Sensitive interferometric force sensor based on multicore optical fibre

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ABSTRACT

A simple, interferometric force sensor based on a multicore optical fiber (MCF) that operates in reflection mode is presented. The device consists of a short segment of MCF inserted at the distal end of a conventional single mode optical fiber (SMF). To demonstrate the concept we used a mechanical piece with grooves to press the MCF. In this way the external force on the MCF is converted in localized pressure on the fiber which causes attenuation losses to the interfering modes and makes the interference pattern to shrink. The changes experienced by the interference pattern can be easily monitored. The sensor here proposed is highly sensitive since it can resolve forces down to 0.01 N.

Keywords: Multicore optical fibre, interferometers, microstructured fibers, force sensors.

1. INTRODUCTION

Force sensors are important in a number of applications of scientific and technological relevance. In robotics, for example, force sensors can provide tactile or touch information while in automobiles, or in industrial equipment, they can be used for safety purposes. Ideally, a force sensor must be accurate, reliable, and as simple as possible (hence cost effective), and due to the trend to miniaturization force sensors must have miniature or microscopic dimensions. In addition, force sensors must be easily embedded inside instruments, devices or mechanical pieces. Electronic force sensors based on load cells deliver most of the aforementioned requirements [1]. However, they are not suitable for all type of applications, particularly in those with electromagnetic interference or in those that require remote interrogation.

As an alternative to well-established electronic force sensors, the optical fiber sensor community has long been striving to devise high performance force sensor for niche applications and for those where electronic ones are not recommended. Optical fibers have a number of well-known advantages to devise force (and many other) sensors. So far, fiber optic force sensors in different platforms have been proposed. Fiber Bragg gratings (FBGs) have been used in different configurations for force sensing [2-5]. The disadvantage of force sensors based on FBGs is the high cost of its interrogation as a high resolution spectrometer is required to decode the shift of the Bragg wavelength. In addition, FBGs are sensitive to strain and temperature, thus, additional gratings or reference sensors are required. A cost effective alternative is to use a filter and a power meter to decode the applied force on the FBG, however, the measuring range is limited [5]. Intensity-based fiber optic force sensors have also been demonstrated [6,7]. The disadvantage of these sensors is the critical alignment of the components or the modest force sensitivity. Interferometers have also been demonstrated for force sensing [8-11]. In most cases, interferometric force sensors present challenges in terms of complexity, manufacturability, or reproducibility that may limit their applications.

Here, we report on a simple interferometric force sensor based on multicore optical fiber (MCF) that operates in reflection mode. The sensor consists of a short segment of MCF inserted in standard single mode optical fiber (SMF), see Fig. 1.To do so, we join the MCF and the SMF by means of the well-established fusion splicing technique. This technique allows the fabrication of cost-effective, robust and stable devices. In our configuration light passes twice the MCF. The MCF that was used to build our sensor consists of seven strongly coupled cores; all with diameter of 11 µm. see Fig. 1. One of the cores is located at the geometrical center of the MCF which simplifies the splicing with conventional single mode optical fiber. Our devices can resolve forces down to 0.01 N (1.01 grams).

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2. DEVICE FABRICATION AND WORKING MECHANISM

Figure 1 shows some details of the proposed device, its interrogation, the cross section of the MCF used to build the interferometer, and images of the SMF-MCF junction. To fabricate the interferometer we fusion spliced 7 cm of MCF to SMF. Thus, a SMF-MCF-SMF structure was formed. The section of SMF at the end was coated with a thick metallic layer to reflect about 99% of the guided light. In this way light passes twice in the MCF which contributes to improve the force sensitivity of our sensor.

To fabricate the structure shown in Fig. 1(b) we used a commercially-available splicing machine (Fujikura FSM 100P+). The default program set up in such a machine for splicing single mode fibers was used with the only difference that the MCF and the SMF were aligned with the cladding alignment method. The typical splice loss of our samples was ~0.1 dB which is much lower than that of other interferometers, see for example Ref. [11]. It is important to point out that our devices are very robust. Moreover, their fabrication takes only a few minutes for which their cost is low.

