Design of large-core single-mode Yb^{3+}-doped photonic crystal fiber*

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The effective index of the cladding fundamental space-filling mode in photonic crystal fiber (PCF) is simulated by the effective index method. The variation of the effective index with the structure parameters of the fiber is achieved. For the first time, the relations of the V parameter of Yb^{3+}-doped PCF with the refractive index of core and the structure parameters of the fiber are provided. The single-mode characteristics of large-core Yb^{3+}-doped photonic crystal fibers with 7 and 19 missing air holes in the core are analyzed. The large-core single-mode Yb^{3+}-doped photonic crystal fibers with core diameters of 50 μm, 100 μm and 150 μm are designed. The results provide theory instruction for the design and fabrication of fiber.

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In recent years, the power emitted by Yb^{3+}-doped fiber lasers has been drastically increased so that they become an alternative to other solid-state lasers. Nevertheless, nonlinear impairments, such as stimulated scatterings (Brillouin, Raman), become resistance to further improve the power level today[1-5]. Their thresholds, which are proportional to the effective mode area and conversely proportional to the length of the fiber, can be increased by use of large-mode-area (LMA) fibers. The step-index profile of common Yb^{3+}-doped fibers is obtained by doping, and the designed value of refractive index cannot be accurately guaranteed, so the mode area of the single-mode fiber is increased difficultly. The core diameter of present fibers is usually between 15 ìm and 25 ìm, which limits the performance of the fiber lasers[6-9]. The two-cladding Yb^{3+}-doped photonic crystal fiber (PCF) can adjust the refractive index of core and the structure parameters to realize single-mode transmission. So the conflict between LMA and single-mode transmission in fiber has been solved[10-14]. It greatly promotes the technology progress of fiber active device.

The single-mode characteristics of pure silica PCF have been studied in many papers, which show endless single-mode behavior when the hole-to-pitch ratio ($d/\ddot{E}$) is less than 0.43[15-17]. To our knowledge, there is no paper to analyze the single-mode characteristics of large-core Yb^{3+}-doped PCF. The refractive index and diameter of core directly affect the single-mode characteristics of PCF. In this paper, the relations of the single-mode characteristics of Yb^{3+}-doped PCF with the refractive index of core and the fiber structure parameters (pitch, hole-to-pitch ratio and diameter of core) are analyzed. The range of the refractive index of core and the fiber structure parameters for large-core single-mode Yb^{3+}-doped PCF are obtained.

Fig.1 shows the cross section of the two-cladding Yb^{3+}-doped PCF. The dark gray region in the center represents Yb^{3+}-doped core. The gray region represents pure silica. The white circles represent air holes. The lattice constant (pitch) in inner cladding is $\ddot{E}$. The diameter of air holes in inner clad-

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ding is d. The hole-to-pitch ratio is $d/Ë$.

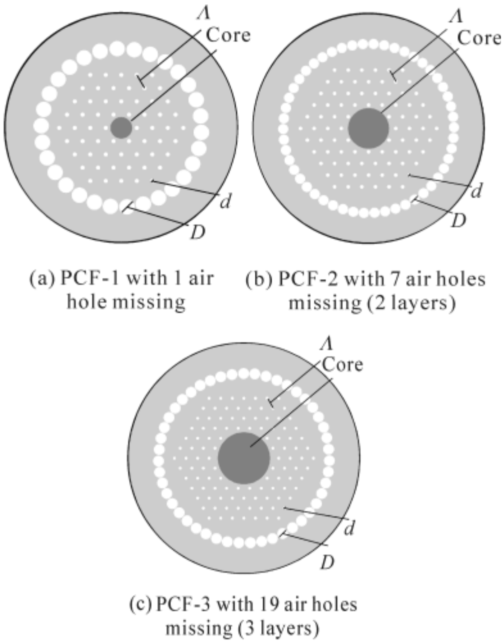

Fig.1 Cross section of the two-cladding Yb^{3+}-doped PCF

The number of modes in fiber is determined by the V parameter. There is a cutoff wavelength for the single-mode fiber. When the wavelength of transmission light is greater than the cutoff wavelength, the V parameter is less than 2.405, and the fiber can be single-mode.

The single-mode requirement of PCF is similar to that of the common fiber. The V parameter can be written as[15-17]

$$V = \frac{2\pi a_{\text{eff}}}{\lambda}\left(n_{\text{core}}^2 - n_{\text{fsm}}^2\right)^{1/2} < 2.405\,, \tag{1}$$

where a_{eff} is the effective radius of the core, n_{core} is the material refractive index of the core, and n_{fsm} is the effective index of fundamental space-filling mode in inner cladding[18,19].

The wavelength (λ) of Yb^{3+}-doped fiber lasers is around 1.06 μm, so we choose λ=1.06 μm in the simulation. n_{fsm} of PCFs for different structure parameters are simulated by effective index method. For d/Λ=0.05, 0.1, 0.2, 0.3, the relation of n_{fsm} with Λ is shown in Fig.2. For Λ= 5 μm, 10 μm and 20 μm, the relation of n_{fsm} with d/Λ is shown in Fig.3. n_{fsm} increases with Λ, but decreases with d/Λ. It can be seen from Eq.(1) that when n_{core} is slightly larger than n_{fsm}, V is less than 2.405, and PCF can be single-mode. According to the relation of n_{fsm} with the structure parameters of PCF, the range of n_{core} can be determined.

