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Temperature sensitivity investigation of tapered plastic optical fiber-Mach Zehnder interferometer for sensor application

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Temperature sensitivity investigation of tapered plastic optical fiber-Mach Zehnder interferometer for sensor application

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Abstract. Mach Zehnder interferometer (MZI) based on plastic optical fiber (POF) is interesting due to its robustness and simple fabrication. In this work, MZI-POF was designed and its sensitivity to temperature change was characterized to investigate its performance for sensor application. The MZI-POF was fabricated by forming two tapers at several distance by simple heat-pull method. The spectra was investigated by launching white light emitting diode (LED) and the output were observed using VIS-NIR spectrometer. It is shown that the wavelength of spectrum peak and spectrum dip were shifted compared to that of un-tapered POF which indicates that the structure serves well as MZI. Sensor sensitivity to temperature was determined by measuring the spectrum for various temperature which was varied from 40^{o}C to 80^{o}C with increment of 5^{o}C. The result showed that the sensor sensitivity is 0.0693nm/^{o}C in terms of peak measurement and 0.0487nm/^{o}C for dip measurement. Therefore, MZI-POF is a potential candidate for temperature sensor.

1. Introduction

In addition to the main usage of optical fiber for telecommunication, optical fiber sensor has received great attention due to its advantages such as immune to electromagnetic interference, wide bandwidth, compactness, geometric versatility, feasibility of miniaturization, and possibility of remote sensing and real time measurement. Optical fiber sensors have been proposed for various applications such as temperature sensor, strain sensors, biosensors and chemical sensors. Since optical fiber sensor technology emerges from optical telecommunications technology, in its early development, most of optical sensor use silica optical fiber. Following the progress of optical fiber technology, optical sensor using other types of optical fiber such as photonic crystal fiber (PCF) [1], plastic clad silica fiber (PCS) [2] and plastic optical fiber (POF) [3] have then been proposed.

Despite its high-power loss, POF-based optical sensor is interesting since it more robust compared to silica fiber due to its high diameter. Various POF-based optical sensors have been proposed using various technique such as intensity based sensor [4], U-bent shaped optical fiber [5], [6], surface plasmon resonance (SPR) [7] and Mach Zhender interferometer (MZI) [8]. In terms of modulation technique, MZI optical sensor is interesting since the working principles relies on wavelength modulation. Therefore, it provides high accuracy since the output does not affected by power fluctuation and power loss due to bending and fiber connection. POF-MZI sensor can be realized by using double taper POF. The first taper serves as power divider which divide the guided light in to core and cladding, while the second taper serves as combiner. MZI using graded index POF

(GI-POF) has been proposed for refractive index and strain measurement [8]. Due to its high thermo-optic coefficient (TOC) which is -1.2×10^{-4} [9], light propagation in POF will also be affected by temperature. Therefore, in designing POF-based MZI, it is important to consider temperature cross sensitivity to determine measurement error due to temperature effect. On the other hand, this thermal property can also be exploited for temperature sensor application. In this work, temperature sensitivity of MZI POF was investigated. Instead of using GI-POF, step index POF (SI-POF) was used to construct the MZI. The advantages of SI-POF is that it has higher dimension and simple in detection equipment which only requires light emitting diode (LED) as light source and spectrometer as detector.

2. Methods

2.1. Mach Zehnder Interferometer Principle

The basis of MZI working principle is the light splitting in to two different route such that the lights travel with different phase. The lights are then recombined which results in interference phenomenon. Various MZIs based optical fiber have been proposed using silica optical fiber with various technique such as splicing single mode optical fiber (SMF) with photonic crystal fiber (PCF) [10], waist-enlarged bi tapers [11] and core-offset SMF [12]. In this work, MZI was developed by using two tapers separated at several distance [8] as shown in Figure 1.

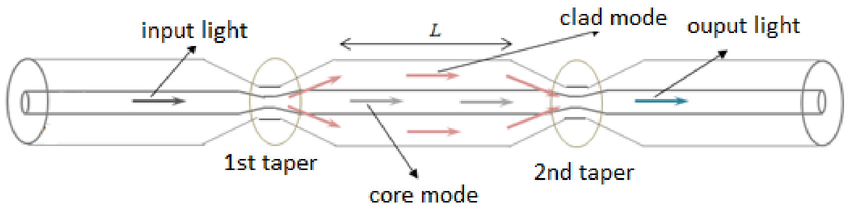


Figure 1. Schematic diagram of MZI POF

At the first taper, cladding modes are excited from the core mode and then propagates across the interferometer region. The light travels at core and cladding are then recombined and interference at the second taper with transmission intensity [8] defined by equation (1)