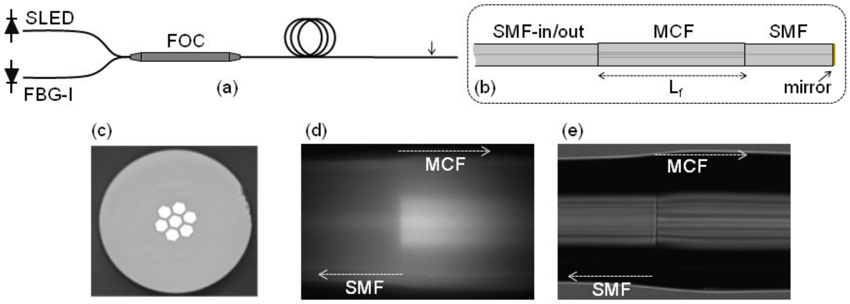

Fig. 1. Illustration of a MCF-based interferometer used to sense force. (a) The interrogation system consists of superluminiscent emitting diode (SLED), a fiber optic circulator (FOC) and a miniature fiber Bragg grating interrogator (FBG-I). (b) Schematic representation of the MCF interferometer. L_f is the length of MCF. (c) Micrograph of the cross section of the 7 core MCF used in the experiments. (d) and (e) are a thermal image and a micrograph of the SMF-MCF junction, respectively.

To understand the operating mechanism of our interferometer we first calculated the modes of the MCF using commercial waveguide software (FimmWave by Photon Design) which uses the finite difference method (FDM) to calculate the modes of a waveguide. Our seven-coupled cores MCF supports seven supermodes, six of them are shown in Fig. 2(a). Some modes are degenerate in intensity with differing phases across the cores. However, only two of the supermodes are excited by the fundamental mode of the SMF-in (modes denoted as 1 and 2 in Fig. 2) due to their circular symmetry and center-core excitation. The interference between these two supermodes will result in a periodic coupling of the power between the center and outer cores as the light propagates down the MCF.

To interrogate the SMF-MCF-SMF structure we launched light from a broadband source and the reflected light was analyzed with a miniature spectrometer (I-MON-512 USB from IBSEN Photonics) connected to a personal computer. As expected, a spectrum with maxima and minima (interference pattern) was observed, see Fig. 3.

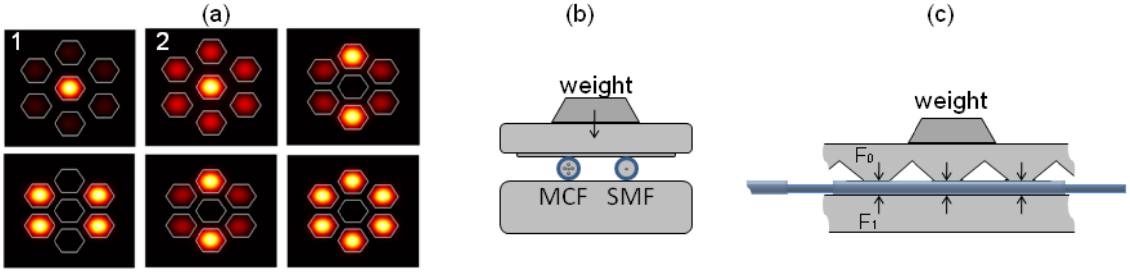

Fig. 2. (a) Simulated supermodes supported by the seven-core MCF used to build the interferometers. Drawings of the mechanical piece used to press the MCF on local points; a segment of SMF was used as a support fiber. (b) Front view of the piece. (c) Lateral view of the mechanical piece. F_0 is the local force on the MCF and F_1 is the reaction force.

