Sensors Based on Dual Supermode Interferometers

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Abstract: Compact interferometers composed by two slightly different segments of asymmetric multicore fiber fusion spliced and rotated 180º with respect to each other are proposed for sensing applications. Examples and advantages of such interferometers are discussed.

1. Introduction

Multicore fibers (MCFs) are novel waveguides that comprise of multiple individual cores sharing a common cladding [1]. The diameters of MCF are similar to that of a conventional telecommunications optical fiber. The cores of an MCF can be well isolated from each other; in this case, each core acts as an independent waveguide. The cores of an MCF can also be close to each other to allow coupling between them. In this case, the MCF supports the so-called supermodes [2]. MCFs are expected that play an important role in future large capacity optical communication systems. Therefore, their mass production will make MCFs and associated devices (fan-in/out, connectors, couplers, multiplexers, etc.), and related instrumentation (light sources, detectors, etc.) cost effective and widely available.

Like conventional optical fibers, MCFs have intrinsic sensitivity to temperature and strain. However, coupled-cores MCF are also highly sensitive to bending [3]. Thus, MCFs offer an additional degree of freedom to devise sensors and other functional devices. So far, MCFs have been used to develop sensors and other devices whose performance cannot be easily achieved with conventional or specialty optical fibers. As an example, we can mention all-fiber shape sensors and lensless endoscopes [4, 5].

Here we propose a new platform based on MCF to devise sensors and other devices. Our platform consists of a supermode interferometer which is built with two segments of strongly-coupled core MCF [3, 6]. The latter consists of three coupled cores that form an equilateral triangle. The two segments of MCF are short and have slightly different lengths, in addition, they are fusion spliced and rotated 180º with respect to each other. The fabrication of the structure was carried out with a fusion splicing machine that has means for rotating optical fibers. It was found that our structure behaves as a two MCF interferometers in series. For sensing applications, our structure has important advantages which include compactness, high sensitivity, and simple interrogation.

The dual MCF interferometer proposed here can be used as a platform for the development of compact, sensitive sensors whose interrogation is simple. Curvature sensors that can distinguish the direction and amplitude of curvature as well as vibration sensors are demonstrated.

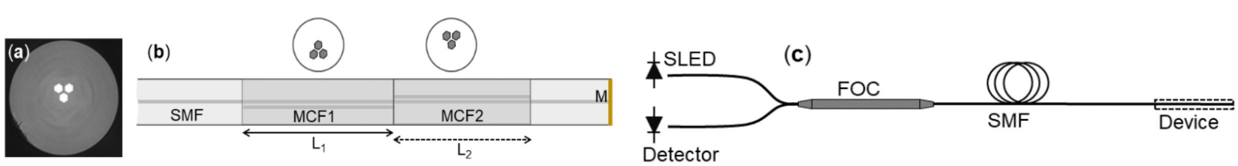

Fig. 1. (a) Cross section of the MCF used in the experiments. (b) Schematic representation of the dual interferometer, M is mirror. (c) Diagram of the interrogation of the interferometer; SLED is superluminescent light emitting diode and FOC is fiber optic coupler.

2. Device fabrication and operation principle

Figure 1 shows the cross section of the MCF used to fabricate the interferometer. The MCF consists of three coupled cores made of germanium-doped silica. Each core has a diameter of 9 μm. The separation between cores is 13 μm approximately. The cladding of the MCF is made of pure silica and has a diameter of 123 μm. The numerical aperture of each core of our MCF is 0.14, which is identical to that of a single mode fiber (SMF). The schematic representation of the dual MCF interferometer is shown in Fig. 1(b). It can be seen that the interferometer is composed by two segments of MCF. The cores of one segment are rotated 180º with respect to the other. Figure 1(c) shows a diagram of the interrogation of the interferometer. Light is launched to the dual MCF interferometer from a SLED by means

