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Fabrication and characterization of Polymer Optical Fiber (POF) based on Mach-Zehnder interferometer for temperature sensor

H Rumiana, S Maimanah, K E Kurniansyah, I Yulianti* and N M D Putra

Physics Departement, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Indonesia

*Corresponding author: ianyulianti@gmail.com

Abstract. A polymer optical fiber based on Mach-Zehnder Interferometer (MZI) was proposed and experimentally demostrated for temperature sensor. The MZI comprises two couplers with length of 2 cm and two POF branches with different length which are 5 cm and 3 cm. The jacket of the 5 cm branch was removed to increase the temperature effect on the MZI. Characterization of the sensor was done by putting the sensor in temperature chamber while the two ends of the MZI were connected to light emitting diode (LED) and spectrometer, respectively. The temperature was varied from 40°C to 80°C with an increment of of 5°C. The results showed that the sensitivity is 0.0822 nm/° C with correlation of 97,66%. The MZI sensor has the highest accuracy at temperature of 55°C and the lowest accuracy at temperature of 70°C.

1. Introduction

Temperature is one of important parameters in various applications, for example in chemical for quality control, in food industries for material stability monitoring, and in environmental industries for contamination assessment [1].

Recently, fiber sensors for temperature sensing have been developed, such as long-period fiber grattings (LPFG) [2], fiber Bragg gratings (FBG) [3], Fabry-Perot (FP) [4], and Mach-Zehnder Interferometer (MZI) [5]. MZI is a fiber optic sensor that use phase modulation [6]. Light from the transmission fiber is split into two waveguides in the sensing arm and reference arm. Sensing arm is a sensing area that is used for external variations such as temperature, refractive index, and others. Whereas, the reference arm is coated with an isolated protective layer. After light passes through both arms, light will be recoupled.

MZI is widely used as optic sensor because it has many advantages such as, has a small size, design flexibility, compact, high sensitivity, electromagnetic immunity, and low cost fabrication process [7]. In previous research, MZI as a temperature sensor has been realized with various techniques, for example core-offset [8], microcavities [9], multi-core fiber [10], and taper [11]. Fabrication of MZI sensor will be easier to do on material that have large core diameters like as polymer optical fiber (POF). POF has advantages properties such as high flexibility, biocompatibility, durable, and low cost production [12]. Based on the advantages of POF, in this study fabrication and characterization of MZI will be carried out with an easy and simple technique to determine its characteristics if applied as a temperature sensor.

2. Methods

2.1. Operating Principle of the Sensor

Due to the different optical paths between reference arm and sensing arm, an interference response with some dips and peaks is generated at the output, which can be expressed by equation (1):

$$I_{out} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \Delta\emptyset \quad (1)$$

where I_1 is sensing arm intensity, I_2 is reference arm intensity, $\Delta\emptyset$ is the phase difference of the two interferometer arms. The phase is shown by equation (2):

$$\emptyset = \frac{2\pi}{\lambda} \int N(L)\, dL \quad (2)$$

where N is effective refractive index along reference arm and sensing arm, λ is the input wavelength. Because the effective refractive index is constant along the path, equation (2) can be simplified to equation (3) and equation (4):

$$\emptyset_1 = \frac{2\pi}{\lambda}\left(N_0 + \frac{\partial n}{\partial T}\Delta T\right) L_1 \quad (3)$$

$$\emptyset_2 = \frac{2\pi}{\lambda}\left(N_0 + \frac{\partial n}{\partial T}\Delta T\right) L_2 \quad (4)$$

where N_0 is the effective refractive index at the room temperature, $\frac{\partial n}{\partial T}$ is the thermal optic coefficient of the polymer material, ΔT is the variation of the surrounding temperature, and L_1 and L_2 are the lengths of the sensing arm and reference arm, respectively. The phase difference $\Delta\emptyset$ can be obtained by equation (5):

$$\Delta\emptyset = \emptyset_2 - \emptyset_1 = \frac{2\pi}{\lambda}\left(N_0 + \frac{\partial n}{\partial T}\Delta T\right) \Delta L \quad (5)$$

ΔL is the length difference between the two arms of MZI sensor. Based on the theoretical analysis, it can be summarized that output light intensity depends on the performances of polymer material, wavelength operating, and the length difference between two arms MZI sensor [13].

