Two-mode photonic crystal fibers

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Abstract: Index-guiding photonic crystal fibers with appropriate structural parameters support the fundamental and second order modes over a practically infinite wavelength range. The polarization principal axes and mode field patterns of the modes can be made stable by having different size air-holes along the orthogonal directions. The potential applications of such two-mode PCFs are discussed.

OCIS codes: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication; (060.2340) Fiber optics components; (060.2370) Fiber optics sensors; (999.999) Photonic crystal fiber

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1. Introduction

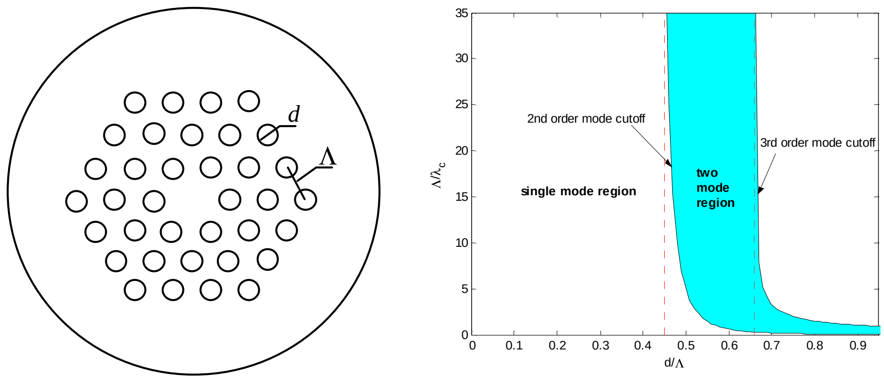
An index-guiding photonic crystal fiber (PCF) has a solid core surrounded by a holey cladding region. A typical index-guiding PCF is fabricated by stacking silica capillaries periodically in a hexagonal close packed array and replacing the central capillary with a solid silica rod of the same outer dimension [1]. This PCF is characterized by two parameters, i.e., the hole-spacing or pitch Λ and the relative hole-size d/Λ. For a small relative hole diameter, i.e., $d/\Lambda < 0.45$, such a fiber support a single mode for any wavelength [2], independent of the value of Λ. This allows for the development of single mode fibers with mode field diameters designable from 5 to 35 μm [3], which are useful for a number of applications including single mode power delivery. With large d/Λs and small Λs (e.g., in the range of 1-3μm), the PCFs can be made to have very small mode field area and with anomalous dispersion in visible & near infra-red regions [3-6]. These fibers are called nonlinear PCFs (NL-PCFs) that have very high effective nonlinearity and have been used for super-continuum generation. Similar small core PCFs have also been used for evanescent wave devices and sensor applications [7, 8].

In this paper, we report our findings that the PCFs with intermediate d/Λs support two-modes over extremely broad wavelength ranges and discuss the possible applications of such PCFs.

2. Two-mode PCF

Figure 1(a) shows the cross-sectional diagram of the PCF considered here. In Fig. 1(a), only three rings of air-holes are shown. In practice, 6 to 10 rings of air-holes are often needed to reduce the confinement loss to an acceptable level. A super-cell method [9] was used to evaluate the modal property of the PCF for various d/Λs, and the normalized cut-off frequency (Λ/λ_c) of the second and third higher order modes as functions of d/Λ are shown in Fig. 1(b). In obtaining the cut-off frequency of the PCF for a particular d/Λ, we calculated the mode indexes of the second and the third order modes as functions of normalized frequency (Λ/λ) and took the cross-point between these curves and the dispersion curve of the fundamental space filling mode of the cladding material as the normalized cut-off frequency

(Λ/λ_c) [10,11]. The normalized cut-off frequency (Λ/λ_c) was found to be independent of Λ due to the scaling property of the Maxwell wave equations.



