Low birefringence depressed cladding photosensitive fiber

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Received January 16, 2009

The highly Ge-doped photosensitive fiber (PSF) has been widely used in the fabrication of fiber Bragg gratings (FBGs). Its birefringence and cladding mode coupling characteristics greatly influence FBG's transmission feature in communication application areas. In this work, a new concept of the PSF is introduced which, along with an optimized birefringence design, a precisely controlled fabrication process, and a cladding mode depressed design, results in a written FBG with −25-dB clad mode-depressed ratio and a polarization mode dispersion value less than 0.045 ps.

OCIS codes: 060.2280, 060.3738, 060.3735.
doi: 10.3788/COL20100801.0004.

Germanosilicate glass fibers have a well-known photoinduced refractive index change initiated by ultraviolet (UV) light at wavelengths near 240 nm. This phenomenon has been used to form reflection gratings at telecommunication wavelengths[1]. As a key optical component, fiber Bragg gratings (FBGs) are widely used in today's fiber optic communication systems as filters, multiplexer, demultiplexers, dispersion compensators, etc. Based on the plasma chemical vapor deposition (PCVD) process, the fiber's refractive index profile and the doping content could be controlled accurately[2]. In most fiber-making processes, germanium (Ge) and fluorine (F) are doped into the fiber. From the analysis of the relationship between fiber photosensitivity and doping material, as well as the doping content, the absorption band located near 242 nm has been found to be connected to the defect centers in the germanosilicate matrix[3]. Irradiation at this wavelength would provoke the bleaching of this band and the creation of other bands that could lead to a change in the refractive index through the Kramers-Kronig principle.

The fabrication of FBGs is usually done through the exposure of optical fibers to the UV fringes resulting from two-beam interference, or generation by a zero-order nulled phase mask. Due to the one-sided exposure process, effective birefringence is created in the fiber core[4]. Being the base material of FBGs, the germanosilicate glass fiber's birefringence feature has also become one of the most important origins of FBGs' birefringence[5].

The highly Ge-doped photosensitive fiber (PSF) is one of the most important types of PSF. Increasing the fiber core's Ge doping content to increase the fiber's photosensitivity[1] allows for an easier FBG writing in the fiber's core. However, with the increase in Ge doping content, the fiber's birefringence feature would become worse, and this would induce the polarization mode dispersion (PMD) of the FBG. When this kind of FBG is used in a telecommunication system[6], it would increase the system's PMD[7]. Therefore, it is very important to reduce this kind of influence of the PSF.

In this letter, we introduce a new concept of a highly Ge-doped PSF. This fiber's cladding mode has been depressed, and its birefringence[8] feature has been optimized. Using this kind of fiber to write FBG could decrease the PMD value of FBG to the maximum.

The fiber was designed with depressed cladding[9] and a highly Ge-doped core. In this design, the depressed cladding would decrease the cladding mode. Therefore, when the fiber has been written with FBG, the reflected cladding mode would be decreased substantially. Another unique characteristic in the fiber's design is the graded changed index interface designed among the highly Ge-doped core, the depressed cladding, and the outer cladding. The graded changed index interface among these layers is doped with Ge and F. When SiO_2 is doped with these two dopants, the viscosity of SiO_2 would be reduced. This means that when the fabricated core rod is drawn under a high temperature, the graded index changed interfaces would become softer than the other parts of the fiber. As a result, they would endure greater tensile stress than the other parts. This would then release the stress assumed to be on the fiber's core during the fiber's fabrication procedure, which reduces the stress-induced birefringence as low as possible. With this design, the birefringence caused from the fiber's fabrication process would be reduced. Then with the use of an advanced PCVD process, the fiber's geometrical

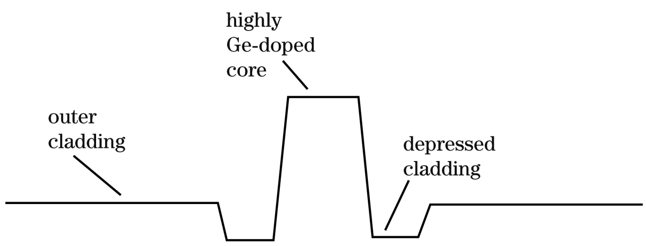

Fig. 1. Concept of a new fiber design.

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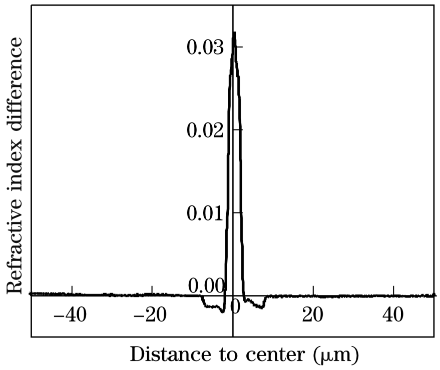

Fig. 2. Test result of the new concept of a fiber's refractive index profile.

symmetry would be optimized to reduce the fiber's PMD value. With this design, the novel fiber would have a low birefringence and a high cladding mode depressed ratio in the FBG's application areas. With the above considerations, the fiber's refractive index profile could be designed, as shown in Fig. 1.

During the fiber's fabrication, every process needs to be precisely controlled to ensure the fiber's good geometrical symmetry. With the adjusted drawing process, the new fiber has been fabricated. The fiber's refractive index profile has been tested by the Exfo NR9200 test model. The test result is shown in Fig. 2.

