Bend sensors based on periodically-tapered soft glass fibers

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ABSTRACT

We demonstrate a technique for tapering periodically an all-solid soft glass fiber consisting of two types of lead silicate glasses by the use of a CO2 laser and investigate the bend sensing applications of the periodically-tapered soft glass fiber. Such a soft glass fiber with periodic microtapers could be used to develop a promising bend sensor with a sensitivity of -27.75 $\mu W/m^{-1}$ by means of measuring the bend-induced change of light intensity. The proposed bend sensor exhibits a very low measurement error of down to ± 1%.

Keywords: soft glass fibers, bend sensors, microtapers, sensing applications, intensity measurement, CO_2 laser.

1 INTRODUCTION

Soft or compound glass fibers have generated widespread interest because of unique optical properties such as high nonlinearity, mid-IR transmission, and high rare earth solubility [1-4]. Conventional fiber designs require the use of a pair of glasses for the fiber's core and cladding regions that are not only thermally and chemically compatible but also have appropriate optical characteristics for guidance. This has hampered the development of practical soft-glass fibers. Thus soft glass fibers usually are designed as microstructured optical fibres in which only a single material is required [1-5]. Recently an all-solid single-mode fiber consisting of three lead silicate glasses arranged in a W-type index profile was developed to achieve flattened and near-zero dispersion profile [6]. Investigations on soft glass fiber are usually focused on the communication applications such as ultrabroad supercontinuum generation [1, 7], all-optical switches [8], wavelength converters [9], optical parametric amplifiers and oscillators. Sensing applications of soft glass fibers are, however, becoming an important and promising research focus [10, 11]. Many in-fiber bend sensors have been developed by the use of fiber devices e.g. long period fiber gratings [12, 13]. However, these bend sensors usually are based on the measurement of the bend-induced wavelength shift, which is of disadvantage to practical engineering applications because expensive wavelength measurement instruments, e.g. optical spectrum analyzers, are required.

In this paper, we demonstrate a technique for tapering periodically an all-solid soft glass fiber consisting of two compound glass materials and investigate the bend sensing properties of the periodically-tapered soft glass fiber. A promising bend sensor based on intensity measurement is proposed and demonstrated by the use of an all-solid soft glass fiber with periodic microtapers.

2 TAPERING SOFT GLASS FIBERS

A novel all-solid soft glass fiber consisting of two types of commercial lead silicate glasses (core: Schott SF57 and cladding: Schott SF6) was designed and drawn. As shown in Fig. 1, the core and cladding diameters of this fiber are 2.4 and 175 μm, respectively. Refractive index in the core and cladding are 1.80 and 1.76, respectively. The measured transmission loss of the soft glass fiber is about 6.1dB per meter at the wavelength of 1550 nm. Compared with the conventional silica glass fiber, the soft glass fiber has a lower drawing temperature of about 600 - 700 ^oC. No polymer or other materials are coated on the surface of the soft glass fiber.

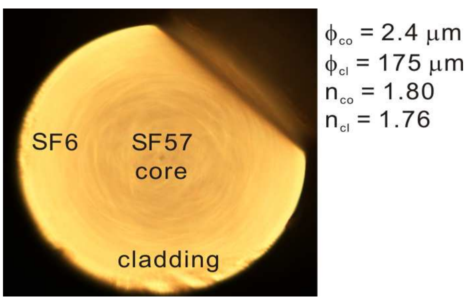

Fig. 1 Cross section image of all-solid soft glass fiber consisting of two types of lead silicate glasses.

We tapered periodically the soft glass fiber by the use of a CO_2

laser grating writing system illustrated in Figure 3 in Ref.[14]. One end of the fiber was fixed, and another end was attached by a small weight of about 10 g to provide a constant stretch force. A focused laser beam with a power of 2.8 W irradiated on the soft glass fiber for 120 second, thus inducing high temperature in the fiber. As a result, the fiber was tapered due to the high-temperature-induced softening of the glass and the stretch force applied. Then the laser beam was moved by a distance of 300 μm along the fiber axis to irradiate another segment of the fiber and to taper the fiber again. Such tapering process was repeated 20 times. Consequently, periodic microtapers were created on the soft glass fiber, as shown in Fig. 2. Although the distance of the laser beam moving along the fiber axis is 300 μm, the actual period of microtapers is 390 μm due to the taper-induced elongation of the fiber. And each microtaper has a waist diameter of 140 μm. The soft glass fiber employed has a length of 1 m. The mircotapers were created at the middle segment of the fiber.

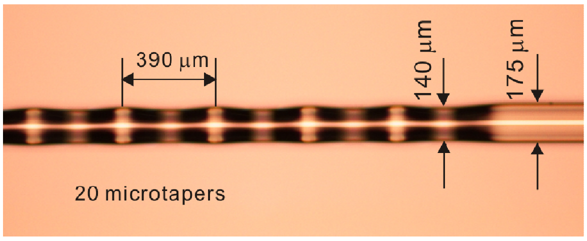

Fig. 2 Image of the soft glass fiber with periodic microtapers.

