Modal cutoff in rare-earth-doped photonic crystal fibers with multi-layer air-holes missing in the core*

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The various mode effective indices of the doped photonic crystal fibers (PCFs) are compared, the mode field distributions of the fundamental mode and the second-order mode are analyzed, and the single-mode condition is presented. The mode effective indices of large-core doped PCFs with different core indices and structure parameters are simulated by the finite element method (FEM). The relations of the core index with the fiber structure parameters of pitch, hole-to-pitch ratio and core diameter are obtained for single-mode propagation. In the design and fabrication of the doped PCF, we can adjust the core index and fiber structure parameters to achieve large mode area and single-mode propagation.

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Compared with traditional optical fiber, the feature of photonic crystal fiber (PCF) is the endless single-mode propagation[1,2]. The single-mode characteristics of pure silica PCF with one air hole missing in the core are analyzed[3,4]. The pure silica PCF can realize single mode operation when hole-to-pitch ratio (d/Λ) is less than 0.43[5,6], which provides the theoretical guidance for the design and fabrication of pure silica PCF.

The large-core Yb^{3+}-doped PCFs used in ultra-high-power fiber lasers have been reported[7-10]. When multi-layer air holes missing in the large core, the index of the doped core is different from that of the pure silica, so the signal mode condition in Refs.[3] and [4] is no longer applicable.

In this paper, the mode field distributions of fundamental and second-order modes of the PCFs with different indices of core n_{co} are analyzed by the finite element method (FEM), and the single-mode condition of PCFs is obtained. The large-core doped PCFs with different structural parameters are simulated. The relations of the core index with the fiber structure parameters of pitch, hole-to-pitch ratio and core diameter are obtained for single-mode PCFs. Those provide the theoretical guidance for the design and fabrication of large-mode-area doped PCFs.

Fig.1 shows the cross sections of three kinds of double-cladding doped PCFs. The doped PCF is usually fabricated by stack-capillary method, and the silica capillary and doped silica glass core are arranged in hexagon, so the core boundary is not round.

In the index-guiding PCFs, the guided light has an effective index n_{eff} which satisfies the condition[11-13]

$$n_{fsm} < n_{eff} = \frac{\beta}{k_0} < n_{co} \quad , \tag{1}$$

where β is the propagation constant along the fiber axis, and n_{co} is the core index. In the higher-order modes, the effective index of second-order mode n_{2eff} is the largest, so the cutoff of the higher-order mode occurs when n_{2eff} equals the effective index of fundamental space-filling mode of n_{fsm}. So single-mode PCFs satisfy the condition

$$n_{2eff} < n_{fsm} < n_{feff} \quad , \tag{2}$$

where n_{feff} is the effective index of the fundamental mode. n_{fsm}, n_{feff} and n_{2eff} can be computed by FEM[14-16].

The wavelength of Yb^{3+}-doped fiber laser is about 1.06 μm, so we select the wavelength as λ= 1.06 μm in the simulation of doped PCF. When Λ=10 μm and d/Λ= 0.1 in PCF-3, the PCFs with different n_{co} are simulated by FEM. The field distributions of fundamental modes and second-order modes are shown in Figs.2-4 which show that mode fields spread out as n_{co} reduces.

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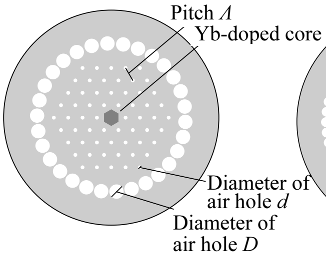
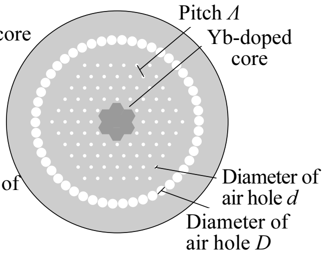
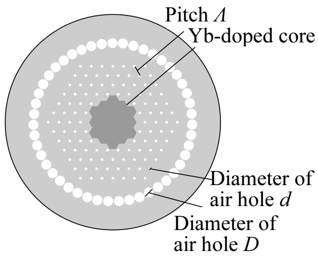


