Simulations of the effect of the core ring on surface and air-core modes in photonic bandgap fibers

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Abstract: We show through computer simulations that the thin silica ring that surrounds the air core of a photonic-bandgap fiber introduces surface modes. The intensity profile and dispersion of these modes indicate that they are the modes of the waveguide formed by the ring surrounded by air on one side and the photonic crystal cladding on the other. The ring also induces small perturbations of the fundamental core mode. Coupling to those surface modes, which have propagation constants close to that of the core mode, are likely to induce substantial loss to the core mode. By reducing the thickness of the ring and/or by suitably selecting its radius the propagation constants of the surface modes can be moved farther from that of the core mode and the loss reduced.

OCIS codes: (060.2280) Fiber design and fabrication: (060.0060) Fiber optics and optical communications

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1. Introduction

The presence of surface modes in air-core photonic-bandgap fibers (PBFs) is a subject of great interest because of the negative impact of surface modes on the loss of these fibers [1–4]. In previous publications [5–7], a detailed investigation of the existence of surface modes in the particular type of PBF illustrated in Fig. 1(a) has been reported. If the surface of the core cuts through the thicker portions of the silica lattice (which we refer to as corners, see Fig. 1(a)), the core will support surface modes. But if the intersection occurs only at the thinner portions of the lattice (referred to as membranes, see Fig. 1(a)), the core will be free of surface modes. The existence of surface modes has been explained based on the perturbation of the photonic crystal bulk mode by the air-core termination [5–6,8]. Based on this interpretation, a simple criterion has been developed to predict the absence or existence of surface modes from the core geometry alone [6]. This criterion has been used to design air-core PBFs that do not support surface modes at any frequency in the bandgap, and thus presumably fibers that exhibit significantly lower losses [6].

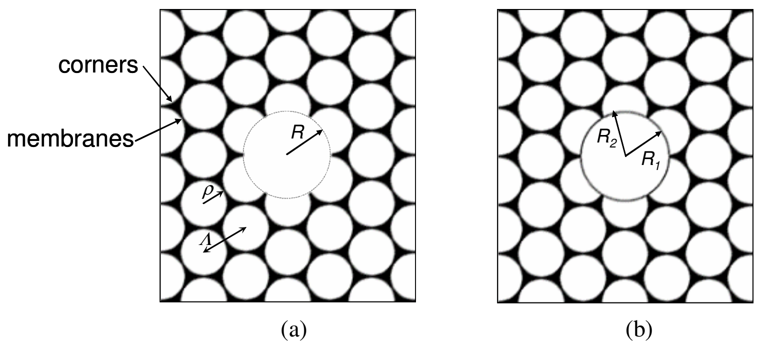

Fig. 1. (a) Cross-section of an air-core photonic-bandgap fiber with a core radius such (R = 0.9Λ) that the core does not support surface modes, and (b) same fiber with a thin silica ring around the core.

In practice, the profile of an air-core fiber is somewhat different from what is shown in Fig. 1(a). A PBF is typically drawn from a preform made of silica capillary tubes stacked in a hexagonal arrangement, and a few tubes are removed from the center of the stack to form the core. One example is illustrated in Fig. 2(a), showing that the air-core is formed by removing seven tubes. During drawing, surface tension pulls on the softened glass walls of the tubes and the originally scalloped outline of the core (see Fig. 2(a)) becomes a smooth thin ring of silica. This ring is a standard feature of current air-core PBFs fabricated. An example is provided in Fig. 2(b), which is a photograph of the cross-section of an air-core PBF fabricated by Crystal Fibre [9]. As far as we aware, similar rings are present in all other commercial air-core fibers [1–4,10].

The presence of a ring at the edge of the core changes the boundary conditions, which are thus different from the boundary conditions for the fiber geometry modeled earlier [5–7]. Consequently, in a ringed air-core fiber we expect new sets of surface modes. The goal of this paper is to describe the results of computer simulations that confirm that a core ring does introduce surface modes, even when the ring is relatively thin (thickness of 0.03Λ, where Λ is the hole-to-hole spacing), which can introduce substantial propagation loss of core modes. The ring also induces small but noticeable perturbations of the fundamental core mode, including intensity profile distortions, increased phase velocity and increased group velocity. Further modeling work is required to understand how to eliminate these surface modes, a step that might be required to further reduce the loss of air-core fibers.

