Evaluation of the performance of a novel low-cost macro-bend fiber based temperature sensor

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ABSTRACT

The performance evaluation of a low-cost macro-bend fiber based temperature sensor is examined in this paper. The temperature sensor is based on a macro-bend singlemode fiber loop employed in a ratiometric power measurement scheme and has a linear characteristic with temperature at a fixed wavelength and bend radius. The sensor head consists of a single turn of a bare bend sensitive singlemode fiber with an applied absorption coating. The temperature of the sensor head is varied up to 75 ^{0}C and the linearity of the response is studied with different applied absorption coatings. The impact of stress on the sensor is investigated by applying external forces to the sensor and an estimation of magnitude of the stress induced variation in the ratio of the system is determined. The proposed temperature sensor, based on a macro-bend fiber, has a wide range of applications such as in composite materials processing.

Keywords: macro-bend fiber, temperature sensor, ratiometric power measurement

1. INTRODUCTION

The bend loss properties of singlemode fiber have been studied very intensively along with applications such as a fiber filter based on the bend loss phenomenon utilized as an edge filter for wavelength measurements [1]. A significant amount of effort has been made by researchers to use the bend loss properties of singlemode fiber for temperature measurements. One method is based on interferometry [2] where the temperature sensitivity arises from the thermo-optic and thermal expansion sensitivity of the buffer coating leading to interference between the whispering gallery modes (WGM) and the core mode. This method requires the determination of phase information at different wavelengths to extract the temperature information. High temperature sensing using whispering gallery mode resonance in bend fibers is also reported [3], which involves measuring the resonance wavelength peak shift with temperature. Both approaches lack a direct linear relation between bend loss and temperature and the need for phase measurements makes the system complex.

In this paper a simple method to measure temperature which uses a bend sensitive bare singlemode fiber loop with an absorption layer utilized in a ratiometric power measurement scheme is presented. The removal of the buffer coating eliminates the effect of the two different thermo-optic coefficients of the buffer and the cladding and the use of an appropriate absorption layer results in a monotonic increase in bend loss with bending radius [4] which is approximately equivalent to a core-infinite cladding structure. Given the simplicity of fabrication and the low cost of the sensor head and the use of an unmodified singlemode fiber, it can be used as a disposable sensor where the sensor is expected to be destroyed after a period of time or is unrecoverable. Preliminary results from the investigation of the performance of macro-bend fiber sensor with different applied absorption coatings and its capability to withstand higher temperature are presented in this paper. The effect of external stress on the sensor and its impact on the temperature measurements is also investigated and is presented in this paper.

2. BACKGROUND AND THEORY

The temperature sensitive sensor head consists of a buffer stripped bend sensitive singlemode fiber arranged in a loop with an absorption layer applied to the cladding as shown in Fig 1(a). The absorption layer is chosen to absorb light at the wavelength of operation, absorbing the WG modes inherent in a bent singlemode fiber and reducing the reflections back from the air-cladding boundary. By eliminating the WG modes, the bend loss variation with temperature at a fixed wavelength and loop bend radius depends only on the thermo-optic coefficients of the cladding and core.

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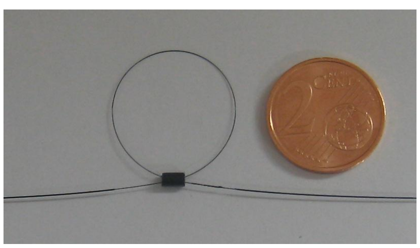
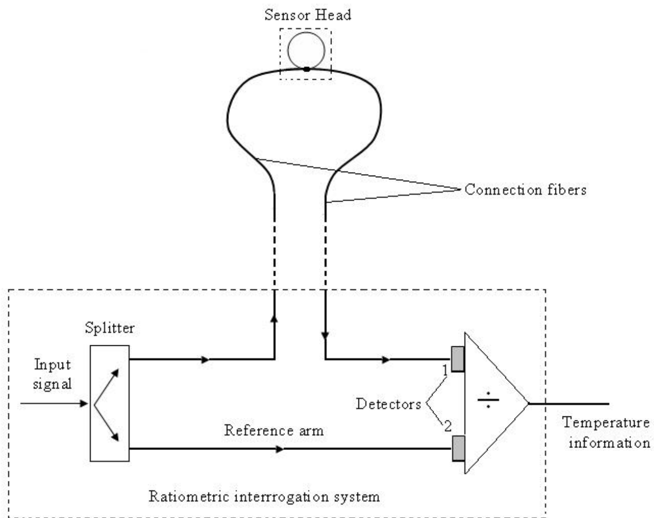
Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 731610

