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A Bend Loss Based Singlemode Fiber Micro-displacement Sensor

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A bend loss based singlemode fiber micro-displacement sensor

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Abstract: An all-fiber displacement sensor with a simple configuration is proposed and investigated theoretically and experimentally. The proposed fiber displacement sensor consists of a half-loop structure of high-bend loss singlemode fiber-1060XP. A ratiometric power measurement system for interrogating the proposed sensor is also presented. By measuring the change in ratio of bend loss in the ratiometric measurement system, a change in displacement can be measured assuming the ratiometric system is calibrated. The proposed macrobending fiber based displacement sensor achieves a competitive resolution of circa 0.33 μm and also benefits from simplicity compared with the conventional fiber Bragg grating based displacement sensor. The bend loss fiber based displacement sensing system is sensitive to temperature, but the ratio response has a linear variation with temperature, which can be corrected by a suitable displacement correction process. Corresponding investigation on the temperature dependence of the macrobending fiber based displacement sensing system is presented in this paper.

Keywords: Macrobending loss, singlemode fiber, displacement sensor, ratiometric measurement

1. Introduction

Optical fiber can be used as a sensing element in a number of ways. Fiber sensors offer advantages such as immunity to electromagnetic interference and ease of fabrication. Recently, several types of optical fiber micro-displacement sensors have been proposed for applications in growth areas, for example, as an essential element in a Micro-Electro-Mechanical Systems (MEMS) for precision measurement of micro-displacement at a micro-scale size. Micro-displacement sensors could also be potentially useful for applications in bio-sensing and atomic force microscopy [1-4].

Existing fiber based displacement sensors have many advantages, but such advantages are often offset by the complexity of the interrogation system. For example Fiber Bragg Grating (FBG) sensors [4-8] are used frequently for displacement sensing but have the disadvantage that the need to measure the small wavelength shifts involved requires a complex interrogation system for extracting the displacement value.

Previous work has shown that fiber macrobending loss can be utilized as the basis of an edge filter and a temperature sensor [9-11]. In particular, in [9, 12], both theoretical and experimental results have shown that that there is a strong relationship between the fiber bend diameter and the bend loss. It is this characteristic that offers the possibility to develop a novel displacement sensor based on a macrobending structure. In this paper the utilization of macrobending loss in a singlemode optical fiber loop to sense displacement is demonstrated. Since only optical fiber bend loss needs to be measured, a simple interrogation system based on a ratiometric optical power measurement technique and a fixed single wavelength source can be used.

An investigation of the macrobending fiber based displacement sensor is presented which includes: 1) the displacement sensing principle and structure of the proposed sensor device; 2) the fabrication method and performance analysis of the proposed displacement sensor. A ratiometric interrogation system for the sensor is also presented and, given the known temperature dependence of bend loss, the temperature dependence of the macrobending fiber based sensor is also investigated. The proposed macrobending fiber based displacement sensor provides a competitive resolution of 0.33 μm, but by comparison with existing FBG based sensors, it also offers the advantages of a much simpler configuration and ease of fabrication.

2. Sensing principle and device structure

In our previous work [9], a bare 1060XP fiber coated with an absorbing layer has been developed as an edge filter for the wavelength measurement application. Both theoretical and experimental results have shown that the bend loss monotonically decreases as the fiber bend diameter increases at a fixed wavelength. Such a characteristic offers the possibility to develop a macrobending based displacement sensor. The operating principle of such a sensor is based on the change in bending loss when the diameter of the bend of the fiber section is changed. By measuring the changes in macrobending loss, the variation of bend diameter can be determined and with thus the displacement can be found.