(a) PCF-1 with 1 air hole missing in the core

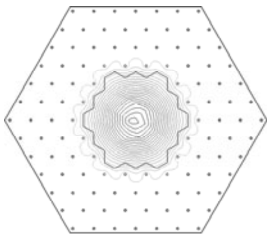


(b) PCF-2 with 7 air holes (2 layers) missing in the core

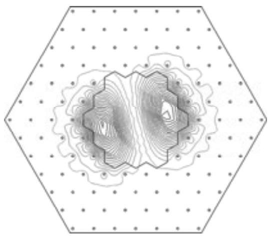


(c) PCF-3 with 19 air holes (3 layers) missing in the core

Fig.1 Cross sections of three kinds of double-cladding doped PCFs

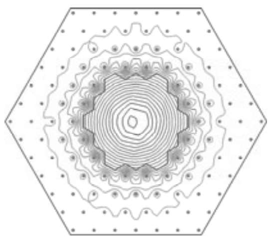


(a) Fundamental mode

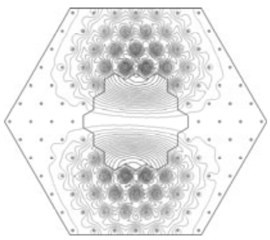


(b) Second-order mode

Fig.2 Field distributions in PCF-3 with n_{co}=1.449500



(a) Fundamental mode



(b) Second-order mode

Fig.3 Field distributions in PCF-3 with n_{co}=1.449370

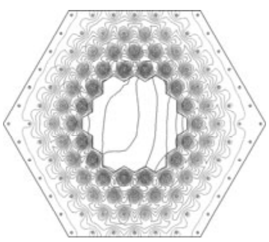


Fig.4 Field distribution of fundamental mode in PCF-3 with n_{co}=1.449300

When n_{co}=1.449500, the relation of n_{fsm}, n_{feff} and n_{2eff} is

$$n_{fsm} = 1.449307 < n_{2eff} = 1.449366 < n_{feff} = 1.449446 . \quad (3)$$

As shown in Fig.2, both of the fundamental mode and second-order mode are transmitted in the core, so the PCF is multi-mode propagation.

When n_{co}=1.449370, the relation of n_{fsm}, n_{feff} and n_{2eff} is

$$n_{2eff} = 1.449294 < n_{fsm} = 1.449307 < n_{feff} = 1.449337 , \quad (4)$$

which satisfies the single-mode condition of Eq.(2). As shown in Fig.3, the fundamental mode is in the core, and the second-order mode is in the cladding, so the PCF is single-mode propagation.

When n_{co}=1.449300, the relation of n_{fsm} and n_{feff} is

$$n_{feff} = 1.449297 < n_{fsm} = 1.449307 . \quad (5)$$

As shown in Fig.4, the fundamental mode is in the cladding, and there is no mode in the core.

According to the single-mode condition of Eq.(2), the range of n_{co} and structural parameters for single-mode doped PCF can be found.

For single-mode PCF-1 with d/Λ=0.1, the regions of n_{co} and Λ are shown in Fig.5. In the region between the two curves, the PCFs can be single-mode, for the higher value of n_{co}, the PCFs are multi-mode, and for the lower value of n_{co}, there is no mode in the core of PCFs. The larger Λ, the larger core diameter, the smaller range of n_{co}, and the more difficult to achieve single-mode PCFs.

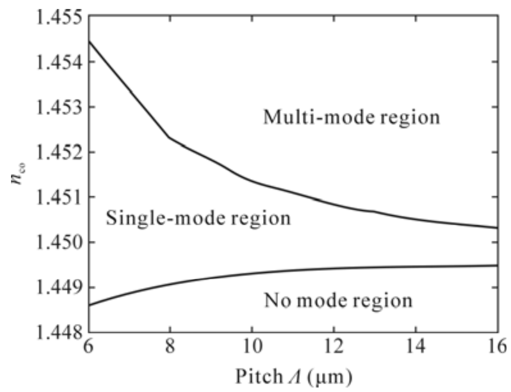


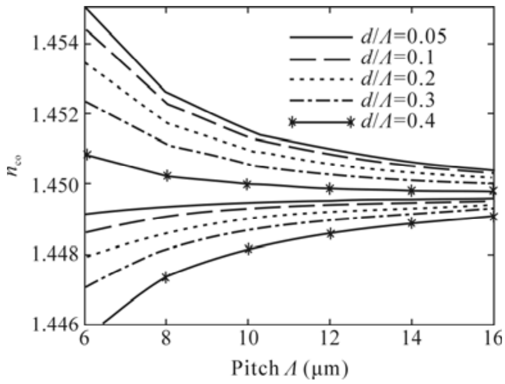
Fig.5 Different mode regions of PCF-1 with d/Λ=0.1

