Broadband dispersion compensating fiber using index-guiding photonic crystal fiber with defected core

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We present a novel broadband dispersion compensating photonic crystal fiber with defected core in this paper. The small central defect of air hole can flexibly control the chromatic dispersion properties of this kind of photonic crystal fiber. This kind of fiber has broadband large negative chromatic dispersion, and the chromatic dispersion coefficient varies from −440 to −480 ps/(nm·km) in the measured wavelength range of 1500 − 1625 nm. The calculated chromatic dispersion curve is well matched to the measured chromatic dispersion coefficient in the range of 1500 − 1625 nm. The proposed photonic crystal fiber can be used to design the dispersion compensating fiber in the desired wavelength range by adjusting its structural parameters.

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Photonic crystal fiber (PCF) technology has rapidly progressed in recent years and attracted much attention for fiber device applications because of its unusual optical properties. In particular, PCF can control the chromatic dispersion over a wide wavelength range and can be expected to provide a novel dispersion compensating fiber (DCF). DCF can be used for long distance high speed transmission in the dense wavelength division multiplexing (DWDM) optical communication systems based on the standard single mode fiber (SMF). Gérôme *et al.* have reported the dispersion compensating fiber based on the equivalent dual-core structure of PCF. The negative chromatic dispersion coefficient of −2200 ps/(nm·km) was theoretically obtained with pure silica PCF[1]. The dual-core structures of PCF with large negative dispersion have been studied subsequently[2−4]. Shen *et al.* have proposed the model by considering the micro-structured cladding with 1-μm-thick pitch. The chromatic dispersion coefficient up to −474.5 ps/(nm·km) was achieved in their PCF structure, and the bandwidth was 236 nm in the communication windows theoretically[5]. Yang *et al.* have reported a modified dual-core structure of PCF to realize the broadband large negative dispersion compensation. They theoretically designed and analyzed the dispersion compensating PCF, and realized the chromatic dispersion coefficient from −380 to −420 ps/(nm·km) in the C band[6].

In this paper, we present a novel broadband DCF by introducing the air hole in the center of pure silica index-guiding PCF, and we theoretically and experimentally demonstrate this broadband DCF based on index-guiding PCF with defected core. The chromatic dispersion properties of PCF with defected core were simulated by the vectorial finite element method (VFEM)[7,8] theoretically. The chromatic dispersion properties can be modified greatly by the central defect of air hole, and the chromatic dispersion coefficient is high negative and flat in the measured wavelength range of 1500 − 1625 nm. Our designed and fabricated PCF with defected core is suitable for broadband dispersion compensation in DWDM optical communication systems.

Scanning electron microscope (SEM) image of the fabricated broadband dispersion compensating PCF with defected core is shown in Fig. 1. And the theoretical schematic cross section of the PCF is shown in Fig. 2.

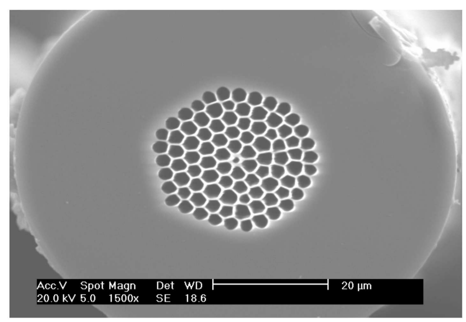

Fig. 1. SEM image of our fabricated dispersion compensating PCF with defected core.

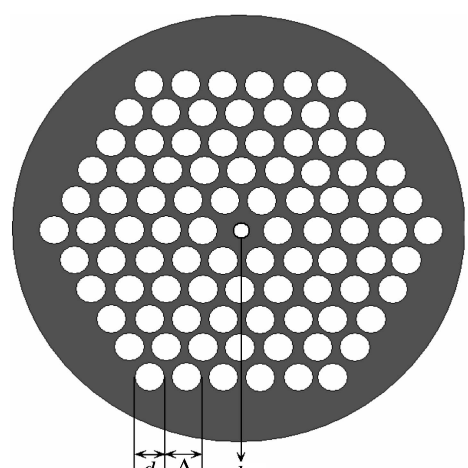

Fig. 2. Theoretical schematic cross section of the dispersion compensating PCF with defected core.

