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A low-cost fiber based displacement sensor for industrial applications

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Abstract

In this paper, a low-cost fiber optic displacement sensor (FODS) using a bundle of plastic optical fiber (POF) as a probe is developed and presented. The sensor consists of a high power light emitting diode (LED) as light source, a probe with multiple receiving plastic optical fiber and a photodiode detector. The sensor is characterized at millimeter distance and the sensor output is analyzed from 0 mm to 13 mm displacement. The sensitivity of the sensor is found to be 5.38 mV/mm over 2.6 mm sensing range. The sensor is very useful for close distance target since it is highly sensitive at the front slope. The low development cost, high degree of sensitivity and simplicity of the design make it suitable for wide range of industrial applications.

Keywords*: fiber bundle, fiber optic displacement sensor, intensity based sensor, light emitting diode, plastic optical fiber*

1. Introduction

Displacement sensing is important in various industrial applications, including for example, position monitoring, vibrations analysis, precision alignment, control applications, robotics, etc [1, 2]. For the past few years, conventional displacement sensors working based on piezoelectric, magnetic, or capacitive principles are reported [3-7]. However, these sensors are limited in application since it is not immune towards electromagnetic interference (EMI) [8, 9]. Fiber optic-based displacement sensor is thus has gained enormous attentions specifically due to its immunity to EMI, electrically passive, compact, lightweight, high sensitivity and also high resistance in harsh environment [10-12].

There are three different types of modulations that are commonly used for fiber optic displacement sensor (FODS) measurement, known as laser interferometry, wavelength modulation and intensity modulation technique [13]. Laser interferometry is based on fringe counting and it has good measurement stability and high resolution. However, its stability and accuracy are rely on the wavelength of light [14]. The measurement process also requires complex instrumentation and is bandwidth limited [13]. On the other hand, wavelength modulation can be very costly since it needs optical spectrum analyzer (OSA) and fiber Bragg grating (FBG) for data acquisition and physical parameter detection, respectively [15]. Most of FODS employed intensity modulation technique [15-21], which is the simplest method to obtain high resolution measurement. The intensity-modulated based sensors (IBS) offer high precision while also having high bandwidth and less expensive components [22]. IBS can be classified into two categories, namely transmissive and reflective FODS.

In evaluating the reflective FODS, sensor's sensitivity has been analyzed. Sensitivity is defined as a change in sensor output, in term of reflected power or wavelength peak, per unit change in displacement of target object [23]. High sensitivity reflective FODS can be achieved by improving the sensor head configuration. There are many type of sensor head configurations that have been proposed and developed for past few years. The first reflective FODS was introduced by W. E. Frank [24, 25]. It has the simplest sensor head configuration which consist

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of one receiving fiber and one transmitting fiber. Distance of the sensor head and target object can be measure from the front slope region or back slope region of the output curve. Then, the sensor is improved by Jianli Zheng in 1998 by increasing the number of receiving fiber to develop a self-referenced reflective intensity modulated FODS [25]. Zheng improved the system by using both of the slope in order to increase the sensing range. Sensitivity of Frank and Zheng proposed sensor still can be improved since both of the sensors collect a small portion of reflected light.

In 2013, a comparison of bundle sensor performance between 16 concentric receiving fiber located around transmitting fiber and 1000 hemicircular receiving fiber probes has been reported [26]. The 16 receiving fiber probe showed a better sensor performance both at the front slope and the first back slope region. So in 2015, Daing Hanum developed FODS using a bundle of plastic fiber and HeNe laser source as the light source [27]. In the research, the FODS is used to measure the concentration of hydrocarbon, an organic water pollution. The sensor probe used in [27] has the same configuration as the 16 concentric receiving fiber in [26] but with less number of receiving fiber. The probe contains bundle of fiber optic which consists of two parts, one transmitting fiber and multiple receiving fiber. The receiving fibers are located around the transmitting fiber. However, the developed sensor is quite expensive due to the usage of Helium-Neon laser as the light source.

Therefore, in this paper, an economical and high sensitivity displacement sensor has been developed based on the sensor head configuration in [27] using light emitting diode (LED) as the light source. A POF-based bundle is used as a probe and a thin gold film as the reflecting surface which in turns offer simplicity, reliability and continuous measurements capability.