2.2. Experiment

Multimode POF with cladding diameter of 1000 µm and core diameter of 980 µm was used in the sensor fabrication. The first step of the manufacturing process was coupler fabrication by cut the POF of 65 cm and removing the jacket and cladding in the middle of POF of 2 cm. Then, coupled two POF using Loctite glue at room temperature for 20 minutes. The formed coupler was characterized using red LED as light input and spectrometer as a detector to see the output spectrum in both branches.

Next, MZI sensor fabrication was done using two couplers with length difference between two arms L_1 dan L_2. L_1 have length of 5 cm while L_2 have length of 3 cm. At L_1 arm, the jacket was removing.

MZI was characterized by white LED as light input and putting the MZI sensor in chamber for temperature effect. The temperature variation from 40°C to 80°C with an increment of 5°C and keep as long as 5 minutes for each temperature increment. Output spectrum of MZI sensor was detect by spectrometer Ocean Optic. Characterization set-up of MZI sensor as shown in Figure 1.

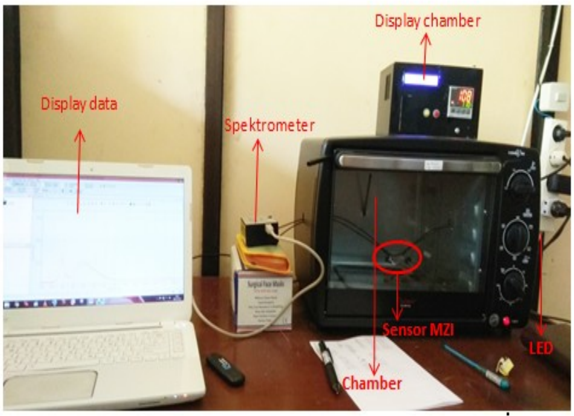

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Figure 1. Characterization set-up

3. Result and Discussion

Coupler fabrication aims to get an optical device that functions to split the light signal into two different branches with the same intensity. Coupler has output branches A2 dan B2. The result of coupler characterization as shown in Figure 2.

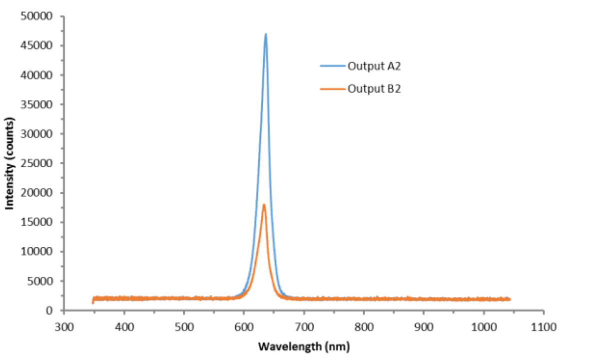


Figure 2. Result of coupler characterization

In Figure 2, we can see that output intensity of branches A2 and B2 are 46986,77 counts and 7674,43 counts, respectively. Based on output intensity, coupler has parameter value of coupling ratio (CR) for branches A2 and B2 are 2:1. These ratio show that the proportion of output power in A2 is greater than the proportion of output power B2. This is caused by several factors, including loss in the coupling part of coupler and incomplete distribution of light on core [14].

MZI sensor characterization was carried out to determine the response of MZI to temperature changes at rising temperature of 40°C to 80°C, and at drop temperature of 80°C to 40°C to obtain the value of sensor reversibility. Output spectrum of MZI sensor at temperature of 40°C to 80°C is shown in Figure 3.

