Theoretical Design of Single-Polarization Single-Mode Microstructured Polymer Optical Fibres *

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Using the full-vector plane-wave expansion method, a kind of PMMA-based polarization-maintaining microstructured optical fibre (PM-mPOF) is theoretically studied. Dependence of the cutoff wavelengths of the two orthogonal polarization states (polarized along the two principal axes of PM-mPOF) on the structure parameters of the fibre is investigated in detail. A single-polarization single-mode (SPSM) PM-mPOF working in the visible region is designed and optimized with the result of the maximum SPSM bandwidth of 140 nm.

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Microstructured optical fibres (MOFs), also called photonic crystal fibres (PCFs), usually consist of a hexagonal arrangement of air holes that run along the length of the fibre, with a single missing air-hole that forms a core region of raised refractive index and that effectively guides light by total internal reflection. Compared to the conventional solid fibre which relies on changing the refractive indices of the fibre core and fibre cladding, fibres with specific optical characteristics can be easily realized in MOFs by simply changing the hole size, hole spacing, hole shape or hole distribution in the cladding. For example, by obtaining different air hole diameters along the two orthogonal axes, highly birefringent MOFs have been realized, which can be an order of magnitude higher than that of conventional highly birefringent fibres.[1,2] Also, in this kind of highly birefringent MOFs, single-polarization single-mode (SPSM) characteristics can be obtained,[3−6] and there appear possibilities of realizing better SPSM property than conventional SPSM fibres.[6] Moreover, MOFs are indicated to be more robust towards bending compared to the solid single-mode fibre.[7]

Recently, polymer optical fibre (POF) technology has attracted significant attention with the expectation of that POF will be an integral part of datacom networks, especially for the last mile of the telecommunications networks. It is well-known that POF has the advantages of high flexibility, large core diameter and numerical aperture, low costs for installation and maintenance, non-sensitivity to vibrations and high bandwidth, etc. Moreover, with both the advantages of PCF and POF, microstructured polymer optical fibres (mPOFs) have received more attention in recent years.[8−10] These include the possibility to combine single-mode behaviour with large mode areas, which is the ideal combination of easy handling and processing and installation.

In this Letter, using the full-vector plane-wave expansion method, highly birefringent polarization maintaining microstructured polymer optical fibres (PM-mPOFs) are studied, in which two air holes that are adjacent to the fibre core have diameters greater than those of the other cladding holes. For the first time to our knowledge, the dependences of the cutoff wavelengths of two orthogonal polarization states (polarized along the two principal axes of the PM-mPOF) on the structure parameters of this kind of fibre are numerically investigated in great detail. An SPSM PM-mPOF working in the visible region (corresponding to the loss window of PMMA-based fibres) is designed and optimized. The SPSM PM-mPOF with the SPSM bandwidth of 140 nm is obtained at the working wavelength of 650 nm. This makes the SPSM PM-mPOF become the potential candidate media for ultra high-speed applications in short distance local-area networks or transmission systems.

PMMA-based fibre has three attenuation minima with the wavelengths around 520 nm, 570 nm, and 650 nm. Thus it is significant to design SPSM PM-mPOFs working at these loss windows. The structure of the PM-mPOF to achieve single-polarization operation is plotted in the inset of Fig. 1(a). It can be seen that two air holes near the core are enlarged, which leads to high birefringence because of the difference air hole diameters along the two orthogonal axes. The fabrication process of casting for such a kind of mPOFs was reported in our previous work.[10]

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In this study, the hole spacing, the diameters of the small and large air holes are denoted by Λ, d_1 and d_2, respectively. Based on this asymmetric core design, the slow- and fast-axis are produced as shown in Fig. 1(a), where the effective index along the slow-axis is larger than that along the fast-axis.

