Design, construction and characterization of fiber extensometer with heart shape structure for detection of displacement

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Abstract. This paper discusses the design, construction and characterization of an optical fiber extensometer with heart shape structure. The extensometer was made from a communication grade fiber loop arranged in a housing and pulling mechanism. As the light source, we used 1310 nm LED and a 1325 nm laser diode/LD. To characterize our extensometer, we used a motorized pulling system controlled by a personal computer. From the bending loss characterization using Fujikura fiber as the sensor, we obtained sensitivity of 0.04 dB/mm and measurement range of 28 mm when using the 1310 nm LED, whereas using the 1325 nm LD allowed us to obtain 0.06 dB/mm of sensitivity and 23 mm of measurement range. Using Thorlabs fiber as the sensor, we obtained sensitivity and measurement range of 0.09 dB/mm and 23 mm, respectively, when using the 1310 nm LED. When we used the 1325 nm LD, we obtained sensitivity of 0.03 dB/mm and 31 mm measurement range but with a noted whispering gallery mode/WGM effect. Compromise has to be considered amongst the high sensitivity, measurement range, WGM existence and noise properties to get best data reading for real application.

1. Introduction

Optical fiber sensors offer many advantages when compared to conventional electronic sensors: they are compact, lightweight, immune to electromagnetic interference, noncontact, exhibiting high accuracy, easy to install, non-electrical, explosion-proof and resistant to high temperatures. A number of varieties of fiber sensors have been developed such as for sensing physical properties (temperature, stress, pressure, displacement) and chemical sensors (pH, chemical concentration, gas analysis) [1, 2]. Based on the operating principle, a fiber optic sensor can be classified into several categories: as an intensity, a phase, a frequency, or a polarization sensor. Fiber optics extensometer is a device for measuring land displacement optically, based on the changes in the intensity of the output light through an optical fiber that suffered losses due to bending treatment (due to land displacement). The land displacement will change the transmission of light through the fiber according to the value of land displacement that occurred.

Several types of optical fiber displacement sensors have been developed, for example, fiber micro displacement sensor using fiber-loop structure by Wang et al. [3] and Martinez-Rios et al. [4]. In the first reference, the authors used a tunable laser and an optical spectrum analyzer to explore the influence of bend diameter range of 18–19 mm at a wavelength of 1550 nm and in the later reference,
authors examined the displacement range of 3.125 mm by using a 1.280 nm broadband low-power LED source and a single Ge-photodetector in a power transmission sensor.

This paper discusses the design, construction and laboratory characterization of optical fiber extensometer with a heart-shape fiber sensor before undergoing field testing. The basic structure of the heart shape fiber sensor is a fiber loop arranged in a sensor housing equipped by a pulling mechanism. The characterization of the heart sensor fiber was conducted using fiber pigtailed light sources, a PC-controlled pulling mechanism, detector, data acquisition system and PC/reading system. The purpose of the research is to compare the performances of the fiber displacement sensor when using two types of fibers (SMF28 Thorlabs and Fujikura single mode fibers) and two kinds of light sources (LED at wavelength of 1310 nm and LD at wavelength of 1325 nm; respectively). Previous study by our group on fiber displacement sensor described fiber loop sensor using SMF 28 and LD light source at wavelength 1310 nm and 1550 nm with a manual pulling mechanism [5].

2. Theory
For single mode optical fiber, bending loss \(L_\alpha\) can be expressed by [6]:

\[
L_\alpha = 10 \log_{10}(\exp(2\alpha L)) = 8.686\alpha L
\]

(1)

where \(2\alpha\) is bending loss coefficient, which is determined by fiber structure, bending radius and wavelength of light, \(L\) is the length of the bent fiber. D. Marcuse with classic theory of bending loss using coupled mode theory has formulated bending loss as [7, 8]:

\[
2\alpha = \left( \frac{\pi \alpha^2 L_c}{2n_1 k a \Delta / b W} \right)^{1/2} - \sum_i \exp \left\{ - \left[ \beta_i - \beta_{1s} \right] \frac{L_c}{2} \right\} J_1^2 \left( \frac{a}{b} J_0(J_{i0}) \right) \exp \left( - \frac{2a^2}{W^2} \right)
\]

