A NOVEL PERIODIC MACROBENDING HETERO-CORE FIBER OPTIC SENSOR EMBEDDED IN TEXTILES

Kubra Alemdar[1], Sumeyra Likoglu[1], Kemal Fidanboylu[1], and Onur Toker[1]

[1]Electrical and Electronics Eng. Department, Fatih University, 34500 Buyukcekmece, Istanbul, Turkey
kubralemdar89@gmail.com, sumeyralikoglu@gmail.com, kfidan@fatih.edu.tr, onur@fatih.edu.tr

Abstract

This paper presents the design of a novel periodic macrobending hetero-core fiber optic sensor embedded in textiles. In order to demonstrate the superiority of the proposed sensor, experiments were done on a macrobending sensor constructed from 62.5-50-62.5 hetero-core fiber and a macrobending sensor constructed from 62.5/125 µm multi-mode fiber having different loops. Experimental results show that the sensitivity of the proposed macrobending sensor constructed using hetero-core optical fiber is much higher than the sensor constructed from plain multi-mode optical fiber. It is also shown that, the sensitivity of the sensor increases as the number of loops is increased. In addition, the forward and reverse loading effects of the designed sensor exhibit a very close behavior indicating the reversibility of the fiber optic sensor.

1. Introduction

In several medical applications, patients' physiological parameters are needed to know that their medical conditions are kept under control. This necessity demands wearable and mobile systems for patients whose physiological measurements such as respiration rate or movements, body activity, sleep condition, cardiac activity are easily accessed [1]. One of the most important parameter of accessing the physiological state is the respiration rate. However, the continuity of the respiratory movements is unpredictable. The patients that need medical assistant should be observed. In literature, several studies were carried out about respiratory monitoring such as respiration rhythm monitoring in sleep [2], Fiber Bragg Grating (FBG) based sensor for respiration [3], smart bed application [4], etc.

Fiber optic sensors are excellent candidates that can be implemented in wearable systems because of several advantages such as light weight, immunity to electromagnetic interference, ease of use under harsh environmental conditions, remote sensing capability, and flexibility [5-6]. Fiber optic sensors embedded in technical textiles and smart textiles are widely used in the development of wearable health monitoring systems. In the literature, three different textile based fiber optic respiratory sensors capable of monitoring respiration activity were reported. These are the bending loss sensor, the FBG sensor and the optical time domain reflectometry (OTDR) sensor [7].

In this paper, the design of a novel periodic macrobending hetero-core fiber optic sensor embedded in textiles is presented. The outer portions of the hetero-core fiber which act as transmission lines of the sensor were constructed using 62.5/125 µm multi-mode fiber. On the other hand, the inner portion of the hetero-core fiber, which corresponds to the fiber in the sensing region was constructed using 50/125 µm multi-mode fiber.

In order to demonstrate the superiority of the proposed hetero-core structure, the experiments were also carried out on macrobending fiber optic sensors constructed using 62.5/125 µm multi-mode fiber.

This paper is organized as follows: The macrobending technique and hetero-core fiber optic sensors are presented in Sections 2 and 3, respectively. The experimental setup is explained in Section 4. The experimental results and discussions are presented in Section 5. Finally conclusions are given in Section 6.

2. Macrobending Theory

Bending on optical fibers qualify guiding properties of fiber and cause power propagating in guided modes which is increasingly lost because of coupling into radiation modes [8]. Therefore, designs of fiber have been optimized for a higher robustness to bending effects. Two forms of bending effects such as micro and macrobend losses are relevant to modulation of measurand information. Generally a microbend is defined to be a sharper bend with a radius of curvature of fiber less than the fiber radius, and a macrobend is a smoother bend with a bending radius much larger than the fiber radius.

Macrobending sensors have major advantages in the application of fiber optic sensors embedded in textiles. They have simple design and require low cost. Macrobending loss measurements are usually detected by measuring the optical loss while the fiber is bent with a curvature radius. Intensity modulation is favorable for this technique. Light travels along into fiber, coupling from guided modes to radiation modes while bending occurs. Since higher order modes are bound less tightly to the fiber core than lower order modes, the higher order modes radiate out of the fiber first (see Fig. 1) [9]. Hence, the total number of modes that can be supported by a curved fiber is less than the total number of modes in a straight fiber.

Eq. (1) shows the relation between the total number of modes supported in a bent and a straight fiber.

$$N_{bent} = N_{straight}\left\{1-\frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R}+\left(\frac{3}{2n_2 kR}\right)^{2/3}\right]\right\} \qquad (1)$$

where α defines the graded-index profile, R is the bent radius, a is the core radius, Δ is the core-cladding index difference, n_2 is the cladding refractive index, k is the wave propagation constant and $N_{straight}$ is the total number of modes in a straight fiber [10].