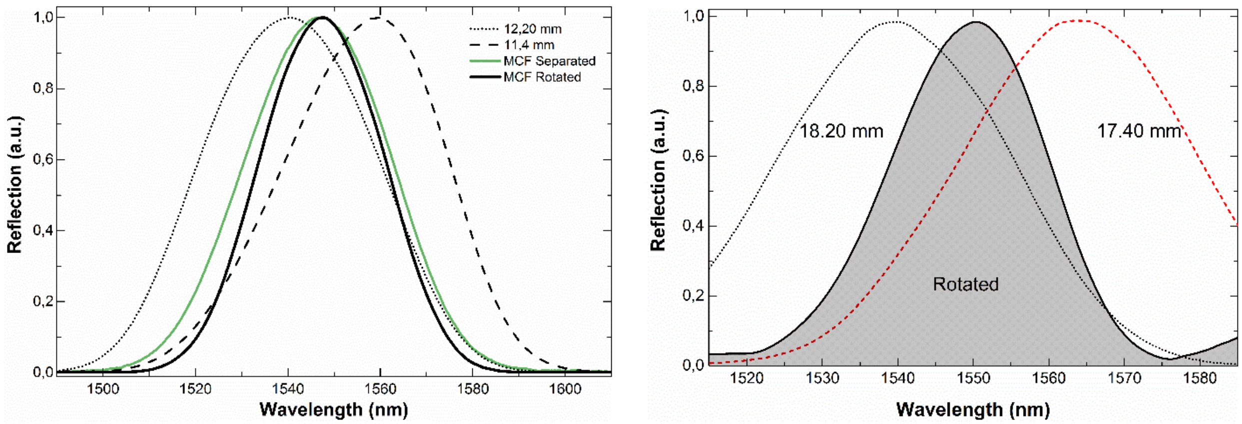

Fig. 2. (Left). The dotted and dashed lines are the reflection spectra of individual SMF-MCF-SMF structures with L_1 =12.20 mm and L_2 =11.40 mm. The green line represents the reflection of the 12.20 mm- and 11.40 mm-long SMF-MCF-SMF structures in series. The black solid line is the reflection of a SMF-MCF-MCF-SMF structure composed with a segment of MCF of 12.20 mm and another of 11.40 mm fusion spliced and rotated 180º. (Right) Reflection of two SMF-MCF-SMF structures composed with segments of MCF with lengths indicated in the plot. The shadowed area is the reflection of an SMF-MCF-MCF-SMF structure in which the 18.20 mm-long and the 17.40 mm-long MCF segments were rotated 180º.

of a fiber optic coupler or circulator. The reflected light is analyzed with a spectrometer.

The architecture shown in Fig. 1(b) is fabricated via the well-established fusion splicing technique. The main requirement is to have a fusion splicer that has means of rotating optical fibers. First, the MCF is fusion spliced to SMF. Then, the MCF is cleaved with a length L_1. The process is repeated to achieve another SMF-MCF structure in which the segment of MCF has length L_2. Finally, the two SMF-MCF structures are fusion spliced but the MCFs are rotated 180º with respect to each other before the splicing. The segment of SMF at the distal end of the device can be short. The cleaved end of such a segment can be used as a low reflectivity mirror.

The operating principle of the interferometer depicted in Fig. 1 was found experimentally as follows. First, two SMF-MCF-SMF structures were fabricated and interrogated with the setup shown in Fig. 1(c). In one of them the length of MCF was L_1 = 12.20 mm (or 18.20 mm); in the other the length of MCF was L_2 = 11.40 mm (or 17.40 mm). The reflection spectrum of each individual structure is shown in Fig. 2 with dotted and dashed lines. Then, the two SMF-MCF-SMF structures were placed in series. Finally, two SMF-MCF-MCF-SMF structures were fabricated with different combinations of L_1 and L_2 in which the two MCF segments were rotated 180º with respect to each other.

An SMF-MCF-SMF structure implemented with the aforementioned MCF is a supermode interferometer [3, 6]. If it is interrogated in reflection mode, the transfer function of such an interferometer can be expressed as: $T = [1+V\cos(\Delta\phi)]^2$, where V is the interferometer visibility and $\Delta\phi$ is the phase difference between the interfering supermodes. If two SMF-MCF-SMF structures are placed in series and are interrogated in reflection mode, the resulting transfer function can be expressed as $T_r = T_1T_2$. This means that the transfer function of the series is the multiplication of the individual transfer functions of the SMF-MCF-SMF structures [7].

The reflection spectra of two SMF-MCF-SMF structures placed in series; one built with 12.20 mm and the other with11.40 mm of MCF, are shown with a green curve in Fig. 2. The figure also shows the reflection spectra two SMF-MCF-MCF-SMF structures, one built with 12.20 mm + 11.40 mm of MCF, and the other with 18.20 mm + 17.40 mm of the same MCF. In the last two cases, the two segments of MCF were rotated 180º with respect to each other. It can be noted that the spectra of the SMF-MCF-MCF-SMF structures coincide with the spectra that results from the multiplication of the spectra of the individual SMF-MCF-SMF structures. Therefore, it can be concluded that the transfer function of an SMF-MCF-MCF-SMF structure is the multiplication of the transfer functions of two SMF-MCF-SMF structures.