Since the cladding and core are made of silica material and have a positive thermo-optic coefficient, the thermally induced effective change in refractive index of the core and cladding is linear in nature, resulting in a linear variation of bend loss with temperature. Furthermore there is a monotonic increase in bend loss with bend radius and wavelength and thus the temperature sensitivity of the sensor can be varied by changing the bend radius or the operating wavelength.

The temperature information is extracted using a simple ratiometric power measurement system as it measures a ratio which is independent of source power variations resulting in a more stable and accurate system. The input signal from the source splits into two equal power signals, one goes to the fiber sensor and the other one is the reference signal as shown in Fig 1(b). Two photodiodes plus associated electronics are used to measure the power at the outputs of the corresponding arms. By measuring the power ratio of the two signals, which is a function of temperature, temperature can be measured, assuming the system is properly calibrated.



(a)



(b)

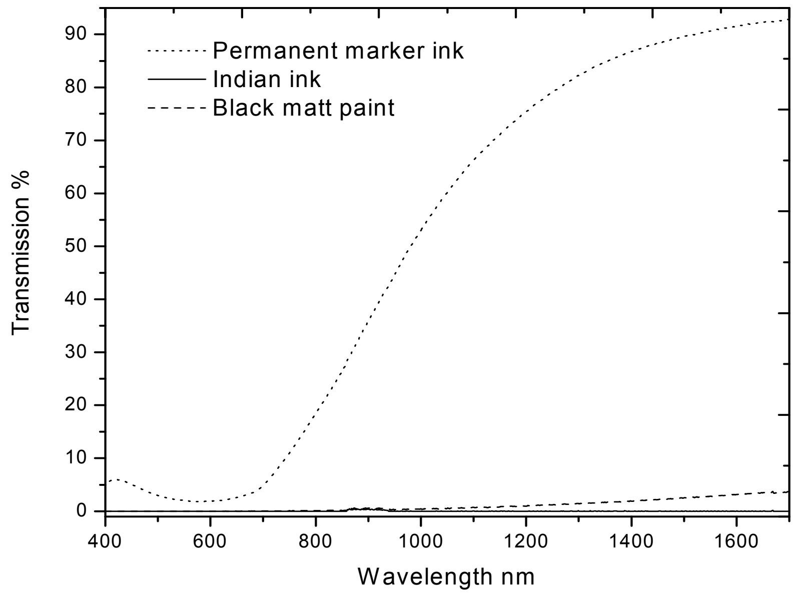
Fig 1. (a) The sensor head (b) Schematic of the macro-bend fiber temperature sensor system