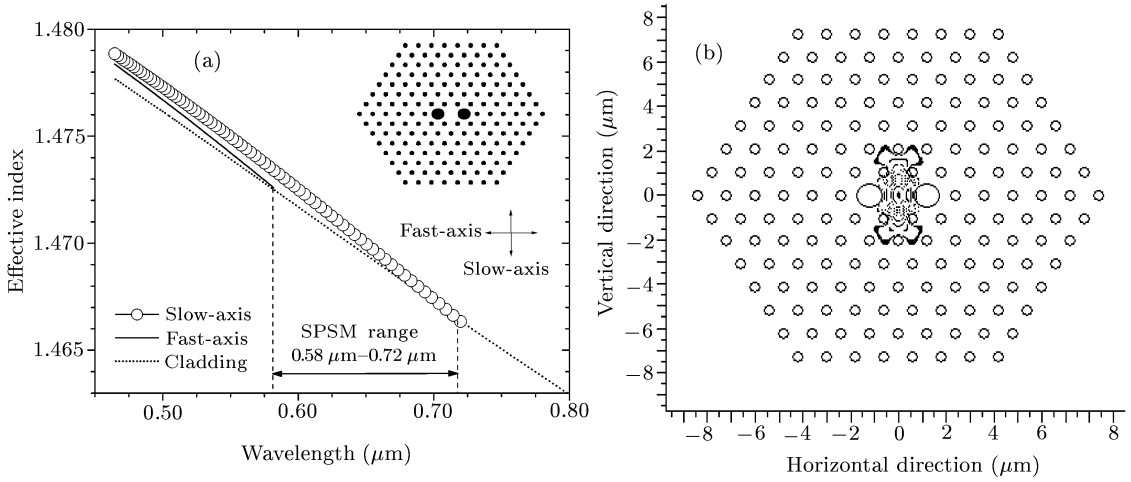

Fig. 1. (a) Dispersion curves as a function of wavelength for the highly birefringent microstructured polymer optical fibre. The inset shows the schematic cross-section. (b) Mode field pattern of the slow-axis mode of the SPSM PM-mPOF.

For microstructured optical fibre, the V-parameter is defined as[11]

$$V_{\mathrm{MOF}}(\lambda) = \frac{2\pi\Lambda}{\lambda}[n_c(\lambda)^2 - n_{cl}(\lambda)^2]^{1/2}, \qquad (1)$$

where $n_c(\lambda)$ is the 'core index' associated with the effective index of the fundamental mode and, similarly, $n_{cl}(\lambda)$ is the effective index of the fundamental space-filling mode in the triangular air-hole lattice. In general, the higher-order mode cutoff can be associated with the value of $V_{\mathrm{MOF}} = \pi$. Theoretical simulations indicate that when $d_1/\Lambda < 0.43$, the MOF has the remarkable property of the so-called endlessly single mode, independent of the value of Λ. Thus we design SPSM mPOF in this contribution under the above-mentioned condition always satisfied.

The working principle of SPSM, as shown in Fig. 1(a), can be described as follows: A wave transmitting in a single-mode fibre has two orthogonally polarized single-modes whose electric fields are polarized along the slow- and fast-axis. These are referred to as the slow- and fast-axis mode, respectively. Either one of these modes has a cutoff wavelength when the corresponding effective refractive index equals to or is less than the cladding effective index of the fundamental space-filling mode. Since the cutoff wavelength of the slow-axis mode is always longer than that of the fast-axis mode, the transmission in the SPSM fibre would be realized with the slow-axis mode provided that the operating wavelength is between the two cutoff wavelengths.

Figure 1(a) corresponds to the SPSM PM-mPOF working at 650 nm, for the material refractive index we use $n = 1$ for the air holes and $n = 1.49$ for the PMMA. The degree of modal birefringence of the PM-mPOF is defined by

$$B = n_s - n_f, \qquad (2)$$

where n_s and n_f are the effective indices of the two orthogonal polarization states corresponding to the slow-axis and fast-axis, respectively.