The displacement variation can be extracted from a measurement of the bend loss which in turn can be found using a simple ratiometric power measurement system as is shown in Figure 1. A ratiometric system is used as it provides independence from optical source power variations resulting in a more stable and accurate system. The input signal from the source is split into two equal signals, one passes through the fiber sensor and the other goes to the reference arm. Two photodiodes are placed at the end of both arms to measure the output power. By measuring the ratio of the two output signals which is a function of fiber bending diameter, displacement can be measured, assuming a suitable calibration has taken place. The fiber used in the present experiment is Nufern 1060XP 5.3/125-μm step index singlemode fiber with a numerical aperture of 0.14. The polyacrylate coating was striped and an absorbing layer based on India ink [10] was coated on the surface of cladding to suppress the interference caused by the reflection from the cladding-air interface. To sense the displacement between two points, the sensor head consists of a half-loop of fiber placed between two points as shown in Figure 1. A half loop structure is employed for the following reasons: 1) the geometric deformation of a half-loop under an external force is much simpler than that of a full loop; 2) the changes induced in the fiber bend as a result of displacement can be treated directly as a variation of bend diameter for a half-loop structure. A full loop structure is not employed since a theoretical investigation using a finite element analysis of the mechanical behavior of a full loop showed that there is an approximate elliptical deformation of the bent fiber in a full-loop structure when force is applied to two opposite points on the loop. This deformation has a significant influence on the stress distribution over the bend section and the load transfer in the fiber materials, decreasing the reliability of bend loss prediction and increasing the risk of fiber breakage.

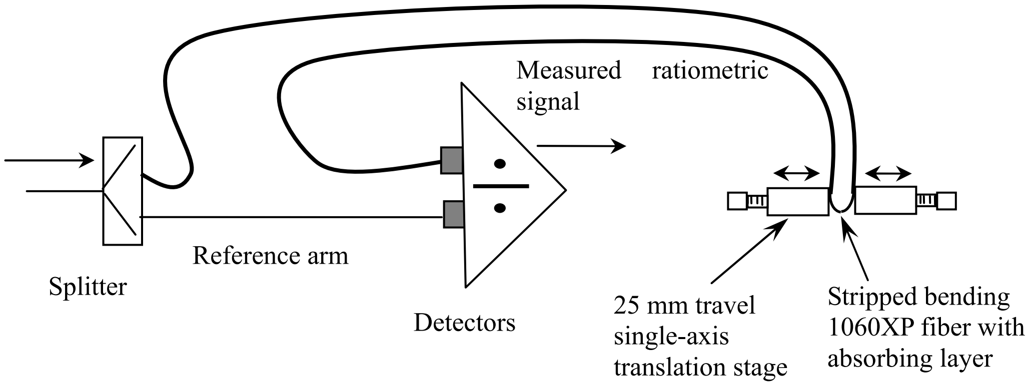


Figure 1. Experimental setup of ratiometric measurement system which involves the proposed displacement sensor.

3. Experimental results and discussion

We measured the change in the bend loss ratio as a function of bend diameter using a tunable laser and an optical spectrum analyzer, for a bend diameter range of 18~19 mm at a wavelength of 1550 nm. This range is chosen since it is found that above a diameter of circa 20 mm the bend loss is too low resulting in very low power ratio values and therefore in a very low sensitivity, while for diameters below 18 mm, the risk of fiber breakage by excessive stress is too high. It should be noted that the parameter "bend diameter" is utilized here instead of the more frequently used "bend radius" since in this application the change in a bend diameter represents the actual displacement change.

In the experiments with the ratiometric measurement system, the ratio response was measured at 50 μm intervals for a bend diameter range from 18 to 19 mm. The measured bend loss ratio responses and a polynomial fit are presented in Figure 2. It is clear from this Figure that the measured ratio response decreases monotonically as the bend diameter increases. For a perfect absorption layer the response in Figure 2 should be linear, However as shown in Figure 2, the measured bend losses over the bend diameter range from 18 to 19 mm show a wave-like variation, which is most likely caused by the limited absorption of the absorbing layer material and imperfections in surface coverage of the material on the bare fiber cladding [10]. These imperfections mean that the layer will not absorb all the radiation from the core at the bend and some part of the radiation will be reflected from the fiber cladding surface and will re-couple with the fundamental propagation mode. This results in a change in the state of the fundamental mode and produces wave-like variations over the entire ratio-displacement response presented in Figure 2.