It is worth noting from Fig. 2 that the resulting spectrum of an SMF-MCF-MCF-SMF structure in which the segments of MCF are rotated is a single and well-defined peak. The wavelength position of such a peak can be easily found and correlated with a measurand. In addition, the referred structure is compact and behaves as a dual MCF interferometer. All these advantages are important for sensing applications. Next, we will see some examples.

3. Applications

The performance of our dual MCF interferometer as curvature or vibration sensor was investigated. The dual MCF interferometer was placed on a thin plastic beam that was secured with two fixed supports. A translation stage with

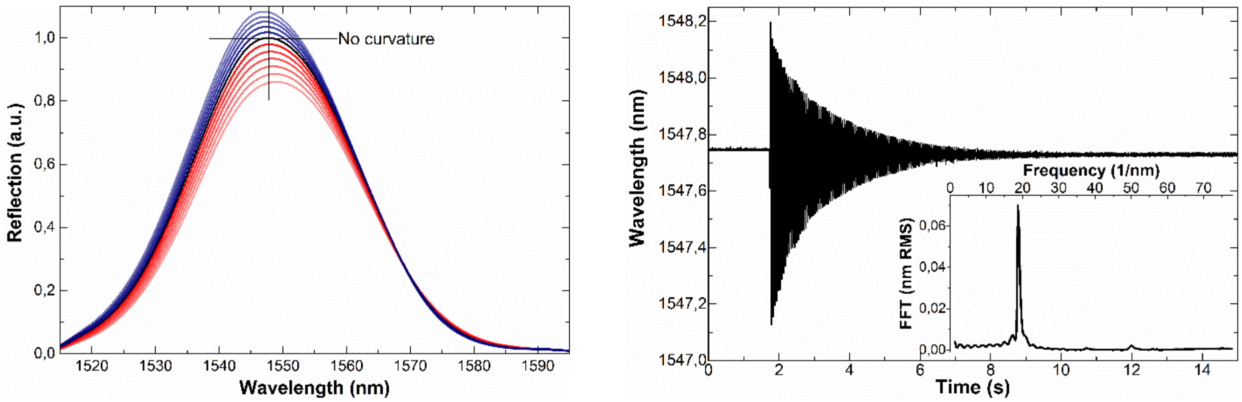

Fig. 3. (Left) Spectra observed when an SMF-MCF-MCF-SMF was curved upwards (blue curves) and downwards (red curves). The curvature step in each case was 0.026 m^{-1}. The cross indicates the position of no curvature. (Right). Position of the peak of an SMF-MCF-MCF-SMF when was subjected to vibrations. The inset graph is the fast Fourier transform (FFT) which gives the amplitude and frequency of the oscillations.

micrometer resolution was used to induce curvature to the beam in a controlled manner. The stage was located in the middle point of the distance between the two supports. The value of curvature (C) on the beam was calculated with the expression: $C = 12h/d^2$, where h was the displacement of the translation stage and d the separation between the two fixed supports. The maximum curvature that was applied to the dual supermode interferometer was 0.16 m^{-1}.

Figure 3 shows the results of our experiments. The plots on the left-hand side of the figure are the reflection spectra of a dual supermode interferometer built with two segments of MCF; L_1 = 12.20 mm and L_2 = 11.40 mm. The interferometer was subjected to convex and concave curvature. It was observed that the shift of the peak depended on the direction of curvature. Therefore, our dual supermode interferometer can distinguish the direction of curvature. The dual interferometer was also subjected to vibrations. Figure 3 shows how the wavelength position of the reflection spectrum changes with time. By means of the FFT, it was possible to know the frequency of the oscillation which is shown in the inset of the figure.

4. Conclusions

We have reported on a dual multicore fiber interferometer that can be used for the development of compact and sensitive sensors. The interferometer is built with two short segments of asymmetric, strongly-coupled MCF; such segments are fusion spliced and rotated 180º with respect to each other. It was found that our device behaves as two MCF interferometers in series. The main advantages of our interferometer include, fabrication via the well-established fusion splicing technique, simple interrogation, and compactness. It was demonstrated that as curvature sensors, our device can distinguish the direction of curvature as well as the magnitude. It is foreseen that other sensors can be devise with the dual supermode interferometer proposed here, as for example, accelerometers, force, or pressure sensors.

Acknowledgments

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