Cost-Effective Optical Fiber Curvature Sensor With Ultrahigh Sensitivity Based on Two Microcollapses in Silica Capillary

Volume 10, Number 4, August 2018

Ruikai Xue
Yu Mao
Yuxi Zhang
Yi Liu
Kunjian Cao
Shiliang Qu

DOI: 10.1109/JPHOT.2018.2846269
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Ruikai Xue,1 Yu Mao,1 Yuxi Zhang,1 Yi Liu,1 Kunjian Cao,1,2 and Shiliang Qu2

1Department of Optoelectronics Science, Harbin Institute of Technology at Weihai, Weihai 264209, China
2Department of physics, Harbin Institute of Technology, Harbin 150001, China

DOI:10.1109/JPHOT.2018.2846269
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Manuscript received March 18, 2018; revised June 3, 2018; accepted June 7, 2018. Date of publication June 12, 2018; date of current version June 28, 2018. This work was supported in part by the National Nature Science Foundation of China under Grants 11504070 and 11574063 and in part by the Science and Technology Development Plan of Weihai under Grant 2015DXGJUS002. Corresponding author: Yi Liu (e-mail: shandongliu2006@163.com).

Abstract: We proposed an optical fiber curvature sensor based on two microcollapses in silica capillary that was spliced between single-mode fibers. Only commercial fiber fusion splicer was needed in the fabrication process. The two microcollapses in the silica capillary can improve the interference effect of light modes with ring distribution surrounding the ultrafine air core (internal diameter of 5 μm), and the axisymmetric mode distribution is easy to be affected by the curving of the capillary. The proposed fiber structure can be used as a cost-effective curvature sensor owing to its simple fabrication process, low fabrication cost, good repeatability, ultrahigh sensitivity (885.62 nm/m−1), and low temperature crosstalk (29 pm/°C).

Index Terms: Optical fiber sensor, curvature, interferometry.

1. Introduction

Fiber optic curvature sensors have outstanding advantages over traditional sensors, such as small volume, high response speed, resistance to erosion and electromagnetic immunity. Therefore, they have been widely used in aerospace, precision machinery, structural health testing and micro-electromechanical systems (MEMS), etc [1], [2]. Some curvature sensors based on intensity demodulation method were proposed [3]–[6]. However, the measurement accuracy is easily disturbed by the power fluctuation of the light source and noise of the photo detector. The curvature sensors based on the dip wavelength monitoring show better stability by employing long period fiber gratings (LPFGs) [7], [8], fiber Bragg gratings (FBGs) [9], and photonic crystal fibers (PCFs) [10]–[13], but their sensitivities are only less than 10 nm/m−1. To improve the curvature sensitivity, Mach-Zehnder interferometers (MZIs) were achieved by using offset fiber splicing [14], [15] or fiber tapering [16], [17], which make them more sensitive to the curving of the fiber (about 10 50 nm/m−1). However, they show poor mechanical properties due to their specific structure shapes. Fiber curvature sensors based on the single-multi-single mode fiber (SMS) structure are also with high sensitivities [18]. Meanwhile, they have advantages of simple fabrication process, low cost and good mechanical property, and their sensitivities can be further improved by replacing the multi-mode fiber section in
the SMS structure with coreless fiber [19], twin-core fiber [20] or multi-cladding fiber [21] to extend the light field distribution. However, the curvature sensitivities of most of these sensors are still less than $100 \text{nm/m}^{-1}$, and some interferometer-based curvature sensors are also impaired by the crosstalk to temperature [20], [21].

In this paper, a cost-effective optical fiber curvature sensor with ultra-high sensitivity based on two micro-collapses in silica capillary was proposed. A section of silica capillary with an internal diameter of $5 \mu\text{m}$ was spliced between two single mode fibers (SMFs) by using the fusion splicer. Two micro-collapses in the silica capillary induced by arc discharging can improve the interference effect of different light modes that transmits in silica capillary, and obvious interference peak is shown in the transmission spectrum. The simulation results by using the finite difference beam propagation method (FD-BPM) show that the light propagates in the capillary with a ring mode distribution surrounding the ultra-fine air core, and its axisymmetric ring mode distribution is easy to be affected by the curving of the capillary. The experimental value of the curvature sensitivity based on the dip wavelength monitoring reaches as high as $885.62 \text{nm/m}^{-1}$. The proposed structure can be used as a cost-effective curvature sensor owing to its simple fabrication process, low fabrication cost, good repeatability, ultra-high sensitivity and low temperature crosstalk.

