Characterization of Mach Zehnder interferometer plastic optical fiber for intensity-based temperature sensor

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Abstract. This paper presents characterization of optical temperature sensor using step-index plastic optical fiber (SI-POF) in intrinsic Mach Zehnder interferometer (MZI) structure. The MZI was developed by forming two tapers at several distance. By exploiting the wavelength dependency of spectrum intensity, measurement was done by using intensity based measurement at two different wavelengths. Characterizations were done to obtain the sensor performance which were sensitivity and hysteresis. The characterization was carried out by launching white LED to the sensor while the sensor was in temperature controlled-oven. The output spectrum was observed at the other sensor tip using spectrometer at various temperature which are 35⁰C to 85⁰C with increment of 10⁰C. It was found that the sensor has sensitivity and hysteresis of 1×10⁻³/⁰C and 1.97×10⁻², respectively.

1. Introduction
Temperature sensor has been developed using various technology due to its importance in various applications. As optical fiber sensor technology evolves, researches on optical sensor for temperature measurement have also been reported numerously. Optical fiber based-temperature sensor is interesting since it does not experience electromagnetic interference, suitable for remote sensor and on-line monitoring. Various configurations and techniques have been used to develop optical fiber temperature sensor such as metal-coated fiber Bragg grating (FBG)[1] multimode interference (MMI) using no core fiber (NCF) [2], interferometric sensor comprises suspended-core fiber (SCF) spliced with two single mode fibers (SMFs) [3] and liquid filled photonic crystal fiber (PCF) [4]. All the previous-mentioned sensors principle are based on wavelength modulation technique. Wavelength based modulation technique is interesting since it has high accuracy. However, complex fabrication process and high cost limits the sensors advantages. On the other hand, intensity based sensor promises low cost, simple fabrication and straight forward measurement [5].

Regardless the above-mentioned advantages, intensity based sensor is highly affected by power loss which contributes to high measurement error. Therefore, various techniques have been proposed to overcome the limitation such as self-referencing techniques [6]–[8] and dual-wavelength compensation [5], [9]. To implement the techniques, additional devices such as collimator, coupler and mirror are required. Thus, it increase cost and complexity. To overcome those drawbacks, simple dual-wavelength compensation can be done using Mach-Zehnder interferometer (MZI) [10]. Basically, measurement using MZI sensors can be accomplished by exploiting changes in intensity or wavelength. Wavelength
based modulation requires high cost equipment and is also not practical, as stated earlier. Intensity-modulated sensor using MZI can be done by measuring power change at two different wavelengths at which resulting high power changes with regard to the change of measurand [10].

Generally, optical fiber sensor could be realized using silica fiber, photonic crystal fiber (PCF) or plastic optical fiber (POF). POF has received great attention in optical fiber sensor research due to some advantages such as low cost, robust due to its high diameter and mechanical strength, and easy to handle [11][12]. POF could be modified into various structures such as D-shaped [13], U-shaped [14], macro-bend loop [15] and MZI [16]. In this paper, we propose intensity-based optical fiber temperature sensor based on POF by using MZI structure (POF-MZI). POF-MZI has been demonstrated for refractive index and strain measurement [16]. The MZI was constructed by using simple heat-pull technique on graded index-POF (GI-POF). The results showed that the sensor has comparable sensitivity to both refractive index and strain. However, the sensor suffers from high power loss due to inefficient coupling between POF with SMF. Considering the high thermo-optic coefficient (TOC) and high thermal expansion coefficient (TEC) of POF material [17][18], POF-MZI can be adopted for temperature measurement. In this work, the proposed sensor used step index POF (SI-POF) since it provides higher dimension (1000µm). Hence, it is sturdier than GI-POF. It also does not require coupling to SMF because the SI-POF can be connected directly to LED and spectrometer using SMA 905 connector. Therefore, power loss can be reduced. The sensor sensitivity and hysteresis to temperature change were characterized to evaluate the sensor performance.

2. Methods

MZI was basically designed by splitting input light into two different path lengths by branching the light path. Due to the difference in path lengths, light propagate with difference phase. The branches are then re-combined so that interference occurs in the output. Light splitting can also be done by forming fiber taper. In this work, MZI was realized using two different waist diameter tapers (asymmetric taper) as shown in Figure 1. Core modes that initially confined in fiber core excite cladding modes due to tapered structure at the first taper. Therefore, at the interference region \((L)\), there are core modes and cladding modes which propagate separately at core and cladding, respectively. The separated modes are the recombined at the second taper. MZI output light depends on temperature due to the thermo-optic effect. In addition, the output intensity is also wavelength dependent as a result of light interference between core modes and cladding modes. By observing output intensity at two different wavelengths, dual-wavelength compensation can be accomplished.

![Figure 1. Schematic diagram of SI-POF MZI](image)

MZI was constructed in SI-POF with core diameter of 980µm (CC2-1000, Sichuan Huiyuan Plastic Optical Fiber Co., Ltd.). The core material and cladding material are PMMA and fluorinated polymer with refractive index of 1.49 and 1.41, respectively. To form the fiber tapers, the POF was pulled and heated using solder at temperature of 80°C [16]. Prior to heating, the polyethylene jacket with diameter of 2.2 mm was removed at where the tapers to be located using fiber stripper. As connector, SMA 905 connectors (Industrial Fiber Optics, Inc) were attached to the two fiber ends so that it can be easily
connected to spectrometer and light source. The resulted intrinsic MZI structure was then observed using CCD-optical microscope to measure the waist diameter of the two tapers.