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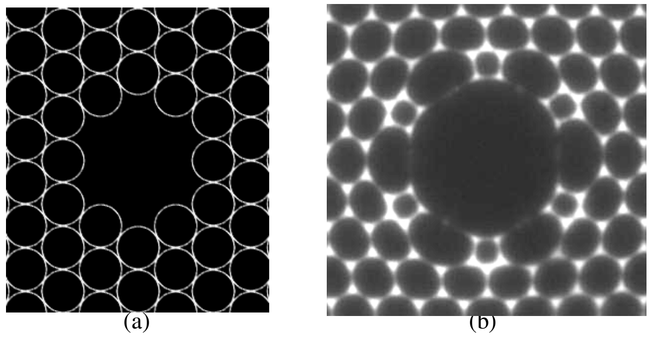


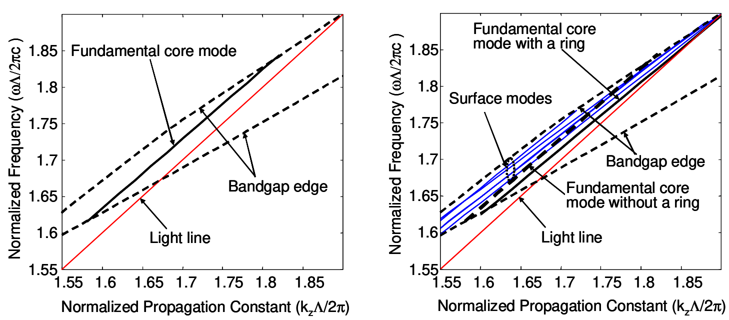
(a) (b)

Fig. 2. (a) Cross-section of a generic preform for an air-core photonic-bandgap fiber, consisting of a stack of silica tubes with the seven center tubes removed to form the fiber's air-core, and (b) photograph of a fiber drawn from such a preform.

2. Simulation of ring surface modes

The air-core fiber modeled in this work is made of a silica photonic-crystal cladding with air holes of radius $\rho = 0.47\Lambda$ arranged in a triangular pattern, as illustrated in Fig. 1(a). A larger air hole of radius R is added to this structure to form an air-core. In a first set of simulations, we investigated the effects of a thin silica ring added at the periphery of the core in the fiber of Fig. 1(a), as shown in Fig. 1(b). The core radius is $R = 0.9\Lambda$. This particular value was selected because with this radius and without the ring, the fiber supports no surface modes [5–7]. The ring has an inner radius $R_1 = 0.9\Lambda$ and a small thickness of 0.03Λ (outer radius $R_2 = 0.93\Lambda$). The bulk, core, and surface modes of this fiber were calculated numerically on a supercomputer using a full-vectorial plane wave expansion method [11]. We used a super-cell size of $8\Lambda x 8\Lambda$ and a grid resolution of $\Lambda/16$.

Figure 3(a) shows the calculated ω-k diagram of this fiber when the core is *not* surrounded by a ring (Fig. 1(a)). For this radius, the core supports only the fundamental mode (which is in fact two-fold degenerate in polarization). The dashed curves represent the bandgap edges of the photonic-crystal cladding.



(a) (b)

Fig. 3. Calculated ω-k diagram of the air-core fiber of (a) Fig. 1(a) (no ring), and (b) Fig. 1(b) (ring present).

When the thin core ring is added, two main changes occur in the dispersion diagram (Fig. 3(b)). First, the dispersion curve of the fundamental mode (solid curve) shifts towards lower frequencies. This shift is apparent when comparing this dispersion curve to the dispersion curve of the fundamental mode of the fiber without a ring, reproduced from Fig. 3(a) as the dashed curve. The intensity profiles of the fundamental modes calculated without and with the ring are plotted in Fig. 4(a) and 4(b), respectively. Without a ring the fundamental mode is strongly confined to the air. When the ring is added, the mode exhibits radial ridges with a

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six-fold symmetry (see Fig. 4(b)), and a slightly higher fraction of the mode energy is now contained in the silica ring. This results in a reduction in both the phase and the group velocities of the fundamental modes, as can be seen in Fig. 3(b).