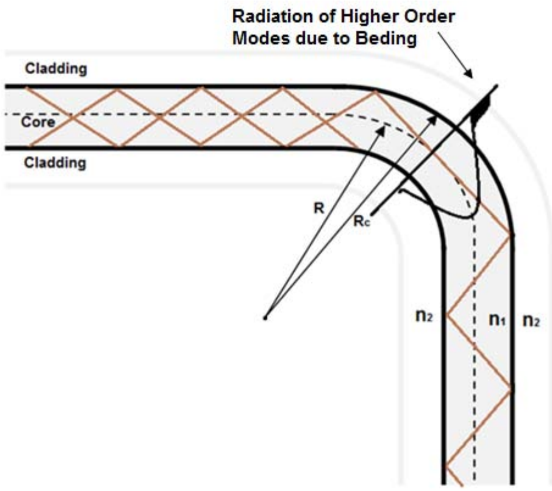

Fig. 1. Radiation of higher order modes in an optical fiber due to bending.

Macrobending losses take place when an optical fiber is bent to a radius of several centimeters. When the bend radius is below the critical bending radius R_c given by Eq. (2), large bending loss occurs [9-11].

$$R_C = \frac{3n_1^2\lambda}{4\pi\left[n_1^2 - n_2^2\right]^{3/2}} \tag{2}$$

where n_1 and n_2 are refractive index of core and cladding, respectively, and λ is the operating wavelength.

As the fiber optic sensor embedded in textile is stretched in the forward direction, fiber curvature radius increases. Hence, from Eq. (1), more modes will be supported in the bent fiber and the light loss will decrease. Thus, output intensity variations are relevant to the changes of the sensors textile elongation.

3. Hetero-core Fiber Optic Sensors

Different types of fiber optic sensor structures were proposed in the literature [5]. The hetero-core optical fiber structure consists of transmission line and sensor portion that is fabricated by splicing a smaller core diameter fiber into two larger core diameter fibers as illustrated in Fig. 2. Sensor portion of the fiber has smaller core diameter than the transmission line fiber, but the claddings of these fibers should be the same for insertion process. The insertion process is called splicing. Fusion splicing is the technique that uses heat to melt the fiber ends and glue them together. The device used for this purpose is fusion splicer. The evanescent field appearing in the hetero-core portion leaks from the cladding, when bending is given to the entrance or exit of the hetero-core region. The principle behind this phenomenon is the same with the evanescent wave sensors, but hetero-core optical fibers are easier to fabricate, since control of section length is easier compared to etching.

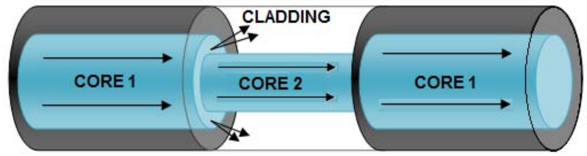

Fig. 2. Hetero-core optical fiber structure.

Hetero-core fiber optic sensors have high sensitivity because of the mode coupling taking place at the splice region. At the splice region, fibers have different core diameters. Hence, the leakage of transmitted light into the cladding region becomes easier when an external perturbation is applied to this region.

4. Experimental Setup

The experimental setup for the periodic macrobending fiber optic sensor embedded in textiles is shown in Fig. 3. The macrobending fiber optic sensor structure is composed of two wooden plates, and a rail system for adjusting displacement. The setup has been designed such that one of the wooden plates is stable and the other one is movable on the rail system. The light source is a solid state laser providing a maximum output power of 16 mW at 650 nm wavelength. The light beam coming out from the laser source is focused into the fiber core by means of a 20X lens. The sensor's sensing region consists of a 10 cm x 4 cm elastic type of textile (white color) and a 35 cm long optical fiber embedded by knitting in the form of periodic "U" turns (see Fig. 4). The textile (blue color) which supports the sensing region from both ends is a non-elastic type of textile.

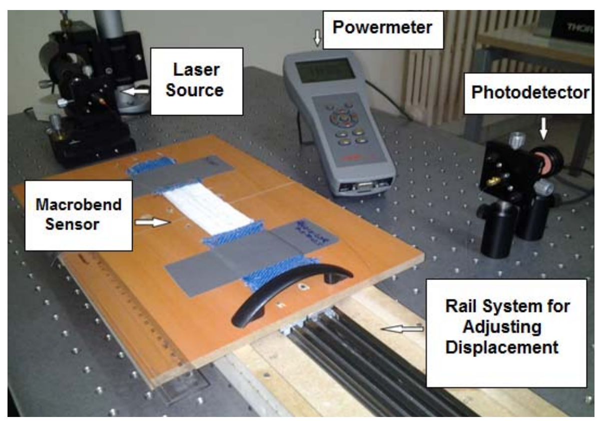

Fig. 3. Experimental setup of macrobend sensor.