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The gray and white areas represent silica and air holes, respectively. It is composed of circular air holes in the cladding arranged in a triangular array with the pitch Λ. A small air hole is introduced in the center of PCF structure, and the diameter $d_{\rm c}$ of the defected core is much smaller than the diameters d of the cladding air holes. The whole fiber is fabricated by the capillary stacking method. The structural parameters of the PCF we fabricated is the pitch $\Lambda = 2.1$ μm, the air-filling fraction $d/\Lambda = 0.95$, and the ratio $d_{\rm c}/\Lambda = 0.61$. In actual fabrications, the defected core would be formed after the stack and drawing process. The diameter of defected core can be controlled by the temperature and the internal pressure in the drawing process. Our designed and fabricated PCF with defected core can realize the broadband dispersion compensation, and the compensating bandwidth is over the measured wavelength range of $1500-1625$ nm. However, the bandwidth of negative dispersion compensation is very narrow in the dual-core structures of PCF, and full width at half maximum (FWHM) is less than 30 nm. The chromatic dispersion can be controlled by the central defect of the defected core, however the dual-core structure control the dispersion by the different rings of the cladding air holes. So the PCF we fabricated can also reduce the difficulty of fabrication.

We numerically simulated the properties of the PCF with defected core by VFEM. The fundamental mode field distribution profile at the wavelength $\lambda = 1550$ nm is shown in Fig. 3, where $\Lambda = 2.1$ μm, $d/\Lambda = 0.95$, and $d_{\rm c}/\Lambda = 0.61$. We can see the strong confinement of light in the core of the PCF, and the mode field is mainly distributed in the silica core region and the peak value of the intensity lies on the outer of the defected core. The light is guided in the silica core region, so this structural PCF is a modified index-guiding PCF. However the existence of the defected core can slightly reduce the effective index, and as a result the field penetrates the cladding more strongly in comparison with the non-defected core PCF[9]. So we have to resolve the issue of low coupling efficiency with SMF. This issue may be effectively solved by using the mode converter[10,11]. The mode converter is made by differential holes inflation of air hole in the cladding to form the taper structure at the end of PCF.

Confinement loss is an additional form of loss that occurs in single-material fibers whose properties are determined by the geometry of the waveguide structure. With the increase of the air-filling fraction and the rings of the cladding air holes, the light leakage to the cladding will be reduced[12,13]. To reduce the confinement loss, the larger air-filling fraction $d/\Lambda = 0.95$ and five rings of air holes are chosen to fabricate. The calculated confinement loss of our fabricated PCF is 0.138 dB/km at $\lambda = 1550$ nm. So the larger air-filling fraction of cladding is benefit to confine the light.

The chromatic dispersion of PCF with defected core is directly calculated from the effective index of the fundamental mode according to Refs. [7,8]. The small defected core has the function to control the waveguide dispersion properties of PCF. The waveguide dispersion depends on the fiber designed structure and parameters. The enlargement of the defected core in the central silica region reduces the waveguide dispersion and as a result there is a compensation of the material dispersion of the silica. Figure 4 shows the impact to the chromatic dispersion curves by varying the defected core diameter with $\Lambda = 2.1$ μm, $d/\Lambda = 0.95$, and $d_{\rm c}/\Lambda = 0$, 0.2, 0.4, 0.6. As shown in Fig. 4, the chromatic dispersion coefficient largely reduces with the enlargement of the diameter of defected core in the wavelength range of optical communication windows. From Fig. 4, we can see that the chromatic dispersion coefficient is over -400 ps/(nm·km) in the very wide band of $1300-1700$ nm with $d_{\rm c}/\Lambda = 0.6$. And in this wide band, the chromatic dispersion is ultra-flattened. So we can control the dispersion properties by the central defect of defected core. The calculated results show that the structure of PCF with defected core is suitable for broadband dispersion compensation theoretically.