3. TEMPERATURE RESPONSE OF THE MACRO-BEND FIBER SENSOR

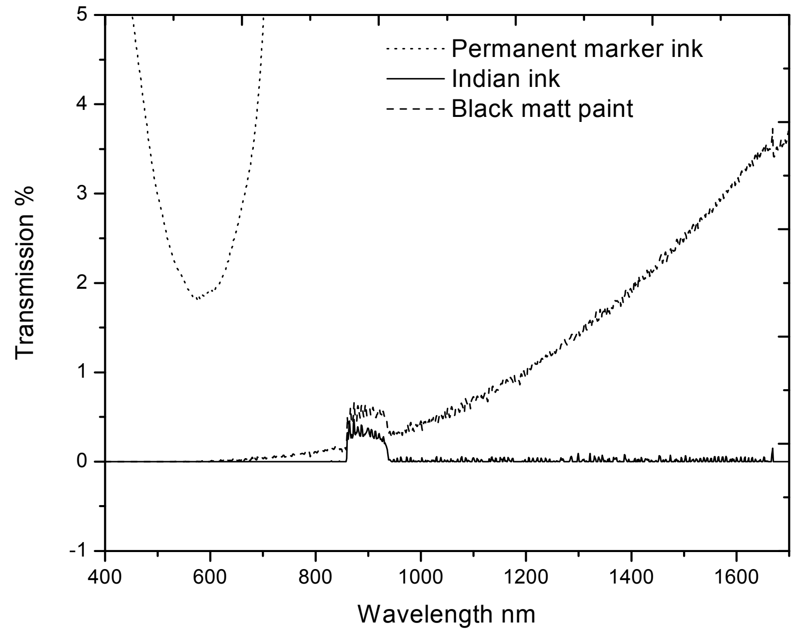
The fiber used in the experimental investigation was a 1060XP singlemode fiber which has a high bend loss in the wavelength region of 1550 nm and gives a good bend loss response with wavelength as we reported earlier [4]. To fabricate the macro-bend fiber temperature sensor, from the middle section of a length of the fiber, the buffer coating is stripped and an absorption layer is applied.

3.1 Absorption properties of the coating materials

The absorption coatings used in this investigation are permanent marker ink, Indian ink and black matt paint. Three pieces fibers are buffer stripped and coated with the three different absorption materials, Indian ink, black matt paint and permanent marker ink respectively, to eliminate the effect of WG modes. The absorption properties of the materials are studied at room temperature. The coating materials are coated on a glass plate (micro slide) and absorption spectrum of the materials are taken using an absorption spectrometer (Perkin Elmer Lambda 900 UV/VIS/NIR Spectrometer) for a wavelength range of 400 -1700 nm with an interval of 1 nm. The measured transmission spectra of the coating materials are shown in Fig 2(a). From the Fig 2(a) it is clear that all the materials have a good absorption at the visible wavelength range. However only the Indian ink shows an approximately 100% absorption of light in the wavelength range of 1500-1600 nm. For further insight the 0-5 % transmission values of the coatings is shown in Fig 2(b). The black matt paint absorbs nearly 96% while the permanent marker ink's absorption is very poor in the IR range making both unsuitable as absorption coating for the macro-bend fiber temperature sensor.



(a)

