Design guidelines and characteristics of large flattened mode photonic crystal fibers

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ABSTRACT

We propose a kind of photonic crystal fiber with flat-top fundamental mode by introducing a depressed central dip into the core of the conventional index-guiding photonic crystal fiber. The design guidelines and characteristics of the large flattened mode photonic crystal fiber (LFM-PCF) are discussed in detail. By appropriate design, the effective area of the LFM-PCF can be increased by a factor of greater than 2 as compared with conventional index-guiding photonic crystal fiber with the same hole and pitch parameters. The improved effective area, single mode operation and flat-top fundamental mode output make LFM-PCF an ideal candidate to realize high power, high beam quality fiber amplifiers and lasers.

Keywords: Large flattened mode photonic crystal fiber, effective area

1. INTRODUCTION

The output power of the high power optical fiber laser is limited by the onset of nonlinear effects [1]. However, using innovative fiber designs such as large-mode-area fibers, a significant reduction in power density in the fiber core can be achieved with the retention of the outstanding thermo-optical properties [2]. Furthermore, by manipulating the fiber index, without increasing the core size, much larger mode area can be achieved, such as using large flattened mode (LFM) optical fiber, which raises the threshold for linear interactions in the fiber core by a factor of 2.5 over conventional large mode area fiber [3,4]. Most applications require diffraction-limited beam quality. The requirement of single-transverse mode confinement translates this into a maximum core diameter of about 15 μm in a conventional, step-index fiber in the one micron wavelength region. A larger core would normally lead to the propagation of higher-order transverse modes. However, several techniques have been demonstrated to ensure single-mode operation in slightly multimode fibers. By applying these techniques, experimentalists have extracted diffraction limited output from a step-index, multimode fiber with a mode-field diameter as large as 30 μm [2].

In recent years, a new class of fibers, so called photonic crystal fibers (PCF), has attracted us much attention [5-10]. Their main advantages of PCFs arise from the enormous design flexibility and novel features, including the capability of being strictly single-mode over a large wavelength range [5-7]. The inverse interpretation of this property means that the mode area of a PCF theoretically can be scaled to infinity at a given wavelength. Of course, this is limited by increased propagation losses with increased core diameter.

In this paper, we propose a new kind of fiber, large flattened mode photonic crystal fiber, which can operate in single mode with large core size, in addition to having the flat-top fundamental mode field. The flat-top intensity distribution in the fiber core can be realized by introducing a depressed index dip. The LFM-PCFs can have large effective area, which is useful in reducing nonlinear effects in fiber amplifiers and lasers with high beam quality. In this paper, we present the theoretical method in Section 2. The design guidelines and the characteristics of the LFM-PCF are discussed in Section 3. An effective area comparison between LFM-PCF and conventional index-guiding PCF is also made. Finally, the conclusions are given.

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2. THEORETICAL ANALYSIS

We consider a LFM-PCF with a triangle lattice of holes, as shown in Fig. 1(a), where d is the hole diameter and Λ is the hole pitch. The cladding is a two-dimensional photonic crystal with air holes running along the length of the fiber. To get a flat-top mode field, we must introduce a low index central dip, which can be realized by doping the core region or inserting an appropriate low-index rod into the central hole. Then the fiber can be fabricated with the conventional stack-and-draw process. The design of PCFs generally requires time-consuming numerical methods due to the complexity of the fiber profile. Here, we use a simpler effective-index method (EIM) that has been developed and improved over the years in the PCF research area [8]. For the fiber, it has an equivalent refractive index profile and $n_0>n_c>n_e$, as shown in Fig.1(b), where n_c, n_0 and n_e are refractive indices of the central dip, the core and the effective cladding, respectively. Note that here the core is the region between the central dip and the cladding, not the central part. The effective core radius a is assumed to be $\Lambda/3^{1/2}$, which can guarantee that the cutoff condition is given by effective normalized frequency equal to 2.405, as in conventional standard step-index fibers [11].

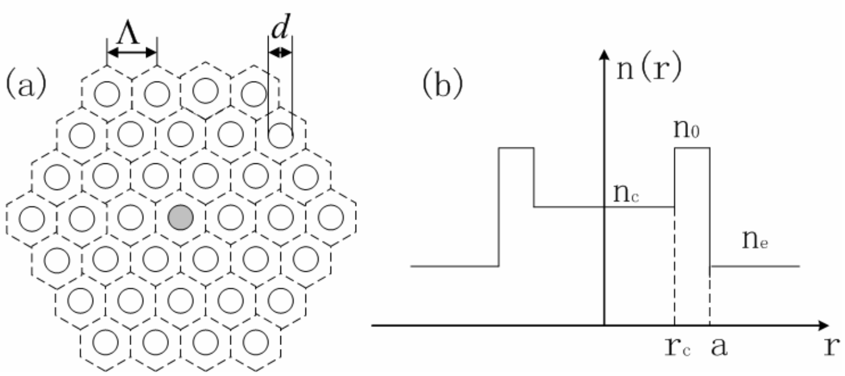

Fig. 1. Cross-section of LFM-PCF: (a) cross Section, (b) effective index profile.