2. Fabrication and Simulation

The fabrication diagram of the proposed structure is shown in Fig. 1. In the first step, a section of silica capillary with the inner diameter of $5 \mu\text{m}$ and the outer diameter of $125 \mu\text{m}$ was spliced to the end surface of SMF by using the commercial fusion splicer, which is shown in Fig. 1(a). The splicing parameters are set as the values (a) listed in Table 1. The inside of the capillary at the splicing point collapsed into a coreless pure silica structure with a length of $D$. The splicing parameters with larger heating current, longer heating time and larger pushing distance were set to make sure that the splicing point can remain good mechanical strength in the actual sensing application. More importantly, these splicing parameters can result in a longer collapse area in the silica capillary at the splicing position, which is necessary to couple the most part of light into the sidewall of silica capillary [22]. In the second step, the silica capillary was moved to the left along the axial direction of SMF for a distance of $L$, and the splicing parameters of the fusion splicer are set as the values (b) listed in Table 1. During this process, the silica capillary was kept in the fusion splicer.
all the time. After the arc discharge once more, the new position of the silica capillary near the electrode collapsed slightly with a length of \( d \). The diagram is shown in Fig. 1(b). Then the second micro-collapse at next periodical position of the silica capillary was achieved by repeating processes mentioned before. In the fabrication process of the micro-collapse, we find through experiments that, if the splicing parameters with the same values (a) listed in Table 1 are used, the silica capillary will collapse greatly with strong deformation, for it is not a normal fiber splicing process. As a result, the diameter and profile of the silica capillary will be changed, which will influence the transmission spectrum. Therefore, in the micro-collapse fabrication process, the splicing parameters were set to be smaller values. In the third step, the silica capillary was placed out of the fusion splicer, and it was cut at the position with the distance of \( 3L \) from the splicing interface between the capillary and SMF. Then it was spliced to the end surface of another SMF by using the fusion splicer again with the parameters of values (a) listed in Table 1, which is shown in Fig. 1(c). The diagram of the final proposed structure is shown in Fig. 1(d). It consists of three ultra-fine air core sections and two micro-collapses in silica capillary.

The fabricated fiber structure based on two micro-collapses in the silica capillary is shown in Fig. 2(a)–(d), and the lateral view profile of the silica capillary is shown in Fig. 2(f). The total length \( 3L \) of the silica capillary is 6 mm. From Fig. 2(a) and (d) it can be seen that, the silica capillary near the splicing interface collapsed into a coreless pure silica structure, which helps to couple the light into the silica capillary and back into the receiving SMF. The length \( D \) of the coreless pure silica section was about 220 \( \mu m \). The air core of the capillary near the collapse was with a shape of taper (about 50 \( \mu m \) long). The splicing area is with good mechanical property. The two micro-collapses in the silica capillary are shown in Fig. 2(b) and (c) respectively. As the values of heating current and time were smaller than that in the fiber splicing process, the length \( d \) of the collapse area was only about 70 \( \mu m \). The air core of the capillary at two sides of the collapse also tapered, and the taper length was about 110 \( \mu m \). Besides, the external diameter of the silica capillary changed a little at the collapse area.

The transmission spectrum of the fabricated fiber structure was measured by using an optical spectrum analyzer (OSA, AQ6370B) and broad-band source (BBS, 1200 nm to 1700 nm). The spectrum result is shown in Fig. 2(e). There is an obvious interference peak near the wavelength of 1450 nm in the spectrum with the wavelength ranging from 1250 nm to 1650 nm. The peak contrast reaches about 35 dB. The insertion loss value of the fabricated fiber structure is about \(-15dB\). Another three fiber structures based on the same silica capillary spliced between the SMFs were also fabricated. There are no micro-collapses in the silica capillary for these three fiber structures as contrast, and the lengths of the silica capillaries are 2 mm, 4 mm and 6 mm respectively. Their transmission spectra were also measured and shown in Fig. 2(e). By comparing the spectra of four fiber structures, it can be seen that, the two micro-collapses can improve the interference effect of light with different modes propagating in the silica capillary.

