A Novel Optical Fiber Sensor Fabricated by Femtosecond Laser Processing for Directional Bending Detection

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A novel optical fiber sensor has been developed using a femtosecond laser which emits single pulses of 210 fs, 3.6 μ J irradiation at a wavelength of 800 nm. Femtosecond laser machining has successfully been applied to create a bending direction sensing function in an optical fiber sensor, which has previously been impossible for conventional fiber sensors. The sensing portion of the fiber has an internal array micro-voids aligned along the optical fiber axis. The non-axisymmetric disposition of the micro-void array allows bending direction to be detected by observing increases and decreases in the light intensity propagated in the core. In this paper, the performances of fiber bending sensors are shown in terms of directional bending detection capability, sensitivity, reproducibility and laser machining conditions for sensor fabrication. A 2 mm-long sensor element gives average sensitivities of -0.08 and $+0.06$ dB/mm over a 5 mm displacement range for bending in opposite directions.

Key Words: Optical fiber sensor, Directional bending detection, Femto-second laser, Internal processing, Micro processing

1. Introduction

Recently, the micro-processing of transparent materials such as glass and acrylic has enabled the development of novel optical devices with functions such as photoregulation and sensing.¹⁻⁴⁾ In particular, it has become feasible to fabricate microscopic structures in transparent materials using a femtosecond laser micro machining technique.⁵⁾ A typical application of such processing is the fabrication of an FBG⁶⁻⁸⁾ (Fiber Bragg Grating) as a fiber sensor for detecting bending. An optical fiber core is processed with a femtosecond laser to create a localized periodic change in its refractive index, called a wavelength filter in LPFG⁹⁻¹¹⁾ (Long-Period Fiber Grating), and the spectrum of light transmitted by the fiber is shifted depending on the degree of bending in the filter portion.

While FBGs are a well-established means of sensing bending, there are alternatives such as LPFG, hetero-core fibers¹²⁾ and POF¹³⁾ (Plastic Optical Fibers). However, because their internal structures are symmetric around the optical axis, it is difficult for them to detect the *direction* of bending. In this work, we use a femtosecond laser to create axially asymmetric structures in close proximity to the core-cladding interface to detect bending direction. Such asymmetric structures have previously been created by femtosecond laser pulses as an array of micro-voids.

In this paper, we propose a novel optical fiber sensor which detects bending direction using a non-axisymmetric sensing portion. We constructed a laser processing system to achieve the fine beam control necessary to precisely create micro-structures in a very thin optical fiber core portion, with a CMOS monitoring camera by which the micro-structures can be viewed. Irradiation conditions were appropriately selected to allow the fabrication of sensor elements with different sensing lengths. Based on the directional detection principle proposed in this work, various sensor performances have been

obtained in terms of the reproducibility, linearity and sensitivity of directional bending detection by observing only intensity changes of light transmitted through the optical fiber core. The directional detection principle in this study is shown concomitantly with experimental measurements of sensor performance.

2. Void creation experiment

A femtosecond laser is essential for creating micro- and nano-scale voids in thin glass materials such as optical fibers because its extremely short pulse duration enables very fast multi-photon absorption at the laser focal point with less thermal effects around the focused region, compared with longer pulse experiments. A single void was created in a one-shot based experiment with varying the fluencies (J/cm^2) of the fundamental wave to obtain optimum processing conditions, allowing micro-voids to be created only in the interior of the optical fiber without cracking or surface damage.

The apparatus used to create micro-voids in a single mode optical fiber (FutureGuide-SM, Fujikura Ltd.) is shown in

Fig. 1 Experimental micro-void fabrication apparatus.