The second change in the ω-k diagram is the appearance of five new modes (three non-degenerate and two degenerate, see blue curves in Fig. 3(b)). The intensity profiles of these modes show that they are all surface modes. The intensity contour profiles of two of these modes are illustrated in Fig. 5. Both profiles exhibit narrow intensity maxima on open segments of the ring and decay sharply into the air-core and the photonic-crystal cladding. In contrast, the intensity maxima of the surface modes induced by the air-core termination of the photonic crystal [5] always occur on the corners of the photonic crystal. Thus, we believe that these new surface modes do not result from perturbation of the photonic-crystal bulk modes but from the introduction of a thin ring of high-index material surrounded by a photonic-crystal structure on one side and air on the other side.

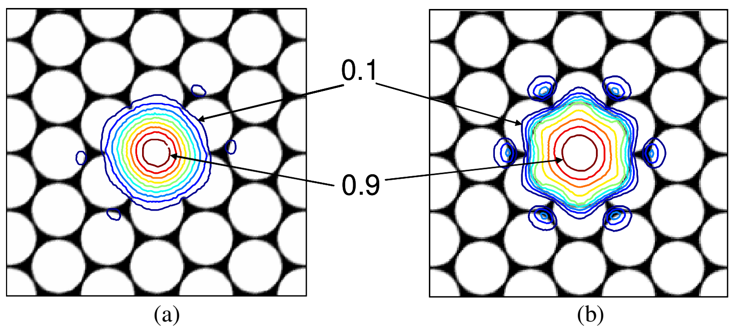

Fig. 4. Intensity contour lines of the fundamental core mode of (a) the fiber of Fig. 1(a) (no ring), and (b) the fiber of Fig. 1(b) (ring present), both calculated at $k_z\Lambda/2\pi = 1.7$. The relative intensity on the contours varies from 0.1 to 0.9 in increments of 0.1.

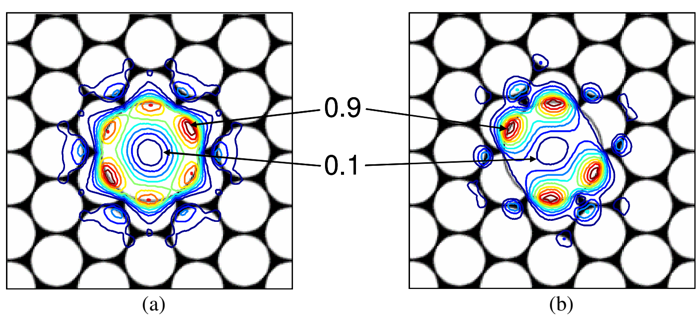

Fig. 5. Intensity contour lines of two exemplary surface modes of the fiber of Fig. 1(b) (ring around the core).

In a second set of simulations, we modeled the effects of adding a thin ring to an air-core fiber that already supports surface modes. To do so, we increased the core radius to $R_1 = 1.13\Lambda$ [5–7]. The profile of this fiber is shown in Fig. 6(a). The calculated ω-k diagram of this fiber is plotted in Fig. 7(a). It shows that this fiber geometry exhibits several surface modes in addition to the two degenerate fundamental core modes.

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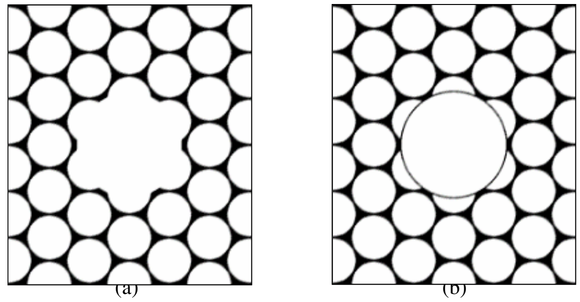

Fig. 6. (a) Cross-section of an air-core photonic-bandgap fiber with a core radius such (R = 1.13Λ) that the core supports surface modes, and (b) same fiber with a thin silica ring around the core.

When a thin silica ring encloses the core (Fig. 6(b)), the ω-k diagram evolves to the new diagram shown in Fig. 7(b). Again, the two nearly degenerate fundamental modes are slightly down-shifted in frequency. For the same physical reasons, the six pre-existing surface modes are also frequency down-shifted. This shift is larger for the surface modes than for the fundamental modes, which means that the surface modes are pushed away from the fundamental modes. Thus a benefit of introducing a thin ring is that it can decrease the coupling efficiency of pre-existing surface modes to the fundamental modes, and thus reduce the fundamental-mode loss due to coupling to these surface modes. However, the addition of the thin ring also introduces a new group of surface modes, as can be seen in Fig. 7(b), and their profiles are qualitatively similar to the profiles of the surface modes introduced by a ring in an air-core fiber (see Fig. 1(b) and Fig. 5).