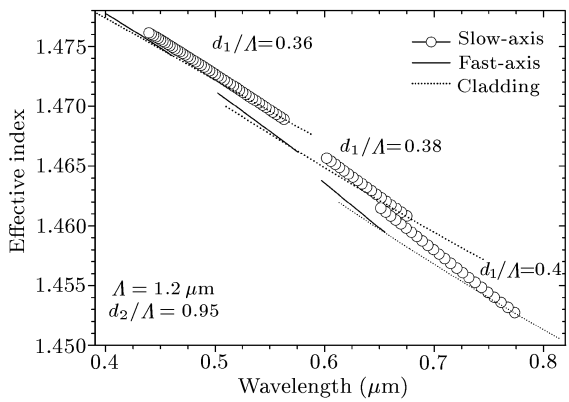

Fig. 2. Dispersion curves for SPSM mPOF with different d_1/Λ. The ratio d_2/Λ and pitch Λ are fixed at 0.95 and 1.0 μm, respectively.

The optimal structure parameters are selected to make sure high birefringence and wide SPSM bandwidth. Here the SPSM bandwidth is defined as the wavelength range between two cutoff wavelengths of slow- and fast-axis modes. It can be seen that the fibre with a large B is important as regarding of designing an SPSM fibre with a wide operating wavelength range. The parameters are taken as follows:

$\Lambda = 1.2\,\mu$m, $d_2/\Lambda = 0.95$ and $d_1/\Lambda = 0.37$. The two cutoff wavelengths are 580 nm and 720 nm, respectively, thus the SPSM bandwidth of 140 nm is obtained. The calculated mode field pattern polarized along the slow-axis is also indicated in Fig. 1(b), while the fast-axis mode is used up due to very high confinement loss along the fast-axis.

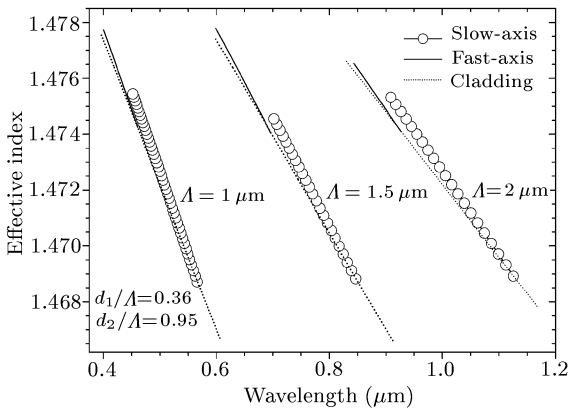

Fig. 3. Dispersion curves for SPSM mPOF with different Λ. The ratios d_2/Λ and d_1/Λ are fixed at 0.95 and 0.36, respectively.

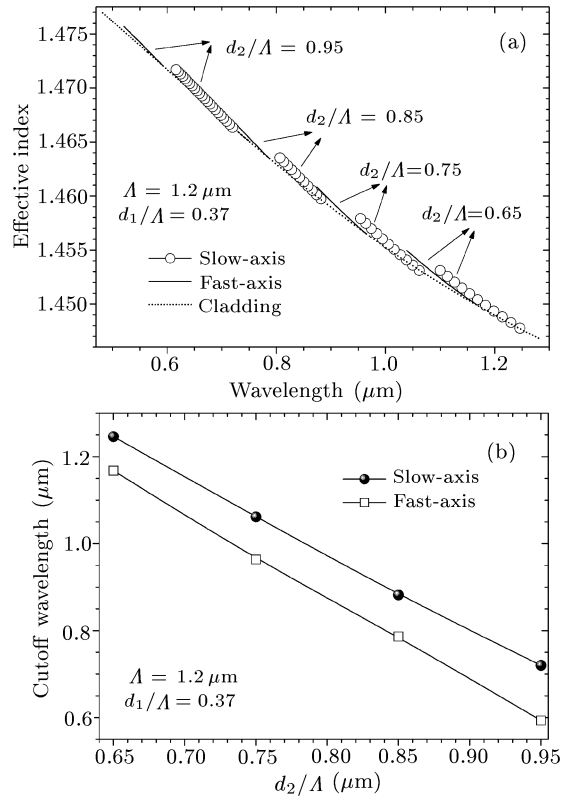

Fig. 4. (a) Dispersion curves for SPSM mPOF with different d_2/Λ. The pitch Λ and ratio d_1/Λ are fixed at 1.2 μm and 0.37, respectively. (b) Cutoff wavelength as a function of d_2/Λ.

