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Use of a Bent Single SMS Fiber Structure for Simultaneous Measurement of Displacement and Temperature Sensing

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***Abstract*—We have proposed the use of a single bent single-multiple-single mode (SMS) fiber structure to measure both displacement and temperature simultaneously and independently. Our experimental results show that this sensor has a sensitivity of 5.89 pm/μm for displacement and 11.6 pm/°C for temperature.**

***Index Terms*—Single-multimode-singlemode fiber, optical sensing**

I. Introduction

Fiber Bragg grating (FBG) based optical sensing has been extensively investigated and is widely used in bridge, civil and aerospace structural health monitoring, river surveillance etc [1-2]. Since a FBG is sensitive to both temperature and strain, it is difficult to determine whether the wavelength shift is introduced by temperature or strain when the FBG sensor is used in a variable temperature environment. Numerous investigations have been carried out to address this problem, for example by use of an additional FBG sensor in the same environment to measure the temperature [3] or by using a specially designed cantilever beam as a strain agent for a FBG sensor [4]. Recently several other authors have published alternative approaches to overcome this problem [5-8]. More recently we have proposed a specially designed Singlemode Multimode Singlemode (SMS) fiber structure to compensate temperature induced errors for a FBG strain sensor [9]. A SMS fiber structure can also be used for sensing and is much easier to fabricate than a FBG and therefore a sensor based on a SMS fiber structure will be more economic than that based on a FBG. As a SMS sensor is sensitive to both strain (displacement) and temperature [10], it should also be possible to use a SMS fiber sensor for simultaneous measurement of displacement and temperature. However the cross sensitivity of the SMS fiber structure causes similar problems to those experienced with FBGs. In this paper we propose for the first time a new way to use just one bent SMS fiber structure as a sensor for measuring both displacement and temperature simultaneously and independently.

II. System Description

A schematic diagram of the SMS fiber structure is shown in figure 1.

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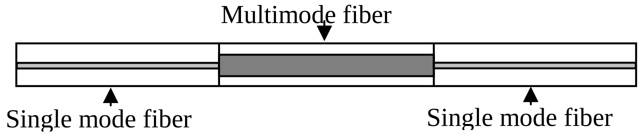

Fig. 1 Schematic diagram of an SMS fiber structure

The multimode fiber (MMF) in figure 1 has a step-index profile. As described in [9], the light injected into the MMF from a single mode fiber will excite multiple modes propagating in the MMF. When these modes are coupled into the output singlemode fiber (SMF), as a result of interference, the transmission spectrum is wavelength dependent. By careful selection of the length of the MMF, the SMS fiber structure can have a bandpass spectral response for a given wavelength range.

The experimental setup used is shown in figure 2.

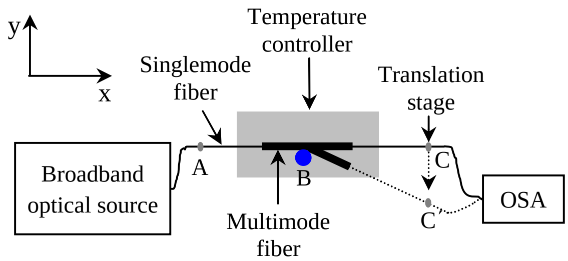

Fig. 2 Schematic experimental setup

The MMF section of the SMS fiber structure is temperature controlled. Point A of the SMF is glued to a fixed object and C is fixed to a translation stage providing displacement along the y axis. Point B lies at the center of the multimode section so that the SMS structure is in contact with a circular mandrel with a diameter of 1.4 mm. When displacement is applied by the translation stage, the fiber section BC will move to the position BC´, so that the multimode section is bent around the mandrel. The bend in the SMS structure is found to significantly influence the transmission characteristics of the SMS structure.

Because of the bend in the fiber structure the refractive index distribution in the multimode section of the SMS structure is no longer symmetric. As a result a simulation based on a guided mode propagation method [11] involves solving for hundreds of excited modes and thus is not feasible. However in order to give an approximate insight into the influence of the fiber bend, a three-dimensional simulation based on the beam propagation method (BPM) is employed to demonstrate the transmission behavior in the MMF section for both straight and bent SMS fiber structures. The simulations results are shown in figure 3 with a semi-vectorial variation at a wavelength of 1550 nm.