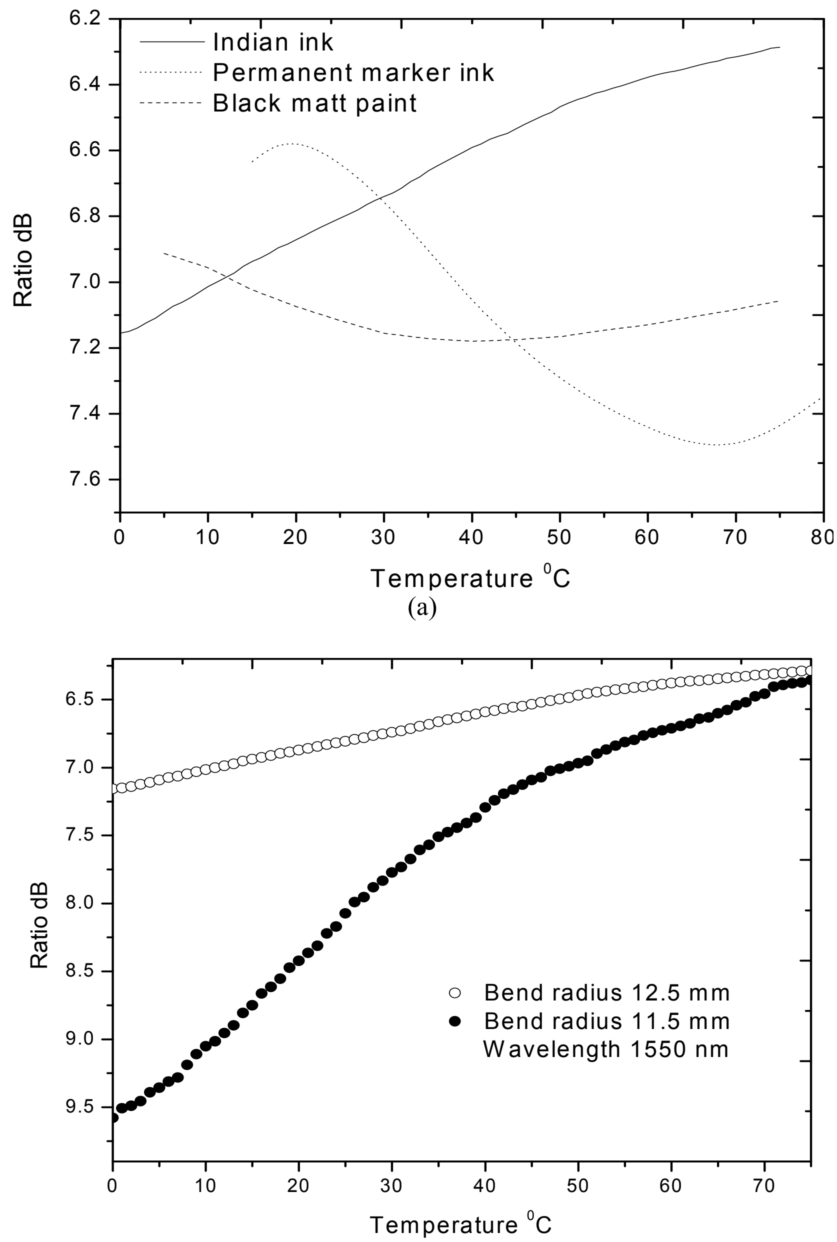


(b)

Fig 2. Transmission response of the different coating materials from 400-1700 nm (a) 0-100 % (b) 0-5 %

3.2 Temperature response of the sensor

To compare the performances and the impact of the WG modes, three bare macro-bend fiber devices were made and coated with each absorption material. The coatings were applied to the buffer stripped region of the fiber manually. Hence the absorption properties of the coatings applied to the fiber may not be exactly the same as the properties mentioned above, however, the overall trend remains the same. The sensor is formed by creating a single 360^0 fiber loop by inserting the fiber ends to a small 2 mm polymer tube and to fix the radius, the junction of the fiber inside the tube is glued. This forms a stable macro-bend fiber temperature sensor. The bend radius used was 12.5 mm which gives a bend loss of 7 dB at 0 ^{0}C for a wavelength of 1550 nm. The sensor is utilized in the ratiometric power measurement scheme as shown in Fig 1(b). The input wavelength to the system was 1550 nm. The fiber loop was fixed to a 5 cm diameter aluminium plate whose temperature is controlled using a Peltier cooler driven by a temperature controller and a full contact between the fiber sensor and the base plate is ensured. The expansion of the aluminium base plate and its effect on bend loss for a radius of 12.5 mm was negligible. Using an accurate independent temperature monitor for the purpose of calibration, the ratio response was measured at 2 ^{0}C intervals for a temperature range of 0 ^{0}C to +75 ^{0}C. A 5 minute time interval was given between each measurement to ensure that the temperature at all parts of the sensor is uniform and stable. The range employed (0 ^{0}C-75 ^{0}C) was limited by the capabilities of the Peltier cooler used. The ratio responses of all the fiber devices were measured individually. The measured ratio as a function of temperature is shown in Fig. 3(a).