Then we fabricated another two similar fiber structures based on one micro-collapse in 4 mm long silica capillary and three micro-collapses in 8 mm long silica capillary respectively. The distances

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (a)</th>
<th>Values (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-heating current</td>
<td>6.9 mA</td>
<td>0.1 mA</td>
</tr>
<tr>
<td>Pre-heating time</td>
<td>100 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td>Heating current</td>
<td>9 mA</td>
<td>4 mA</td>
</tr>
<tr>
<td>Heating time</td>
<td>1800 ms</td>
<td>300 ms</td>
</tr>
<tr>
<td>Pushing time</td>
<td>4 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Pushing distance</td>
<td>13 ( \mu m )</td>
<td>1 ( \mu m )</td>
</tr>
</tbody>
</table>
between neighboring micro-collapses are all 2 mm. The transmission spectra of these two fiber structures were also measured and are compared with that of the first fiber structure in Fig. 3(a). It can be seen that, when there is one micro-collapse in the silica capillary, the interference peak is also shown in the transmission spectrum. The two micro-collapses can help to improve the contrast of the interference peak. When the number of micro-collapses reaches three, more disordered interference peaks are shown in the transmission spectrum, which will influence the signal demodulation in the actual sensing application. Meanwhile, the insertion loss increases as well. To show the influence of the micro-collapse length on the interference spectrum, we changed the arc discharge parameters to achieve micro-collapses with different lengths, and fabricated another two fiber structures the parameters of which are the same as that of the first fiber structure except the length of the micro-collapse. The lengths of the micro-collapses of these two fiber structures are 84 μm and 110 μm.
respectively. Their transmission spectra were also measured and compared with that of the first fiber structure in Fig. 3(b). We can see that the length of micro-collapses will influence the wavelength position of the interference peak. The two micro-collapses with different lengths will excite different light modes, which induces the variation of the effective refractive index difference of light modes implicated in the interference. Therefore the central wavelength of the interference peak changes as well. In addition, though the length of the micro-collapse can be increased to a certain extent by increasing the heating current and time, once the splicing parameters are set to be inappropriate, silica capillary will collapse greatly with strong deformation. Therefore the length of the micro-collapse cannot be a very large value.

FD-BPM was used to simulate the light distributions of the fiber structures based on the silica capillaries without and with two micro-collapses respectively, and the simulation results are shown in Fig. 4(a) and (b). The total lengths of the silica capillaries are both 6mm, and the sizes and shapes of the collapse areas in the numerical mode are based on the fabricated structures. The core and cladding refractive index (RI) of SMF are set to be 1.45205 and 1.44681. The RI of silica capillary is same to the cladding RI of SMF. The input light in the SMF has a fundamental mode field distribution, and the light wavelength is set to 1450 nm. From Fig. 4(a) and (b), it can be seen that, when the incident light reaches the splicing area between the SMF and the silica capillary, the input light field is coupled into higher-order modes. For the air core of the silica capillary near the splicing...
area was with a shape of taper, the light modes propagate only in the sidewall of the capillary. There is almost no light intensity distribution in the hollow core of the capillary. It is worth mentioning that, if the silica capillary is spliced to the SMF without the collapse at the splicing position, part of light can propagate through the hollow core of the silica capillary. In this case, the sidewall of the silica capillary forms a Fabry–Perot resonator, and anti-resonant reflecting guidance of light can be achieved in the hollow core [23]. As shown in Fig. 4(a) and (b), light modes in the sidewall of the capillary interfere with each other. The intensity distribution of the light field generated by the interference shows periodic pattern as the propagation of the light. The light intensity distribution in Fig. 4(a) is identical with that in Fig. 4(b) before the light reaches the first micro-collapse position. The optical field of the capillary section can be calculated by [22]

$$E(r) = \sum_{m=1}^{M} \alpha_m E_m(r) \exp(i \beta_m L)$$ (1)

where $M$ is the count of cladding modes, $\alpha_m$ is the coupling coefficient from the LP$_{01}$ mode in the SMF to the eigenmode LP$_{0m}$ in the capillary, $E_m(r)$ is the field distribution of the eigenmode LP$_{0m}$ in the capillary, $\beta_m$ is the longitudinal propagation constant, and $L$ is the propagation length along the capillary. From Fig. 4(a) and (b) it can be seen that, the lower-order modes are with higher energy and they are distributed surrounding the ultra-fine air core of the capillary. The intensity distribution of the light field shown in Fig. 4(a) and (b) generated by the interference in the capillary can be expressed as [22]

$$I(r) = E(r)E^*(r) = \sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_m \alpha_n^* E_m(r)E_n(r) \exp[i(\beta_m - \beta_n)L]$$ (2)

The interference occurs when the value of the $(\beta_m - \beta_n)L$ equals to the integer times of $\pi$.