2. Research Method

In this study, the fiber optic displacement sensor (FODS) is developed using light intensity modulated technique. The schematic experimental setup is shown in Figure 1. A bundle POF was employed as a probe. The bundle fiber optic contains of two parts, first is a single transmitting fiber and the second part is multiple receiving fiber. The transmitting fiber used a high power LED as a light source. Meanwhile the receiving fiber was connected to a photodiode detector.

Light from high power LED is injected into a transmitting fiber and emitted at the end of the bundled fiber. A highly reflective thin gold film is used to reflect the beam from the transmitting fiber and send back to the receiving fiber. The distance between the fiber optic probe and reflector is varied by mounting the reflector on a translation stage. The range of displacement accomplished in this study is in between 0 to 13 mm. Before developing the proposed displacement sensor, several experiments have been carried out to determine the compatibility of component involved.

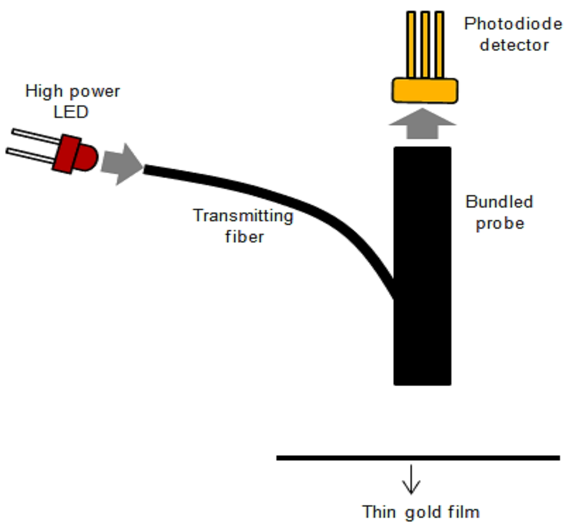


Figure 1. Experimental setup of fiber optic displacement sensor

2.1. Light Source Characterization

In this study, common low power LED with four different colours and high power LED are characterized in term of wavelength, photon count and photodiode output voltage in order to determine the most suitable light source for displacement sensor application. For common LED, four different colours have been characterized which are blue, orange, white and green. Each of it is connected to 51 ohm resistor and 3 V power supply. For high power LED, only white colour is characterized and it is connected directly to 3.7 V and 0.68 A power supply. A Thorlab FDS 100 photodiode is used to measure voltage which represents light intensity of LED with 1 mm air gap while wavelength and photon count are measured using optical spectrometer with 0 mm air gap.

Table 1 shows photodiode generated voltage for different LED. High power LED has the highest output voltage compared to low power LED which is 10.8 V. The optical spectrometer output for all LED is shown in Figure 2. For low power light source, white LED has the broadest spectral bandwidth which is 154 nm while blue, green and orange LED has narrow spectral bandwidth which is 22 nm, 14 nm and 16 nm respectively. Besides, green LED has the lowest intensity which is 1821 photon count while white LED generated the highest light intensity which is 15630 photon counts. For high power LED, it has the broadest spectral bandwidth and largest photon count compare to other LED. Both of the values are unidentifiable due to spectrometer limitation.

Table 1. Photodiode Output Voltage for Different LED

Type of LED	LED colour	Photodiode voltage (V)
Low power LED	Blue	87
	White	301
	Orange	7
	Green	59
High power LED	White	10800

