Fabrication of fiber-embedded multi-core photonic crystal fibers

Weimin Sun (孙伟民), Xiaoqi Liu (刘晓颀), Fenghua Fu (付枫华), and Jianzhong Zhang (张建中)

College of Science, Harbin Engineering University, Harbin 150001

Received July 15, 2008

A novel fabrication method of multi-core photonic crystal fibers is proposed on the basis of a fiber-embedded technique. A taper tower is used to modify the structures of the fiber preform, and four steps of fiber fabrication and different structures of fiber samples are given. The mode structures and beating characteristics of a photonic crystal fiber sample with two successive cores are investigated in detail with the help of a supercontinuum light source, a charge-coupled device (CCD) camera, and an optical spectrum analyzer. The test results show a clear beating phenomenon between two orthotropic polarization modes with a 2.8-nm peak interval in wavelength.

OCIS codes: 060.5295, 220.4000.

doi: 10.3788/COL20080610.0715.

The photonic crystal fiber (PCF) was firstly fabricated by Knight *et al.*[1]. Since then, many kinds of PCFs with different structures have been designed and fabricated for different purposes[2]. For example, the index-guiding PCF with small ratio of air-hole diameter to pitch ensures single-mode transmission within very wide bandwidth[3]. The hollow core bandgap PCF can guide high-power energy of special wavelength[4,5]. Some other designs of PCF realize the nonlinearity[6], flat dispersion[7], large guide mode, polarization-maintaining, and so on. Aside from the usual PCFs, which consist of pure silica glass only, some specially designed PCFs were investigated on the basis of various materials doped to enhance the nonlinearity[8,9], to form a laser by rare-earth dopant[10,11], etc. All these PCFs are drawn from special preform, which is fabricated by stacking silica capillaries and a stick of other materials. A novel fiber-embedded method is proposed here to provide a candidate to fabricate special multi-core PCF on the basis of an ordinary pure-silica preform.

A drawing tower was rebuilt as a taper tower to draw some specially designed PCF components. This taper tower is shown in Fig. 1. It consists of three translation stages, a furnace, and a series of shelves. The main moving shelf A was mounted on a high power translation stage controlled by a step motor. Two translation stages B and C were mounted on the main shelf A. Both B and C have 30-cm translation distance. Two cane holders, which can move along the stages B and C, were used to nip the modified PCF preform and were controlled by two step motors. The angle and position of the holders were adjustable to guarantee that the preform kept straight when it was pulled. The hot zone inside the furnace was about 10 cm in length. The scale of the hot zone could be controlled by the speed of the argon air flow and the set temperature. The temperature inside the furnace could be as high as 2000 °C, which was monitored by using a remote thermometer of a response curve as shown in Fig. 2.

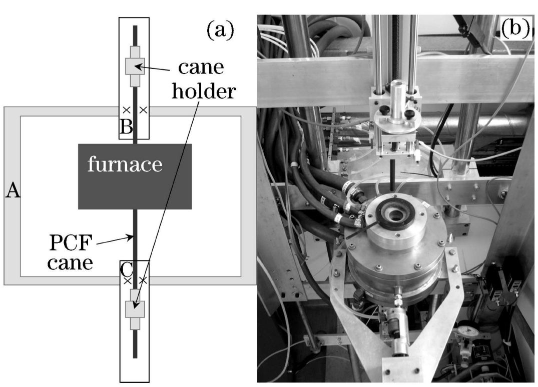

Fig. 1. (a) Structure and (b) photo of the taper tower.

A preform of seven-circle hexagonal honeycomb pattern (Fig. 3(a)) was chosen to be the roughcast of the modified preform for the multi-core embedded PCF. Four steps should be done from the roughcast to the final multi-core embedded PCF. The first step is to choose the holes to embed fibers and to block all other holes with glue, so the blocked holes will not collapse when we use vacuum to remove the gaps in the third step (Fig. 3(b)). The second step is to insert some multimode fibers into these selected holes to make the initial modified preform. The third step is to eliminate the gaps (Fig. 3(c)) between the embedded fibers and the holes to form the final processed preform (Fig. 3(d)) with the help of a vacuum pump and a high temperature over 1600 °C. The last step is to draw the modified preform to the desired multi-core PCF (Fig. 3(e)).

The embedded fiber was a multimode one with a 50-μm

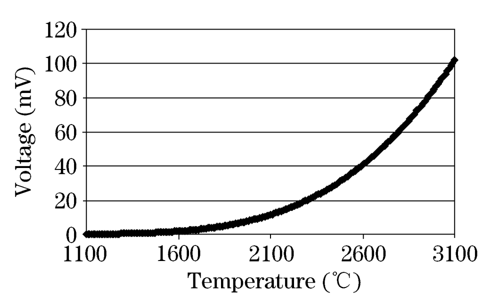

Fig. 2. Response curve of the temperature monitor.