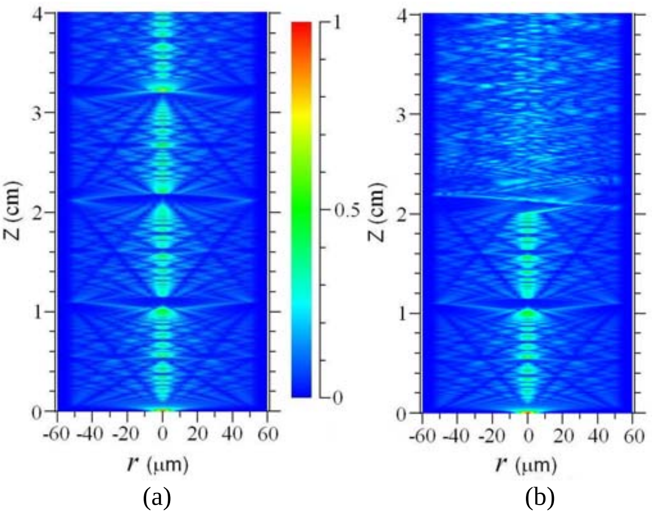

Fig. 3 Simulated light propagation within the MMF for (a) straight and (b) bent SMS fiber structure

In our simulation, the single mode fiber has a core diameter of 8.3 μm and the MMF has a diameter of 105 μm and the refractive indices of the core and cladding are 1.4446 and 1.4271 respectively. The bent diameter of the MMF portion is 1.4 mm. The length of the MMF section which undergoes a bend is estimated from the experimental setup to be 25 μm. The equivalent refractive index distribution used in our simulation for the bent fiber portion is Eq. (4) in [12].

The visual results of the simulation presented in figure 3 provide with an approximate idea of how physically the bend influences the transmission within the SMS fiber structure. Figure 3(a) shows that the field distribution in the MMF section for a straight SMS is symmetric, relative to the propagation direction (the z direction in the figure). However for the bent SMS structure, while the field distribution is symmetric up to the bend point (at z = 20 mm in figure 3 (b)), beyond this point since the bent fiber portion has effectively an asymmetric refractive index distribution [12], the modes excited in the bent fiber portion are also asymmetrically distributed. As a consequence in the remaining straight section of the MMF, the field distribution is also asymmetrical, in particular at the reimaging point where the SMF is attached. The bend therefore, even though it occupies only a small proportion of the total MMF length has a profound effect on the overall transmission characteristics of the SMS structure.

III. EXPERIMENTAL INVESTIGATION

Experimental investigations were also carried out for the proposed sensor based on a bent SMS fiber structure. The single- and multimode fibers used in our experiments were SMF28 and AFS105/125Y respectively. The MMF section has a length of 39 mm. Point B is located at a distance of 3 mm from the centre of the MMF section. The lengths AC and BC were 158 and 75.5 mm respectively and were chosen for experimental convenience.

Firstly for comparison purposes the spectral response of a straight SMS fiber structure was investigated. The spectral responses at three different displacement and temperature values are shown in figure 4(a). For a straight SMS fiber structure the displacement is applied along the x axis running from A to C as shown in figure 2. The results show that as displacement increases, the spectrum shifts to shorter wavelengths. As temperature increases, smaller but detectable spectral shifts also occur toward longer wavelengths. In all cases, the spectral shape remains unchanged. Since spectral shift can be introduced by either displacement or temperature, it is therefore not possible to discriminate between these two measurands using only a straight SMS fiber structure.

However this cross sensitivity issue can be solved using a bent SMS fiber structure. The spectral responses of the SMS fiber structure at different temperatures and displacements are shown in figure 4(b). In our experiments, an initial displacement of 2.7 mm along CC´ was applied to the SMS structure to provide a bend at the point B in figure 1. Subsequent displacements along CC´ are all relative to this initial displacement.