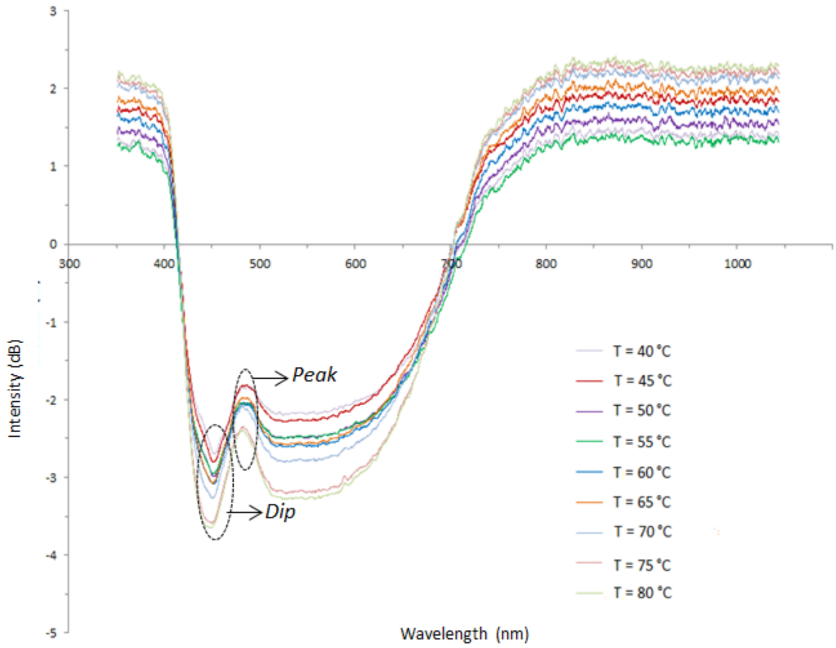
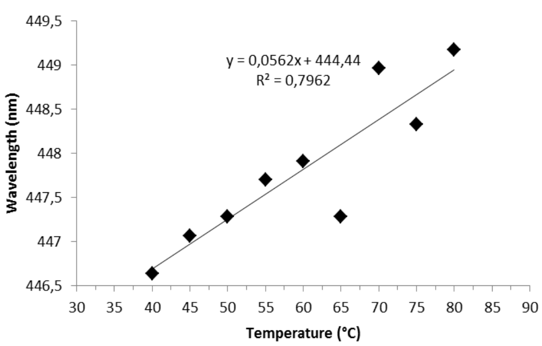


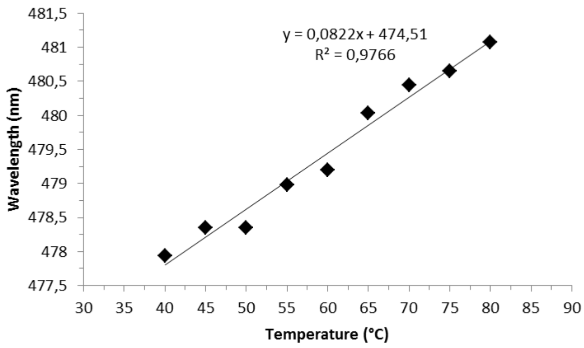
Figure 3. Output spectrum of MZI sensor at 40°C to 80°C

In Figure 3, wavelength of output spectrum of MZI sensors on the dip and peak shifted to a larger wavelength to the temperature increase, while the intensity of the output spectrum decrease. A longer wavelength shift is induced by thermo-optic coefficient (TOC) value. POF has a negative TOC value $-1{,}2 \times 10^{-4}\ °C^{-1}$ so when temperature increase, it cause refractive index of the core mode decreases. The change of refractive index of the core affect the effective refractive index value, which is characterized by the wavelength shift of output spectrum MZI sensor in dip and peak [15].

The sensor's sensitivity was obtained by making plot of wavelength shift against temperature. Wavelength shift was observed on the dip and peak of output spectrum MZI in Figure for each temperature increment. Graph of wavelength shift vs temperature shown in Figure 4.



(a)



(b)

Figure 4. Graph of wavelength shift vs temperature. (a) In the dip. (b) In the peak

The value of the MZI sensor sensitivity in the dip and peak area are 0,0562 nm/°C and 0,0822 nm/°C with correlation coefficient 79,62 % and 97,66 %, respectively. This is show wavelength will shift of 0,0562nm/°C and 0,0822 nm/°C for each temperature increment of 5°C. The positive gradient indicate that high temperature around MZI cause longer wavelength shift. Based on Figure 4, peak area have higher sensitivity than dip area. This is due to the light source that is used has a maximum intensity at peak area which is about 480 nm – 500 nm.