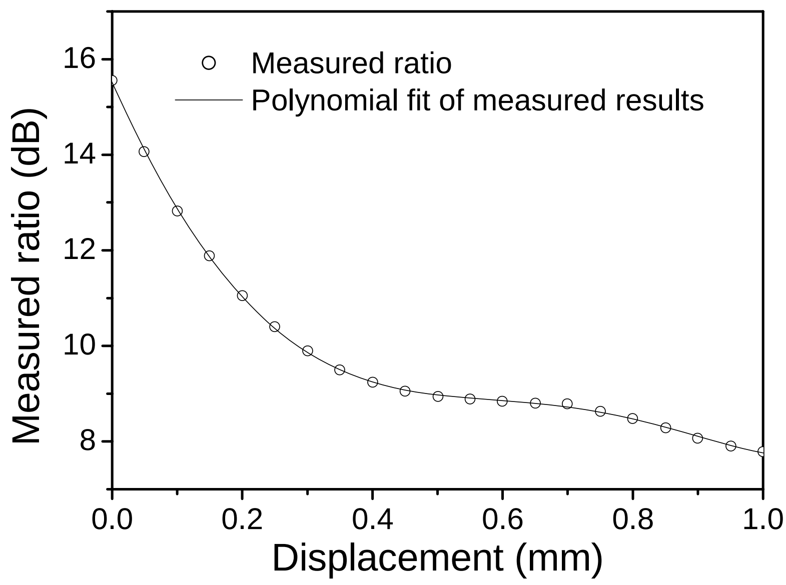


Figure 2. Measured bend loss response as a function of displacement position with a polynomial fit.

A key specification of the proposed sensor is displacement resolution. From Figure 2 it can be seen that the ratio over the bending diameter range from 18 to 18.4 mm is more sensitive to displacement compared to bending diameters above 18.4 mm. For this reason, for the purpose of experimental demonstration of the displacement resolution of the sensor and ratiometric measurement system, a bend diameter range from 18 to 18.4 mm is used for displacement sensing over a range from 0 to 400 μm. Experimentally an incremental displacement step change of +50 μm is applied to the fiber sensor over a displacement range of 0~400 μm, in a time period of 80 seconds, with changes in displacement occurring every ten seconds approximately. The corresponding measured ratio variation is shown in Fig. 3, which proves that the system is very capable of resolving small displacement changes. From the figure, one can see that the bend loss difference from the position of 0 to +50 μm is 1.5 dB. Given that the minimal value of the detectable ratio variation is circa 0.01 dB, the estimated limit for the displacement measurement resolution of the sensor is better than 0.33 μm, when using the ratiometric measurement system.