For the fiber, there are propagation constants β available to light in the core but not to light propagating in the cladding:

$$\beta_{FSM} \leq \beta \leq k n_c \tag{1}$$

where k is free space wave number, n_c is index of the central dip, and β_{FSM} is the propagation constant of the fundamental space-filling mode (FSM). The FSM is the fundamental mode of the infinite photonic crystal cladding if the core is absent, so β_{FSM} is the maximum β allowed in the cladding [5].

In order to obtain the flat-top fundamental mode field over the entire central dip region, the effective index (n_{eff}) of the mode should be equal to the refractive index of the central dip. The mode field (ψ) of the fundamental mode of the fiber can be obtained by solving the following wave equation [12]:

$$\frac{d^2\psi}{dr^2}+\frac{1}{r}\frac{d\psi}{dr}+k^2(n^2(r)-n_c^2)\psi=0 \tag{2}$$

After solving Eq. (2) in different regions and applying the continuity conditions, one can obtain the following equations:

$$\frac{Y_0'(Ur_c/a)}{J_0'(Ur_c/a)}=-\frac{WK_0'(W)Y_0(U)-UK_0(W)Y_0'(U)}{UK_0(W)J_0'(U)-WK_0'(W)J_0(U)} \tag{3}$$

where $U=ak(n_0^2-n_c^2)^{1/2}$, $W=ak(n_c^2-n_e^2)^{1/2}$, J_0, Y_0 are Bessel functions of the first and the second kinds, I_0 and K_0 are modified Bessel functions of the first kind and the second kind. All the values of n_0 , n_c, a and r_c must satisfy Eq.(3).

3. RESULTS AND DISCUSSIONS

We take silica fibers as an example to demonstrate the characteristics of the LFM-PCFs. In this case, the central dip is made from doped silica, the core and the host glass in the cladding is made from pure silica glass. The refractive index of pure silica glass at different laser wavelength can be referred to [1], and the effective index of cladding is calculated with a plane wave method [13]. For the index of the central dip, it can be calculated from Eq. (3).

In the calculation, wavelength λ=1.0 μm and hole pitch Λ=10 μm. When the holes are much larger than the wavelength of light, the optical properties are not sensitive to the cladding geometry [14]. Fig. 2 shows the index of the central dip, the core and the effective index of cladding as a function of laser wavelength. As can be seen from this figure, both the index of the central dip and that of the core are decreased with increasing laser wavelength, and the index difference between them increases as laser wavelength increases. Because the core index is larger than the effective index of cladding for a fixed laser wavelength, we can deduce that light is trapped in the core region by total internal reflection.

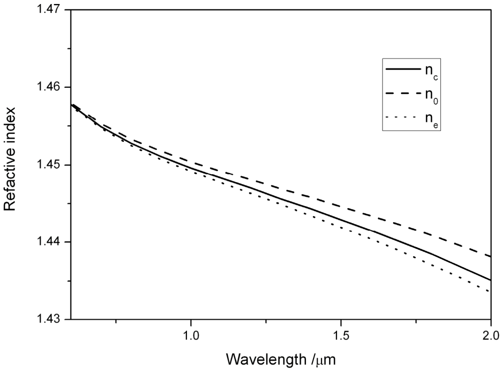

Fig. 2. The central dip index, the core index and the effective index of the cladding versus wavelength, where Λ=10 μm, r_c=0.2Λ.

In fiber design, we also care about the dependence of the index of central dip on the size of air holes and itself. In Figs. 3 and 4, the indices of the central dip and the core are demonstrated as a function of diameter of air hole and size of the central dip. From these figures, it can be easily found that the central dip index is decreased when the diameter of air hole and the size of the central dip increase.

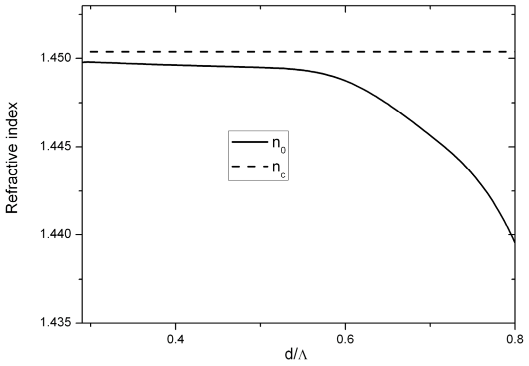

Fig. 3. Refractive indices of the central dip and the core region versus air hole diameter with λ=1.0 μm, Λ=10 μm, r_c=0.2Λ.