We find that it is possible to tune the wavelength range for SPSM operation by varying the fibre structural parameters. Thus we investigate the dispersion characteristics under the influence of parameters d_1/Λ, d_2/Λ and Λ, respectively. First, as shown in Fig. 2, d_1/Λ is varied from 0.36 to 0.38 and 0.40, where and d_2/Λ are fixed at 1 μm and 0.95, respectively. It can be seen that the cutoff wavelengths of slow-axis mode and fast-axis mode both shift to longer wavelengths with the increasing of d_1/Λ. Second, we change the air hole pitch Λ among 1, 1.5 and 2 μm while fixing the ratios d_1/Λ and d_2/Λ, respectively, at 0.36 and 0.95, the simulation results are presented in Fig. 3. We can see that the SPSM window also shows red shift with the increasing Λ, and the SPSM wavelength range increases slightly. Third, we fix d_1/Λ at 0.37 and Λ at 1.2 μm and change d_2/Λ from 0.65 to 0.95 in steps of 0.1 (Fig. 4(a)), it is indicated that the two cutoff wavelengths shift to longer wavelength accordingly and the SPSM bandwidth increases gradually with the increasing d_2/Λ. More clear results about the cutoff wavelength corresponding to Fig. 4(a) are plotted in Fig. 4(b). Therefore, d_2/Λ should be selected as high as possible to attain a wider SPSM bandwidth. As far as the practical fabrication of mPOF is concerned, d_2/Λ of 0.95 is a reasonable parameter.

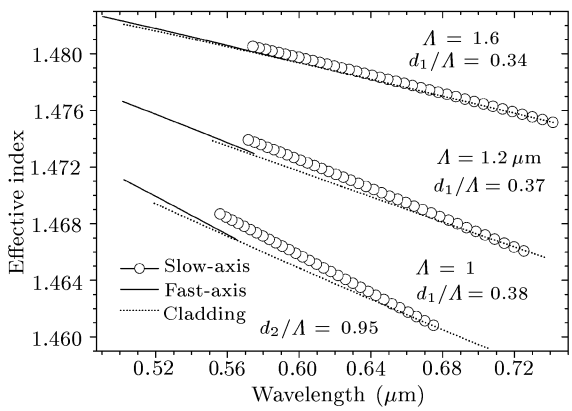

Fig. 5. Dispersion curves for SPSM mPOF with different ratio d_1/Λ and pitch Λ. The ratio of d_2/Λ is fixed at 0.95.

Moreover, in order for the fibre to be an SPSM over the working windows of PMMA at 650 nm, it must tune the ratio d_1/Λ and the pitch Λ simultaneously. Figure 5 shows dispersion curves for three set of parameters of $d_1/\Lambda = 0.38$ and $\Lambda = 1\,\mu$m, $d_1/\Lambda = 0.37$ and $\Lambda = 1.2\,\mu$m, $d_1/\Lambda = 0.34$ and $\Lambda = 1.6\,\mu$m. The corresponding cutoff wavelengths are respectively 560 nm and 680 nm, 580 nm and 720 nm, 590 nm and 740 nm. We can see that a smaller ratio of d_1/Λ requires a larger pitch Λ to support an SPSM within a particular wavelength range, and SPSM bandwidths are nearly the same with the increasing of pitch.

We design mPOF for SPSM operation working at

the loss window (around 650 nm) of PMMA-based fibre. The dependence of dispersion characteristics of the slow-axis mode and the fast-axis mode on the structural parameters are numerically calculated in great detail based on the full-vector plane-wave expansion method. The optimal microstructure parameters are found to obtain wider SPSM bandwidth and higher birefringence in mPOF, they are 1.2 μm for hole spacing, 0.37 for the ratio of small air hole diameter to hole spacing, and 0.95 for the ratio of big air hole diameter to hole spacing. The SPSM bandwidth of the PM-mPOF designed for 650 nm operation is 140 nm, within which only one polarization state is transmitted while the orthogonal polarization state is used up.

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