When the light reaches the first micro-collapse position, the light intensity distributions shown in Fig. 4(a) and (b) respectively become different because of the collapse of the capillary. The energy distributions of cross sections at the positions marked as C$_1$ and C$_2$ in Fig. 4(a) and (b) are simulated respectively and the results are shown in Fig. 5(a) and (b). The circular pattern of the cross section distribution results from the interference of different modes, and each circular
section means the area with maximum light intensity of the interference, which partly represents
the distribution of the light modes. Comparing Fig. 5(b) with (a) we can see, lower-order modes
are coupled back to the center of the cross section at the collapse area. The most part of the light
energy centralizes at the collapse area as shown in Fig. 4(b). After the light propagates through
the collapse area, the light energy is coupled back into the higher-order modes. The simulated
energy distributions of cross sections at the positions marked as C₃ and C₄ in Fig. 4(a) and (b) are
shown in Fig. 5(c) and (d) respectively. It can be seen that, new different higher-order modes are
excited because of the collapse. Therefore, the intensity distribution of the light field in the capillary
between the two micro-collapses in Fig. 4(b) is different from that in the capillary without collapses.
At the second micro-collapse area the same phenomenon occurs for the light, which can also be
seen from Fig. 4(b). When the light reaches the final splicing area between the SMF and the silica
capillary, it is coupled back into the receiving SMF. The two micro-collapses can help to achieve a
certain extent of superposition of the interference between different modes. One part of the optical
path differences results from the effective refractive index difference of different modes multiplied by
light propagation distance 2 mm, and the other part of the optical path differences results from the
effective refractive index difference of different modes multiplied by light propagation distance 4 mm.
As a result, interference fringes with different spacings are induced and the transmission spectrum
is shown as the superposition of these interference fringes. The interference peaks at certain
wavelength can be superposed to be more obvious, while the interference peaks at some other
wavelength can be counteracted. Therefore the final interference peak shown in the transmission
spectrum can be with a high contrast.

In addition, the light distributions of the fiber structures based on the multi-mode fiber (MMF) and
coreless fiber (CLF) respectively were also simulated by using FD-BPM as contrast to show the
reason why the fiber structure based on the silica capillary can be with higher curvature sensitivity.
The core diameter of MMF is 105 μm. The RI of CLF is same to the cladding RI of SMF. The total
lengths of the MMF and CLF are also both 6mm. The simulation results are shown in Fig. 4(c)
and (d) respectively. The input light field are also coupled into higher-order modes at the slicing
area. Different from the silica capillary, the low-order modes with higher energy are distributed in
the center of the MMF and CLF along the fiber direction. The distribution of the high-order modes
in the CLF is wider than that in MMF.

Then the light distributions of four different fiber structures based on the silica capillary, the
silica capillary with two micro-collapses, MMF and CLF respectively were simulated again by using
FD-BPM under the same curvature condition of 0.5568 m⁻¹. The simulation results are shown in
Fig. 4(e)–(h). Typically, the field profiles of these four fiber structures are all symmetrically distributed
along the direction of propagation. When curving is applied, this symmetry is broken. From Fig. 4(e)–
(h) we can see, during all these four fiber structures, the asymmetric of the light field distribution
induced by the curving of the fiber is the most obvious in the silica capillary with two micro-collapses.
To evidently show the difference of the influence of the curving on the light distributions of the fiber
structures based on the silica capillary, the silica capillary with two micro-collapses, MMF and CLF
respectively, the energy distributions of cross sections at the positions marked as C₅, C₆, C₇ and
C₈ in Fig. 4(e)–(h) are simulated under the same curvature condition of 0.5568 m⁻¹, and the results
are shown in Fig. 5(e)–(h) respectively. It can be seen that, the circular interference patterns shift
to one side under the effect of the same curvature, which means that some light modes also shift
along with the curving of the structures [24]. By comparing Fig. 5 (f) to Fig. 5 (e), (g) and (h) it can be
seen that, some of the interference circles in Fig. 5 (f) shift more obviously than that in other figures.
It can be inferred that the offsets of certain modes in the silica capillary with two micro-collapses
are obviously larger than that of other three fiber structures. Therefore, the fiber structure based on
the silica capillary with two micro-collapses is expected to be with higher curvature sensitivity.

3. Experimental Results and Discussions
The setup of the fiber curvature sensing experiment is shown in Fig. 6. The fiber structure based
on silica capillary with two micro-collapses was fixed between two 3D move stages, and it was
firstly straightened by increasing the distance $L$ between two 3D move stages. Then one 3D move stage was moved toward the other for the distance $d$. The fiber structure curved under the effect of its own gravity, and the curvature $C$ of the fiber can be changed along with different values of $d$. Meanwhile, the transmission spectrum of the structure was monitored simultaneously by using the OSA and BBS mentioned before at constant room temperature. When the value of $d$ is small, the curved fiber structure can be approximated as an arc of circle, and the curvature $C$ of the fiber structure can be calculated by [15]

\[
C = \frac{1}{R} = \frac{2}{L} \sin\left(\frac{L}{2R}\right)
\]

By this way, the response of the fiber structure based on silica capillary with two micro-collapses to curvature was investigated.