The sensing region of the macrobending fiber optic sensor was fixed on the middle of the two wooden plates. Displacement measurements were accomplished by moving the movable plate on the rail system at 1 mm intervals and measuring the output light intensity at each interval. Fig. 5 shows a typical setup when the movable plate is moved by an amount of Y_1 on the rail system.

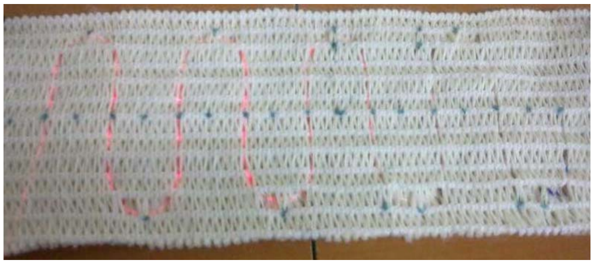

Fig. 4. Sensing region of the periodic macrobending fiber optic sensor.

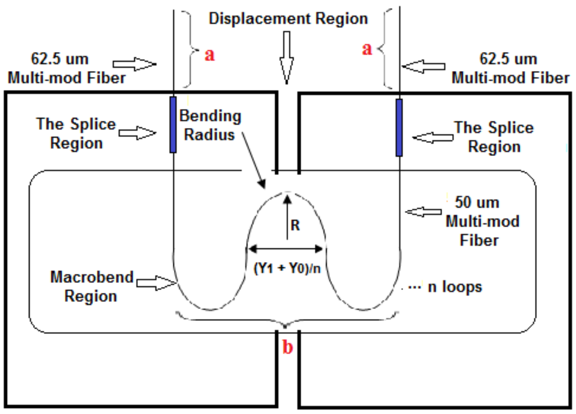

Fig. 5. Periodic macrobending sensor configuration with displacement.

Experiments were carried out using a hetero-core fiber consisting of three portions; two outer sections represented by letter "*b*" and one inner portion represented by letter "*a*" as shown in Fig. 5. The outer portions of the hetero-core fiber which act as transmission lines of the sensor were constructed using 62.5/125 µm multi-mode fiber. On the other hand, the inner portion of the hetero-core fiber, which corresponds to the fiber in the sensing region was constructed using 50/125 µm multi-mode fiber. This configuration will be represented throughout the paper as 62.5-50-62.5 hetero-core structure. The splicing was done using a FUJIKURA FSM 100M fusion splicer. The bending radii of the fiber forming the "U" turns in the sensing region were adjusted to be 1 cm. In order to test the sensitivity of the proposed macrobending sensor, several sensors having different number of "U" turns (loops) were constructed.

5. Experimental Results and Discussions

5.1. Experimental Results Obtained from a Macrobending Sensor Constructed Using 62.5/125 µm Multi-mode Fiber

In order to demonstrate the superiority of the proposed hetero-core structure, the first experiment was done on a macrobending fiber optic sensor constructed using 7 loops of 62.5/125 µm multi-mode fiber. Experimental measurements were carried out by moving the movable plate on the rail system in 1 mm intervals until a 40 mm of displacement was reached (forward direction) and measuring the output light intensity at each interval. Data was also taken in the reverse direction by decreasing the displacement in 1 mm intervals (reverse direction) and measuring the output light intensity at each interval. Fig. 6 shows the experimental results obtained in the forward and reverse directions using this sensor. From this figure, it can be observed that the displacement is inversely proportional with the normalized output intensity. This is in agreement with the theory, because as the displacement Y_1 is increased, the bending radius R increases too. From Eq. (1), it can be seen that R is inversely proportional with the number of supported modes. Hence, as R is increased (larger displacement) more modes will be supported in the fiber which will result in less light loss. These results also show that the forward and reverse loading effects exhibit a very close behavior indicating the reversibility of the fiber optic sensor.