(b)

Fig 3. (a) Comparison of temperature response of the macro-bend fiber with different absorption coatings (b) Temperature response of the sensor coated with Indian ink for two different bend radii

From Fig 3(a) it is clear that other than the fiber coated with Indian ink, which has a perfect absorption of radiations in the IR range, none of the macro-bend fiber devices coated with other materials gave a linear spectrum. This indicates that the radiation modes are not efficiently suppressed in bend fibers coated with black matt paint and the permanent marker ink and a 100% removal of the WG effect is required for the bend loss phenomenon to be used for temperature sensing. In the case of fiber coated with Indian ink, since the WG modes effect is eliminated completely, the macro-bend fiber gives a linear variation of bend loss with temperature and can be used as a temperature sensor. The temperature sensitivity of the sensor can be improved by using a fiber loop of smaller radius. In Fig 3 (b) a comparison of measured ratio of sensors with a bend radius of 11.5 mm and 12.5 mm is shown. It is clear from the figure that temperature sensitivity is substantially increased by reducing the bend radius. However a small bend radius will introduce higher stress on the sensor and the life time of sensor may be reduced compared to a higher bend radius. Hence there is a trade off between life time and the sensitivity of the sensor.

3.3 Temperature resolution of the sensor

To measure the temperature resolution of the system, a step change of 1 ^{0}C from 30 ^{0}C to 25 ^{0}C is applied to the fiber sensor over a time period of 60 seconds. The measured ratio variation is shown in Fig 4, which proves that the system is very capable of resolving temperature changes less than 1 ^{0}C. Fiber temperature sensors such as a fiber Bragg grating (FBG) typically provide a 10 pm wavelength shift for a 1 ^{0}C temperature change. To resolve temperature change less than 1 ^{0}C (or less than 10 pm), expensive active interrogation systems with high resolution are required. Hence most of the low cost FBG interrogation systems use a passive wavelength demodulation system, which has a low resolution when compared to active system. To illustrate this for an FBG interrogation system based on an edge filter, if a filter slope of 0.5 dB/nm is assumed (Most edge filters slopes are circa 0.5 dB/nm [5, 6]), then the ratio variation is approximately 0.005 dB/^{0}C. By comparison a ratio variation of 0.012 dB/^{0}C for the sensor proposed here confirms the competitive temperature sensitivity of this sensor.

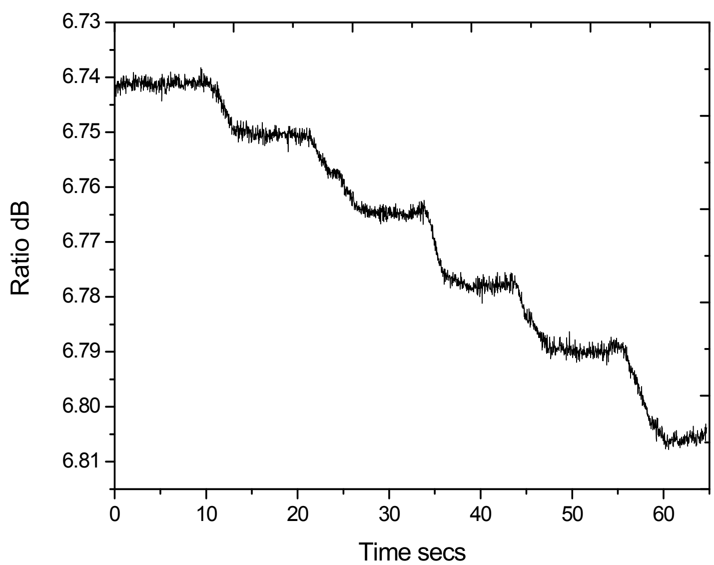


Fig 4. Variation in ratio for a step change of temperature of 1 ^{0}C from 30 ^{0}C to 25 ^{0}C

3.4 Response of the sensor at higher temperature

To study the performance of the sensor at high temperatures, the sensor (radius 12.5 mm) is subjected to a temperature variation up to 130 ^{0}C. The sensor used for this study was the one coated with Indian ink. The sensor is fixed to a hot plate (IKA RCT basic) and the temperature is varied up to 130 ^{0}C with an interval of 5 ^{0}C. The measured temperature response of the sensor is shown in Fig 5. From the figure it is clear that the sensor loses its linearity after a temperature of 90 ^{0}C. This indicates that either there is degradation in the Indian ink absorption coating at higher temperature or the absorption properties of the material is changed at higher temperature. Further research is underway to study the absorption properties of the materials at high temperature and also to find suitable absorption coatings to withstand higher temperature.