Fig. 1. A Ti-sapphire laser (Cyber Laser Inc. IFRIT) with an initial beam diameter of 6 mm emits short pulses of 210 fs at a wavelength of 800 nm. The laser pulses are introduced to a final focal lens through a train of reflecting mirrors, collimating optics and a dichroic mirror to focus the beam at the core-cladding interface of a target optical fiber. The collimating optics reduce the beam diameter to 3 mm to allow it to be introduced to the 3.6 mm aperture of the final focal lens, which focuses the beam to a design spot size of $1.36\text{ }\mu\text{m}$ at the focal point, based on the use of the effective beam diameter of 3 mm at the lens incidence plane for the approximate Gaussian shape. A commercially-available glass optical fiber was mounted on an X-Y-Z mechanical stage equipped with a rotating mechanism to rotate the fiber about its axis. The cladding and core diameters of the fiber were $125\text{ }\mu\text{m}$ and $9\text{ }\mu\text{m}$, respectively. To measure the light loss through the machined optical fiber core created by internal processing, 1310 nm-wavelength light from an LED source was guided into one end of the optical fiber and the intensity of the transmitted light emerging from the other end was measuring with a power meter (OP508, Opto Test Co.). The laser focal point was adjusted by moving the stage positions in terms of X, Y, Z and θ_x . The focal point, defined as the center of the Rayleigh distance of $1.81\text{ }\mu\text{m}$, was set at $1\text{ }\mu\text{m}$ above the core-cladding interface to create micro-voids near the interface. These micro-voids thence reached the fiber core and induced optical scattering sites. The created micro-voids were observed by means of an optical microscope with a CMOS digital camera viewing through a dichroic mirror from all directions along the circumference of fiber by rotating the axis.

During internal processing, the cladding surface of the optical fiber might be damaged by excessive irradiation fluencies. Since such damage can cause fractures or strength degradation of fiber, it must be avoided during the fabrication of micro structures in the vicinity of core-cladding interface. The fluencies of the experimental system could be adjusted between 70 J/cm^2 and 10 kJ/cm^2 per pulse, and it was found that damage to the cladding surface appeared at fluencies greater than 6.0 kJ/cm^2 , while no damage occurred at fluencies less than 5.5 kJ/cm^2 . From this result, the fluencies of this experiment were chosen to be less than 5.5 kJ/cm^2 .

Microscopic examination confirmed that all created micro-voids were elliptically shaped because the laser beam is subjected to a cylindrical lens effect by the optical fiber surface. Figure 2 (a) and (b) show monitoring microscope views from the laser beam entry direction for irradiation fluencies of 0.25 kJ/cm^2 and 3.9 kJ/cm^2 , respectively. The micro-voids produced were $10\text{ }\mu\text{m}$ in length and $1.1\text{ }\mu\text{m}$ in width in Fig. 2 (a), and $18.0\text{ }\mu\text{m}$ in length and $1.69\text{ }\mu\text{m}$ in width in Fig. 2 (b). It is apparent that the more intense the laser fluence, the larger the void. The change in the intensity of LED light transmitted through the fiber core due to a single laser shot producing a single void as shown in a Fig. 2 (a) was measured as -0.01 dB for a straight optical fiber.

Fig. 2 Microscopic top views of micro-voids produced in close proximity to optical fiber core by laser fluencies of (a) 246 J/cm^2 and (b) 3.89 kJ/cm^2 .

Fig. 3 Non-axisymmetric disposition of micro-voids.

3. Arranging voids

Our proposed optical fiber sensor to detect bending direction has a non-axisymmetric linear arrangement of micro-voids which are created as closely as possible to the interface region of the core and cladding, as shown in Fig. 3. It is possible to create closely-spaced voids only along the fiber axis, and if the interval between the voids is small they can combine to form a channel. Internal structures to perform sensing were fabricated by creating micro-voids at an interval of $10\text{ }\mu\text{m}$ along the fiber axis using the irradiation parameters such as fluence of 0.25 kJ/cm^2 and focal conditions using the apparatus described in section II above.