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

where $\Delta\phi$ is the phase difference between core mode and cladding modes, I_1 and I_2 are the intensity of light propagates at core and cladding, respectively. The phase difference is defined by equation (2)

$$\Delta\emptyset = \frac{2\pi}{\lambda}\int(n_{clad} - n_{core})\,dz \quad (2)$$

where λ is the wavelength of the light propagates along MZI, and n_{core} and n_{clad} is the effective refractive index of core mode and cladding modes, respectively. For SI-POF, refractive index along core and cladding remain constant, thus equation (2) can be written as equation (3)

$$\Delta\emptyset = \frac{2\pi}{\lambda}\Delta N_{eff}L \quad (3)$$

where $\Delta N_{eff}=n_{clad}-n_{core}$ and L is the optical route length of the interferometer. Maximum transmission intensity occurs if the phase difference satisfies $\Delta\emptyset = (2k+1)\pi$, where k is an integer. Therefore, peak wavelength (λ_p) of transmission spectra occurs at equation (4)

$$\lambda_p = \frac{2\Delta N_{eff}L}{(2k+1)}. \quad (4)$$

Meanwhile, both n_{core} and n_{clad} depend on temperature related by TOC of the fiber [13]. Moreover, due to coefficient of thermal expansion (CTE), the interferometer length also change with temperature. For PMMA, the CTE is 0.68×10^{-4} /°C [9]. Thus, any change of temperature of fiber and its surrounding will affect the peak wavelength of the MZI transmission spectra defined by equation (5)

$$\frac{d\lambda_p}{dT} = \frac{2}{(2k+1)}\left(\Delta N_{eff}\frac{dL}{dT} + L\frac{d\Delta N_{eff}}{dT}\right). \quad (5)$$

2.2. Fabrication and Characterization

The MZI was fabricated by forming two tapers with different diameters at POF. The POF used step index type with core diameter of 980µm with core refractive index and cladding refractive index of 1.49 and 1.41, respectively. The first step in forming the tapers was removing the POF jacket using POF stripper at which the tapers to be located, resulting unjacketed POF for 10cm. Next, the unjacketed part of the POF was cleaned using alcohol. The two ends of the POF were polished using fiber polishing kit to obtain smooth fiber tips and then SMA 905 connector was coupled to one of the tips. The tapers were formed by heating the unjacketed part using solder at temperature of 80°C at two different points and then full it [8]. To measure the waist diameter and to observe the tapers shape, the tapers were viewed using CCD-optical microscope.

The spectrum of the fabricated MZI were observed by connecting the tip with SMA 905 connector to VIS-NIR spectrometer (Ocean Optics USB4000), while the other tip was connected to white LED. To obtain temperature sensitivity, the MZI was put inside temperature controlled-oven during spectrum measurement as shown in Figure 2. The temperature of the oven was varied from 40°C to 80°C with increment of 5°C and was kept at each values for 1 minute before being further increased. The spectrum was recorded every 1 second.

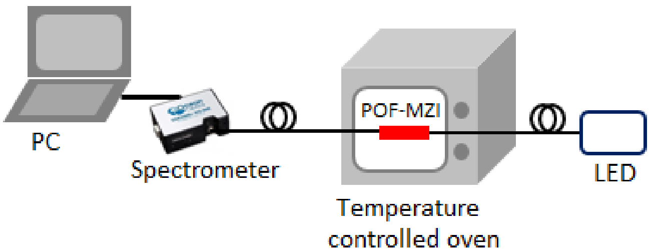


Figure 2. Characterization set up of the POF-MZI

3. Results and Discussions

MZI-POF has been fabricated with specification as shown in Table 1. It is shown from optical microscope images that smooth tapers were obtained as depicted in Figure 3.