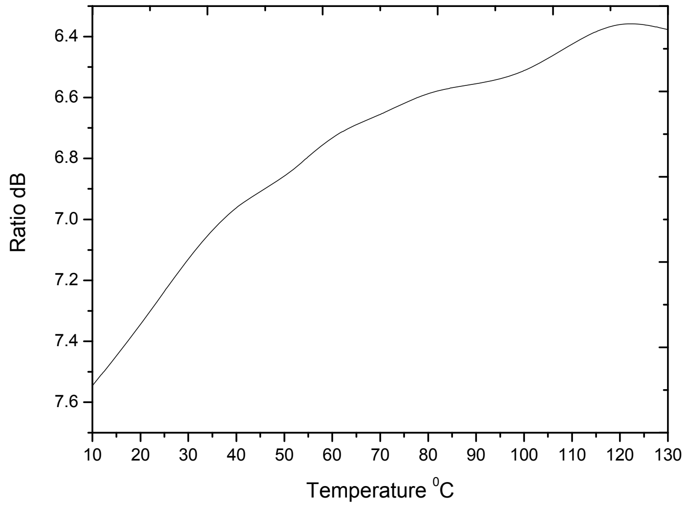


Fig 5. Temperature response of the sensor for a temperature up to 130 ^{0}C

4. EFFECT OF STRESS ON TEMPERATURE MEASUREMENTS

It is well known that lateral stress applied to a bend fiber change the bend loss due to stress induced change in refractive index. In applications of the proposed macro-bend fiber temperature sensor, for example in composite materials processing and in concrete curing, the sensor would be subjected to lateral stress. In such applications the sensor can be packaged in such a way to minimize the stress effects. In this present study, the sensor is embedded in an epoxy and impact of force on bend loss of the sensor is carried out. The sensor embedded in the epoxy is shown in Fig 6(a). In a packaged sensor, the temperature response would be different from the one measured at room temperature and hence a calibration taking account of the temperature gradient between the surface of the material and the real sensor is required. Such a calibration of the packaged sensor is ongoing. This study focuses on the impact of stress on such a packaged sensor. The experimental setup used for the stress analysis is shown in Fig 6(b). The epoxy embedded sensor is placed between two solid metal blocks for a stable application of the load. A load cell (SLB 250) is used to measure the applied load. The output of the load cell is measured using load cell data acquisition module SCC-SG24 combined with a data acquisition card PXI6221 from National Instruments. The system was programmed using LabVIEW 8.0 to obtain the applied load. The load was varied from 0 N to 20 N and the ratio is recorded for each load at 1550 nm. The measured ratio variation as load increases is shown in Fig 7. The ratio variation is approximately linear and for the sensor under test, the measured ratio variation is approximately 0.2 dB for an applied load of 20 N. Considering the temperature sensitivity of the sensor this gives rise to approximately 1.5 ^{0}C/N inaccuracy in the temperature measurements. However since the stress response is linear, a correction can be applied to the temperature response and accurate temperature measurement is possible using the macro-bend temperature sensor even at loaded conditions.

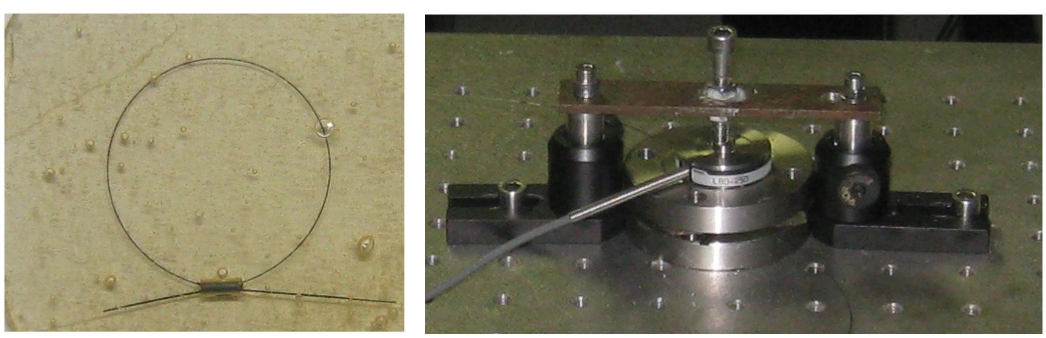


Fig 6. (a) Sensor embedded in epoxy (b) Experimental arrangement to study the effect of stress