Sensor characteristics to temperature change i.e. sensitivity, hysteresis and repeatability were obtained by performing sensor characterization. The sensor was placed in our modified temperature controlled-oven, while the tips were connected to spectrometer and LED as shown in Figure 2. Characterization were done at various temperature ranging from 35°C to 85°C with increment of 10°C. While the sensor was in the oven, the output spectrum was observed and was recorded every second using spectrometer which connected to PC. The sensor was then taken out from the oven and let it in room temperature before conducting characterization for decreased temperature. The cycle was repeated for three-time measurements.

![Figure 2. Set up of the temperature characterization of the SI-POF MZI.](image)

3. Results and Discussions

Figure 3 shows side view of the first taper and the second taper of the fabricated MZI taken by optical microscope. The waist diameters obtained were 872 μm and 678 μm for first taper and second taper, respectively, while the interferometer region was 20 mm.

![Figure 3. Optical microscope image of the first taper (a) and second taper of the fabricated POF-MZI](image)

To evaluate the sensor performance, transmission at wavelength of 455.28 nm (λ₁), 464.11 nm (λ₂), 501.68 nm (λ₃) and 585.86 nm (λ₄) were observed as shown in Figure 4. It is shown that as temperature is increased to 75°C, the transmission at the whole wavelength range also increased. However, at wavelength of 85°C, the transmission decreased. These results agree with those obtained by Zhong et al. [19]. The transmission increased due to the increase of the local numerical aperture (NA) [20]. Based on the manufacturer specification, the maximum limit of working temperature of the POF is 85°C.
Therefore, it confirms the decrease of the transmission. At this temperature, the POF experiences deterioration in optical as well as physical properties. The deterioration could be in the form of local deformation, fluctuation of density and amorphous domain distribution and local surface defects which causes scattering and refraction [19].

![Transmission spectrums for various temperature values of the fabricated POF-MZI](image)

**Figure 4.** Transmission spectrums for various temperature values of the fabricated POF-MZI

It also can be noticed that the wavelengths of peaks and dips are slightly shifted. To detect the wavelength shift, high accuracy wavelength interrogation system is required. However, in this work, we focused on intensity changes rather than wavelength shift. Sensor sensitivity to temperature change was observed in terms of transmittance ratio of a pair of selected wavelengths. To obtain calibration curve, the transmittance ratio corresponding to temperature obtained from the three cycles experiments were averaged and then plotted against temperature. It was found that transmittance ratio for $\lambda_1/\lambda_2$ has a very weak linear fitting to temperature which is 0.1718. Therefore, $\lambda_1/\lambda_2$ was not considered for further characterization. Transmittance ratio for $\lambda_1/\lambda_3$, $\lambda_2/\lambda_3$ and $\lambda_3/\lambda_4$ were plotted against temperature as shown in Figure 5.

![Calibration curve of the fabricated POF-MZI for transmittance ratio of $\lambda_1/\lambda_3$, $\lambda_2/\lambda_3$ and $\lambda_3/\lambda_4$](image)

**Figure 5.** Calibration curve of the fabricated POF-MZI for transmittance ratio of $\lambda_1/\lambda_3$, $\lambda_2/\lambda_3$ and $\lambda_3/\lambda_4$
It is shown that sensitivity of each transmittance ratio to temperature change are $1 \times 10^{-3} \degree C$, $7 \times 10^{-4} \degree C$ and $8 \times 10^{-4} \degree C$ for $\lambda_1/\lambda_3$, $\lambda_2/\lambda_3$ and $\lambda_3/\lambda_4$, respectively. The linear regression coefficient of each transmittance ratios are 0.924, 0.9231 and 0.9277, respectively. Clearly, $\lambda_1/\lambda_3$ provides highest sensitivity. Meanwhile, transmittance ratio for $\lambda_3/\lambda_4$ provides the highest linearity. The sensitivity of the proposed sensor is comparable to that proposed by Tapetado et al. [20].

Hysteresis of the sensor was evaluated by calculating the hysteresis value ($H$) defined by [21]

$$H = \max\{I(i) - D(i)\} / I(i)$$

(4)

where $I(i)$ and $D(i)$ is the increased and decreased measurement at temperature $i$, respectively. It was found that hysteresis for $\lambda_1/\lambda_3$, $\lambda_2/\lambda_3$ and $\lambda_3/\lambda_4$ are $1.97 \times 10^{-2}$, $2.20 \times 10^{-2}$ and $1.95 \times 10^{-2}$, respectively. Hysteresis behaviour of the three transmittance ratios are shown in Figure 6. The main factor that contribute to the high hysteresis is the fluctuation of the oven temperature. More accurate temperature control is required to measure more accurate sensor hysteresis.

![Figure 6. Hysteresis for transmittance ratio of $\lambda_1/\lambda_3$ (a), $\lambda_2/\lambda_3$ (b) and $\lambda_3/\lambda_4$ (c).](image)
4. Conclusion
SI-POF MZI sensor has been fabricated and the intensity modulation-based measurement has been demonstrated using dual-wavelength compensation. The sensor’s response to temperature change in terms of sensitivity and hysteresis have been characterized. The results showed that the sensor has comparable sensitivity to other intensity-based sensor which is $1 \times 10^{-3}/\circ$C. Relative high hysteresis behavior occurred mainly due to temperature fluctuation in temperature chamber. On the other hand, the sensor is robust, low cost and simple in fabrication process.

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