFs, seem also very promising for future sensor applications.

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