Three sensing portion lengths of 0.5, 1, and 2 mm were fabricated that had 51, 101 and 201 voids, respectively, and their directional bending detection performances were investigated in terms of reproducibility, linearity, and sensitivity. Three samples were prepared for each of the three sensing lengths. Insertion loss due to internal processing increases with sensing length and the number of voids, and the insertion loss is presented concomitantly with the sensor performance results in section IV. Figure 4 shows the created void arrays; the top (a) and side (b) of the figure respectively show schematic drawings and photomicrographs of the void arrays, and the left (i), center (ii) and right (iii) columns of the figure respectively show top, side, and cross sectional views of the void structure. From Fig. 4 (b)-i and ii, it is confirmed that the micro-voids are arranged along the centerline of the fiber core at the core-cladding interface. The micro-voids appear to have merged to form a linear structure since each void extends $10\text{ }\mu\text{m}$ in length along the optical axis of fiber. The cross sectional view in Fig. 4 (b)-iii, which was obtained by scanning electron microscopy (SEM), confirms the existence of a cavity (colored black) at a micro-void site which from SEM photograph characteristics must contain almost a vacuum or low density gas made of the glass material species. The dimensions of the void in the cross-sectional image are $0.182\text{ }\mu\text{m}$ in width and $1.92\text{ }\mu\text{m}$ in length, and the length is very close to the Rayleigh length of focused laser beam.

Fig. 4 (a) Schematics of void structures and (b) photomicrographs of array of micro-voids forming a channel. Photographs are: i from the direction of laser beam entry, ii perpendicular to the beam, and iii SEM cross-sectional view.

4. Sensing performance

To determine the performance of each sensing portion length, we performed an experiment to measure the intensity of light transmitted through the sensing portion while varying the degree of bending. The apparatus is shown in Fig. 5. Light of 1310 nm wavelength from an LED source was guided into one end of an optical fiber with a void arrangement sensor and the intensity of light emitted at the other end of the fiber was measured by a power meter to obtain intensity changes of light transmitted through the sensing portion. The fiber was set between two stages of a computer-controlled linear traverse mechanism and the distance between the stages was varied to precisely control the degree of bending of the fiber. The sensing portion was located in the middle of the portion of the fiber between the stages. Each experiment began with the stages separated by 50 mm and zero bending. The distance between the stages was then reduced to 45 mm in 0.05 mm steps, giving a calculated curvature radius of 32 mm at the maximum displacement of 5 mm, before being increased back to the 50 mm. This was repeated ten times to obtain data.

The experiment was repeated with the voids structure located at the outside and inside of the curvature radius, as shown in Fig. 6 (b) and (c), respectively. In the following discussion, the cases in Fig. 6 (b) and (c) are defined as bending directions A (out-curvature) and B (in-curvature), respectively. If an array of micro-voids fabricated in the sensing portion reaches

Fig. 5 Experimental apparatus to produce bending by linear displacement. Curvature radius is 32 mm for a 5 mm displacement.

Fig. 6 Directional bending detection by core light loss for (a) straight path, (b) out-curvature and (c) incurvature cases.

the core/clad interface region, they work as scattering sites that dissipate light transmitted through the core. Transmitted light is subjected to scattering loss even with a straight path as shown in Fig. 6 (a). When the fiber is bent in the forms of Fig. 6 (b) and (c), the center of the transmitted power distribution is shifted to the off-axis direction. As shown in Fig. 6 (b), it was expected that transmitted light would be significantly influenced by micro-voids located at the outside of the curvature radius (out-curvature), resulting in a larger drop in light intensity than the straight path case. On the other hand, when the void structure is inside the curvature radius (in-curvature) as shown in Fig. 6 (c), it was expected that transmitted light would be less affected compared to the cases in Fig. 6 (a) and (b) because the optical field moves away from the void structure. Thus, the transmitted light intensity in Fig. 6 (c) is expected to be greater than in the cases of Fig. 6 (a) and (b). As a result, the direction of the bending can be detected by observing the increase and decrease in light intensity transmitted through the core.