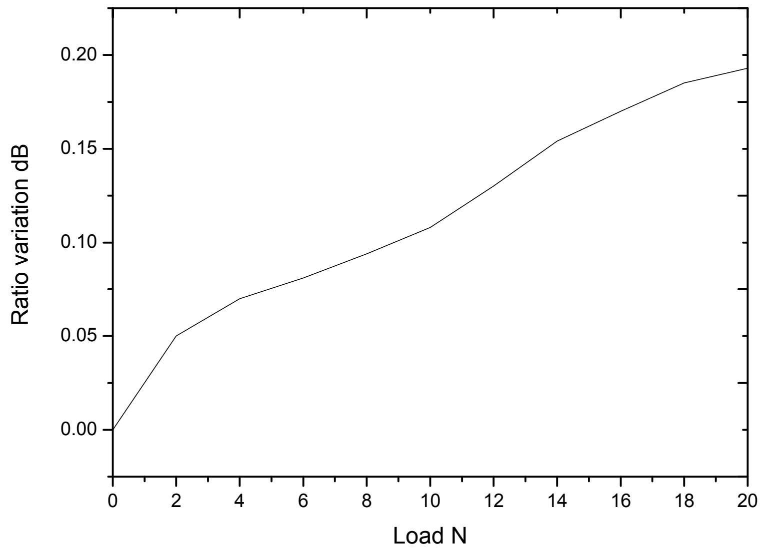


Fig 7. Measured variation in the ratio response of the sensor embedded in an epoxy at 1550 nm when load is applied

5. ADVANTAGES AND APPLICATIONS OF THE TEMPERATURE SENSOR

As the sensor head is a silica fiber, then together with a high temperature capable absorption layer, it has a potential to be used for wide range and high temperature applications. Given the simplicity of fabrication of the sensor head and the use of single-mode fiber, it can also be used as a disposable sensor for use in harsh environments or to measure the internal temperature of materials used as composites, where the sensor is expected to be destroyed after a period of time or is unrecoverable. Compared to existing fiber optic sensors, this is one of the biggest advantages of this macro-bend single-mode fiber temperature sensor. For temperature measurements during the processing of composite material components such as wind turbine blades, the present practice is to use thermocouples at the outer edges of the composite preform to obtain the data of the temperature profile. However the actual temperature away from the edges is not measured [7]. This can be overcome by using the proposed disposable fiber temperature sensor. It is also important to note that even though the sensor is disposable, if required it can continue to operate while embedded in the material giving the material smart characteristics. Another promising application of the sensor is in the medical field. Disposable optical fiber sensors are useful for clinical environment where sterilization is an important challenge [8]. Even the most efficient sterilizing methods cannot assure 100 % perfection. So the proposed macro-bend fiber sensor could be utilized in such applications.

6. CONCLUSION

An all-fiber temperature sensor based on macro-bend single mode fiber employed in a ratiometric power measurement scheme is proposed and demonstrated. A linear variation in bend loss with temperature is obtained by using a buffer stripped singlemode fiber with an absorption layer applied. Different absorption materials were tested and their influence on the linearity of the temperature response is studied. It is shown that a linear temperature response is achievable only when the absorption layer absorbs 100% of the radiation modes and eliminates the effect WG modes completely. The impact of stress on the temperature sensor is also studied and it is demonstrated that the stress induced ratio variation is linear in nature. A correction in the temperature ratio response to compensate the stress induced ratio variation is possible and hence the sensor can be used for accurate temperature measurements. The sensor has a high temperature resolution and can reliably resolve temperature variations less than 1 ^{0}C. The proposed low cost sensor can be used as a disposable sensor in a range of application areas.

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