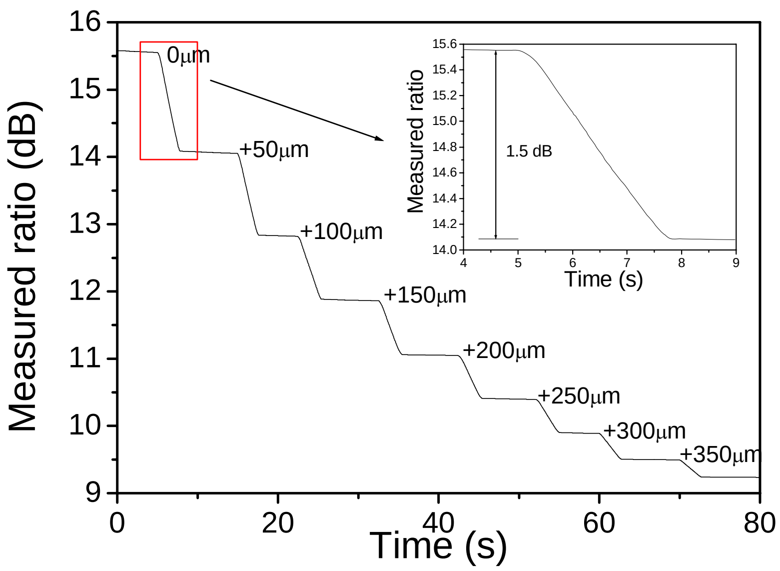


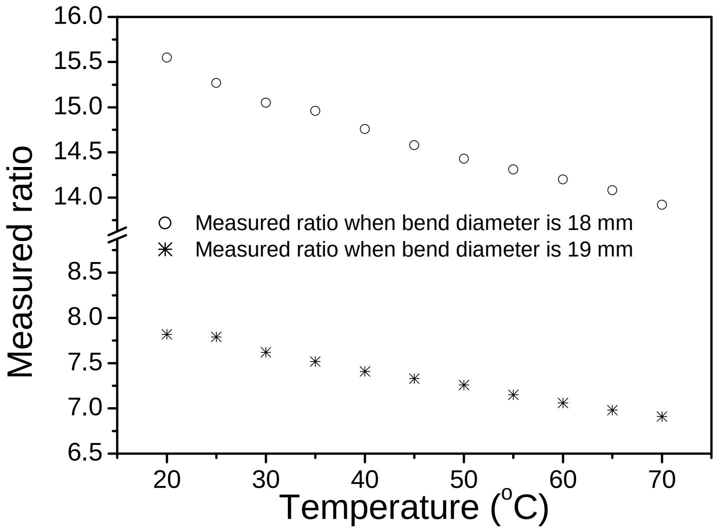
Figure 3. Measured ratio for displacement intervals of 50 microns over a displacement range of 0~400 μm.

4. Temperature induced variations in the sensing system

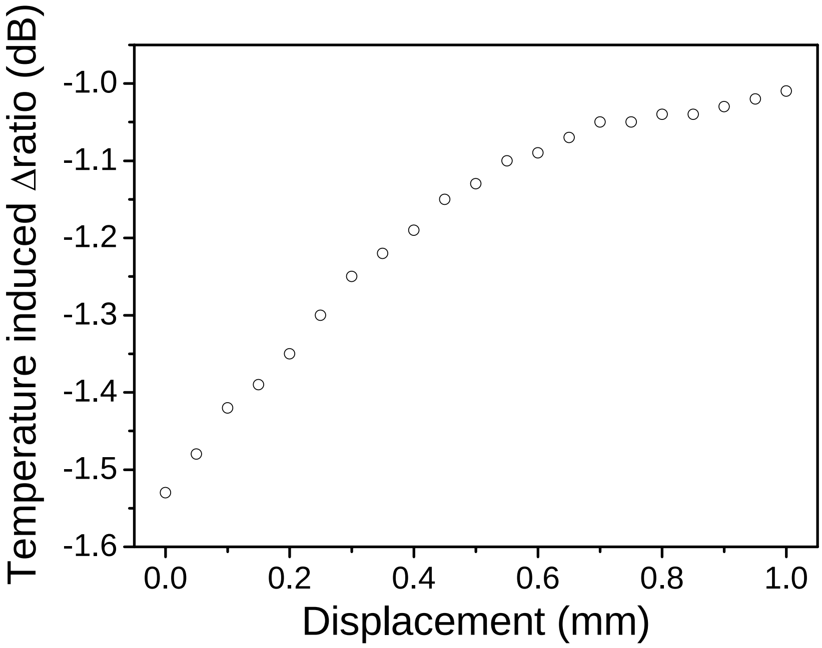
Frequently in real-world fiber optic sensing applications, a fiber sensor will be exposed to environments where there are significant variations in temperature. Temperature effects are known to have a significant influence on the properties of a fiber optic sensor, given the thermooptic and thermal expansion effects of fiber materials. Therefore it is worthwhile and necessary to investigate the temperature dependent behavior of the proposed displacement sensor.

Two experiments were carried out for 18 amd 19 mm bend diameters to investigate the temperature dependence of the displacement sensor. In each of the two experiments, to avoid the experimental variations induced by thermal expansion of the translation stages, the macrobending fiber sensor head with a half-loop structure was fixed on a hollow plastic polyvinyl chloride tube with precise diameter of 18 and 19 mm, and placed into a temperature controlled heating oven. A reference ratio response of the system was obtained at 20 ^{o}C. The thermal expansion coefficient of polyvinyl chloride plastic material is circa 7×10^{-5} μm/μm/^{o}C and both the plastic tubes are 2 mm in thickness, therefore the thermal expansion rate of the rods is about 14 nm/^{o}C, and thus the influence of the thermal expansion of the plastic rods can be neglected in this experiment. The variation in the ratio from the reference response at 20 ^{o}C was measured for a temperature range from 20 ^{o}C to 70 ^{o}C with an interval of 5 ^{o}C. The ratio responses with temperature for the two bend diameters of 18 mm and 19 mm, are shown in Fig. 4(a). The measured average slopes are 0.0326 dB/^{o}C and 0.0202 dB/^{o}C respectively.

