Intensity-measurement bend sensors based on periodically-tapered soft glass fibers

Yiping Wang,[1,2*] David Richardson,[1] Gilberto Brambilla,[1] Xian Feng,[1] Marco Petrovich,[1] Ming Ding,[1] and Zhangqi Song[1]

[1]Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, U.K.
[2]Photonic Research Center, Harbin Engineering University, Harbin 150001, P. R. China.
**Corresponding author: ypwang@china.com*

We demonstrate a novel technique for tapering periodically an all-solid soft glass fiber, consisting of two types of lead silicate glasses, by the use of a focused CO_2 laser beam 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 promising bend sensors with a sensitivity of - 27.75 μW/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%.

A large number of in-fiber bend sensors have been developed by the use of various fiber devices, e.g. long period fiber gratings (LPFGs) [1, 2] and Fabry-Perot cavity [3]. However, these bend sensors usually are based on the measurement of the bend-induced wavelength shift, which requires expensive instruments, e.g. e.g. optical spectrum analyzers, to measure wavelength shift. In contrast, bend sensors based on intensity measurement overcome the disadvantage [4]. 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 [5-9]. Sensing applications of soft glass fibers are becoming an important and promising research focus [10, 11]. Conventional soft glass fibers usually are designed as microstructured optical fibres in which only a single material is required [5-9]. 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 [12]. Such all-solid soft glass fibers could have potential bend sensing applications owe to unique light transmission ability.

In this letter, we presented a novel all-solid soft glass fiber, consisting of two compound glass materials, in which light could be well guided in both core and cladding of the optical fiber. Moreover, we demonstrate a technique for tapering periodically an all-solid soft glass fiber and investigate the bend sensing application of the periodically-tapered soft glass fiber. A promising bend sensor based on intensity measurement is developed by the use of an all-solid soft glass fiber with periodic microtapers.

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 conventional silica glass fibers, the soft glass fiber has a lower drawing temperature of about 600 - 700 °C. No polymer or other materials are coated on the surface of the soft glass fiber. Light launched into the cladding of the soft glass fiber can be well guided as cladding modes, as discussed below.

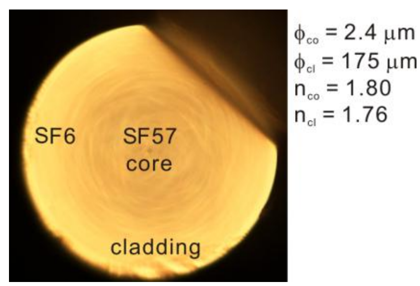

Fig. 1 Cross-section image of the all-solid soft glass fiber. The image was obtained by the use of a microscope (Nikon Eclipse LV100) with a 50x objective.

We tapered periodically the soft glass fiber by the use of a CO_2 laser grating fabrication system illustrated in Figure 3 in Ref. [13]. 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 seconds, thus inducing high temperature in the soft glass 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 and taper another segment of the fiber. Such tapering process was repeated 20 times. Consequently, periodic microtapers were created on the soft glass fiber, as shown in Fig. 2. Although the moving distance of the laser beam is 300 μm along the fiber axis, 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 total length of 1 m. The mircotapers were created at the middle segment of the fiber.

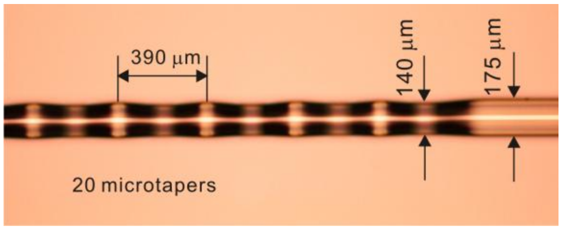

Fig. 2 Image of the soft glass fiber with periodic microtapers. The image was obtained by the use of a microscope (Nikon Eclipse LV100) with a 5x objective.

During tapering the fiber, 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. Another end of the fiber was directly connected to the OSA. It is interesting to observe from Fig. 3(b) that the attenuation induced by each microtaper decrease gradually with the increased number of microtapers, where the first microtaper induced an attenuation of 2.2 dB and the second microtaper induced a smaller attenuation of 1.4 dB. 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. The total attenuation induced by microtapers hardly increase even if more tapers are fabricated in the fiber.

