Study on single-mode photonic crystal fibers in wide wavelength range

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Received January 15, 2007

The comparatively large mode field single-mode photonic crystal fibers (PCFs) were fabricated, the lightwave from 600- to 1600-nm wavelength along this PCF could be transmitted in single mode. The manufacturing process technologies of the PCFs were exploited, and the drawing parameters of PCFs were also presented. The structure parameters on the single-mode performance of PCFs were theoretically studied, and in practice the design was proved. The measurements of cut-off wavelength and light intensity distribution showed that the PCF had comparatively wide single-mode operating wavelength range.

OCIS codes: 060.2280, 060.2330, 060.2430.

Recently, the basic application studies on various kinds of photonic crystal fibers (PCFs) have been promoted greatly in the photo-electronic fields, including high power fiber lasers, super-continual light spectrum, dispersion compensation, mode transformer, medical treatment, biosensors, etc..

The properties of endless single-mode (ESM) PCFs are very different from the common standard single-mode optical fibers[1,2], for example, they have very wide single-mode operating wavelength range. What's more, they could have ESM performance while they have very large mode field. ESM property is advantageous to attain good beam quality of high power laser, large mode field is good for reducing nonlinear effect and for transmitting higher laser power, at the same time good thermal dissipation performance for high power fiber laser could be gotten by using large mode field PCFs. Raising the fiber transmission power and acquiring good beam quality are the hotspot in the high power laser fields[3−6], so in this article the comparatively large mode field ESM PCFs are studied.

For common standard single-mode optical fibers, their normalized transmission frequency ν_{smf} could be written as

$$\nu_{\mathrm{smf}} = \frac{2\pi a}{\lambda}\left(n_{\mathrm{core}}^2 - n_{\mathrm{cladding}}^2\right)^{0.5}, \tag{1}$$

where a is the fiber core radius, λ is the wavelength, n_{core} is the core refractive index, n_{cladding} is the cladding index. When $\nu_{\mathrm{smf}} < 2.405$, the second order mode is cut off.

For PCFs, the micro-hole arrays are distributed regularly in the PCFs, these periodical micro-hole arrays make great action on the transmission light. The shorter the transmission light wavelength is, the more centralized to the higher index domain the light intensity is, so the effective refractive index of the cladding will be raised. The cladding effective refractive index is decided by the fundamental space-filling modes (FSMs) in the microstructure optical fiber, β_{FSM} is defined as the transmission constant of the FSMs. So the effective refractive index of fiber cladding $n_{\mathrm{eff}} = \beta_{\mathrm{FSM}}/k$, where $k = 2\pi/\lambda$. The normalized transmission frequency ν_{pcf} could be written as[2]

$$\nu_{\mathrm{pcf}} = \frac{2\pi\Lambda}{\lambda}\left(n_{\mathrm{core}}^2 - n_{\mathrm{eff}}^2\right)^{0.5}, \tag{2}$$

where Λ is the micro-hole pitch. When $\lambda \to 0$, the mode field distributions of the transmission light do not change basically, they do not depend on the light wavelength and the hole's distance, but are related to the relative dimension between the diameter of micro-hole (d) and transmission wavelength (λ). When $\nu_{\mathrm{pcf}} < \pi$, light could transmit in the PCFs in the single-mode way[1,2]. The relations between the normalized transmission frequency (ν_{pcf}) and different d/Λ, Λ/λ were theoretically calculated. Figure 1 shows the calculation results. Light could transmit in the PCFs in the single-mode way when $d/\Lambda < 0.42$ and the dimensions of holes and light wavelength are in the same order.

The core diameter and numerical aperture (NA) of common optical fibers must meet certain conditions, so the light could transmit in the single-mode way along the fiber waveguide. When the NA was kept constant, and the core diameter was increased, the light could not transmit in single mode, this would decrease the laser beam quality. In order to realize the large mode field

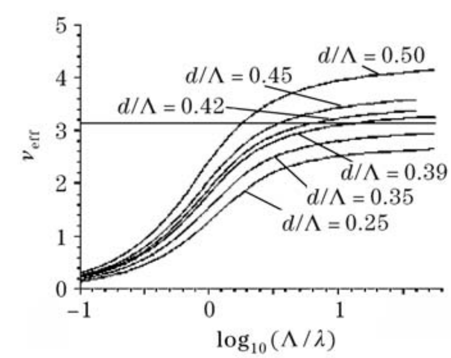

Fig. 1. Relation between ν_{eff} and Λ/λ.

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Fig. 2. Simulative light transmission stable mode field.

and decrease the nonlinear effect, in the mean time, laser beam quality could be very good, the structures of ESM PCF were designed. The PCF with the structures $d/\Lambda = 0.39$ and $d = 3.15$ μm was simulated theoretically, the PCFs with such structural parameters could have ESM properties. The simulative result showed that the mode spot took on hexagon and the light energy was bound up around the fiber core, as shown in Fig. 2.