To better illustrate and evaluate the influence of temperature on a macrobending based 1060XP fiber displacement sensor over the whole displacement range the experimental temperature induced ratio differences between 20°C and 70°C over the bend diameter from 18 mm to 19 mm at a wavelength of 1550 nm are presented in Fig. 4 (b). As shown in Fig. 4(b), one can see that the temperature induced change in the ratio monotonically increases as the displacement increases from 0 to 1000 μm. The temperature induced change in ratio is circa 1.53 dB at a bend diameter of 18 mm and is circa 1.01 dB at a bend diameter of 19 mm.



(a)



(b)

Figure 4. (a) Ratio variations at 1550 nm when temperature varies from 20^{o}C to 70^{o}C, the bend diameters are 18 mm (hollow circle points) and 19 mm (star points); (b) Temperature induced ratio difference over a bend diameter range of 18~19mm between 20^{o}C and 70^{o}C.

This result shows that the sensor has a strong temperature dependence. This behavior of bend loss ratio with the changes in temperature is expected and the physical insights into this phenomenon have been discussed in our previous published work [10, 11]. However because the measured system ratio monotonically decreases with an increase in temperature, it is feasible to apply a correction factor to mitigate the temperature-induced errors. To verify this, the required temperature correction for the ratio response, which is effectively a correction factor for displacement, is calculated using the polynomial fit presented in Figure 2 and shown in Fig. 5 for different temperatures with an interval of 5^{o}C in the range from 20^{o}C to 70^{o}C at the displacement range of 0~250 μm.

From the monotonic characteristic of the temperature dependence presented in the figure 4 (a), it is clear that the temperature-dependent ratio and resulting in displacement errors can be easily mitigated by the use of a correction factor to account for temperature.

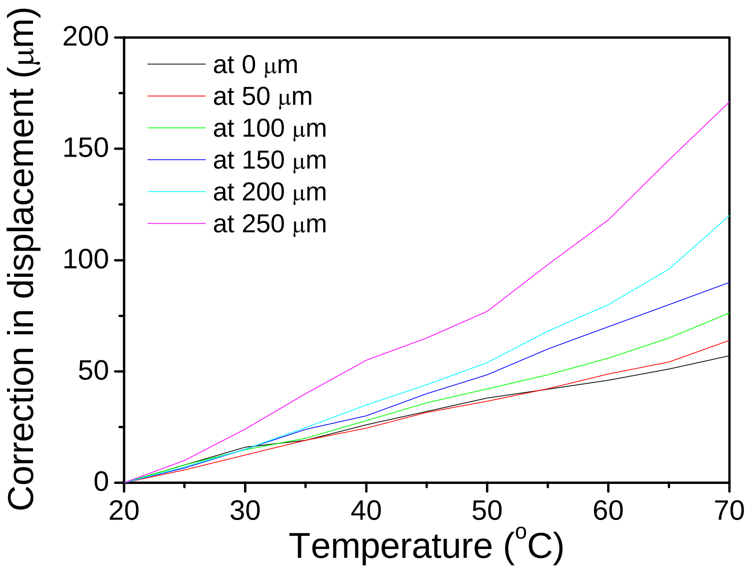


Fig. 5. Required correction in displacement when temperature changes from 20°C to 70°C over a displacement range of 0~250 μm.

From overall results presented in both Fig. 4 and Fig. 5, the required correction factor for the calibrated ratio response at different temperatures over the entire measurable displacement range can be obtained. By monitoring the temperature of the displacement sensor itself and by applying an appropriate correction to the calibration ratio response, precise displacement measurements can be obtained with a sensing system based on 1060XP fiber sensor head, even with significant ambient temperature changes.

5. Conclusion

In conclusion, an all-fiber displacement sensor with a simple configuration has been developed. The presented fiber displacement sensor consists of a half-loop structure of coating stripped 1060XP singlemode fiber, with an absorbing layer. A ratiometric system involving the sensor has been built, corresponding results have been presented, which show a competitive resolution of 0.33 μm for displacement measurements, verified by experimental results. The temperature induced variations in ratio and displacement have been investigated and presented in the paper. Compared with conventional FBG displacement sensor, the proposed 1060XP fiber based displacement sensor does not require complex fabrication and also benefits from a simple interrogation configuration.

6. Acknowledgement

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