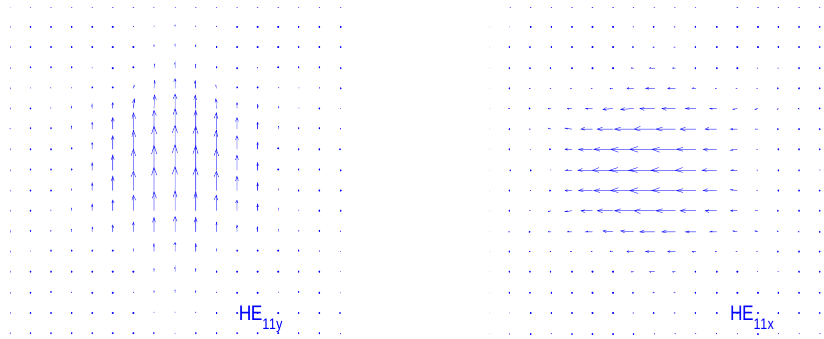
(a) (b)

Fig. 1 (a) Cross-section of a PCF with triangular lattice; (b) Λ/λ_c – d/Λ plot showing the two-mode operation range.

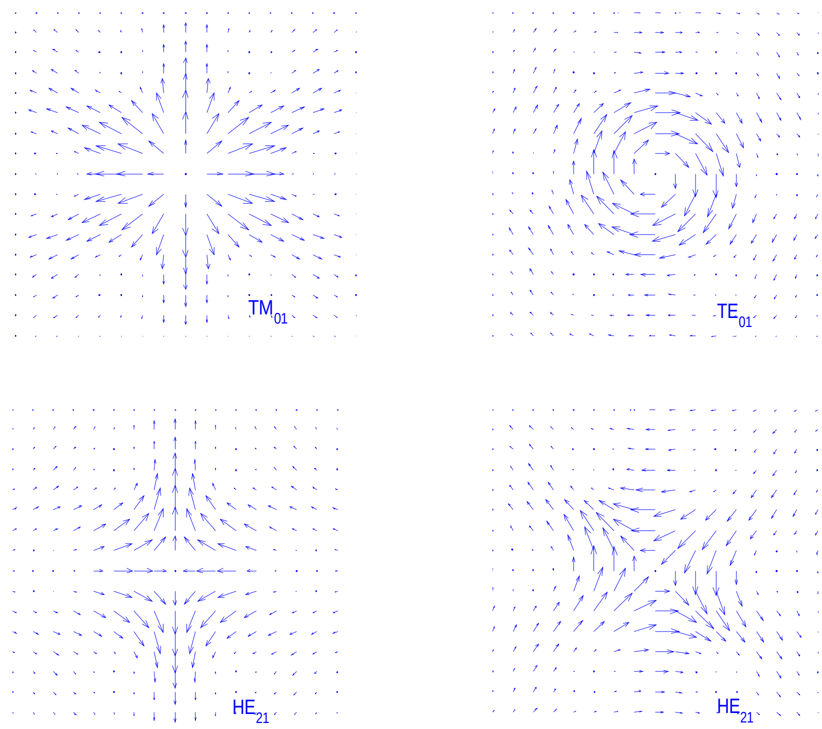
As shown in Fig. 1(b), the PCF supports only the fundamental mode below cut-off line of the second order modes, and is endlessly single mode for $d/\Lambda<0.45$. Within the shaded-region in between the cut-off lines of the second and the third order modes, the PCF supports both the fundamental mode and the second-order hybrid mode comprising of four true modes as shown in Fig. 2(b). These four true modes resemble the TE_{01}, TM_{01} and the two HE_{21} modes in a conventional step index fiber. The two-mode region shown in Fig. 1(b) corresponds to d/Λ from approximately 0.45 to 0.65. Within this range of d/Λ, the PCF supports only the fundamental and the second-order modes for wavelength satisfying $\lambda<\lambda_c$, where λ_c is the cut-off wavelength of the PCF, i.e., the cut-off line of the second order modes as shown in Fig. 1b. This two-mode property holds in principle for any value of Λ, as long as the d/Λ is within the specified range as shown in Fig. 1(b). Take $d/\Lambda=0.55$ as an example, the fiber supports two hybrid modes for $\Lambda/\lambda>\Lambda/\lambda_c\approx1.6$. This corresponds a two-mode wavelength range of $\lambda<\lambda_c$ with λ_c approximately equals to 1.9μm and 3.3μm for Λ=3μm and 5μm, respectively. These wavelength ranges are practically infinite for silica fibers as they are usually not used for light transmission at wavelength beyond 1.8 μm due to the very large attenuation loss of silica material. These PCFs may then be regarded as “endlessly two-mode”, i.e., fibers that support two modes for any wavelength within the low loss window of the silica material.