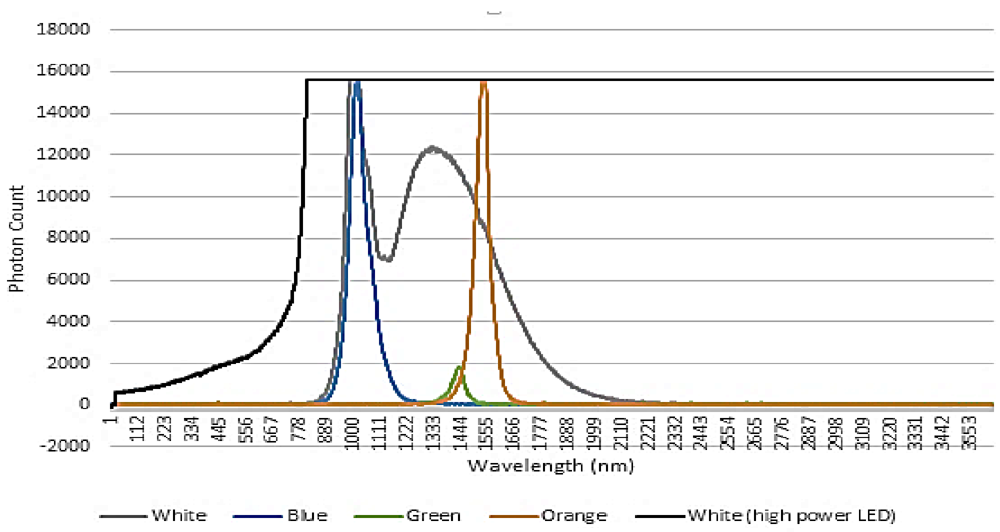
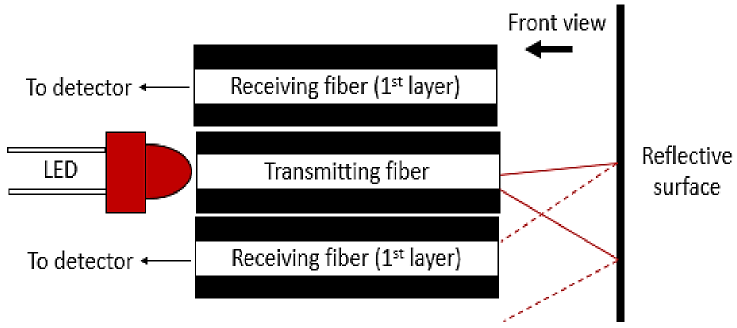


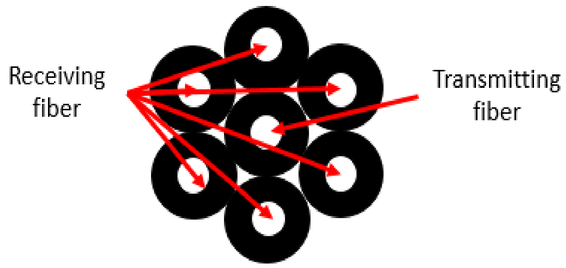
Figure 2. Spectrometer output

2.2. Sensor Characterization

There are two reflective FODS has been developed for this research which is FODS 1 and FODS 2. FODS 1 is reflective FODS based on Frank sensor head configuration in [24] while FODS 2 is the proposed sensor based on Daing Hanum sensor head configuration in [27] with LED as the light source. Figure 3 shows the FODS 2 configuration. For both sensors, high power LED is used as light source and connected to the fiber with 0.7 mm air gap. Power supply for LED is set to 3.7 V and 0.68 A. The length of transmitting and receiving fiber is 6 cm and 3 cm respectively. Thin gold film is used as target object or reflective surface.



(a)



(b)

Figure 3. FODS 2 configuration: (a) side view (b) front view

Both of the sensors are characterized in term of distance between sensor head and target object. Initial distance between sensor head and gold film is set to 0 mm and increase to 13 mm with 0.1 mm increment. The reflected light intensity that pass through the receiving fiber or photodiode output voltage, *V* represented the distance between the sensor head and target object, *d*. Sensitivity of both sensor is given by

$$S = \frac{\Delta V}{\Delta \mathrm{d}} \quad (1)$$

3. Results and Analysis

Figure 4 shows the variation of the output voltage of the sensor with respect to the displacement. The displacement represents the distance of the thin gold film from the fiber probe and output voltage is the intensity signal of the reflected light. Each output curve exhibits a peak voltage with a steep front slope while the back slope obeys an almost inverse square law function.

The output signal is zero at zero displacement because the light cone does not reach the receiving fiber. However, as the displacement is increased, the size of cone of the reflected light become larger and starts to overlap with the receiving fiber cores leading to a drastic change of the output voltage at the front slope of the graph. After reaching a maximum or peak value, the output voltage starts decreasing for higher displacements. This is due to the fact that the power density decreases with larger size of the cone of light. Thus, only small fraction of light is received by the probe. As a result, an almost inverse square law is obtained at the back slope of all curves of output signal against the displacement. For both cases, 5.0 mm is found to be the optimum displacement between the thin gold film and fiber probe.