(2)

For step index fiber, it applies the Bessel function zero and first order \((J_0, J_1)\) and root of Bessel function \((J_{01}, J_{10})\) with border condition \((J_0(J_{00}) = 0, J_1(J_{10}) = 0\). Practically, an optical fiber consists of not only the core and cladding but also the protection coating. Theoretical formula of bending loss using perturbation theory for step index fiber resulted the following equation [9]:

\[
2\alpha' = \frac{2u^2}{\omega_{\nu_{ir}} V^2 K_1^2(w)} \int_{\zeta=0} \exp \left( - \frac{(w^2 + \zeta^2 a^2 u^2)^{1/2}}{w^2 + \zeta^2 a^2 u^2} \right) A(\zeta) B(\zeta) d\zeta
\]

(3)

With \(\alpha' = w' L_c / a\), \(u = w' \sqrt{n_{ir}^2 - \beta^2} \) and \(V = \omega' \sqrt{n_{ir}^2 - \beta^2} \), \(\zeta\) is angular distance around bend axis of the bent fiber, \(K_1^2(W)\) is Bessel function, \(A_i\) and \(B_i\) are Airy functions, which are the solution of 2 dimensions scalar equation; while \(\beta_{ir}\) is the real propagation velocity for straight fiber with the same refraction index. Wang et al. has theoretically and experimentally formulated the bending loss coefficient for optical fiber with more than one layer coating as follows [10]:

\[
2\alpha = -2 \frac{K^2}{2\pi \beta V^2 K_1^2(a\gamma)} \text{Im} \left( \int_{-\infty}^{\infty} H_1(\zeta) A[X_2(0, \zeta)] d\zeta \right)
\]

(4)

where \(x\) is layer thickness, \(n\) refractive index, \(R\) bending radius, \(\beta\) propagation constant, \(A_i\) and \(B_i\) are Airy functions and \(H(\zeta)\) amplitude function. More details on bending loss fiber phenomenon can be found in references 6-10. The three above equations describe how bending loss was formulated if the
fiber consists of only core and cladding (see equation 2), if the fiber is a step index type (see equation 3) and if the fiber consists of core, cladding and multiple coatings (see equation 4).

Meanwhile, the sensor part in the fiber extensometer was formed from one fiber loop, which one of its end was tied into a pulling stick [11]. If the stick is pulled (because of displacement), the loop will be bent and changed into a heart shape form (see figure 1). We do not describe the theoretical calculation of bending loss in heart shape fiber in detail. Equation 1-4 only give brief illustration on what happen inside the fiber if it is bent. Here, we will only investigate the experimental trend between the fiber bending loss and the fiber output intensity.

The optical fiber extensometer consists of light source, optical fiber cable (diameter 3 mm), sensor and reference fibers in a housing system (see figure 1), optical detector, and data acquisition and reading system, which is connected to personal computer. The cable fiber was from flare flex and contains 12 fibers with total diameter 7 mm.

![Figure 1. Heart shape optical fiber extensometer.](image1)

The sensor and reference fibers are spliced in, each, to one fiber in the fiber cable; and packed in a housing system which was equipped by a pulling stick for displacement accessory. The pulling process here is a simulation of the displacement process at a certain direction. The pulling process will change the fiber sensor loop diameter and consequently the output of light through the fiber.