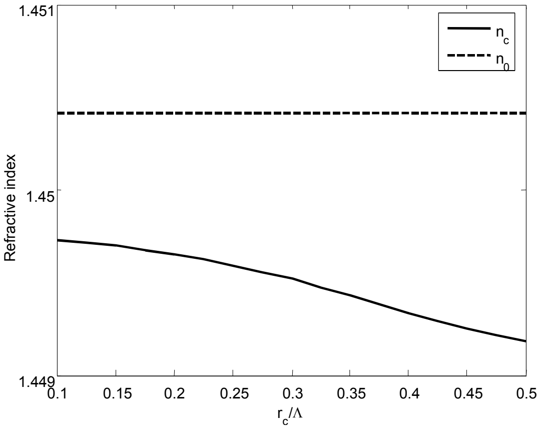

Fig. 4. Refractive indices of the central dip and the core region versus the central dip size with λ=1.0 μm, Λ=10 μm, d/Λ=0.4.

Figure 5 shows the normalized intensity distribution of the fundamental mode with r_c=0.4Λ at d/Λ=0.4. The computation is based on the equivalent refractive index profile, treating the cladding of LFM-PCF as a homogeneous one with index n_e. The approximation can reflect the characteristics of the fiber qualitatively. It can be seen that the LFM-PCF has a flat-top intensity distribution of fundamental mode.

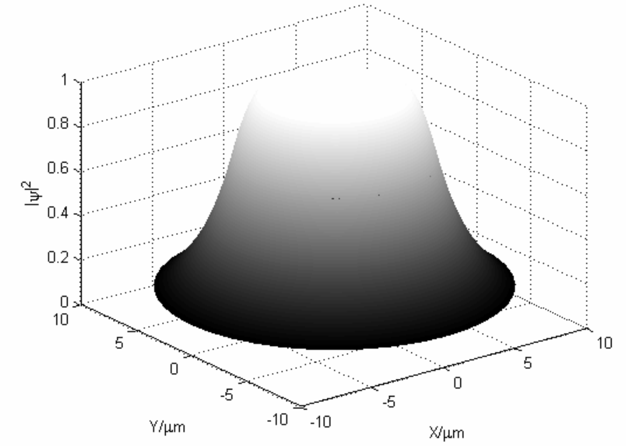

Fig. 5. Normalized intensity distribution of the fundamental mode of LFM-PCF with λ=1.0 μm, Λ=10 μm, r_c=0.4Λ.

It was shown by Baggett et al that large core conventional step-index fiber (SIF) and PCF can have a similar mode field diameter (MFD) at any particular wavelength in case of PCF with a single capillary defect [14]. However, PCF remains single mode over a large range of frequencies, while SIF starts to be multimode close to the designed wavelength. In the following discussion, we compare effective areas of the conventional PCF and LFM-PCF based on the definition in Ref. 1, as shown in Fig.6. The LFM-PCF and conventional PCF all can guide light by total internal reflection mechanism, but LFM-PCF differs from conventional PCF by inclusion of a depressed central index dip. For these discussed fibers, Λ=10 μm, d/Λ=0.4. Fiber 1 is the conventional PCF and Fiber 2-4 are LFM-PCFs with r_c=0.2Λ, 0.3Λ and 0.4Λ, respectively. It can be seen clearly that the LFM-PCFs have larger effective area. Compared with Fiber 1, the effective area of the Fiber 2-4 can be increased by a factor of about 1.2, 1.5 and 2.3, respectively.

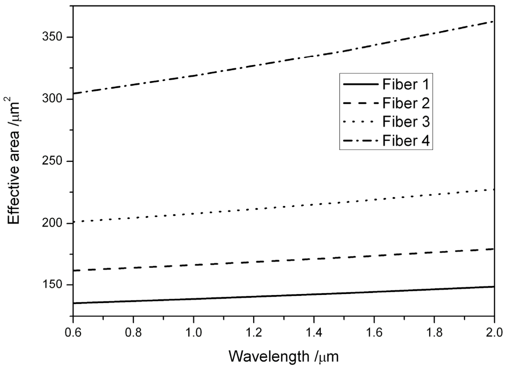

Fig. 6. Effective area comparison between Fiber 1: conventional PCF, Fiber 2: LFM-PCF with r_c=0.2Λ, Fiber 3: LFM-PCF with r_c=0.3Λ and Fiber 4: LFM-PCF with r_c =0.4Λ. In the calculation, Λ=10 μm, d/Λ=0.4.

By discussion, it can be found that the index difference between the central dip and the core is small for the LFM-PCFs. With nowadays technique, however, the refractive index step can be reduced to ~10^{-5} [15], so it is not difficult to fabricate this kind of LFM-PCFs. For the small index step, the larger bending loss must be considered. To avoid the problem, we can adopt the method proposed by Limpert [16].