Figure 4 (a) shows the sensor output for FODS 1. The maximum sensor output generated by FODS 1 is 3.6 mV. From the output curve, there are two linear regions with different sensitivity and sensing range that can be used to measure displacement which are front slope and back slope. The front slope sensitivity is 0.92mV/mm with 4mm sensing range. The back slope able to measure displacement with 7.5mm sensing range, higher compared to the front slope. However, back slope has poor sensitivity which is 0.32 mV/mm.

Figure 4 (b) shows the FODS 2 output curve. The maximum sensor output generated by FODS 2 is 15 mV, almost 5 times larger compared to FODS 1. The output of FODS 2 also consists of two linear curves that can be used to measure displacement. Both of the slopes have their own advantages. The front slope has higher sensitivity which is 5.38 mV/mm while the sensitivity of the back slope is 1.36 mV/mm. However, the back slope has higher sensing range compared to the front slope which is 8.1 mm while the sensing range of front slope is only 2.6 mm.

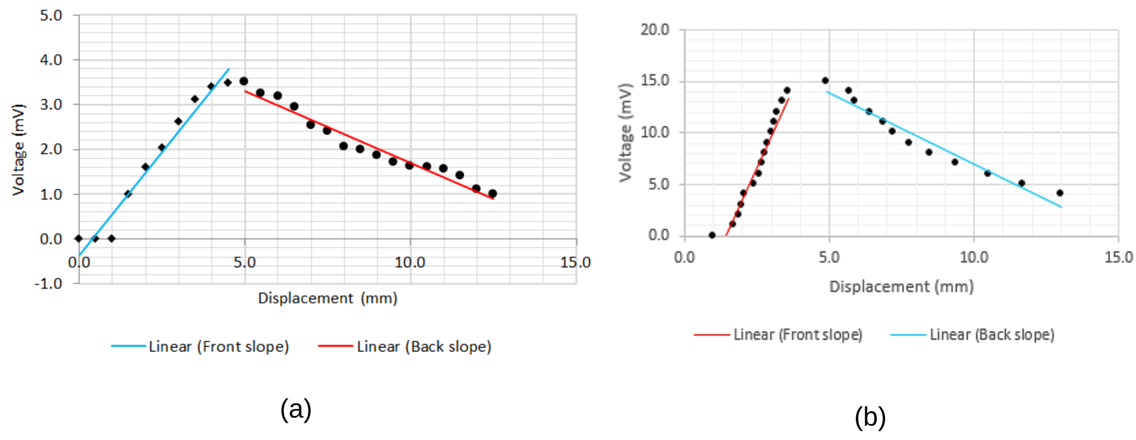


Figure 4. Output curve for (a) FODS 1 (b) FODS 2

In both of the sensors, the front slope is highly sensitive and useful for close distance target and the back slope is less sensitive and useful for long distance. As mentioned before, sensitivity is the change in sensor output per unit change in displacement. FODS 2 front slope sensitivity is higher than FODS 1 because FODS 2 able to receive more reflected light as the light cone angle increases since it has more receiving fibers. On the other hand, FODS 1 has only single receiving fiber which in turn causes the photodiode to trap only small portion of reflected light. Data collected from both FODS 1 and FODS 2 indicated that the sensitivity of reflective FODS can be improved by increasing the number of receiving fiber.

4. Conclusion

An economical reflective FODS based on intensity modulation technique with multiple receiving fiber and high power LED as light source is developed and presented in this paper. The developed sensor output is analyzed from 0 mm to 13 mm of displacement and is compared with another fiber-based displacement sensor with single receiving fiber which is FODS 1. Both the compared sensors have similar configurations. From the experiment, FODS with multiple receiving fiber with sensitivity of 5.38 mV/cm and 2.6 mm sensing range is obtained. This developed sensor is very beneficial for applications that require millimeter displacement. The applications of the sensor can also be extended to wide range of applications due to its simplicity, high sensitivity and low development cost.

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