During the fiber tapering, the taper-induced attenuation was monitored by employing a super-continuum light source and an optical spectrum analyser (OSA, YOKOGAWA AQ 6370). Light from the source was directly launched into the soft glasss fiber via butt-coupling and another end of the fiber was directly connected to the OSA. The first microtaper induced an attenuation of 2.2 dB. The second microtaper induced a smaller attenuation of 1.4 dB. It is interesting to observe from Fig. 3(b) that the attenuation induced by each microtaper decrease gradually with the increased number of microtapers. As shown in Fig. 3(a), a total attenuation of about 9.3 dB was induced within the whole measured wavelength range from 600 to 1700 nm after the 20th microtapers was created. Provided more tapers are fabricated in the fiber, the total attenuation induced by microtapers hardly increase.

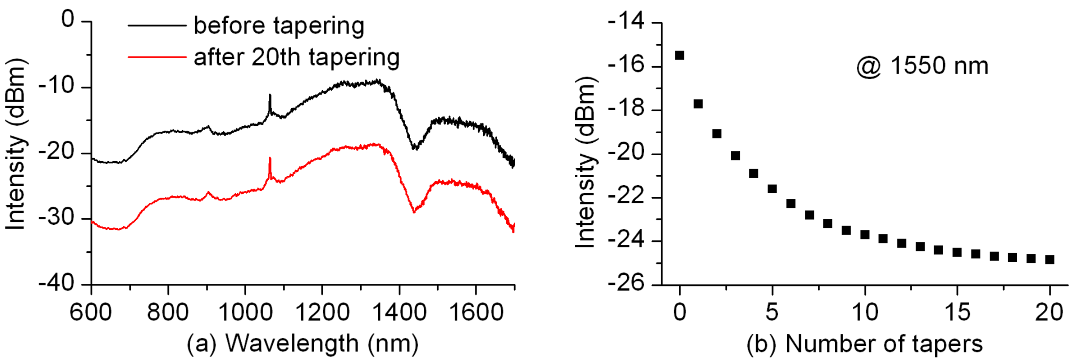

Fig. 3 (a) Light intensity measured at the output end of the soft glass fiber before tapering and after the 20th taper was fabricated; (b) Evolution of the measured intensity at the wavelength of 1550 nm with the increased number of tapers.

As well-known, periodic microtapers in conventional glass fiber will induce a long period fiber grating (LPFG) [15, 16]. However, no wavelength-dependent attenuation was observed within the broad wavelength range from 600 to 1700 nm in our experiments, as shown in Fig. 3(a). In other words, no LPFG was induced in our soft glass fiber with periodic microtapers. The reason of this is the soft glass fiber has a very large difference of 0.04 between refractive index in the core and cladding. Such an index difference requires that the period of designed LPFGs must be less than 43 μm to observe the wavelength-dependent attenuation within the wavelength range of less than 1700 nm. However, the period of the achieved microtapers is 390 μm in our experiments. And the CO_2 laser beam cannot be used to fabricate microtapers with a period of less than 43 μm because the laser beam has a large focus size of about 100 μm.

3 BEND SENSORS

We investigated the bending properties of the periodically-tapered soft glass fiber by the use of an experimental setup illustrated in Fig. 4. The left end of the soft glass fiber with 20 periodic microtapers was fixed, and the right end was moved toward the left side to bend the tapered fiber. Single-wavelength (1550 nm) light from a tunable laser source (Photonetics TUNICS-SW) was launched into the tapered fiber via butt-coupling and the output light was measured with a two-channel power meter (IQS-1600 Power Meter Modules). In practice, the input light could be tapped with a 10:90 fiber coupler and be measured with the second channel of the power meter to provide intensity referencing.

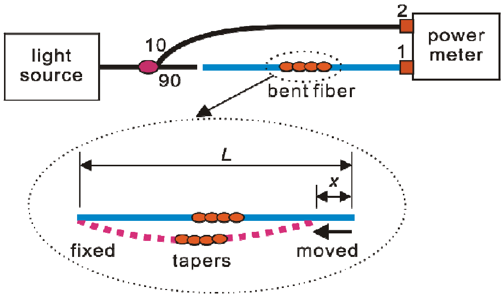

Fig. 4 Experimental setup for measuring the bending properties of the periodically-tapered soft glass fiber.