The designed value of refractive index cannot be accurately guaranteed in the fabrication of the Yb^{3+}-doped core of PCF. Nevertheless, according to the material refractive index of core, we can design proper structure parameters to achieve single-mode transmission in large-core PCF.

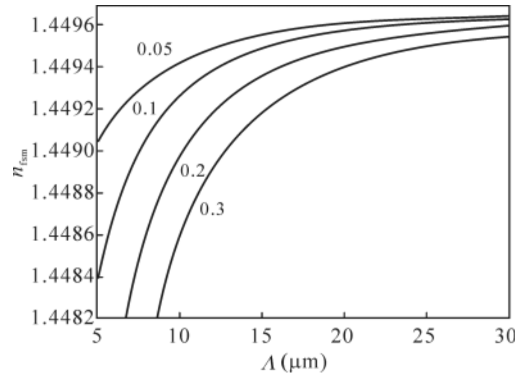

Fig.2 Relation of n_{fsm} with Λ for different d/Λ

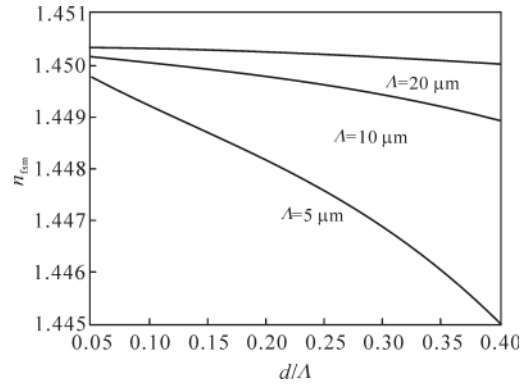

Fig.3 Relation of n_{fsm} with d/Λ for different Λ

Using Eq.(1) and n_{fsm} above, V of PCF-1 with different n_{core} and structure parameters are simulated. Fig.4 shows V as a function of $d/Ë$ for n_{core}=1.4490, 1.4495, 1.4500, 1.4505, 1.4510, and $Ë$=10 ìm. V increases with n_{core} and $d/Ë$. For each n_{core}, there is a range of $d/Ë$ to make V very low. When n_{core}=1.4495, in a large range of $d/Ë$ (0.05<$d/Ë$<0.30), V is always less than 2.405, and PCF can be single-mode. Fig.5 shows V as a function of $Ë$ for n_{core}=1.4496, 1.44965, 1.4497, 1.4499, 1.4520, and $d/Ë$=0.1. For each n_{core}, there is a range

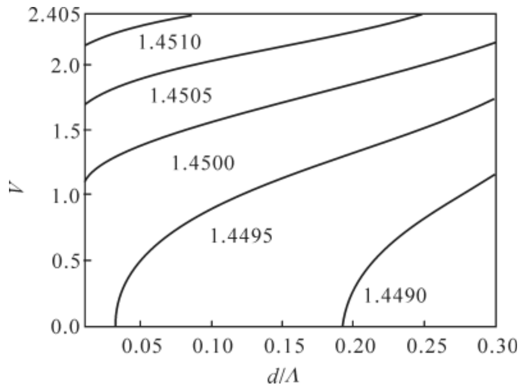

Fig.4 V as a function of $d/Ë$ of PCF-1 for different n_{core} ($Ë$=10 μm)

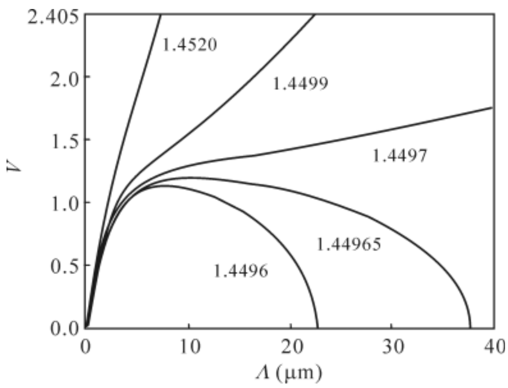

Fig.5 *V* as a function of *Λ* of PCF-1 for different n_{core} (*d*/*Λ*= 0.1)

of *Λ* to make *V* very low. When n_{core} is in the range of 1.4496–1.4499, and *Λ*>20 μm, *V* can be less than 2.405, and PCF can be single-mode. According to the relations of *V* with n_{core} and structure parameters of PCF in Figs.4 and 5, the large-core single-mode Yb^{3+}-doped PCF can be designed and fabricated.

