Design and fabrication of a heterostructured cladding solid-core photonic bandgap fiber for construction of Mach-Zehnder interferometer and high sensitive curvature sensor

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Abstract: A heterostructured cladding solid-core photonic bandgap fiber (HCSC-PBGF) is designed and fabricated which supports strong core mode and cladding mode transmission in a wide bandgap. An in-line Mach-Zehnder interferometer (MZI) curvature sensor is constructed by splicing single mode fibers at both ends of a HCSC-PBGF. Theoretical analysis of this heterostructured cladding design has been implemented, and the simulation results are consistent with experiment results. Benefiting from the heterostructured cladding design, an enhanced curvature sensing sensitivity of 24.3 nm/m$^{-1}$ in the range of 0-1.75 m$^{-1}$ and a high quality interference spectrum with 20 dB fringe visibility are achieved. In order to eliminate the interference of longitudinal strain and transverse torsion on the result of the curvature sensing experiment, we measure the longitudinal strain and transverse torsion sensing properties of HCSC-PBGF, and the results show that the impact is negligible. It is obvious that this high-sensitivity and cost-effective all fiber sensor with a compact structure will have a promising application in fiber sensing.

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References and links


1. Introduction

Due to its high stability, high sensitivity, anti-electromagnetic interference and simple structure, Mach-Zehnder interferometric has been widely applied in the field of fiber sensor, mainly for measurement of refractive index [1–3], temperature [4–9], curvature [10–12], pressure [13], strain [14–17], magnetic field [18] and other physical parameters. Many methods have been proposed to construct Mach-Zehnder interferometer, and most of which generate the interference by exciting cladding mode and core mode within fiber [19]. The cladding mode can be effectively excited by the particular structures, and the SMF-MMF-SMF structure is the easiest one [20]. When light in MMF is coupled to SMF, a strong cladding mode would be excited in the SMF because of the occurrence of mismatching mode field. However, the bare fiber should be used for lower loss of cladding mode in the SMF, which consequently enlarge the influence of environment on fiber sensor’s property.

Curvature sensors based on MZIs generally have two fiber mode couplers, one for excitation of modes and the other for coupling of modes. Many technologies have been created to construct MZIs based curvature sensors, such as core diameter mismatch, fiber tapers and collapsed splicing [21, 22]. For example, a MZI based on identical low-loss fused fiber tapers has been reported and can be used in curvature sensing [23]. However, whatever methods are used, the fragility of these structures influence the stability and repetitiveness of fiber sensor. Furthermore, MZIs formed by photonic crystal fiber have drawn wide attention.
due to their well-known superior advantages, such as diverse structures, unique optical waveguide properties and simple fabrication [24, 25]. These specialty photonic crystal fibers have shown simplicity, high sensitivity and firm structure to curvature due to their unique characteristics. However, the highest sensitivity of these sensors only reaches 3 nm/m$^{-1}$. To the best of our knowledge, there is no report on MZI based fiber curvature sensor with high stability, high sensitivity, strong structure and high repetitiveness, which are important for sensing applications.

In this paper, we design and fabricate a heterostructured cladding solid-core photonic bandgap fiber which supports strong core mode and cladding mode transmission in a wide bandgap. A compact and stable all fiber M-Z interferometer curvature sensor is constructed by splicing single mode fiber at both ends of HCSC-PBGF. Experiment results show that this MZI with stable structure and high sensitivity has excellent performance when applied to curvature sensing.

2. Fiber design and theoretical analysis

We expect to excite the innate cladding mode via the microstructural design of photonic crystal fiber to construct MZI and ensure to be strong in its structure and be superior in its performance. However, a strong innate cladding mode is hard to be excited in common photonic crystal fiber (PCF), because its cladding has lower refractive index compare to the core. Furthermore, in consideration of the splicing of the all fiber sensor, we prefer the all solid photonic bandgap fiber design for the following reasons. Firstly, the fiber core of the photonic fiber has lower refractive index, while the cladding has higher refractive index, thus the cladding mode can be effectively excited and stably transferred. Secondly, the bandgap position of the all solid photonic bandgap fiber is affected by the refractive index and the diameter of the high refractive index rod, and the structure and number of layers of the cladding only influence fundamental mode loss. Based on above features, we can increase the fundamental mode loss and also excite the cladding mode through unique design of structure of the high refractive index rod in cladding. Last but not least, the size of the fiber microstructure can be precisely controlled in the fiber fabricating process because of the no-air-pore structure of all solid photonic bandgap fiber. What’s more, the splicing will be very easy in the construction of all fiber sensor.

Fig. 1. Structure schematic diagram of the fiber: (a) All-solid photonic bandgap fiber; (b) Heterostructured cladding solid-core photonic bandgap fiber.