We investigated the performance of two types of heart shape fiber sensor using SMF 28 Thorlabs and Fujikura fibers. The optical fiber used consisted of the core and cladding (both are glass, 9/125 µm size) and the outer coating, often called the buffer. In this experiment the fiber buffer was uncoated until only acrylic coating left with total fiber diameter 900 nm. Light source was coupled into the input port of the optical fiber loop and the output was detected at the output port. If the fiber sensor loop is pulled in the middle, then the loop will turn into a heart shape and the intensity of light propagating through the fiber will be reduced in accordance with the decreasing of the fiber diameter. The performance of the fiber extensometer depends on the bending properties of the optical fiber therefore bending measurement was conducted for all fibers. The set-up of the bending loss measurement consisted of fiber extensometer, a motorized pulling mechanism, a fiber pigtailed light source (LED or LD) and detector as well as reading system/PC as presented in figure 2.

![Figure 2. Experimental set up for automatic characterazation of fiber extensometer.](image2)
Before bending loss measurement, both fibers were checked its full transmission by launching white light source to the fiber and detecting the output at several pulling-distance using optical spectrum analyzer to examine the sensitive bending area in its intensity-wavelength output graphs. The bending loss measurement was then conducted to obtain the intensity versus distance graphs outputs and analyze the data to find the measurement range, sensitivity and resolution of the sensor structure.

3. Experimental results and discussion

The first experiment was the measurement of the full transmission curve for both fibers using Stabilized White Light Source SLS201/M from Thorlabs and optical spectrum analyzer ANDO AQ 6312 to check the sensitive bending loss area. Output intensity were measured at three positions of the fiber loop sensor at its housing with pulling distances $x = 0$ cm, 2 cm and 3 cm for Fujikura fiber. For SMF 28 Thorlabs fiber, the pulling distances were 0 cm, 1 cm and 2 cm. The results are presented in figure 3(a) (for Fujikura fiber) and figure 3(b) (for SMF 28 Thorlabs fiber). We can see that at wavelength around 1310 nm and 1325 nm both fibers showed good respond to bending.

![Figure 3](image)

**Figure 3.** (a) Transmission curve of Fujikura fiber, at pulling distances $a = 0$ cm, $b = 2$ cm and $c = 3$ cm. (b) Transmission curve of SMF28 Thorlabs fiber, at pulling distances $a = 0$ cm, $b = 1$ cm and $c = 2$ cm.

The second experiment was the characterization of bending loss properties of both fiber with experiment set up shown in figure 2. It used two kinds of light sources, LED and LD at 1310 nm and 1325 nm, alternately; to compare its performances. The fiber was pulled automatically from 0-30 mm using a PC controlled pulling mechanism and its output was recorded and read using a PC.

The experiment results were output intensity as a function of distance as shown in figure 4(a) and 4(b) for Fujikura fiber and figure 5(a) and 5(b) for SMF 28 Thorlabs fiber. The data were examined on their linearity and existence of whispering gallery mode (WGM) and further analysed to examine their performances as displacement sensor. The required criteria for good fiber extensometer are free from noise and WGM and possessing high sensitivity, good resolution as well as wide range measurement.

The full data analysis for both fibers with its light source combination is presented in table 1. The combination of the Fujikura fiber with 1310 nm LED, resulted in a quite noisy spectrum but small WGM effect (see figure 4(a) and table 1, first left part) with coefficient linearity $R^2 = 0.98511$. When it was used as displacement sensor it had 0-28 mm of measurement range ($x$) with sensitivity of 0.04 dB. Since that the smallest value of the intensity that can be read is 0.05 mV; we can calculate the resolution as 0.05 mV / 0.04 mV/mm = 1.25 mm.

As for comparison, the resulted sensitivities for Fujikura SM fiber were 0.04 dB/mm when using the 1310 nm LED and 0.06 dB/mm when using the 1325 nm LD. The measurement ranges were 28 mm and 23 mm, respectively. In contrary, for SMF28 Thorlabs fiber, the sensitivity value was higher when using the 1310 nm LED compared to that of 1325 nm LD (0.09 dB/mm for 1310 nm LED compare to 0.03 dB/mm for 1325 nm LD), resulting in the resolution of 0.55 mm and 1.60 mm, respectively.
Figure 4. (a) Bending loss curve for Fujikura fiber using LED at 1310 nm, \(x = 28\) mm (0-28 mm). (b) Bending loss curve for Fujikura fiber using LD at 1325 nm, \(x = 23\) mm (3.5-26.5 mm).