High sensitivity of MZI sensors is caused by length difference between two arms in the sensor. The larger length difference would generate the larger phase difference between the two interferometer arms. Therefore, the wavelength shift will be larger and can increase the sensor sensitivity [13]

If characterization do at decrease temperature, the temperature response of sensor has hiterisis as shown in Figure 5.

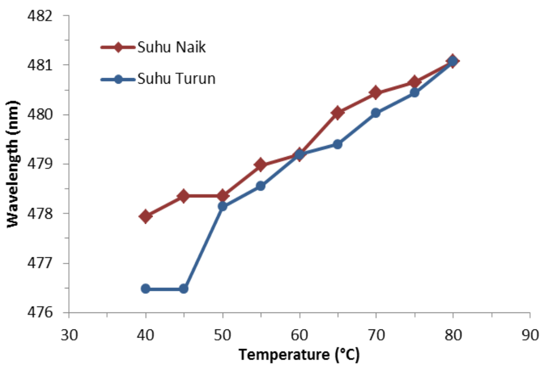


Figure 5. Reversibility temperature response

Maximum histerisis occurs at temperature of 40°C and 45°C are 1,47°C and 1,88°C. For decrease the value of histerisis need to be used a chamber with small fluctuation temperature.

Response time is the time that takes for sensor to provide a constant response. MZI response time is shown in Figure 6. MZI need very short time i.e 1 s to reach steady state with chamber fluctuation ±1°C. When temperature 40°C – 80°C is given, the output on the spectrometer indicate spectrum with peak value and remain stable during 5 minutes measurement.

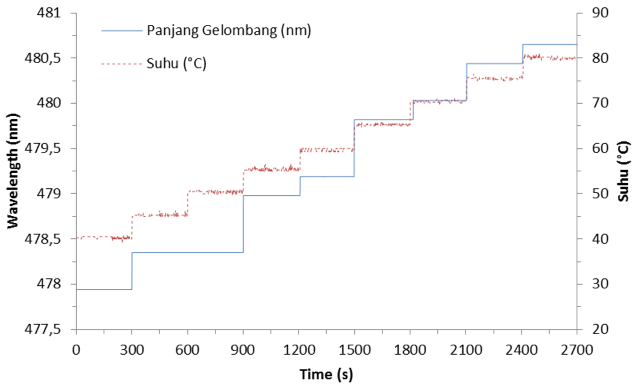


Figure 6. MZI response time

MZI sensor accuracy was determined by taking the difference value of temperature that obtained from a linear regression equation with temperature measurement on the chamber using thermocouples is shown in Figure 7.

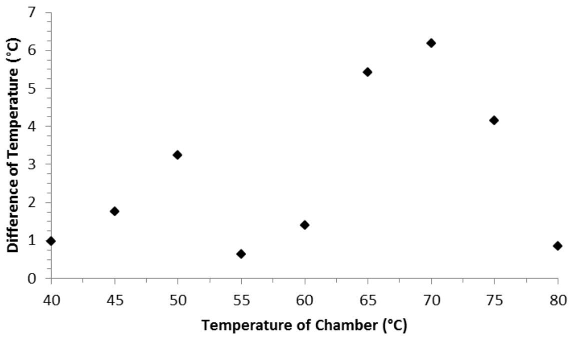


Figure 7. MZI sensor accuracy

The smaller difference between the measured temperature, the more accurate the temperature sensor. The highest temperature difference occurs at temperature of 70°C i.e 6,197°C, while smallest temperature difference on the temperature of 55°C i.e 0,634°C. A large difference temperature due to temperature fluctuations on the chamber or the measurement of the wavelength and intensity are less accurate.

4. Conclusion

Fabrication and characterization of polymer optical fiber based on Mach-Zehnder Interferometer for temperature sensor have been demonstrated experimentally. The temperature sensitivity of the proposed sensor is 0,0822 nm/°C with correlation of 97,66%. When the temperature decreased the obtained chart changed. Hysteresis occurs due to temperature fluctuations in the space during the characterization process. The MZI sensor has the highest accuracy at temperature of 55°C and the lowest accuracy at temperature of 70°C.

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