Figure 2 shows the mode field patterns of the first and the second order modes for a PCF with Λ=5μm and $d/\Lambda=0.6$, at wavelength 1550nm. For the same set of parameters, the beat lengths between the fundamental and the four second order modes, defined as the lengths of fiber over which the phase difference between the respective modes changes by 2π, as functions of wavelength are shown in Fig. 3. The four curves in Fig. 3 are almost identical, indicating the approximately degenerate nature of the four second order modes.

The modal properties of index-guiding PCFs have been studied previously [12-14], including theoretical investigation of the second-order modes cutoff [12,13] and experimental investigation of cutoff phenomena in NL-PCFs with pitch Λ from 1.2 to 1.41μm [14]. However, previous investigations focused on the boundary between the single- and the second order modes that determines single mode operation region. We here report the boundary, in terms of a Λ/λ_c – d/Λ plot, between the second and the third order modes, which, coupled with the boundary between the fundamental and the second-order mode, determines a region for two-mode operation.



(a)



(b)

Fig. 2 Field patterns of (a) the two polarizations of the fundamental mode; (b) the four approximately degenerate second-order modes

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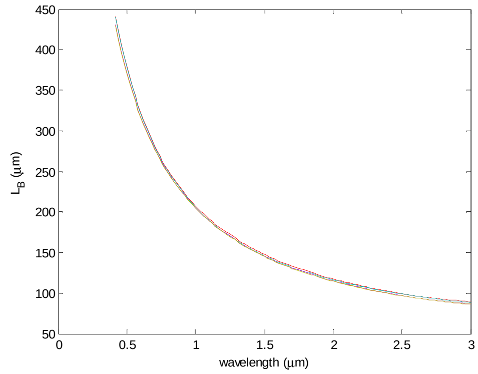

Fig. 3 Beat lengths between the fundamental mode and the four second-order modes as functions of wavelength.

3. Highly birefringent two-mode PCF

As discussed in Section 2, the four second-order modes are actually not exactly degenerate and the hybrid mode field intensity pattern actually varies along the fiber length due to the coherent mixing of the four modes and is not stable against environmental disturbance. The same applies to the polarization states of the fundamental mode. One way to overcome this problem is to intentionally introduce birefringence by for example having air-holes with different diameters along the two orthogonal directions [15, 16]. Figure 4 shows a particular PCF in which the pair of holes on the opposite sizes of the core is made bigger than the rest of the holes. This fiber is birefringent and the four second-order modes are in general non-degenerate.

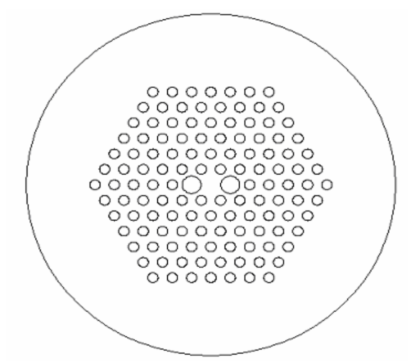

Fig. 4. Cross-section of a Hi-Bi PCF

It has been reported that disorder in the air-holes leads to deformation of the higher order modes in small-core PCFs [17]. The second-order modes split into two groups, resemble the LP_{11}(even) and LP_{11}(odd) hybrid modes in elliptical core fibers [18] and other asymmetric waveguides [19]. The difference between the cutoff wavelengths of the two groups in small-core PCFs have been investigated experimentally and found to be as big as 42nm [14]. For the PCF shown in Fig. 4, we found that when the two bigger holes are sufficiently large, the cutoff wavelengths between the two groups can be several hundreds of nanometers [20]. The remaining second-order modes have stable mode field pattern and polarization directions, which resemble the two orthogonal polarizations of the LP_{11}(even) mode as in the elliptical-core fibers [18].

