Robust strain sensor based on multimode interference in single-mode–multimode–single-mode fiber structure

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Single-mode–multimode–single-mode (SMS) structure is demonstrated as a strain sensor. The device is fabricated by splicing a section of multimode optical fiber (MMF) in between single-mode fibers (SMFs). The modal interference inside the structure produces a strong resonant transmission notch, which is sensitive to external perturbation. It was found that the position of the notch changed with strain at sensitivity of 1.3 nm/N. The device introduced here is simple to fabricate, robust and suitable for high temperature operation; hence, it is adequate for diverse sensing applications .

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1. Introduction

Advanced concreate and composite structures are now being widely used in civil engineering, ships, aerospace industry, submarines and modern vehicles. In those structures, the location and the extent of strain are important information in order to understand their behavior under loading condition. Recently, a lot of interest has been created for fiber optic sensing of strain, as it provides real time and in situ measurement. Fiber optic sensing is most suitable for structural health monitoring of those advanced structures, as they are compact, responsive, sensitive, stable and resistant to electromagnetic interference [1-3].

To date, various fiber optic sensors have been proposed for measuring strain in different structures and beams. For instance, fiber Bragg gratings (FBG) have been widely employed for measuring strain in composite structures and beams [4–5]. This is attributed to the measurements that are independent of source intensities and losses in the system. However, the grating writing is slightly complex where the efficiency depends on the precise control of focusing of optical beams. Fiber sensors based on Brillouin scattering have also been the focus of great attention for measuring strain distribution in cantilever beams [6-7]. By analyzing the Brillouin back-scattered light power spectrum, the strain and the measurement position may be determined for a beam to which a concentrated load is applied.

On the other hand, the multimode interference (MMI) theory has been extensively investigated and proposed as a basis for a number of novel fiber devices such as beam splitters, combiners, multiplexers for optical communications, comb filters and fiber sensors [8-10]. Recently, the multimode interference occurring in a single-mode–multimode–single-mode (SMS) fiber structure has also been studied and proposed for various sensing applications such as refractometer [11], and temperature sensors [12], edge filter for wavelength measurements [13] and a bandpass filter [14]. These optical devices based on an SMS fiber structure offer all-fiber solutions for optical communications and optical sensing with the advantages of ease of packaging and connection to optical fiber system.

In this paper, we report the use of modal interference in the SMS structure for measuring strain. The SMS structure generates a sufficient bandpass spectral response for a given wavelength range. The relationship between the transmission spectrum and length of MMF is also experimental investigated. The proposed sensor is also much easier to fabricate than an FBG and exhibits the strain sensitivity of 1.3 nm / N.

2. Experimental arrangement

The proposed SMS fiber structure is presented schematically in Fig. 1. The structure was formed by splicing the multimode fiber (MMF) with Ericson FSU-975 fusion splicer between two single mode fibers (SMFs). The fabrication was carried out by means of the conventional and straightforward fusion splicing technique. A micro-positioning and cleaving system consisting of a microscope and a translation stage was implemented. This allowed us to cleave the MMF and SMF with the desired lengths. The fibers were spliced with the default program for splicing SMFs set in a commercial fusion splicing machine. To monitor the fabrication process, we implemented a simple transmission setup that consisted of an amplified spontaneous emission (ASE) source operating at 1550 nm region and an optical spectrum analyzer (OSA). We used step-index MMF with a core diameter of 50 µm and standard SMF with a core diameter of 9 µm, both with external diameters of 125 µm. The splicing loss was less than 0.1dB. The SMS fiber structures were fabricated with different MMF lengths of 1 cm, 3 cm, 5 cm, 7 cm, 9 cm and 11 cm. Two SMFs in between the MMF was about 30 cm long.