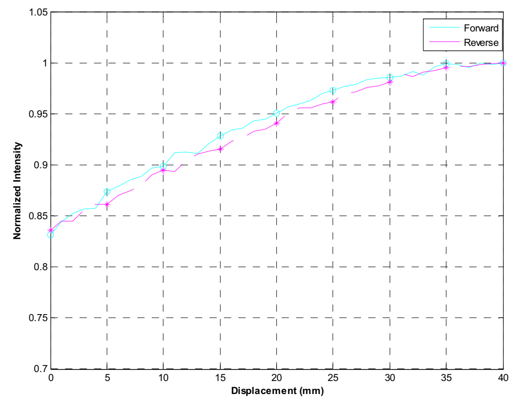

Fig. 6. Forward and reverse loading effects of the macrobending fiber optic sensor constructed using 7 loops of 62.5/125 µm multi-mode fiber.

In order to demonstrate the repeatability of the sensor, the above experiment was repeated 5 times both in the forward and reverse direction and the results are shown in Fig. 7.

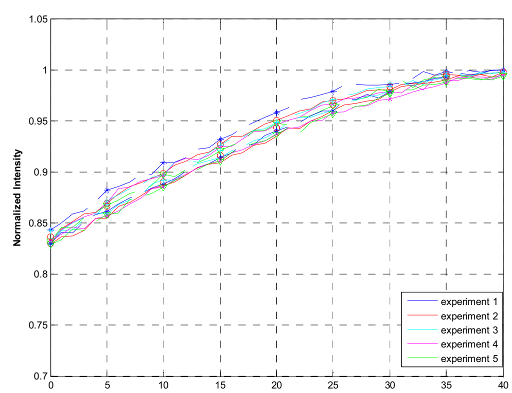

Fig. 7. Repeatability test results of the macrobending fiber optic sensor constructed using 7 loops of 62.5/125 µm multi-mode fiber.

From this figure, it can be seen that the proposed sensor is very repeatable.

In order to observe the effect of the number of loops on the sensor performance, sensors were constructed and tested with different number of loops. Fig. 8 shows the comparison of the forward loading effects for these sensors. From this figure, it can be seen that the sensitivity of the sensor increases as the number of loops are increased, which is also in agreement with the theory.

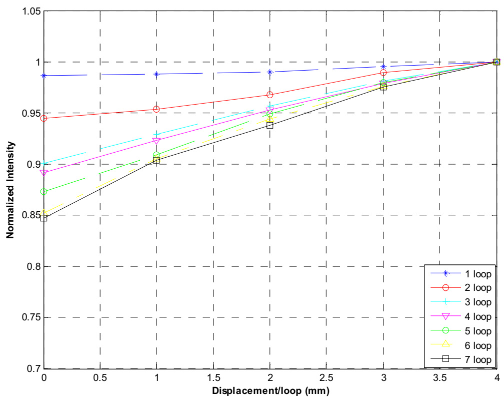

Fig. 8. Comparison of forward loading effects for the macrobending fiber optic sensor constructed using different loops of 62.5/125 µm multi-mode fiber.

5.2. Experimental Results Obtained from a Macrobending Sensor Constructed Using a 62.5-50-62.5 Hetero-core Fiber

The second experiment was done on a macrobending 62.5-50-62.5 hetero-core fiber optic sensor constructed using 7 loops. Experimental measurements were carried out by moving the movable plate on the rail system in 1 mm intervals until a 40 mm of displacement was reached (forward direction) and measuring the output light intensity at each interval. Data was also taken in the reverse direction by decreasing the displacement in 1 mm intervals (reverse direction) and measuring the output light intensity at each interval. Fig. 9 shows the experimental results obtained in the forward and reverse directions using this sensor. These results are also in agreement with the theory. The forward and reverse loading effects exhibit a very close behavior indicating the reversibility of the fiber optic sensor.

In order to demonstrate the repeatability of the sensor, the above experiment was repeated 5 times both in the forward and reverse direction and the results are shown in Fig. 10. From this figure it can be seen that the proposed sensor is very repeatable.

In order to observe the effect of the number of loops on the sensor performance, sensors were constructed and tested with different number of loops. Fig. 11 shows the comparison of the forward loading effects for these sensors. From this figure, it can be seen that the sensitivity of the sensor increases as the number of loops are increased, which is also in agreement with the theory.

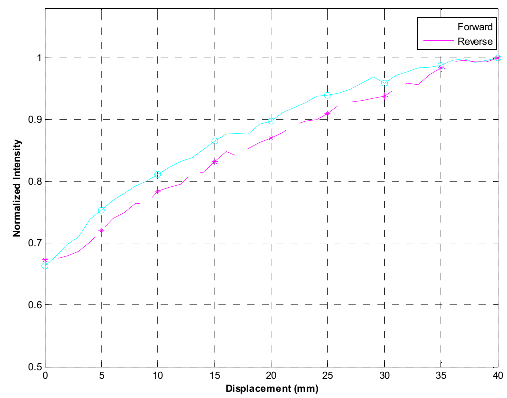

Fig. 9. Forward and reverse loading effects of the macrobending 62.5-50-62.5 hetero-core fiber optic sensor constructed using 7 loops.