1671-7694/2008/100715-03

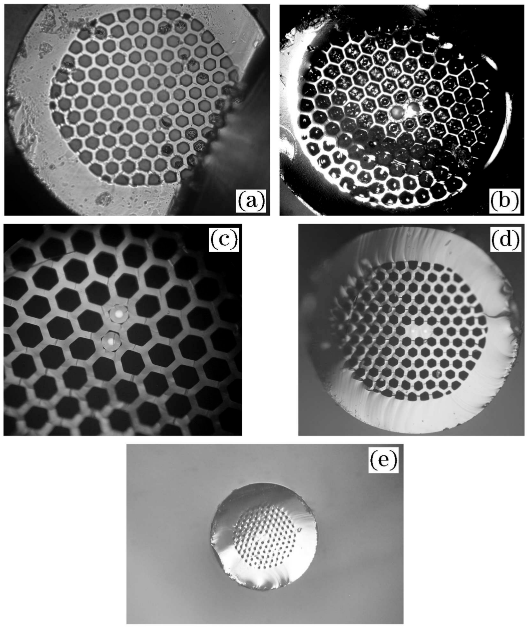

Fig. 3. Process to draw the modified preform to multi-core PCF. (a) Structure of the initial preform; (b) end of glued preform; (c) cross section of half-processed preform; (d) processed preform; (e) multi-core PCF.

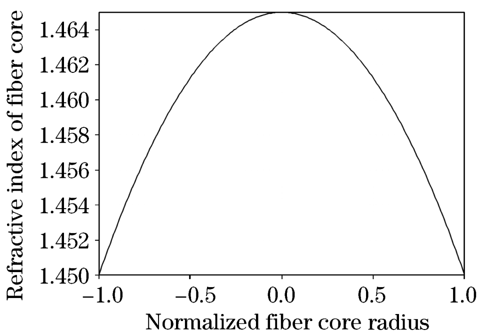

Fig. 4. Distribution of the refractive index of the embedded multimode fiber.

core. The distribution of refractive index of the multimode fiber is shown in Fig. 4. After these multimode fibers were embedded, the modified preform was drawn to a PCF fiber. The diameter of a multimode fiber core was attenuated about 10 times and became an embedded PCF core. In these fabricated PCFs, the refractive index around the core area is not uniform. In the central area of the PCF cores, the refractive index keeps the same distribution as the initial embedded fiber core. This structure makes the fiber-embedded PCFs confine energy inside cores stronger than pure-silica PCFs.

Some specially designed multi-core embedded PCFs were fabricated, for example, PCFs with two-circle cores, two successive cores, two separate cores, and three successive cores, as shown in Fig. 5.

A 65-mm fiber-embedded PCF with two successive embedded cores was chosen as the test sample to investigate the light propagation characteristics, including the mode structure and the light coupling between different modes. Firstly we observed the near-field image of one end of the PCF sample and obtained its mode structures. Secondly we tested the coupling between two orthotropic

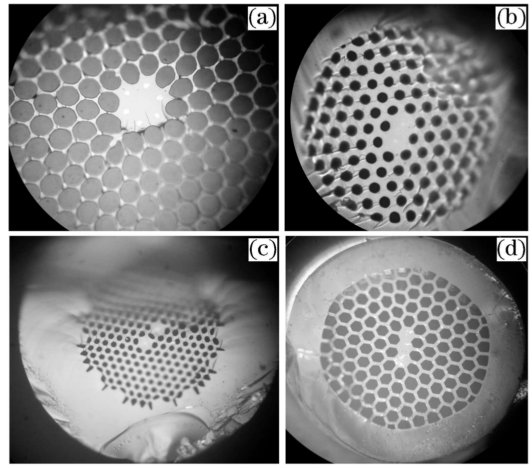

Fig. 5. Different structures of multi-core embedded PCFs. (a) PCF with two-circle cores; (b) PCF with two successive cores; (c) PCF with two separate cores; (d) PCF with three successive cores.

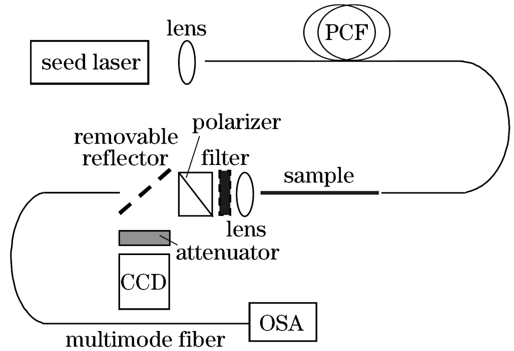

Fig. 6. Setup of the test system.

polarization modes and between two embedded cores of this sample. Clear beating phenomenon was observed between two orthotropic polarization modes.

A test system was set up, as shown in Fig. 6. The light source was a length of supercontinuum (SC) PCF pumped by a seed laser. This fiber was straight aligned to the fabricated fiber sample. By careful alignment, the SC light could be injected into one core of the two-core PCF sample or into the middle of the two cores. To monitor the mode structure and transmission spectrum of the fiber cores, an objective lens was used to obtain the near-field image of one end of the PCF sample.