From this result, the fiber's refractive index profile has been realized. The graded index change between the fiber's core and depressed cladding, as well as the depressed cladding, was achieved with the precise control of the fabrication process.

The fiber's geometrical features were tested by the PK2400 model, while the optical features were tested by the PK2200 model. (PK2200 and PK2400 are Photo Kinetics Company's fiber test system models. PK2200 can test the fiber's attenuation spectrum, cutoff wavelength, and mode field diameter (MFD) features, while PK2400 can test the fiber's geometrical features such as core diameter, cladding diameter, coating diameter, core circularity, cladding circularity, and other features.) For this fiber, its core circularity and inner cladding circularity would influence the FBG's birefringence feature. The test results are shown in Table 1.

From the results, we can see that the fiber's numerical aperture (NA) value reaches 0.27. This was caused by the high Ge doping content in the fiber's core and the depressed cladding concept. The fiber core's noncircularity decreased to 1.5%. With this good characteristic, the fiber's geometrical birefringence could be decreased.

Table 1. Parameters of the New Fiber

Parameter	Value
Core Noncircularity (%)	1.50
Depressed Cladding Noncircularity (%)	0.28
NA	0.27
MFD at 1550 nm (μm)	4.2
Attenuation at 1550 nm (dB/km)	0.68

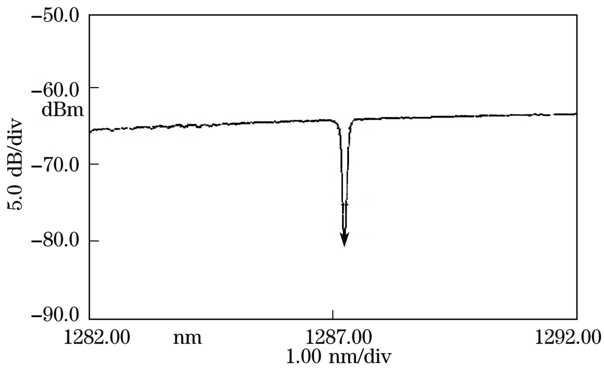

Fig. 3. FBG transparency property with the new fiber.

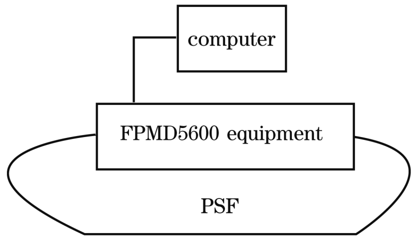

Fig. 4. Experimental setup for the PSF's PMD measurement.

Then the fiber's attenuation at 1550 nm was controlled to remain at 0.68 dB/km. The attenuation value indicates the good fabrication process control and the match between the drawing tension and drawing temperature. This high-NA, low-attenuation PSF should have the high photosensitivity and low birefringence in the applications.

To evaluate its photosensitivity, this new PSF was used to write FBG. The writing conditions are as follows: 248-nm laser wavelength, 15-mJ laser power, 500-Hz pulse frequency, and writing pulse number of 2500. The FBG's features are shown in Fig. 3 with a reflectivity of about 15 dB (96.8%).

The PSF's birefringence features were measured by a femtosecond polarization mode dispersion (FPMD) test equipment. The fiber's birefringence feature would represent its PMD value. The fiber length for measurement was about 1 − 2 m. The test setup is shown in Fig. 4. The measured feature is the short fiber's PMD value (Δt).

The formulas for the conversion from PMD value to birefringence are listed below:

$$\Delta\beta_l = \beta_x - \beta_y, \tag{1}$$

$$B = \frac{\Delta\beta_l}{k_0} = \frac{\beta_x - \beta_y}{k_0} = n_x - n_y, \tag{2}$$

$$n_x L = ct_x, n_y L = ct_y, \tag{3}$$

$$L = vt = \frac{c}{n}t, \tag{4}$$

$$\Delta n = n_x - n_y = \frac{c}{L}(t_x - t_y) = \frac{c}{L}\Delta t, \tag{5}$$

where β is the light propagation coefficient in the fiber, n is refractive index, L is the fiber length, v is the light speed in the fiber, c is the light speed in vacuum, t is the time, k_0 is a constant, and the subscripts "x" and "y" represent x and y directions, respectively. In the formula, the birefringence coefficient $B = \Delta n$ can be

Table 2. FBG's Birefringence Feature

Parameter	Value
Fiber Length (m)	2
PMD Value (ps)	10.198
Birefringence Coefficient	1.53×10^{-6}

calculated from the short fiber's PMD value Δt. The experimental setup for measuring the short PSF's PMD value is shown in Table 2.

As shown in Fig. 3. the main reflective peak is about 15 dB, and the short-wavelength cladding couple-induced reflective peak is about 0.6 dB. Hence, the FBG's cladding mode depressed ratio is about −25 dB. Using the test setup shown in Fig. 4, the obtained FBG's PMD value was about 0.045 ps. This small PMD value would guarantee that no additional PMD values using this kind of FBG would be contributed to the system.

In conclusion, the highly Ge-doped PSF's birefringence coefficient is measured by the short fiber's PMD value. Due to the optimization of the fiber design related to doping level, profile shape, and depressed cladding and drawing condition, the new concept of the fiber demonstrates good birefringence performance. The highly Ge-doped PSF's birefringence coefficient could reach 10^{-6} level. Due to this good birefringence performance, the PSF could be used to write better FBGs. This could provide a good solution for the low PMD FBG devices used in high-speed communication network systems.

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