Table 1. Specifications of the fabricated POF-MZI

Parameters	Values
Waist diameter of taper 1 (µm)	629.007
Waist diameter of taper 2 (µm)	562.439
Distance between tapers (mm)	20

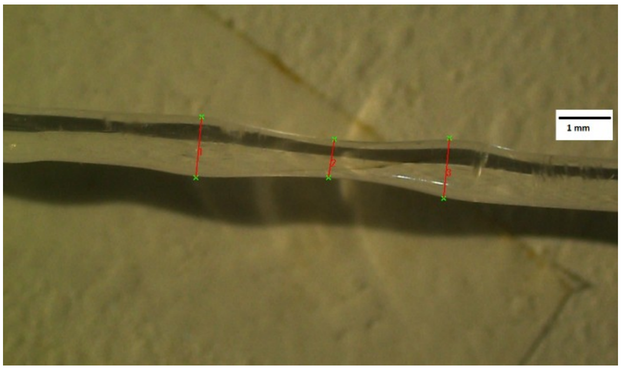


Figure 3. Second taper of the fabricated POF-MZI.

Normalized transmission spectra of POF-MZI sensor is shown in Figure 4. It is shown that the transmission of the guided light varied as function of light wavelength. It can be observed that there are three main peaks which are occurred at wavelength of 451.7nm, 459.66nm and 587.47nm, respectively. From the spectrum, it is also clearly seen that there are three main dips located at wavelength of 451.91nm, 477.10nm and 582.48nm, respectively. The main power loss occurred due to connection between POF and LED since the sensor tip was directly attached to LED without using connector.

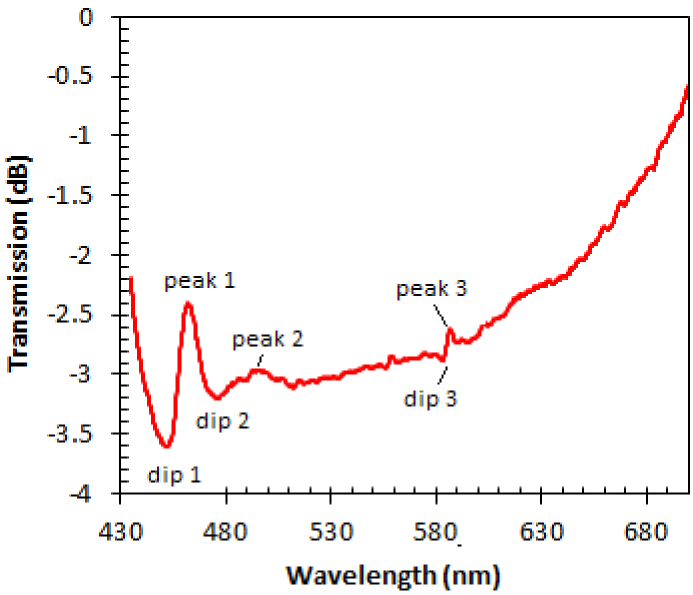


Figure 4. Transmission spectra of the fabricated POF-MZI.

Spectra of the MZI at temperature of 40°C, 60°C and 80°C at wavelength ranging from 430nm to 700nm are shown in Figure 5(a). It is shown that as temperature increased, all peaks and dips are red-shifted. Peak 3 and dip 3 were chosen to be more observed since they have sharp spectrums. Thus, determination of peak and dip wavelength would be more accurate compare to that of other peaks and dips. A zoom view of peak 3 and dip 3 spectrums is shown in Figure 5(b). The red-shift was occurred since, even though the refractive index of both core and cladding were decreased due to the negative TOC, the effect of thermal expansion is more dominant than the thermo-optic effect which results in positive wavelength change as defined by Equation (5).