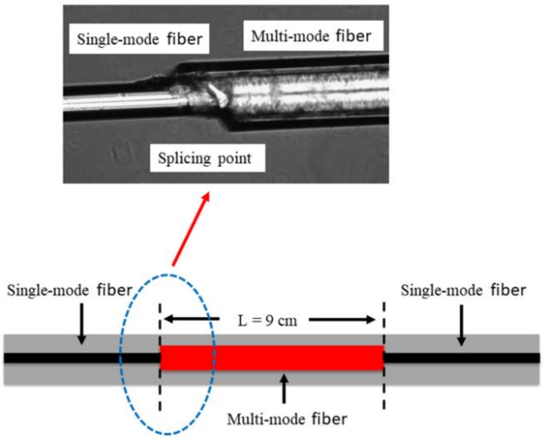

Fig. 1. Schematic diagram of the SMS fiber structure. Inset shows the microscope image at the splicing joint

3. Result and discussion

The incident field from the SMF typically excites higher-order modes together with the fundamental mode of the MMF, consequently, the excited field is a complete set of guided modes. However, if the SMFs and multimode fiber are axially aligned at the splicing points, the power will be coupled only to the first few circularly symmetric modes. And these modes will propagate along the MMF and be subject to the multimode interference effect. At the second splicing point, these circularly symmetric modes will be recoupled to the second SMF. The transmission loss of an SMS structure is given by [15]

$$P_{out}(L) = 10log_{10}(|\sum_{n=1}^{N} \eta_n^2 \exp(j\beta_n L)|^2) \quad (1)$$

where L is the length of the MMF, η_n and β_n are the excitation coefficient and propagation constant of higher order mode, respectively, and N is the total number of guided modes within the MMF. Based on the equation, it seems that the transmission loss depend on the MMF length. The observed transmission spectra of the proposed SMS structure at different MMF lengths is shown in Fig. 2. It is shown that the SMS structure exhibited one or more strong resonant transmission notches, >20 dB, in the 1535–1560 nm wavelength range depending on the MMF length. For instance, at MMF length of 7 cm, the notch operates at 1537.7 and 1556.8 nm. This is attributed to the mode coupling between higher order modes to fundamental mode, which is wavelength dependent. It also seems that the transmission loss depends on few other parameters from equation (1). These parameters are sensitive to external perturbation such as strain.

The configuration shown in Fig. 3 is constructed to test the SMS sensor for strain measurement. The fabricated SMS structure was placed vertically with both SMF parts were fixed. The upper part of the SMF was fixed on a stationary platform and the other SMF was set on a movable stage, which was clamped to the Instron 5582 static machine. In the experiment, the center of the SMS is vertically aligned with the position of applied load. Amplified spontaneous (ASE) source at 1550 nm wavelength band is used as a light source while optical spectrum analyzer (OSA, Aritsu MS9710C) is used to capture the spectral change at the output of the sensor, as shown in Fig. 3. The strain value was controlled by setting the speed of the machine in millimeters per second unit. The established speed was required to set in order to avoid machine error or the fiber reached the breaking point too fast. In this setup, we applied 0.1 millimeters per second speed. The reading was measured for each 0.5N strain.

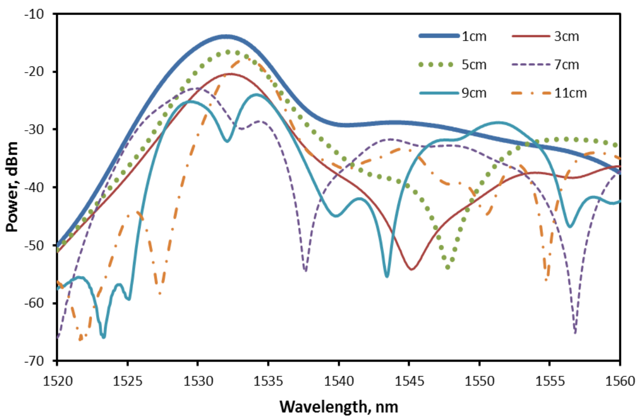

Fig. 2. Output spectrum for SMS fiber structure at different MMF lengths

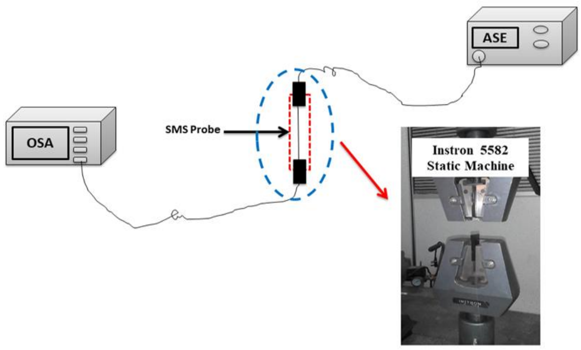

Fig. 3. Experimental setup for strain measurement with Instron 5582 static machine