We measured the chromatic dispersion in the wavelength range from 1500 to 1625 nm with the sample length of 1 km by the phase-shift method. The measured band is over C+L band in the optical communication windows. The calculated chromatic dispersion curve and the test results of our fabricated dispersion compensating PCF with defected core are shown in Fig. 5. From Fig. 5, we can see that the calculated chromatic dispersion curve is largely negative in a wide ultra-flattened band. And the bandwidth is over C+L band that can provide the function of broadband dispersion compensation. The measured chromatic dispersion coefficient varies from -440 to -480 ps/(nm·km) in the $1500-1625$ nm. The nonuniformity of the cladding air holes and the abnormal holes arrangement lead to that our fabricated PCF has the property of birefringence. For this reason, the polarization of input measured light does not well match with the axis of PCF. So the experimental result is discrete. The calculated and experimental chromatic

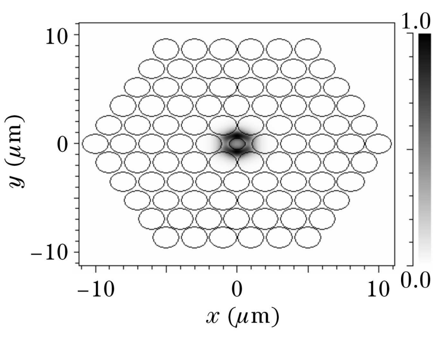

Fig. 3. Calculated field distribution profile of the fundamental mode at the wavelength of 1550 nm.

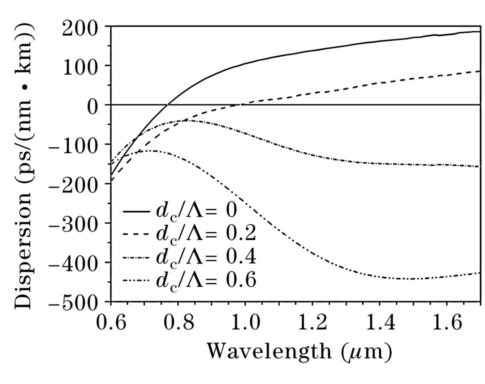

Fig. 4. Calculated dispersion curves of fundamental mode of different $d_{\rm c}/\Lambda$ with $\Lambda = 2.1$ μm, $d/\Lambda = 0.95$.

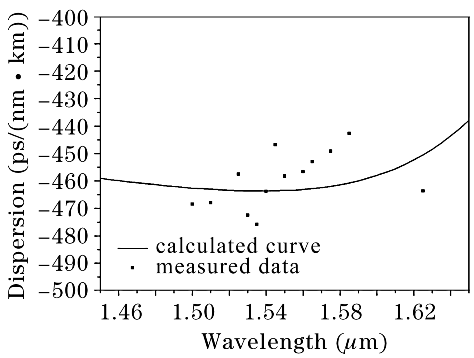

Fig. 5. Measured data and calculated dispersion curve of the fabricated dispersion compensating PCF with defected core.

dispersion coefficients at 1550 nm are −463.47 and −458.25 ps/(nm·km), respectively. The large negative chromatic dispersion coefficient is enough to compensate SMF used in the DWDM optical communication systems. As shown in Fig. 5, there is a reasonable agreement between the experimental result and the calculated chromatic dispersion curve. So we can confirm that PCF with defected core can provide high dispersion compensation in the wide range of optical communication windows.

In conclusion, we have theoretically and experimentally investigated the novel broadband dispersion compensating fiber using the index-guiding PCF with defected core based on pure silica. Our fabricated PCF with defected core has broadband large negative chromatic dispersion, and the chromatic dispersion coefficient varies from −440 to −480 ps/(nm·km) in the measured wavelength range of 1500 − 1625 nm. The compensating property can easily be controlled by the defected core. This kind of PCF can effectively compensate anomalous dispersion accumulated by transmission fibers currently deployed in DWDM optical communication systems.

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