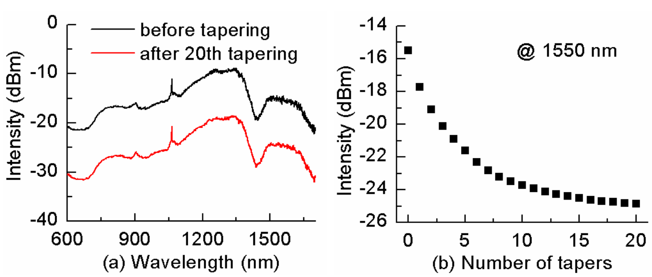

Fig. 3 (a) Light intensity measured at the output end of the soft glass fiber before tapering and after the 20th taper was created, (b) Evolution of the measured intensity at 1550 nm with the increased number of tapers.

As well-known, periodic microtapers in conventional glass fiber will induce a LPFG [13-15]. In our experiments, however, no wavelength-dependent attenuations were observed within the broad wavelength range from 600 to 1700 nm while the soft glass fiber was periodically tapered, 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 indexes in the core and cladding. Such an index difference requires that the period of designed LPFGs must be less than 43 μm to observe wavelength-dependent attenuations within the wavelength range of less than 1700 nm. But the period of the achieved microtapers is 390 μm in our experiments. In addition, our 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.

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 engineering applications, the input light could be tapped by the use of a 10:90 fiber coupler and be measured by the use of the second channel of the power meter to provide intensity referencing, which will be done in the future work.

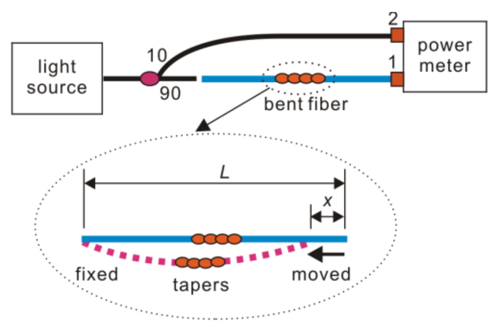

Fig. 4 Schematic diagram of experimental setup for measuring the bending properties of the periodically-tapered soft glass fiber.

While the right end the fiber is moved toward the left side, the curvature of the tapered fiber 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 distance of the moveable fiber end, and L = 120 mm is the length of the bent fiber segment. In our experiments, the maximum movement distance of the moveable fiber end is x = 3 mm. As shown in Fig. 5(a), the light power at the output end of the bent soft glass fiber 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 bend sensor based on intensity measurement. We also monitored the power fluctuation at the output end of the periodically-tapered soft glass fiber while the curvature of the fiber maintained a value of 0.5 m^{-1}. As shown in Fig. 5(b), the power fluctuation induced by the variations of light source and of external environment is less than 1 μW while the output light power is about 56.5 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 source, as shown in Fig. 4.

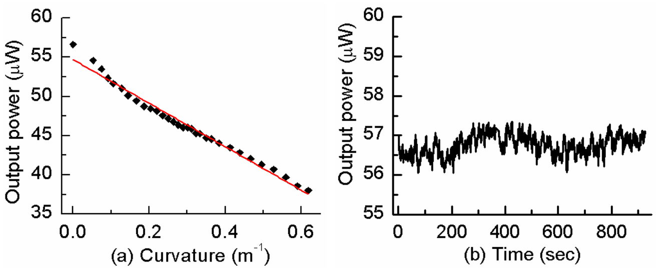

Fig. 5 (a) Output power of the bent soft glass fiber with 20 microtapers as a function of the curvature, (b) Power fluctuation at the output end of the bent fiber while the curvature of the periodically-tapered fiber maintained a value of 0.5 m^{-1}.

Our all-solid soft glass fiber was designed as a single mode fiber. Provided light is completely launched into the core, rather than the cladding, of the soft glass fiber by the use of microscope objectives in free space, light could be guided as single mode in the fiber. In our experiments, the pigtail fiber of the light source was, however, directly butt-coupled to the input end of the soft glass fiber, and no microscope objectives 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, an alcohol-based graphite adhesive with high absorption coefficient was painted on the 10 cm length surface of the soft glass fiber. Consequently, 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 leaked 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.

In conclusion, all-solid soft glass fibers consisting of two types of lead silicate glasses have unique light transmission ability. Light launched into the fiber cladding can be well guided as cladding modes due to ultrahigh 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. Intensity of light transmitted in the periodically-tapered soft glass fiber is almost linearly decreased with a sensitivity of - 27.75 μW/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 with a very low error of down to ± 1%. 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 (ID. 200940).

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