Figure 5 shows the field patterns of the fundamental and the second-order modes for a highly birefringent PCF with d/Λ=0.54, d_{big}/Λ=0.98 and Λ=6μm at wavelength 1550nm. Our theoretical modeling based on the intersections of the dispersion curves of waveguide modes

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and the fundamental space filling mode of the cladding [11], and on the observation of the mode field distributions shows that the fiber supports and only supports the fundamental LP_{01} and the second order LP_{11}(even) modes within wavelength range of 0.6μm to 2μm, which covers almost the entire low loss window of the silica fibers.

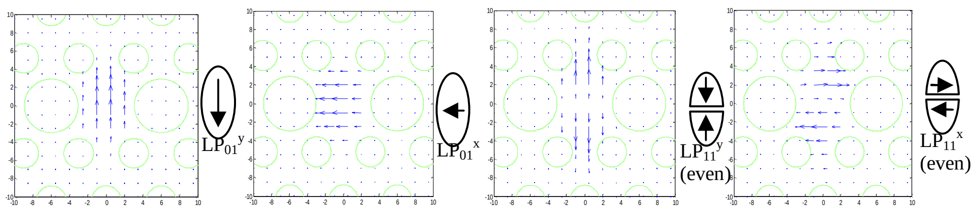


Fig. 5. mode field patterns of the fundamental LP_{01} and the second-order LP_{11}(even) modes.

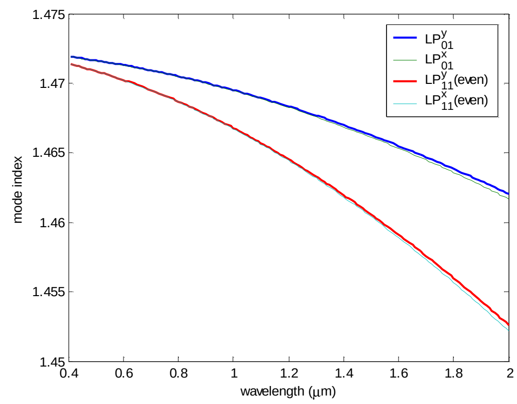
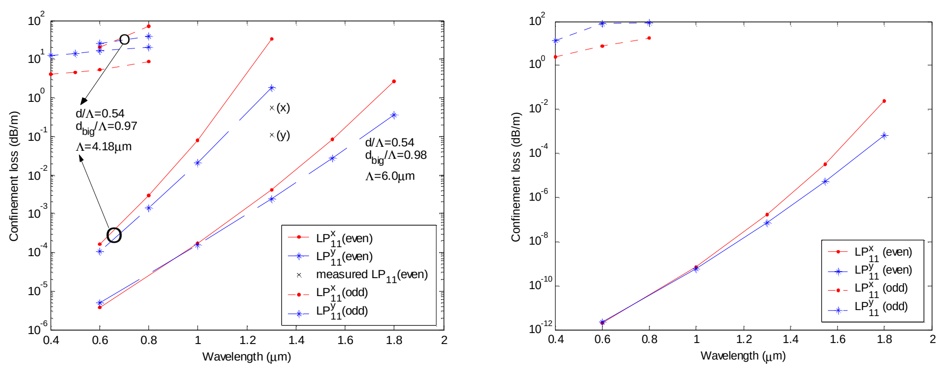


Fig. 6. Mode indexes of the fundamental and the 2nd order modes as functions of wavelength



(a) (b)

Fig. 7. Confinement losses of the second-order LP_{11}(even) and LP_{11}(odd) modes as functions of wavelength. (a) Two types of PCFs with 6 rings of air-holes; the parameters of the fibers are respectively Λ=4.18μm, d/Λ=0.54, d_{big}/Λ=0.97 and Λ=6μm ,d/Λ=0.54, d_{big}/Λ=0.98. (b) The two-mode fiber designed for operation from 0.6μm to 1.8μm with 10 rings of air-holes and with Λ=6μm, d/Λ=0.54, d_{big}/Λ=0.98.