In the first experiment, we used a mirror to reflect the near-field image of the fiber end to a charge-coupled device (CCD) camera, and used an 850-nm narrow-band filter to monitor the mode structure at this wavelength. When the SC light entered one core of the two-core PCF or injected into the middle between the two cores, the mode pattern was obtained, as shown in Fig. 7. The mode pattern shows its multimode behavior, which makes the coupling phenomenon very complex.

On the next stage of the experiment, we wanted to measure the coupling characteristics between the two embedded cores. To obtain the spectra of these two cores separately, we got a magnified image with the help of an objective lens. Then we put the end of a multimode fiber at the image position of an embedded core to collect the

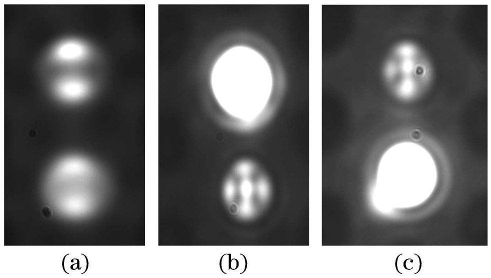

Fig. 7. Mode structures of a two-core PCF. (a) Light into the middle of two cores; (b) light into one core; (c) light into the other core.

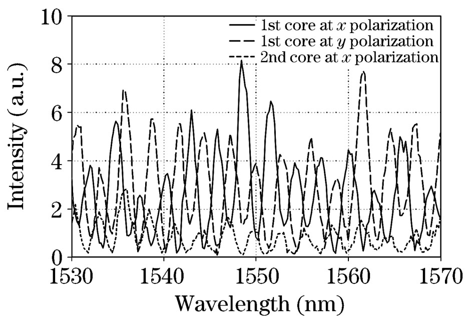

Fig. 8. Beating phenomenon of two orthotropic polarization modes of two cores.

light of this core. The other end of this multimode fiber was connected to an optical spectrum analyzer (OSA).

Firstly we carefully rotated the PCF sample to make its two cores in the vertical direction, i.e., y axis. Then we adjusted the direction and the position of the end of the SC fiber to inject light into one core of the PCF sample. A multimode fiber was laid at the image position of the same embedded PCF core (i.e., the first core). We adjusted the polarization of the polarizer to y axis and recorded the transmission spectrum. Then we rotated the polarization of the polarizer to x axis and recorded the spectrum again. After that, we shifted the multimode fiber to the image of the other embedded core and repeated above procedures.

The spectra of the two-core PCF are shown in Fig. 8. Comparing the spectra of the two orthotropic polarization modes, we can find clear beating phenomenon. The wavelength interval between two successive peaks is about 2.8 nm. On the other hand, the beating phenomenon between the spectra of two cores is not as strong as that reported in Ref. [12].

In conclusion, the fiber embedded technique has been successfully used to produce PCFs with different modified structures. The number and the location of the embedded fiber could change the characteristics of the PCFs dramatically. For the two-core PCF sample, the beating phenomenon of different polarization modes is clear, but the coupling between two cores is not so strong.

The authors thank Professor T. A. Birks and other members of Center of Photonic and Photonic Materials, University of Bath, Bath, UK for the help in this work. They also thank the support of the China Scholarship Council (CSC) and the Research Foundation of Harbin Engineering University. W. Sun's e-mail address is weimin_sun2003@yahoo.com.cn.

References

1. J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, Opt. Lett. **21,** 1547 (1996).
2. P. St. J. Russell, J. Lightwave Technol. **24,** 4729 (2006).
3. T. A. Birks, J. C. Knight, and P. Russell, Opt. Lett. **22,** 961 (1997).
4. R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts, and D. C. Allan, Science **285,** 1537 (1999).
5. J. Dai and B. Yang, Opt. Commun. Technol. (in Chinese) (1) 61 (2008).
6. T. Gong, F. Yan, L. Wang, Y. Li, P. Liu, and S. Jian, Chinese J. Lasers (in Chinese) **35,** 559 (2008).
7. Q. Wang, B. Yang, L. Zhang, H. Zhang, and L. He, Chin. Opt. Lett. **5,** 538 (2007).
8. T. Sun, G. Kai, Z. Wang, S. Yuan, and X. Dong, Chin. Opt. Lett. **6,** 93 (2008).
9. H. Fang, S. Lou, T. Guo, and S. Jian, Acta Opt. Sin. (in Chinese) **27,** 202 (2007).
10. K. Li, Y. Wang, W. Zhao, G. Chen, Q. Peng, D. Cui, and Z. Xu, Chin. Opt. Lett. **5,** 347 (2007).
11. B. Liu, M. Hu, Y. Song, L. Chai, and Q. Wang, Chinese J. Lasers (in Chinese) **35,** 479 (2008).
12. Z. Wang, T. Taru, T. A. Birks, J. C. Knight, Y. Liu, and J. Du, Opt. Express **15,** 4795 (2007).