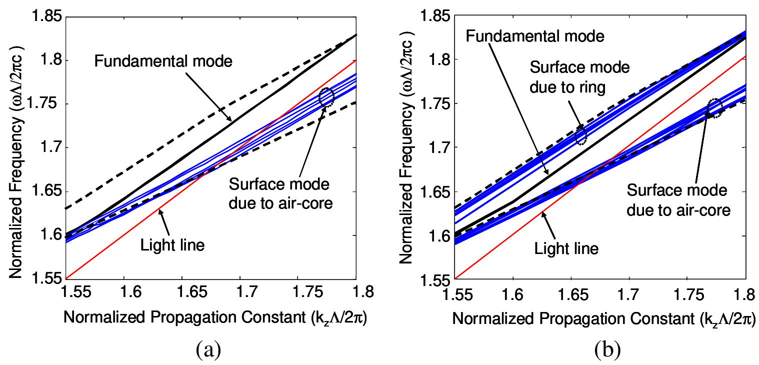

Fig. 7. Calculated ω-k diagram of the air-core fiber of (a) Fig. 6(a) (no ring), and (b) Fig. 6(b) (ring present).

Detailed theoretical investigations of the surface modes of air-core PBFs with geometries comparable to that of manufactured fibers have been reported recently [1–2,5,6,7,12]. We used cross-sectional profile similar to those of Refs. [7,12] to investigate the characteristics of the surface modes existing in this fiber geometry. In our current simulations, the thin ring surrounding the air-core has been simplified to a circular ring, as shown in the inset of Fig. 8, which is slightly different from the fiber geometry used in reference 12. The dispersion curves of core and surface modes, and intensity profiles of four exemplary surface modes are shown in Fig. 8. With this fiber geometry, we found two groups of surface modes. In the ω-k diagram, one group lies just below the upper band edge (labeled group 1 in the lower diagram of Fig. 8) and the other group lies just above the lower band edge (labeled group 2). The overall dispersion behavior is similar to the results given in earlier reports [1–2, 7, 12]. Looking at the intensity profile (Fig. 8), surface modes in group 1 are mainly localized on the open segments of the core ring of the fiber. We believe that the origin of these surface modes

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is the same as that of the ring surface modes in Fig. 7(b). On the contrary, the surface modes in group 2 now exhibit their intensity maxima at the corners of the photonic crystal, which is similar to the surface modes generated by the air-core termination described as the pre-existing surface modes in Fig. 7(b). The localization of the surface modes of group 2 is different from what was reported in reference 12, in spite of their similar dispersion curves. These differences are believed to be due to the slight changes in the modeling core geometry, which suggests that very small perturbations in the silica geometry surrounding the air-core can affect the surface mode behavior significantly.

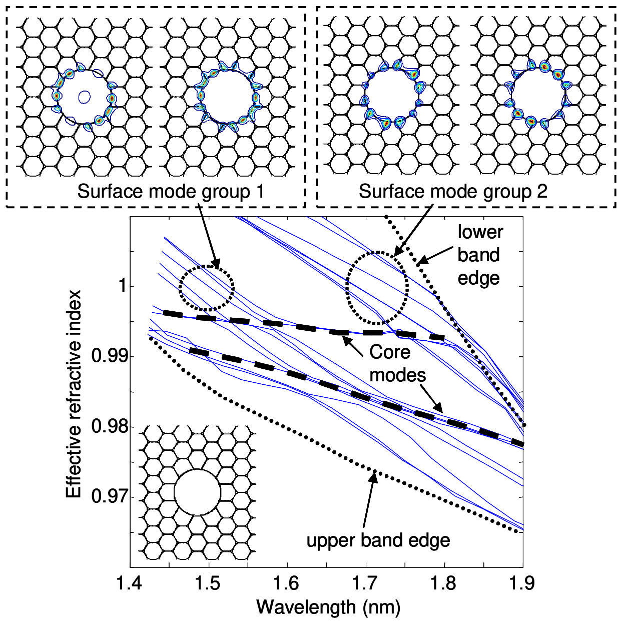

Fig. 8. Dispersion curves of core modes and surface modes, and intensity profiles of four exemplary surface modes simulated with the simplified air-core fiber geometry in references 7 and 12.