For PCF, large mode areas can be engineered by increasing the lattice pitch of the photonic cladding, decreasing the air hole diameter or removing more than one of the central air holes [17]. Compared with conventional PCF, the LFM-PCF has larger effective area without increasing the physical size of the fiber core. So the design of the LFM-PCF provides a new method to increase the effective area further. Moreover, LFM-PCF can act as a beam shaper to get the flat-top fundamental mode output.

4. CONCLUSIONS

In conclusion, design guidelines and characteristics of LFM-PCFs are discussed in this paper. The refractive index of the central dip and the effective cladding index vary with the structure parameters. Numerical results indicate that a carefully chosen low-index central dip in the fiber core can realize flat-top fundamental mode field output. This is because the light can't be confined well in the central dip well for the index of central dip is lower than that of the core. Compared with conventional index-guiding PCF with the same hole and pith parameters, the LFM-PCFs have larger effective area. For the case r_c=0.4Λ, the effective area of the LFM-PCF can be increased by a factor of greater than 2. If we can integrate other techniques into the fabrication of LFM-PCFs, much larger effective area can be scaled up. So much higher power can be achieved in future high power fiber amplifiers and lasers with this technology.

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REFERENCES

[1] G. P. Agrawal, *Nonlinear Fiber Optics*, Academic, Boston, 1989.

[2] A. Tünnermann, T. Schreiber, Röser F, A. Liem, S. Höfer, H. Zellmer, S. Nolte and J. Limpert, "The renaissance and bright future of fibre lasers," J. Phys. B: At. Mol. Opt. Phys. **38**(9), S681-S693 (2005).

[3] A. K. Ghatak, I. C. Goyal, and R. Jindal, "Design of waveguide refractive index profile to obtain flat modal field," SPIE **3666**, 40-44 (1999).

[4] J. W. Dawson, R. Beach, I. Jovanovic, B. Wattellier, Z. Liao, S. A. Payne, and C. P. J. Barty, “Large flattened mode optical fiber for reduction of non-linear effects in optical fiber lasers,” SPIE **5335**, 132-139 (2004).

[5] T. A. Birks, J. C. Knight, and P. St. J. Russell, “Endlessy single-mode photonic crystal fiber,” Opt. Lett. **22**(13), 961-963 (1997).

[6] J. C. Knight, Nature, “Photonic crystal fibers,” Nature, **424**(6950), 847-851(2003).

[7] P. Russell, “Photonic crystal fibers,” Science, **299**(5605), 358-362(2003).

[8] Y. Li, C. Wang, N. Zhang, C. Y. Wang, and Q. Xing, "Analysis and design of terahertz photonic crystal fibers by an effective-index method," Appl. Opt. **45**(33), 8462-8465 (2006).

[9] Q. L. Zhou, X. Q. Lu, J. R. Qiu, D. P. Chen, X. W. Jiang, C. S. Zhu, “Beam-shaping microstructure optical fiber”, Chin. Opt. Lett. **3**(12), 686-689 (2005).

[10] X. Q. Lu, Q. L. Zhou, J. R. Qiu, C. S. Zhu, and D. Y. Fan, “Design guidelines and characteristics of beam shaping microstructure optical fibers,” Opt. Commun. **259**(2), 636-639 (2006).

[11] M. Koshiba, and K. Saitoh, “Applicability of classical optical fiber theories to holey fibers,” Opt. Lett. **29**(15), 1739-1741 (2004).

[12] A. W. Snyder, and J. D. Love, *Optical Waveguide Theory*, Chapman and Hall, London, 1983.

[13] Z. Zhu and T. G. Brown, “Analysis of the space filling modes of photonic crystal fibers,” Opt. Exp. **8**(10), 547-554 (2001).

[14] J. C. Baggett, T. M. Monro, K. Furusawa, and D. J. Richardson, "Comparative study of large-mode holey and conventional fibers," Opt. Lett. **26**(14), 1045-1047 (2001).

[15] J. Limpert, A. Liem, M. Reich, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, “Low-nonlinearity single-transverse-mode ytterbium-doped photonic crystal fiber amplifier,” Opt. Express **12**(7), 1313-1319 (2004).

[16] J. Limpert, N. Deguil-Robin, I. Manek-Hönninger, F. Salin, F. Röser, A. Liem, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, Opt. Express **13**(4), 1055-1058 (2005).

[17] K. Saitoh, Y. Tsuchida, M. Koshiba, and N. A. Mortensen, Opt. Express 13, 10833 (2005). K. Saitoh, Y. Tsuchida, M. Koshiba, and N. A. Mortensen, "Endlessly single-mode holey fibers: the influence of core design," Opt. Express **13**(26), 10833-10839 (2005).