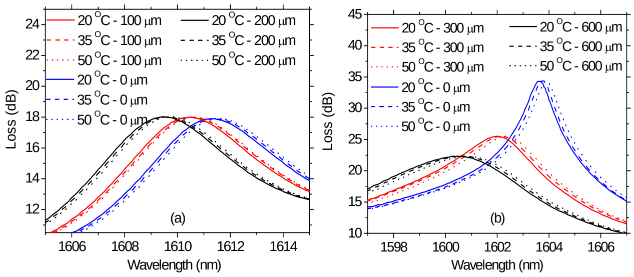

Fig. 4 Spectral response at different temperatures and displacements for (a) straight and (b) bent SMS fiber structure

Figure 4 (b) shows that at a fixed displacement, as temperature increases, the centre wavelength increases but the bandwidth variation is very small; at a fixed temperature, as displacement increases, there is a blue-shift for the centre wavelength and the bandwidth increases considerably. This result indicates that the displacement and temperature can be discriminated by measuring changes in both the central wavelength and bandwidth of the spectrum for a bent SMS fiber structure. Further investigations for the central wavelength and bandwidth shifts vs. displacement and temperature were carried out and the experimental results are shown in figure 5. The slope values (K coefficients) are calculated and are also shown in figure 5, for use later in this paper.

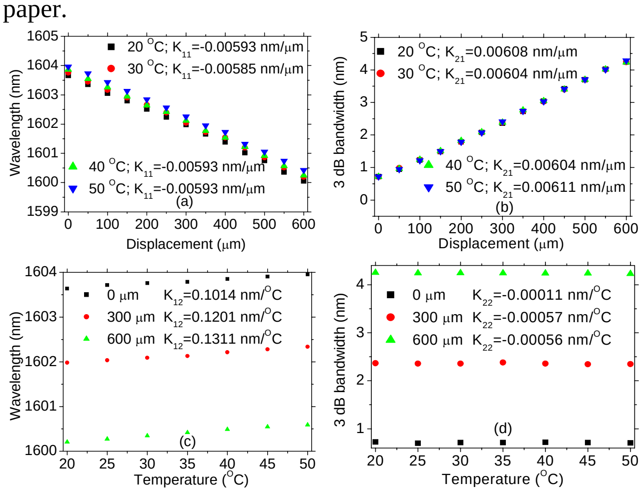

Fig. 5 Measured (a) central wavelength and (b) bandwidth shifts vs. displacement at fixed temperatures and (c) central wavelength and (d) bandwidth shifts vs. temperature at fixed displacements

To determine the wavelength and 3 dB bandwidth shift vs. displacement, measurements were carried out firstly by applying displacements with an increment of 50 μm while keeping the temperature constant at fixed values of 20, 30, 40 and 50 ºC respectively. Figures 5(a) and (b) show that at a fixed temperature, as displacement increases the centre wavelength and 3 dB bandwidth linearly decrease and increase respectively. Further experiments were carried out to measure the centre wavelength and 3 dB bandwidth changes vs. temperature for displacement values of 0, 300 and 600 μm. The experimental results are shown in figures 5 (c) and (d). Figures 5(c) and (d) show that for different displacement values, the central wavelength shift is proportional to the measured temperature but the 3 dB bandwidth remains unchanged. The relationship between the central wavelength, 3 dB bandwidth shifts, displacement and temperature can be expressed using a matrix as follows:

$$\begin{bmatrix} \Delta\lambda \\ \Delta B \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{bmatrix} \Delta D \\ \Delta T \end{bmatrix} \quad (1)$$

where $\Delta\lambda$ and ΔB are the central wavelength and 3 dB bandwidth shifts, ΔD and ΔT are the displacement and temperature changes. K_{11}, K_{12}, K_{21}, K_{22} are the matrix coefficients for wavelength/displacement, wavelength/ temperature, bandwidth /displacement, bandwidth /temperature respectively. To obtain the matrix coefficients, a linear fit is applied to each measured characteristic in figures 5(a-d). It is noted that all the data in figures 5(a-c) display a good linearity with R^2>0.992, but the data in figure 5(d) display poor linearity. This is due to the fact that the bandwidth shift in figure 5(d) is very small and thus the value K_{22} is very small and in practice is difficult to determine in a repeatable fashion due to random factors such as temperature variations, noise and vibrations. Thus in this paper K_{22} is set to zero. The coefficient matrix in Eq. (1) is thus:

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} -5.89 \pm 0.04\, pm/\mu m & 11.625 \pm 1.5\, pm/{}^\circ C \\ 6.075 \pm 0.035\, pm/\mu m & 0\, pm/{}^\circ C \end{bmatrix} \quad (2)$$

Hence we have

$$\Delta B = K_{21}\Delta D \quad (3)$$

$$\Delta\lambda = K_{11}\Delta D + K_{12}\Delta T \quad (4)$$

Eq. (3) demonstrates that the 3 dB bandwidth is only sensitive to displacement so that once the 3 dB bandwidth is measured, the displacement can be determined using Eq. (3). Since both central wavelength and 3 dB bandwidth can be simultaneously measured using an optical spectrum analyzer (OSA), the displacement and temperature can be determined using Eq. (3-4).