Based on anti-resonant reflecting optical waveguide (ARROW) theory, most of the light will be scattered back to the fiber core under the circumstances of phase matching and strong overlap with a leaky rod mode, where the light is on surface of the high refractive index rod with grazing incidence [27,28]. What’s more, the scatter property is mainly influenced by the
diameter and refractive index of high refractive index rod. It is difficult to achieve the coexistence of fiber core mode and cladding mode in conventional all solid photonic bandgap fiber because the high refractive index rod mode is a leaky mode. It is noteworthy that there is no obvious change of bandgap position when the structures and the layers of the high refractive index rods in cladding is changed. However, it has big impact on confinement loss of fiber core mode. Figure 1 shows two different all solid photonic bandgap fiber structures. Figure 1(a) is the conventional one, and Fig. 1(b) is the heterostructured cladding structure. The cladding of the fiber is consisted of high refractive index resonance rods, which has the refractive distribution of parabola, and those refractive index is 0.03 higher than pure silica. The resonance diameter is 1.75 μm as shown in Fig. 1, we replace part of the Ge-doped rod with pure silica as shown in Fig. 2(b). Calculations indicate that there’s only one fiber core mode in the bandgap position for common cladding of all solid photonic bandgap fiber as shown in Fig. 2(a). Figure 2(b) illustrates the change of effective refractive index and confinement loss of fiber core mode along with wavelength, from which we can see that the confinement loss gets higher when the wavelength gets longer within bandgap, and there is only one mode all the time. However, the simulation results of heterostructured cladding structure in Fig. 1(b) draw our attention. The fiber core mode transferring is valid in the same wavelength, but a strong cladding mode is found in the heterostructured cladding as shown in Figs. 2(c) and 2(d). Due to decrease of some high refractive index rods, the confinement loss of its fiber core mode increases by an order of magnitude compared with the fiber core mode of common all solid photonic bandgap fiber as shown in Fig. 2(e).

According to the results of these simulations, we have fabricated the heterostructured cladding solid-core photonic bandgap fiber (HCSC-PBGF). First we prepare high refractive index Ge-doped and pure quartz rods with the diameter of 1 mm, then stack the structure of the preform as shown in Fig. 1(b). Then the stacked preform is put into pure quartz tube to draw to fiber. Keeping negative pressure state in the process of drawing fiber is perfect for eliminating the air space between the rods. Figure 3(a) shows the section of the HCSC-PBGF. We use the high resolution microscopy to measure the diameters of the HCSC-PBGF, the cladding diameter is 125 μm, the fiber core is 10 μm, the high refractive index rod is 1.75 μm, the pitch between the rod is 3.5 μm, similar to the HCSC-PBGF used in previous experiment [26]. Then we measure the visible and near infrared transmission spectra of HCSC-PBGF by splicing single mode fiber at both ends of it. The short wavelength of bandgap ends around 1100 nm, and M-Z interference spectrum can be observed in the vicinity of 1550 nm as shown in Fig. 3. This suggests that there are two modes within the bandgap, when the two modes are coupled into the single mode fiber, a strong interference is produced due to the phase difference.
We measure the transmission spectra of HCSC-PBGF around 1550 nm with different lengths. Figure 4(a) shows the interference spectra of three different lengths of HCSC-PBGF, it can be seen that with the reduction of the length, the FSR become larger, this is a nature property of a standard M-Z interferometric. It is worth noting that this kind of M-Z interference spectrum stripe is very clear, and the fringe contrast reaches more than 20 dB, which is very beneficial to the application in the fiber sensor. For two-beam interference, its free spectral range (FSR) can be expressed as:

$$FSR = \frac{\lambda^2}{\Delta n_{eff} L}$$

Where $\Delta n_{eff}$ is the effective refractive index difference between the core mode and cladding mode, L is the length of HCSC-PBGF. We have constructed many MZIs with different lengths of HCSC-PBGF and measured their FSR around 1550 nm, it is obvious that FSR is an inverse function of L which is consistent with the Eq. (1), as shown in Fig. 4(b). Using Eq. (1), it can be calculated that the effective refractive index difference between these two modes is $4 \times 10^{-4}$, which is very close to the theoretical calculated value in Fig. 2. Therefore, it can be seen that a strong core mode and cladding mode is excited and M-Z interference is formed within the HCSC-PBGF.

In order to further validate the interference spectrum is produced by the core mode and cladding mode, the interference spectrum of Fig. 4(a) is Fast Fourier transformed to obtain the
spatial spectrum, as shown in Fig. 5. It is obvious that even if the length of the fiber is
different, but each spatial spectrum only has two strong frequencies, corresponding to core
mode and cladding mode of the HCSC-PBGF. When fiber length are 41.5 cm, 29 cm, and
16.5 cm respectively, the maximum frequency amplitude points are 0.07331, 0.05998 and
0.02666, which means the average space period are 13.64 nm, 16.67 nm and 37.5 nm.
Therefore, according to the Eq. (1) we can calculate the effective refractive index difference
between the core mode and cladding mode near 1550 nm, which are $4.24 \times 10^{-4}$, $4.97 \times 10^{-4}$
and $3.88 \times 10^{-4}$ respectively. These results are very close to the effective refractive index
difference of core mode and cladding mode calculated by finite element method in Fig. 2.
Then we can draw a conclusion that it is the core mode and the cladding mode produce strong
interference phenomenon.