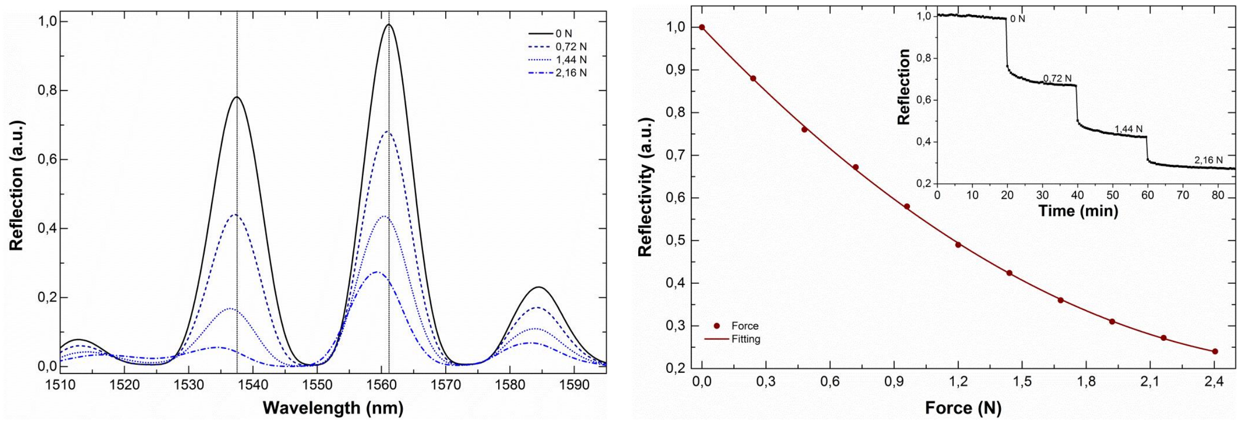

Fig. 3. (Left) Observed reflection spectra of an interferometer built with 7 cm of MCF at different forces on the MCF. As the force increases the interference pattern shrinks and shifts to shorter wavelengths. (Right) Absolute maximum of the reflection spectrum as a function of force on the MCF. The plot in the inset shows the evolution of the absolute maximum of the reflection spectrum as a function of time at different forces.

3. RESULTS AND DISCUSSION

The physical origin of the interference pattern shown in Fig. 3 is the difference in the propagation constants ($\Delta\beta$) of the two excited supermodes in the MCF. The wavelength dependence of $\Delta\beta$ causes the MCF to act similarly to a directional coupler. The period of the interference pattern depends primarily on the length of MCF while the modulation depth is highly dependent on geometry of the MCF [12-14].

To demonstrate the use of our interferometer for force sensing we applied force on the MCF with two metal plates, one with grooves and the other was flat, see Fig. 2. The width of each groove of the serrated piece was 1 mm and the separation between grooves was 7.5 mm. A short segment of SMF was used as a supporting fiber. The MCF and the SMF were placed as shown in Fig. 2(b). It is important to point out that the MCF and the SMF were coated with polymer and that the serrated mechanical piece pressed both fibers on 5 points.

We placed aluminum blocks of 24.5 (±0.1) grams on the mechanical piece and waited 20 minutes before putting a following block on the previous one as this was the time to reach stable reflections. We believe that this is due to the properties of the polymer that protects the optical fibers. It can be noted from Fig 3 that as the weight (force) on the MCF increases the amplitude of the interference pattern decreases. When the force on the MCF was greater than 1 N a shift of the interference pattern was also observed.

The changes experienced by the interference pattern can be easy detected. It can be noted from Fig. 3 that the fringe contrast (expressed in dB), i.e., the difference between the maxima and minima of the interference pattern, changes. Note also that the local and the absolute maxima of the pattern change too. In the right-hand plot of Fig. 3 we show the peak value of the highest peak of the reflection spectrum (absolute maximum) as a function of force on the MCF. The calibration curve (peak reflection versus force) that was obtained was fitted with the following equation: $R_m = 1\text{-}0.5263F + 0.0874F^2$, where R_m is the maximum of the reflected spectrum and F is the applied force on the MCF. To compensate minute power fluctuations of the optical source or losses in the lead-in SMF which can be misinterpreted as minute force changes on the MCF, a reference power meter can be used. A more powerful method to quantify force on the MCF is by means of the fast Fourier transform (FFT) which is calculated from the reflection spectra. The FFT is immune to power fluctuations or losses in the SMF, and also to temperature [11]. Such results will be presented during the conference.

To understand the behavior of our device we shown in Fig. 2 the forces that act on the MCF. An external force (F_0) applied perpendicular to the MCF axis will induce stress on the fiber. Stress is defined as F_0/A, where A is the area of the MCF that experiences the external force [15,16]. As a consequence, the MCF experiences transversal and axial strain. Stress and strain on the MCF modify the intensity and propagation constant of the supermodes, as a consequence the interference pattern shrinks and shifts.

4. CONCLUSIONS

In conclusion, we have reported on a simple force sensor based on a seven coupled cores optical fiber fusion spliced with conventional single mode fiber. Our device operates in reflection mode. The main features of the sensor here reported are: *i*) simple fabrication process as only a pair of fusion splices is required to build the interferometer. This simplicity may allow the fabrication of cost-effective interferometric force sensors. *ii*) Simple interrogation as a low-power LEDs and a low-cost optical spectrum analyzer are sufficient to analyze the reflected light. *ii*) High sensitivity, as our device is based on interferometry, one of the most sensitive optical detection methods. The force sensors based on the interferometer here proposed can be inserted into fiber optic catheters and therefore may be suitable for medical applications.

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