IV. Conclusion

In conclusion we have reported an experimental study of a novel and cost effective bent SMS fiber sensor for measuring displacement and temperature. The sensor has an experimentally demonstrated displacement sensitivity of 5.89 pm/μm and a temperature sensitivity of 11.6 pm/ ºC. Experimentally we have noted that the bent point along the MMF section has an influence on the spectral response, displacement measurement range and sensitivity. However our experiments show that such deviations need to be in the order of mm before an adverse effect occurs, for example for a 2 mm bent point deviation, the measurement range and sensitivity will be reduced by a half.

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References

[1]. Y. B. Lin, C. L. Pan, Y. H. Kuo, K. C. Chang and J. C. Chern, “Online monitoring of highway bridge construction using fiber Bragg grating sensors”, Smart Materials & Structures, vol. 14, no. 5, pp. 1075-1082, Oct. 2005.

[2]. A. Hongo, S. Kojima and S. Komatsuzaki, “Applications of fiber Bragg grating sensors and high-speed interrogation techniques”, Structural Control & Health Monitoring, vol. 12, no. 3-4, pp. 269-282, Jul.-Dec. 2005.

[3]. F. M. Hanran, J. K. Rew, P. D. Foote, “A strain-isolated fiber Bragg grating sensor for temperature compensation of fiber Bragg grating strain sensors”, Measurement Science & Technology, vol. 9, no. 8, pp. 1163-1166, Aug. 1998.

[4]. Y. L. Yu, H. Y. Tam, W H. Chung, and M. S. Demokan, “Fiber Bragg grating sensor for simultaneous measurement of displacement and temperature”, Optics Letter, vol. 25, no. 16, pp. 1141-1143, Aug. 2000.

[5]. L. Lin, W. G. Zhang, H. Zhang, B. Liu, H. Zhao, Q. C. Tu, G. Y. Kai and X. Y. Dong, “An embedded FBG sensor for simultaneous measurement of stress and temperature”, IEEE Photonics Technology Letters, vol. 18, no. 1, pp. 154-156, Jan. 2006.

[6]. L. Y. Shao, X. Y. Dong, A. P. Zhang, H. Y. Tam and S. L. He, “High-resolution strain and temperature sensor based on distributed Bragg reflector fiber laser”, IEEE Photonics Technology Letters, vol. 19, no. 17-20, pp. 1598-1600, Sep.-Oct. 2007.

[7]. D. P. Zhou, L. Wei, W. K. Liu, Y. Liu and J. W. Y. Lit, “Simultaneous measurement for strain and temperature using fiber Bragg gratings and multimode fibers”, Applied Optics, vol. 47, no. 10, pp. 1668-1672, Apr. 2008

[8]. L. V. Nguyen, D. Hwang, D. S. Moon, Y. Chung, “Simultaneous measurement of temperature and strain using a Lyot fiber filter incorporated with a fiber Bragg grating in a linear configuration”, Measurement Science & Technology, vol. 20, no. 3, Article Number: 034006, March 2009.

[9]. Q. Wu, A. M. Hatta, Y. Semenova and G. Farrell, “Use of a SMS fiber filter for interrogating FBG strain sensors with dynamic temperature compensation”, Applied Optics, vol. 48, pp. 5451-5458, 2009

[10]. D. P. Zhou, L. Wei, W. K. Liu and J. W. Y. Lit, “Simultaneous strain and temperature measurement with fiber Bragg grating and multimode fibers using an intensity-based interrogation method”, IEEE Photonics Technology Letters, vol. 21, no. 7, pp. 468-470, Apr. 2008.

[11]. L. B. Soldano, E. C. M. Pennings, “Optical multi-mode interference devices based on self-imaging: principles and applications”, J. Lightwave Technol., vol. 13, no. 4, pp. 615-627,April 1995.

[12]. R. T. Schermer, J. H. Cole, “Improved bend loss formula verified for optical fiber by simulation and experiment”, J. Quantum Electronics, vol. 43, no. 10, pp. 899-909, 2007