Figure 5. (a) Bending loss curve for SMF28 Thorlabs fiber using LED 1310 nm, \(x = 23\) mm (3.5-26.5 mm). (b) Bending loss curve for SMF28 Thorlabs fiber using LD 1325 nm, \(x = 31\) cm (0-31 mm).

Table 1. Bending loss properties of Fujikura and SMF28 Thorlabs fibers.

| Fiber type       | Source wavelength | LED at 1310 nm | LD at 1325 nm |
|------------------|-------------------|----------------|---------------|
| SM Fujikura Fiber| Spectrum: Noisy   | WGM effect: small | R\(^2\): 0.98511 |
|                  | WGM effect: small | R\(^2\): 0.98549 | Measurement range: 28 mm (0-28 mm) |
|                  | Sensitivity: 0.04 dB/mm | Sensitivity: 0.06 dB/mm | Resolution: 1.25 mm. |
| SMF28 Thorlabs   | Spectrum: Not noisy | WGM effect: notable | R\(^2\): 0.90701 |
| Fiber            | WGM effect: small | Measurement range: 23 mm (3.5-26.5 mm) | Sensitivity: 0.09 dB/mm |
|                  | R\(^2\): 0.98389 | Measurement range: 31 mm (0-31 mm) | Resolution: 0.55 mm. |
|                  | Measurement range: 23 mm (3.5-26.5 mm) | Sensitivity: 0.03 dB/mm | Resolution: 1.60 mm. |

The measurement range for SMF 28 Thorlabs fiber is wider when using the 1325 nm LD if compared to when using the 1310 nm LED (31 cm with 1325 nm LD compared to 23 mm with 1310 nm LED); but the WGM effect is notable when using the 1325 nm LD. Oscillation of the bending loss with bending radius has been observed by many researchers and this was explained by the WGM modes [8]. This might be caused by the type of material coating of the Thorlabs fiber which made more back-reflected light in the fiber’s bent structure compared to that in the Fujikura fiber. WGM
phenomenon should be studied further. The results of this work are comparable to the patented work by Gupta et al. [12] and to our earlier work.

From those results, it can be seen that using a laser diode instead of LED in characterizing bending loss of SMF 28 Thorlabs fiber does not guarantee to have a better performance of the heart shape sensor but there are still other affecting factors. We can get a higher sensitivity of fiber extensometer by using a laser source but it would result in a very narrow measurement range. Furthermore, we have to compromise in choosing a sensor configuration which has a better sensitivity, a wider measurement range, smooth data and acceptable WGM to get the best data reading.

4. Conclusion

We have presented the design, construction and characterization of optical fiber extensometer with heart shape sensor structure for detection of displacement using two types of fiber and light sources. From the bending loss characterization using Fujikura fiber as the sensor, we obtained sensitivity of 0.04 dB/mm and measurement range of 28 mm when using the 1310 nm LED, whereas using 1325 nm LD allowed us to obtain 0.06 dB/mm of sensitivity and and 23 mm of measurement range. Using Thorlabs fiber as the sensor, we obtained sensitivity and measurement range of 0.09 dB/mm and 23 mm, respectively, when using the 1310 nm LED. When we used the 1325 nm LD, we obtained sensitivity of 0.03 dB/mm and 31 mm measurement range but with a noted WGM effect.

Acknowledgments

This research was funded by Program Tematik, Research Center for Physics, Indonesian Institute of Sciences Year 2016. The authors are gratefully acknowledging Mr. Prabowo Puranto, M.T., who have developed the automatic pulling system. The authors also wish to thank Mr. Imam Mulyanto, S.T. for all technical assistances during the experiment.

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