When d/Λ=0.05, 0.1, 0.2, 0.3 and 0.4 for PCF-1, PCF-2 and PCF-3, the ranges of n_{co} and Λ for single-mode PCFs are shown in Fig.6. The regions between two same lines correspond to the single-mode condition of PCFs with a value of d/Λ. For the same Λ and d/Λ, the more layers of air holes missing in the core, the larger core diameter, the smaller single-mode region, the more stringent conditions of n_{co} and structure parameters in the fabrication of single-mode PCFs.

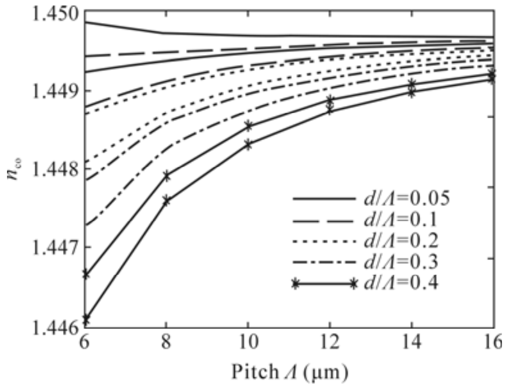
For the PCF-1 with d/Λ<0.4 in Fig.6(a), when n_{co} is about 1.449680 (the index of pure silica), the PCFs can always be single-mode propagation. The range of n_{co} is large for PCF-1, so it's easy in the fabrication of doped core. PCF-1 can be widely used in the fiber amplifier and nonlinear wavelength conversion.

For the PCF-3 in Fig.6(c), n_{co} increases with Λ. n_{co} is between 1.446000 and 1.449400 for Λ=6 μm, and between 1.449200 and 1.449500 for Λ=16 μm. The value of n_{co} is slightly lower than the index of pure silica (1.449680). The range of n_{co} is small, so it needs to be precisely controlled in the fabrication of the doped core material. When n_{co} of core material is fabricated in the range of the index profile of Fig.6(c), the large-core single-mode doped PCF-3 can be obtained by selecting appropriate d/Λ. It can be used in ultra-high-power Yb-doped fiber laser, which can reduce the nonlinear effects of the fiber, and improve the beam quality and the cooling effect.

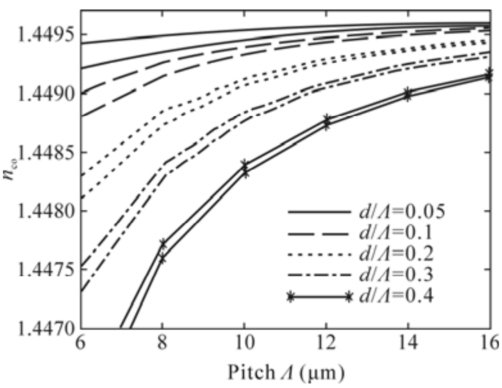
In the design and fabrication of doped PCF, by selecting appropriate n_{co}, Λ, d/Λ and the core diameter according to the single-mode regions in Fig.6, the desired single-mode doped PCF can be obtained.



(a) PCF-1



(b) PCF-2



(c) PCF-3

Fig.6 Single-mode regions of PCF-1, PCF-2 and PCF-3

The large-core doped PCFs with multi-layer air holes missing in the core are presented. The mode field distributions of fundamental and second-order modes of the PCFs with different n_{co} are analyzed by FEM, and the single-mode condition of PCFs is obtained. The PCFs with different n_{co}, Λ, d/Λ and core diameters are simulated, and the range of n_{co} and structural parameters of single-mode PCFs are obtained. The results show that the larger Λ, the larger core diameter, the smaller range of n_{co} in single-mode doped PCFs, so it needs to be precisely controlled in the fabrication of doped core. On the other hand, Λ and d/Λ can be adjusted according to n_{co} in the fabrication of single-mode PCFs. These provide theory guidance for the design and fabrication of large-core single-mode doped PCFs.

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