3. Reducing the effects of ring surface modes

The main implication of these results is that even if the core radius of a ring-less PBF is selected to avoid surface modes, as prescribed in earlier studies [5–7], surface modes are still likely to be present due to the ring-like geometry surrounding the air-core, which may be formed during the drawing the fiber.

The ring surface modes can be alleviated in several ways. The first approach is to fabricate fibers without a core ring, as suggested earlier [5–7]. This design leads to fibers that carry a single mode and no surface modes across the entire bandgap. Alternatively, the radius and/or thickness of the ring can be selected to reduce the number of ring-induced surface modes, to move them away from the fundamental mode in the ω-k diagram, or both; all cases result in a reduction in fiber loss. Our simulations show that for a constant ring thickness (0.03Λ), when the ring radius is increased from 0.8Λ to 1.13Λ the number of ring surface modes remains unchanged. So over the range of core radii for which the fiber is single-moded, there is no choice of radius that reduces the number of surface modes. However, increasing the ring radius from 0.8Λ to 1.13Λ does shift the dispersion curve of the ring surface modes up in frequency, i.e., away from the dispersion curve of the fundamental mode (compare Fig. 3(b) and Fig. 7(b)). Using a large core radius will therefore increase the detuning between the

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fundamental and surface modes, and thus possibly weaken the coupling between them and lower the fiber loss.

Simulations also indicate that for a fixed ring radius ($R = 0.9\Lambda$), the number of ring surface modes increases with increasing ring thickness, from five modes for thicknesses of 0.03Λ to ten modes for a thickness of 0.09Λ. Selecting a thinner ring therefore helps reduce the number of surface modes. It would be interesting to establish whether ring surface modes are completely eliminated by making the ring thin enough. However, accurate modeling of PBFs with a ring substantially thinner than 0.03Λ requires a much lower grid resolution than used in this work ($\Lambda/16$), which increases computation time and RAM requirement considerably. As an alternative, we modeled a planar photonic crystal (PC) terminated across its membranes by an infinite thin plane slab, as illustrated in Fig. 9. The PC has the same triangular hole pattern in silica and the same air hole radius ($\rho = 0.47\Lambda$) as the PBFs modeled above. The advantage of modeling a photonic crystal instead of a fiber is that because of the PC symmetry, a much smaller super-cell size can be used, in this case $1\Lambda \mathrm{x} 16\sqrt{3}\Lambda$ instead of $8\Lambda \mathrm{x} 8\Lambda$, and consequently for a given computation time the grid resolution can be much smaller ($\Lambda/64$). These simulations showed that the number of slab surface modes inside the bandgap decreases with decreasing slab thickness. Simultaneously, their frequencies increase. We found that in this planar photonic-crystal structure, the frequency of the lowest band surface mode starts to be detuned from the bandgap region when the thickness of the thin slab is below some finite value (0.005 in this simulation), and no surface modes exists inside the bandgap for slab thicknesses smaller than this value.

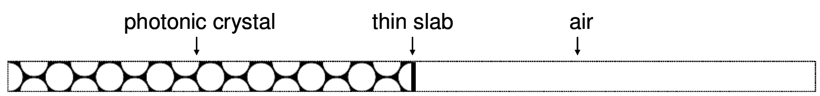

Fig. 9. Photonic crystal terminated by a thin slab used to model very thin PBF core ring.

4. Conclusions

We have studied through computer simulations the effects of the thin silica ring that typically surrounds the air-core of photonic bandgap fibers on the existence of surface modes. We found that even a very thin ring (thickness = 0.03Λ) introduces new surface modes with intensity maxima centered on the open segments of the ring, which is likely to increase the propagation loss of the fundamental mode. The presence of a ring also induces small intensity profile distortion and an increase in the group velocity of the fundamental core modes. We showed that reducing the number of ring surface modes and detuning their frequencies from the core modes can be achieved by designing the ring thickness and its radius suitably, which could alleviate the effect of ring surface modes on the core modes. In addition, the pre-existing surface modes that were present without the ring still exist, but they can be moved in frequency by changing the thickness and radius of the ring.

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