Air-guiding photonic bandgap fiber with improved triangular air-silica photonic crystal cladding

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Abstract

We introduce a small-core air-guiding photonic crystal fiber whose cladding is made of improved air-silica photonic crystal with non-circular air holes placed in triangular lattice. The fiber achieves un-disturbed bandgap guidance over 350nm wavelength range.

1. Introduction

Lightwave delivery in a hollow-core photonic crystal fiber (PCF) is of significant importance for applications like laser beam handling, nonlinear optics in gases, sensing, atom/particle guiding, and even for low-loss optical communication etc.¹,² Current air-guiding PCF [Fig. 1(a)] explicitly uses air-silica photonic crystal (PC) made from a bundle of thin silica tubes (triangular placement) in its cladding.² Such fiber has two main disadvantages: surface-mode interference and multimode operation. Though theoretically, there does exist some design which eliminates the surface-mode problem,³ such fiber hasn’t been fabricated, largely due to difficulties in preform preparation and maintaining the core shape during drawing. In this paper, we introduce a hollow-core PCF [Fig. 1(b)] whose cladding is made of newly proposed air-silica PC.⁴ The improved PC allows designs with smaller core size and/or wider transmission window, etc.⁴ We will show that the air-guided mode in our proposed fiber has an un-disturbed transmission over 350nm wavelength range, owing to the fact that the surface modes stay very close to the bandgap edge. Potential single-mode operation with such type of hollow-core PCF is also suggested.

2. Design and Numerical Analysis

In Fig. 1 we show three air-guiding PBG fibers. In fact, both cladding PCs in Fig. 1(a) and (b) are derived from the rods-in-air PC shown in Fig. 1(c). Guiding mechanisms of three fibers are of no difference — all of them can guide light with a cladding bandgap that exists between the PCs 4th and 5th bands (computed using the plane-wave method with primitive
basis vectors); and we find the mode profiles in low-order bands are equivalent for three PCs. One portion of the cladding PC unit in Fig. 1(b) is sketched in Fig. 2. For the particular fiber shown in Fig. 1(b), its cladding has $\Lambda = 2.6 \mu m$, $d = 0.98\Lambda$ ($s = 0.02\Lambda$), $r = 0.14\Lambda$, and $\theta = 40^\circ$. The core is formed by removing 12 silica pillars. Though we can easily get rid of the surface-mode problem theoretically by using a design rule suggested in,\(^5\) we stick to a practical core shape [Fig. 1(b)] to facilitate easy stacking and pressurization. Extra silica veins surrounding air core are of thickness $s$.

![Fig. 1. (a) Air-guiding PCF reported in Ref. 2. (b) Proposed air-guiding PCF. (c) Ideal rods-in-air PCF. Black is for air.](image)

The photonic bandgap (PBG) region possessed by the cladding PC is shown in Fig. 3(a) by the white patch. It is noticed that the region is extending beyond air line to $n_{eff} = 0.922$ (not shown), which is significantly smaller than the value achievable with PC in Fig. 1(a) (0.968). This feature allows us to design air-guiding fibers with smaller core and/or lower-loss air-guiding PCFs. We then use a full-vector finite-difference mode solver\(^6\) to compute guided defect modes with four air-hole rings in the cladding. Numerical resolution is at $dx = dy = 0.12\mu m$ with $11 \times 11$ sub-grid index averaging. Perfectly matched layers have 12-grid thickness. The two degenerate fundamental air-guided modes (HE\(_{11}\)-like) are shown

![Fig. 2. Schematic diagram of a portion (1/6) of the improved PC unit. Thick line is air-silica interface, with air to its left.](image)
Fig. 3. Dispersion (a) and loss (b) curves of the defect modes. Photonic bandgap region of the cladding PC is represented by the white patch in (a).

by the thick solid curve in Fig. 3(a). It is found the modes are un-disturbed in 1.35 ~ 1.70µm wavelength range. Their loss spectrum is shown by the thick curve in Fig. 3(b). Minimum loss is about 1dB/m.

The $|E_x|$ field distributions of modes at point A ($\lambda = 1.55\mu$m, air-guided mode) and B ($\lambda = 1.3\mu$m, surface mode) are shown in Fig. 4(a) and (b), respectively. The core mode at 1.55µm is very well confined, and it has leakage loss of 1.2dB/m, which will decrease to 0.053dB/m and 0.003dB/m when the number of rings in cladding is five and six, respectively. Though the six-ring loss value is higher than that for the fiber given in Fig. 1(a), it should be reminded that our core size is significantly smaller (diameter $\sim$ 7.4µm v.s. $\sim$ 13.6µm). Loss should be decreased if additional pillars are removed in core region.

The proposed fiber is still multimode, largely because the gap region extends quite far beyond air line. The dispersion curves of second-order modes (TE$_{01}$-, two HE$_{21}$- and TM$_{01}$- like modes) are shown in Fig. 3(a) by four thin solid lines. Their loss values (in dB/m),
Fig. 4. Air-guided mode at $\lambda = 1.55\mu m$ (a) and surface mode at $\lambda = 1.30\mu m$ (b). Contour lines are in 1-dB separation.

represented by thin lines in Fig. 3(b), are about 30 times higher than that of the fundamental modes. It should be noticed that, due to the small core size, the dispersion curves of the fundamental and second-order mode groups in Fig. 3(a) stay further apart as compared to the fiber reported in.\textsuperscript{2} This means the coupling between the two mode groups is smaller. With careful excitation, we can achieve single-mode operation for applications like laser beam delivery, in which severe fiber bending can be purposely avoided.

Surface modes are denoted by dotted lines in Fig. 3. An obvious advantage of our fiber is that the surface modes stay very close to the bandgap edge. We attribute this to the analogousness between silica pillars nearby core and those in cladding. It is observed from Fig. 4(b) that a nodal line appears in each silica pillar adjacent to core. Such surface modes are similar to 5\textsuperscript{th}-band bulk cladding mode. They are pulled into gap region because the pillars nearby core have slightly more silica than those in cladding PC. Hence their modal energy is lower (higher in $n_{\text{eff}}$). By varying cladding PC parameters, we should be able to further reduce the impact of these modes, \textit{i.e.}, to push them closer to the gap region boundary.

3. Conclusion

We have proposed a low-loss air-guiding PCF design which has 350nm un-disturbed PBG guiding wavelength range.

Acknowledgements

M. Yan acknowledges Optical Fibre Technology Centre, University of Sydney for providing computing facility. He is partially supported by a scholarship provided by A*STAR, Singapore.
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