![Fig. 5. Spatial frequency spectrum by taking the FFT with the length of HCSC-PBGF is 41.5 cm, 29 cm and 16.5 cm.](image)

3. Curvature sensing experiment

Using HCSC-PBGF to construct MZI to measure the curvature sensing performance, as
shown in Fig. 6. The input and output ends of light can be constructed by using fusion splicer
(Fujikura FSM-60S) to splice single mode fiber at both ends of HCSC-PBGF. Without air
holes, the splicing of HCSC-PBGF with single mode fiber is very simply and quickly, which
is similar to the splicing of the single mode fiber with single mode fiber, so there is no need to
grope for splicing parameters. Its splicing diagram is shown in Fig. 6(a), it can be seen that it
did not produce any problems such as collapse, bubble or core shift. However, the splice loss
is probably 3 dB at 1550 nm which mainly caused by mode field mismatch. After completion
of the splicing, we coat the fiber splice points with coating machine (VYTRAN PTR-200-
MRC), which makes the splice points very strong. It is conducive to construction of all fiber
sensor, and we don't have to worry about the fracture of splice points compared to these
proposed work when testing or using the MZI [21–23]. A supercontinuum source is linked to
the input end as the signal light, and the spectrometer (YOKOGAWA AQ6370D) is
connected with the output end to monitoring the transmission spectrum response to curvature.
Then, we fix the HCSC-PBGF under the surface of a steel ruler, and ensure the HCSC-PBGF
can be moved longitudinally under the surface of the steel ruler. The steel ruler is placed on a
displacement platform which is fixed on the experimental platform, it is worth noting that we
place two pulleys each on the input and output of single-mode fiber and place two weights on
the single mode fiber, as shown in Fig. 6(b). Because the HCSC-PBGF will bend when the steer ruler bends. In order to keep the fiber in the strain state, we must exert certain strain at HCSC-PBGF. Then we use high-precision displacement ruler to press the center of steel ruler, and the curvature can be expressed as the following equation:

\[
C = 2d / (d^2 + L^2)
\]

Where \(d\) is the variation of high-precision displacement ruler, \(L\) is the half distance of the displacement of two stage and the value is 20 cm. When the fiber is bent, the refractive index profile of HCSC-PBGF become asymmetric due to the elasto-optical effect and geometric change, which makes a phase difference between the core mode and cladding mode and the interference spectrum will shift. Therefore, we can obtain the curvature by monitoring the shift of interference spectrum.

We selected a 15 cm sample for measure, the results are shown in Fig. 7. And the wavelength of 1559.38 nm and 1585.44 nm are selected as the monitoring wavelength, named dip A and dip B respectively, when HCSC-PBGF is straight. It can be seen that with the increased of curvature the interference spectrum blue-shifted. The relationship between curvature and dip A/B within the range of 0-1.75 m\(^{-1}\) are shown in Fig. 7(a), and both are very linear variations and the sensitivities are 21.7 nm/m\(^{-1}\) and 24.3 nm/m\(^{-1}\), respectively. Figure 7(b) is the shift of interference spectrum with curvature variation, it can be seen that as the curvature increases, the interference spectrum fringes are still clear, and the fringe contrast is as high as 20 dB. Compared to the work of others [11, 12], our HCSC-PBGF based curvature sensor has higher sensitivity, simpler structure, lower fabrication cost, and also has a great advantage in practical application.

In order to eliminate the impact of longitudinal strain and transverse torsion on the result of the curvature sensing experiment, we measure the longitudinal strain and transverse torsion sensing properties of HCSC-PBGF respectively. In the experiment, HCSC-PBGF is fixed on two rotatable fiber fixtures, and then the fiber fixtures are fixed on two displacement
platforms which can be shifted longitudinally. We can measure the strain sensing property by moving displacement platform and transverse torsion sensing property when rotating fiber fixture, the results are shown in Fig. 8. It can be seen that the MZI is insensitivity to longitudinal strain and transverse torsion with a sensitivity of four orders lower than curvature sensitivity. Then we may safely draw the conclusion that the longitudinal strain and transverse torsion have little impact on curvature sensing.

4. Conclusions

In conclusion, we have designed and fabricated a HCSC-PBGF for high sensitive curvature sensing. And the theoretical analysis and experimental results prove this unique cladding structure design supports core mode and cladding mode transmission within the bandgap and the two modes will produce strong M-Z interference due to the existence of phase difference. We only need to splice single mode fiber at both ends of HCSC-PBGF to construct MZI for high sensitive curvature sensing. The experimental results show that the sensitivity of curvature is up to 24.3 dB/m in the range of 0 to 1.75 m⁻¹, and the interference spectral remains clear with a fringes visibility as high as 20 dB. In order to eliminate the interference of longitudinal strain and transverse torsion on experimental results, we measure its strain and torsion sensing property respectively. The results show that this MZI is not sensitive to strain and torsion. The sensor we design and fabricate has the advantages of compact structure, high stability, high repetitiveness, simple fabrication process and high sensitivity, which indicates the great potential in high sensitive curvature fiber sensing application.

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