Fig.6 shows *V* of PCF-1, PCF-2 and PCF-3 as a function of *d*/*Λ* for n_{core}=1.4493 and *Ë*=10 μm. *V* increases with *d*/*Λ*. In a range of *d*/*Λ*, *V* can be less than 2.405, and PCF can be single-mode. In a large range of *d*/*Λ*, PCF-1 can achieve single-mode transmission, but the range is smaller for PCF-3. Fig.7 shows *V* of PCF-1, PCF-2 and PCF-3 as a function of *Ë* for n_{core}=1.4495 and *d*/*Λ*=0.1. *V* decreases with *Λ*. In a range of *Ë*, *Λ* is smaller than 2.405, and PCF can be single-mode. In a large range of *Λ*, PCF-1 can achieve single-mode transmission, but the range is smaller for PCF-3. The core is larger, the ranges of structure parameters of single-mode PCF are smaller. In the design and fabrication of PCF, we need to precisely control the structure parameters to achieve large-core single-mode transmission.

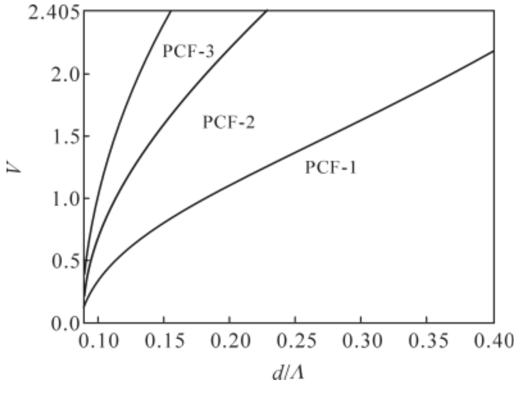

Fig.6 *V* as a function of *d*/*Ë* of three PCFs for n_{core}=1.4493 and *Ë*=10 μm

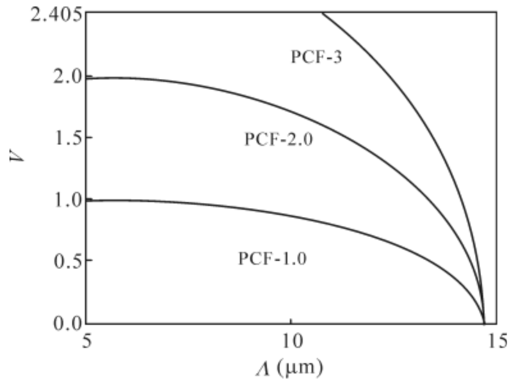

Fig.7 V as a function of *Λ* of three PCFs for n_{core}=1.4495 and *d*/*Λ*=0.1

According to the analyses above, the structure parameters of PCFs are designed. For *Λ*=30 μm, *d*/*Λ*=0.1, the core diameters of PCF-1, PCF-2 and PCF-3 are 50 μm, 100 μm and 150 μm, and n_{core} are 1.44970, 1.4496 and 1.44964, respectively. The values of *V* are shown in Fig.8. When *Λ* is around 30 μm, the values of *V* for PCF-1, PCF-2 and PCF-3 are less than 2.405, so the PCFs can be single-mode. The modal properties of the three kinds of PCFs are simulated by finite element method. Fig.9 shows the distributions of modes. All of the PCFs are single-mode, which are closely matched to the analysis by the *V* parameter in Eq.(1).

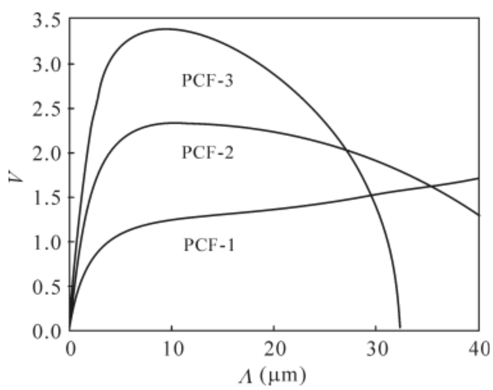

Fig.8 *V* as a function of *Λ* for the designed PCFs (*d*/*Λ*=0.1)

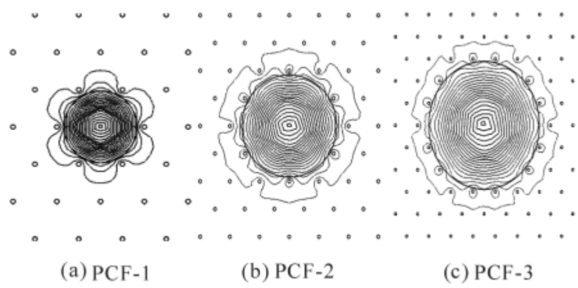

Fig.9 Mode distributions of the designed large-core Yb^{3+}-doped PCFs

The variations of n_{fsm} with the structure parameters of PCF are obtained. For different n_{core}, the relations of V with the structure parameters are provided. We also analyze the single-mode characteristics of large-core Yb^{3+}-doped PCFs with 7 and 19 missing air holes in the core, respectively. The large-core single-mode Yb^{3+}-doped PCFs with core diameters of 50 μm, 100 μm and 150 μm are designed. The analysis results provide theory instruction for the design and fabrication of large-core single-mode rare-earth doped PCFs.

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