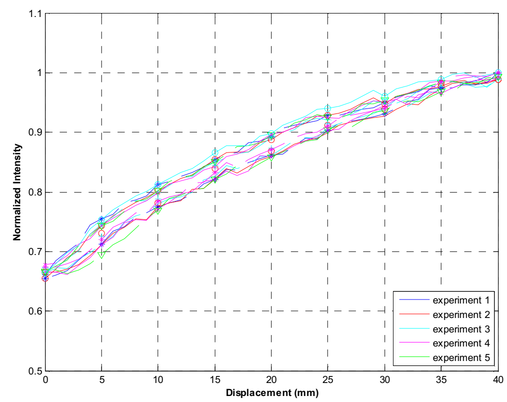

Fig. 10. Repeatability test results of the macrobending 62.5-50-62.5 hetero-core fiber optic sensor constructed using 7 loops.

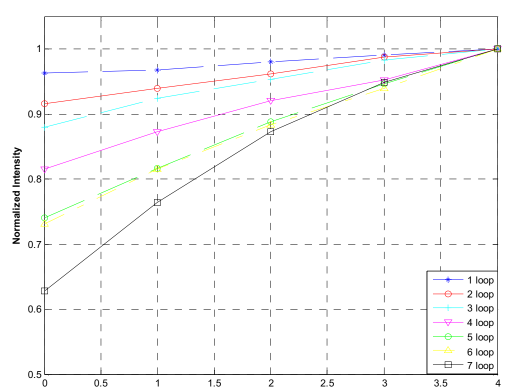

Fig. 11. Comparison of forward loading effects for the macrobending 62.5-50-62.5 hetero-core fiber optic sensor constructed using 7 loops.

5.3. Comparison of Experimental Results Obtained from a Macrobending Sensor Constructed Using 62.5-50-62.5 Hetero-core Fiber and 62.5/125 µm Multi-mode Fiber

Fig. 12 shows the comparison of forward loading effects for the macrobending 62.5-50-62.5 hetero-core fiber optic sensor and 62.5/125 µm multi-mode fiber optic sensor constructed using 7 loops. From this figure, it can be seen that the sensitivity of the proposed macrobending sensor constructed using hetero-core optical fiber is much higher than the sensor constructed from plain multi-mode optical fiber.

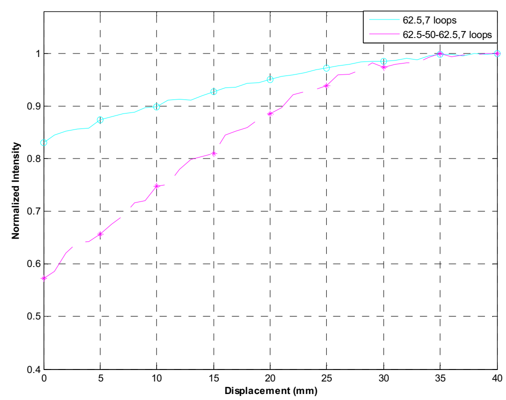

Fig. 12. Comparison of forward loading effects for the macrobending 62.5-50-62.5 hetero-core fiber optic sensor and 62.5/125 µm multi-mode fiber optic sensor constructed using 7 loops.

6. Conclusions

In this paper, the design of a novel periodic macrobending hetero-core fiber optic sensor embedded in textiles was presented. The superiority of the proposed sensor was demonstrated by experiments done on a macrobending sensor constructed from 62.5-50-62.5 hetero-core fiber and a macrobending sensor constructed from 62.5/125 µm multi-mode fiber having different loops. Experimental results have shown that the sensitivity of the proposed macrobending sensor constructed using hetero-core optical fiber is much higher than the sensor constructed from plain multi-mode optical fiber. It was also shown that, the sensitivity of the sensor increases as the number of loops is increased. Furthermore, the forward and reverse loading effects of the designed sensor exhibit a very close behavior indicating the reversibility of the fiber optic sensor. Repeatability tests done on the sensors also indicate that the designed sensors are very repeatable.

The proposed sensor was embedded in a belt shape elastic textile and was used in measuring the elongation of the abdominal circumference during breathing movements of a human being. Preliminary data obtained from these measurements shows that the proposed sensor will be a very good candidate in health-care applications for monitoring patients' respiratory movements.

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7. References

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