The curvature of the tapered fiber during the bending can be approximately expressed by

$$c = \frac{1}{R} \cong \sqrt{24x/L^3} \tag{1}$$

where R is the radius of the bent fiber, x is the movement of the moveable fiber end, and L = 120 mm is the length of the bent fiber segment. In our experiments, the maximum movement of the moveable fiber end is x = 3 mm. As shown in Fig. 5(a), the measured intensity of light at the wavelength of 1550 nm is almost linearly decreased with a sensitivity of -27.75 μW/m^{-1} while the curvature of the tapered fiber is increased, thus indicating that such a periodically-tapered soft glass fiber could be used to develop a promising bending sensor by means of measuring the change of light intensity. We also monitored the intensity change at the output end of the periodically-tapered soft glass fiber that was not bent. As shown in Fig. 5(b), the intensity fluctuation induced by the variation of light course and the change of external environment is less than 1 μW while the output light intensity is about 55 μW. Hence, the measurement error of our proposed bend sensor is down to ±1% and could be further improved by means of tapping 10% light to monitor the intensity variation of light course, as shown in Fig. 4.

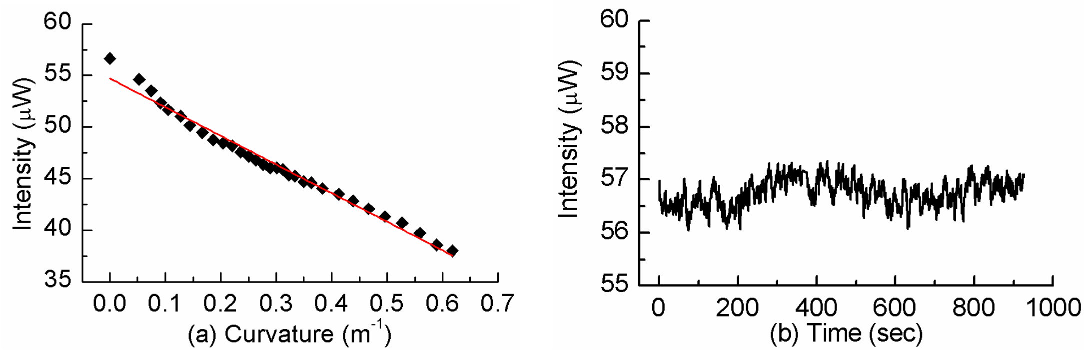

Fig. 5 (a) Intensity of the 1550 nm single-wavelength light measured at the output end of the soft glass fiber with 20 microtapers as a function of the curvature; (b) Intensity fluctuation at the output end while the periodically-tapered fiber was not bent.

4 DISCUSSIONS

Our all-solid soft glass fiber was designed a single mode fiber. Provided light was completely launched into the core, rather than the cladding, of the soft glass fiber by lenses in free space, light could be guided as single mode in the fiber. In our experiments, the pigtail fiber of light source was, however, directly butt-coupled to the input end of the soft glass fiber, and no lenses were used. As a result, almost all of light was launched into the fiber cladding, rather than the fiber core, due to the much larger cross section of the fiber cladding than that of the fiber core. Moreover, no polymer or other materials are coated on the surface of the soft glass fiber. And the fiber cladding has a very high refractive index of 1.76. Hence, light launched into the fiber cladding can be well guided as cladding modes. To testify the analysis above, we painted alcohol-based graphite adhesive with high absorption coefficient on the surface of the 10 cm length segment at the fiber end. Consequently, the light transmitted in the fiber is attenuated by about 35 dB, hence certifying that almost all of light is actually transmitted in the cladding of the soft glass fiber.

We also bent the soft glass fiber and measured the light intensity at the output end before microtapers were created. Experimental results show that the soft glass fiber without microtapers is insensitive to the bending. After the soft glass fiber is periodically tapered, periodic microtapers perturb the waveguide (geometric) structure, resulting that light guided in the fiber cladding is leak as evanescent wave. Thus the total attenuation induced by microtapers increase gradually with the increased number of tapers, as shown in Fig. 3(b). When the periodically-tapered fiber is bent, the influence of microtapers on light is enhanced. Consequently, light guided in the fiber cladding is further leaked as evanescent wave with the increased curvature, as shown in Fig. 5(a). Hence, the periodically-tapered soft glass fiber could be used to develop a promising bend sensor by means of measuring the bend-induced change of light intensity.

5 CONCLUSIONS

Unique optical properties are demonstrated in the all-solid soft glass fiber consisting of two types of lead silicate glasses. That is, light launched into the fiber cladding can be well guided as cladding modes due to high refractive index of the fiber cladding. Periodic microtapers can be created in the all-solid soft glass fiber by the use of CO_2 laser irradiation technique. The intensity of light transmitted in the periodically-tapered soft glass fiber is almost linearly decreased with a sensitivity of $-27.75\ \mu W/m^{-1}$ while the curvature of the fiber is increased. Hence, such a soft glass fiber with periodic microtapers could be used to measure the curvature of engineer structure by intensity measurement. This work was supported by a Marie Curie International Incoming Fellowship within the 7th European Community Framework Programme, and a Foundation for the Author of National Excellent Doctoral Dissertation of PR China (No. 200940).

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