The strain sensitivity of our SMS device was investigated in the 1 to 5N range. Fig. 4 shows the output spectrum of the SMS sensor configured with 7 cm MMF at various applied strains. As expected, the notch position shifted to shorter wavelengths as the strain increased. Note that we did not observe changes in the transmission spectra of the fiber after the strain test. The notch wavelength against the strain is also plotted and the result is shown in Fig. 4. By linear fitting of the experimental data the temperature sensitivity was found to be 1.3 nm/N, which is comparable to that reported for FBG based sensors. The FBG based strain sensor can only operate in temperature of less than 300°C since the grating structure disappears at high temperature. However, the melting temperature of silica fiber is higher than 1000°C. Therefore the SMS structure is expected to sustain high temperature and thus it is suitable for sensing in hostile environments. Li et. al. [16] reported that the SMS structure has a temperature sensitivity of 0.0615 nm/°C. In another work, Jiang et al. [17] demonstrated the Mach–Zehnder interferometer (MZI) in a conventional single-mode optical fiber can sustain the temperature up to 1200 °C. This indicates that our SMS sensor can also operate at 1200°C, but the temperature change will affect the strain sensing results. Therefore, a calibration or special packaging is required to compensate for the temperature influence.

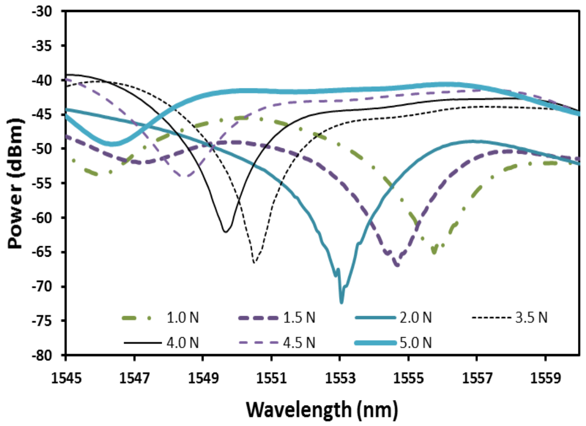

Fig. 4. Spectral response output from the SMS fiber structure at different strain values

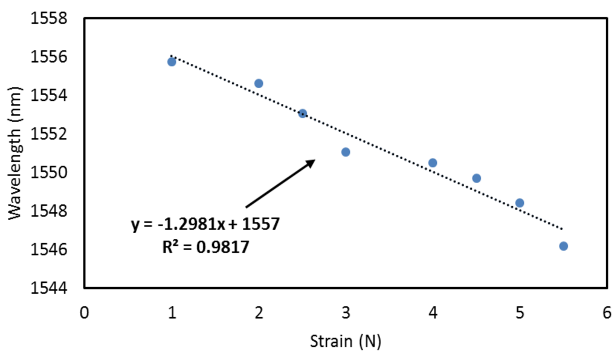

Fig. 5. Notch wavelength against the applied strain

4. Conclusion

We have successfully demonstrated a SMS fiber structure for strain measurement. The structure was fabricated by splicing a MMF segment between a SMF. It generates a strong resonant transmission notches, which is depending on the MMF length. It is obtained that the notch operates at 1537.7 and 1556.8 nm when the MMF length was fixed 7 cm. The notch wavelength shifts to a shorter wavelength with the increase of applied strain. The sensitivity of the strain sensor was found to be 1.3 nm/N. We believe that the SMS fiber structure device introduced here is appealing as it is simple to fabricate and can sustain high temperature for hostile environment application.

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