Fig. 7(a) shows the central wavelength shift of the interference peak in the transmission spectrum when the calculated curvature changed from 0.0195 m$^{-1}$ to 0.0702 m$^{-1}$. With the increasing of the curvature, the center of the interference peak had a red-shift from 1440.1 nm to 1462.2 nm. The detailed relationship between the central wavelength of the interference peak and curvature is shown in Fig. 7(b). At the beginning of the sensing experiment, as the fiber structure was straightened horizontally between two 3D move stages, there was longitudinal strain force in the fiber structure. When the value of $d$ was increased from 0 to 60 $\mu$m (0 to 0.0447 m$^{-1}$), the strain of the fiber structure decreased firstly before it began to curve. Therefore, the calculated curvature value in this step was not accurate, and the response of the interference peak to curvature was not obvious. When the $d$ was further increased from 60 $\mu$m to 130 $\mu$m (0.0447 m$^{-1}$ to 0.0702 m$^{-1}$), the fiber structure indeed curved, and the central wavelength of the interference peak exhibited linear response to the curvature. In order to show the curvature response repeatability of the fiber structure based on the silica capillary with two micro-collapses, the 3D move stage was then moved toward opposite direction after the fiber structure curved to 0.0702 m$^{-1}$, which resulted in the decreasing of the curvature. The central wavelength change of the interference peak in the curvature decreasing process is also shown in Fig. 7(b). It can be seen that, in both curvature increasing and decreasing processes, the central wavelengths of the interference peaks under the same curvature condition are nearly identical, and there is no obvious hysteresis in the forward and backward curves. The changes of peak loss in both curvature increasing and decreasing processes are also recorded and shown in Fig. 7(c). There is no monotonous relationship between the peak loss and curvature. The interference peak shown in the transmission spectrum results from the superposition of different interference fringes which are with different curvature response.
Therefore, the change of peak loss along with the variation of the curvature is irregular. Then the whole curvature sensing experiment was repeated for another 2 times. We calculated the mean central wavelength of the interference peak and error bars of measurements at each repeated curvature condition between 0.0447 m\(^{-1}\) and 0.0702 m\(^{-1}\) in the curvature increasing and decreasing processes respectively. The linear fitted results are shown in Fig. 7(d). The curvature sensitivities reach as high as 885.62 nm/ m\(^{-1}\) and 874.40 nm/ m\(^{-1}\) in the curvature increasing and decreasing processes respectively. This sensitivity value is almost one order of magnitude higher than that of fiber structures based on MMF [18] and CLF [19]. Besides, we can see from Fig. 7(d) that the fiber structure based on the silica capillary with two micro-collapses is with good curvature sensing repeatability and reliability.

To show the strain crosstalk of the fiber structure based on the silica capillary with two micro-collapses, it was fixed again between two 3D move stages and strained by increasing the distance \(L\). The strain was increased from 100 \(\mu\varepsilon\) to 225 \(\mu\varepsilon\). The central wavelengths of the interference peak in the transmission spectrum at different strain condition were recorded and linear fitted. The results are shown in Fig. 8(a). As the increase of the strain, the interference peak shifted to shorter wavelength direction, and the strain crosstalk sensitivity is \(-7\) pm/\(^\circ\)C. The change of temperature can also affect the stability of the structure in curvature sensing process. In order to
analyze the influence of temperature on the fiber structure based on the silica capillary with two micro-collapses, the structure was placed in air environment in a tube furnace, which was heated from 40 °C to 65 °C with the interval of about 5 °C. The relationship between the central wavelength of the interference peak and the temperature is shown in Fig. 8(b). The interference peak shifted to shorter wavelength direction as the increase of the temperature, and the temperature crosstalk sensitivity is only 29 pm/°C.

4. Conclusion
A section of silica capillary with the internal diameter of 5 μm and the length of 6mm was spliced between SMFs by using the fusion splicer. The simulation results by FD-BPM show that the light propagates in the capillary with a ring mode distribution surround the ultra-fine air core. The two micro-collapses in the silica capillary induced by arc discharging can improve the interference effect of light with different modes in the capillary, and the axisymmetric mode distribution is easy to be affected by the curving of capillary. The experimental value of the curvature sensitivity based on the central wavelength shift of the interference peak reached as high as 885.62 nm/m. The proposed structure can be used as a cost-effective curvature sensor owing to its simple fabrication process, low fabrication cost, good repeatability, ultra-high sensitivity and low temperature crosstalk.

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