The fabrication technologies of PCFs include many different ways, the most popular ones are the stack-and-drawing method and ways of drilling holes of large diameter fiber preforms. The former way has many merits, such as flexible design, convenient operation, and easier fabricating complex structured PCFs. So the PCF was fabricated by the former method. The capillaries, their outer diameters are 600 μm and inner diameters are 230 μm, and 600-μm silica micro-rod were stacked and formed to hexagonal PCF preform, the fiber preform were drawn at 2100 °C in the drawing tower. Table 1 shows the drawing process parameters of the fibers.

Figure 3 shows the scanning electron microscope (SEM) photo of the PCF, its structural parameters are in the following: fiber core diameter $2a = 13.1$ μm, $d = 3.2$ μm, $\Lambda = 8.2$ μm, holes' domain diameter $D_1 = 55.6$ μm, cladding diameter $D_2 = 124.8$ μm, secondary coating diameter $D_3 = 245.2$ μm, its mode field diameter at 1550 nm is 14.6 μm. The attenuation of the PCF is 0.6 dB/km at 1550-nm wavelength, 14.9 dB/km at 1383-nm wavelength. The main cause of the comparatively high attenuation of the PCF is the hydroxyl loss, the absorption of 1240- and 940-nm wavelength was obviously raised, i.e., 2.9 and 5.8 dB/km respectively. This is caused by the hydroxyl serial resonance of γ_1 and γ_3, the hydroxyl loss must be decreased firstly for reducing the attenuation of the PCF.

Table 1. Drawing Parameters of the PCF

Furnace Power (kW)	13
Controlling Pressure (mbar)	280
Drawing Speed (m/min)	232
Drawing Stress (g)	190
Primary Coating Pressure (bar)	0.52
Secondary Coating Pressure (bar)	0.59
Cladding Diameter (μm)	125 ± 2
Coating Diameter (μm)	245 ± 10

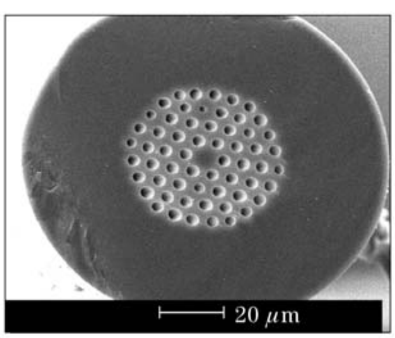

Fig. 3. SEM photo of the PCF.

The theoretical design and simulation showed that the PCF was endless single mode. In order to prove this conclusion, two ways were adopted. Firstly, the cut-off wavelength testing curve was nearly a beeline from 600 to 1600 nm in Fig. 4, it showed that there was no cut-off wavelength in the wavelength range from 600 to 1600 nm. In general, when the second mode is cut, there is a cut peak that can be found in the cut-off wavelength testing curve. Secondly, in order to prove their single-mode performance below 600-nm wavelength, the green light at 532-nm wavelength was launched into 100-m PCF, the output light power at the other end was tested along the x- and y-axis. The normalized light intensity of the fiber was shown in Fig. 5, the intensity distribution was submitted to Gaussian distribution, Gaussian distribution was the fundamental mode characteristic, this indicated that the light below 600-nm wavelength could work in single mode. The theoretical calculation and practical proof showed that the PCF really had comparatively wide single-mode operating wavelength.

In conclusion, the comparatively large field mode single-mode PCF was fabricated successfully, the practical fiber structure parameters were basically consistent with the theoretical design. The PCF's manufacturing

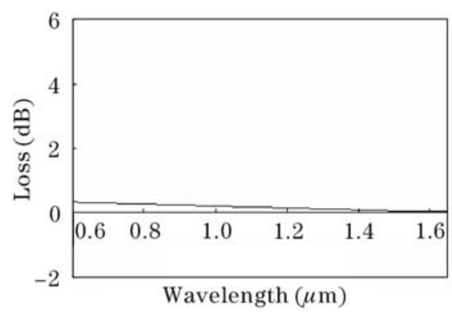

Fig. 4. Cut-off wavelength testing.

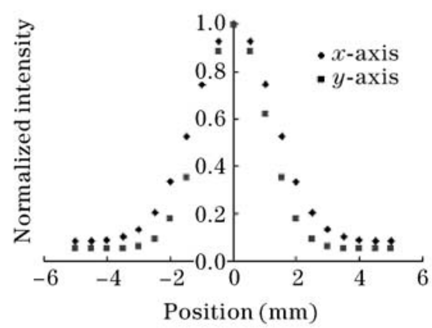

Fig. 5. Light intensity distribution.

processes and fiber drawing parameters were also presented. The measurements of cut-off wavelength and the intensity distribution of its near field showed that the PCF really had comparatively wide single-mode operating wavelength range.

This work was supported by the National "973" Plan under Grant No. 2003CB314905. W. Chen's e-mail address is chenwei@fiberhome.com.cn.

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