The computed mode indexes of the orthogonal polarizations of the two modes as functions of wavelength are shown in Fig. 6. The computed confinement losses of the LP_{11}(even) and LP_{11}(odd) modes, for claddings consisting of 6 and 10 rings of air-holes, as functions of wavelength are shown in Figs. 7(a) and 7(b) respectively. With 10 rings of air-holes, the confinement losses of the LP_{11}(even) modes are less than 0.025dB/m for wavelength below 1.8μm, sufficient low for many devices applications. The LP_{11}(odd) modes are found leaky with losses of bigger than 17dB/m for wavelength at 0.8μm and beyond. The confinement

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losses of the LP_{11}(even) and LP_{11}(odd) modes for an idealized model of a real PCF from Blazephotonics, which was designed as a single mode polarization maintaining fiber at 1.55µm, were also computed and shown in Fig. 7(a). The fiber has 6 rings of air-holes with idealized fiber parameters of Λ=4.18µm, d/Λ=0.54, d_{big}/Λ=0.97 [3]. This fiber was found to guide two modes (LP_{01} and LP_{11}(even)) within wavelength range from ~0.65 to ~1.32µm. The measured loss of the LP_{11}(even) mode for the two orthogonal polarization states of the Blazephotonics fiber are also shown in Fig. 7(a). The measured losses are actually smaller than those of computed ones due to discrepancies between the real fiber structure and the idealized model, as have been observed for other PCFs [21]. The LP_{11}(odd) mode was not observed within wavelength range ~0.65 to ~1.3µm even when the launching condition was varied, indicating that the PCF does not support this mode over this wavelength range.

4. Potential application

Similar to the conventional and elliptical core two-mode fibers, the two-mode PCFs discussed above can be used for a number of applications [18, 22-31] such as mode converters, mode selective couplers, bandpass/bandstop filters, acousto-optic frequency shifters, acoustic-optic tunable filters, wavelength tunable optical switches, add-drop multiplexers, nonlinear frequency conversion, dispersion compensator, variable optical attenuator, and interferometric fiber sensors. However, the wavelength range for two-mode operation in the PCFs is many times bigger than that of the conventional core elliptical fibers, allowing for two-mode devices with much broader wavelength range to be created. The wavelength range for two-mode operation in an elliptical core is typically limited to around 150nm [29], which sets a limit to the operating wavelength range of the two-mode devices using a particular two-mode fiber. To develop two-mode devices suitable for different operating wavelength, elliptical core fibers with different structural parameters need to be used. This requires complicated fiber design and fabrication process. Two-mode devices with different operating wavelength range may be made by using the same two-mode PCF, without going through the re-designing process. The two-mode PCFs, coupled with the use of endlessly single mode PCFs or endlessly single mode polarization maintaining PCFs as lead-in/lead-out fibers, would allow for extremely broadband devices that can not be created with conventional technologies. The dimension (e.g., Λ) of the two-mode PCF can also be scaled up and down in order to optimizing coupling to various pigtail fibers while still keeping working in the two-mode regime.

Two-mode PCF-based inteferometric strain sensors have been experimental demonstrated at wavelengths from 650nm to 1300nm [20]. Efficient couplings from the fundamental mode to the second-order modes and to the anti-symmetric cladding modes in index-guiding PCFs have been demonstrated by periodic axial deformation [32] and by flexural acoustic waves [33], respectively. These demonstrations, coupled with the availability of various two-mode fiber over practically infinite wavelength range, will allow extremely broadband devices to be developed.

5. Conclusion

Index-guiding PCFs with appropriate structural parameters were found to support the fundamental and second order modes over a practically infinite wavelength range. Highly birefringent index guiding PCFs with different size air-holes along orthogonal directions support only the LP_{01} and LP_{11}(even) modes with stable mode field intensity patterns and polarization principal axes. These two-mode PCFs will have important applications in all fiber devices such as an all fiber optical filter that can be tuned from 600nm to 1800nm.

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