Figure 7 (a)–(c) show the intensity of light transmitted through the fiber core as a function of stage displacement for sensing lengths of 0.5, 1 and 2 mm, respectively, for each of the three fabricated samples i, ii and iii of each sensor length to verify the reproducibility of fabrication. Insertion losses for the zero displacement (straight fiber) case were approximately 0.5, 1, and 2 dB for the sensing portion lengths of 0.5, 1, and 2 mm respectively. The plots in Figure 7 show the differences with respect to these zero displacement losses averaged over 10 bending cycles with error bars. Decreases (solid green line) and increases (blue broken line) of light intensity with respect to zero displacement indicate the cases of bending directions A and B, respectively.

As shown in the figure, for case (a), the 0.5 mm sensing portion length, the transmitted light intensities of the three samples decreased to 0.14, 0.14 and 0.12 dB when the sensor was bent in direction A by a displacement of 5 mm, whereas bending direction B shows less sensitivity with the increases of 0.04, 0.03 and 0.04 dB. These slight differences in the light intensity for each sample might be caused by variations in the fabrication process of the micro-void arrays. A second source of experimental variation might be slight differences in the bending plane alignment each time a sample fiber sensor is mounted on the traverse stages.

As shown in Fig. 7 (b) and (c), as the length of the sensing portion becomes larger the sensitivity for each bending direction improves, particularly for direction B. For the longest sensor portion length, case (c) (2 mm), the sensitivity to direction B becomes comparable to that in direction A, although it remains smaller, with an averaged sensitivity of -0.08 dB/mm over the 5 mm displacement range. It is found from Fig. 7 that the sensitivity for bending direction A (the out-curvature void arrangement) is larger than for direction B (the in-curvature case), although the sign is opposite. This is because the out-curvature case has a greater influence on the optical mode distribution in terms of scattering process than the in-curvature case, as was expected.

The sensor performance results are summarized in Table 1, which also demonstrates the reproducibility of the fabrication technique.

5. Conclusions

This work shows that directional bending detection, in which the intensity of light transmitted by an optical fiber core increases or decreases depends on the direction of bending,

Fig. 7 Sensor light intensity output versus displacement for bending directions A (solid line) and B (broken line). Three samples (i, ii and iii) were tested for each sensing length (a) 0.5 mm, (b) 1 mm and (c) 2 mm.

Table 1 Summary of insertion loss, intensity change and average sensitivity for bending directions A and B for each sensing length.

Sensing length (mm)	Insertion loss (dB)	Intensity change in bending direction A		Intensity change in bending direction B	
		Decrease (dB at 5 mm)	Average sensitivity (dB/mm)	Increase (dB at 5 mm)	Average sensitivity (dB/mm)
0.5	0.51	-0.14	-0.03	+0.04	+0.01
1	1.05	-0.20	-0.04	+0.13	+0.03
2	2.01	-0.41	-0.08	+0.27	+0.06

has been successfully realized by a proposed fiber sensor scheme in which single pulses of 210 fs, 3.6 μ J radiation at a wavelength of 800 nm were used to create non-axisymmetric micro-void structures in the very thin optical fiber core region. Such micro-voids play a key role in making possible the detection of bending direction. The micro-voids used in the sensing experiments were created with dimensions 10 μ m in length and 1.1 μ m in width by a laser spot size of 1.36 μ m at the focal point and irradiation fluencies of 0.25 kJ/cm².

Sensors with sensing portion lengths in which micro-voids were arranged of 0.5, 1 and 2 mm were fabricated and tested to determine their performance and the repeatability of the fabrication process. The test data could be useful for designing a required sensitivity level for practical applications. The size and precision of positioning of the array of micro-voids produced by a processing with a femtosecond laser are a very important factors that affect the changes in light intensity due to bending. The longer the sensing length, the greater the insertion loss and the higher the sensitivity. A 2 mm-long sensor element showed averaged sensitivities of -0.08 and +0.06 dB/mm over a 5 mm displacement range for the directions A and B, respectively. This work has shown that a non-axisymmetric structure made of an array of micro-voids has proved very practical in the design of a new sensor function using a commercially available optical fiber.

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