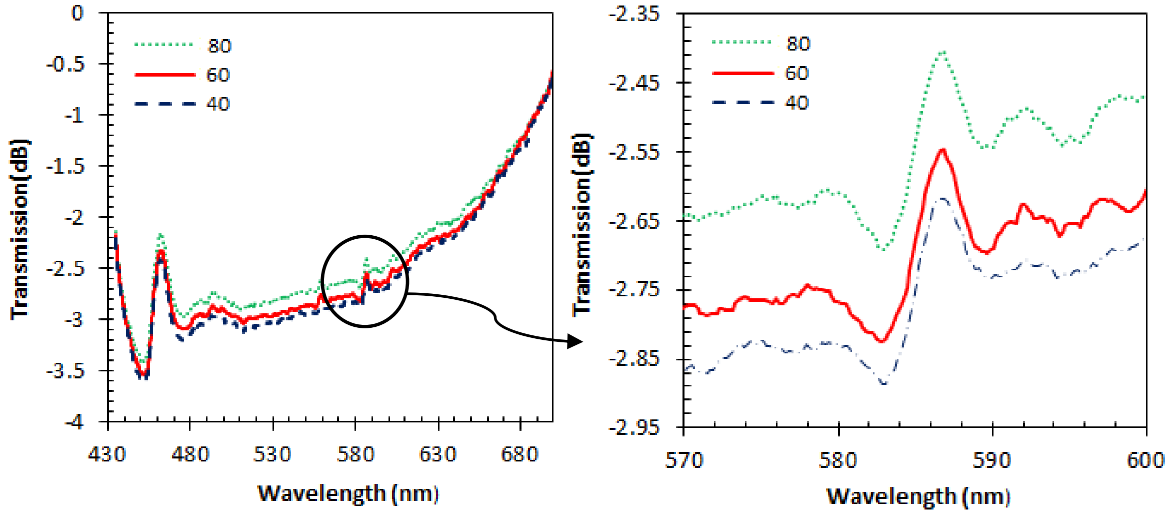
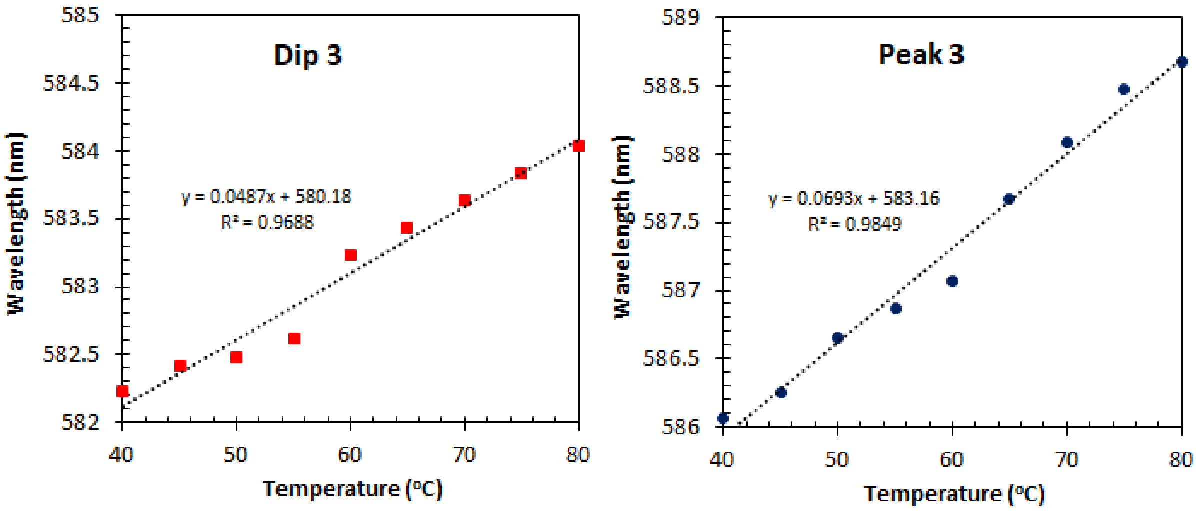


Figure 5. Transmission spectra of POF-MZI at temperature of 40°C, 60°C and 80°C (a) and zoom view of dip 3 and peak 3 (b).

The wavelength of dip 3 and peak 3 were plotted as function of temperature as shown in Figure 6(a) and 6(b), respectively. It is shown that dip wavelength was shifted with temperature dependence of 0.0487 nm/°C with correlation coefficient of 0.9688. Meanwhile, for peak wavelength, the sensitivity and also the linear dependence are higher than that of dip wavelength which are 0.0693 nm/°C and 0.9849, respectively. Compared to the sensitivities of other wavelength based-temperature sensors, such as no-core fiber sensor [14] and fiber Bragg grating sensor (FBG) [15], the proposed MZI provides higher sensitivity. The sensitivities also are in the same order with other in-line MZI sensor [16]. Therefore, the proposed MZI is a potential candidate for temperature sensor. However, due to its low melting temperature (160°C) [9], the sensor is not suitable to be used at high temperature.



(a) (b)

Figure 6. Temperature sensitivity of POF-MZI sensor for dip 3(a) and peak 3(b).

4. Conclusions
SI-POF based MZI has been fabricated using heat-pull method. Transmission spectra of the fabricated MZI were red-shifted as the surrounding temperature was increased which contributed to temperature sensitivity of 0.0693 nm/^{o}C with high linearity. The value is higher than that of other wavelength-based optical sensor. However, the sensor has limited working range due to its material thermal property. Thus, the sensor is suitable for low temperature application. In addition, it also can be concluded that temperature effect should be considered in measurement if the proposed MZI will be used for other sensor application such as humidity, refractive index and strain measurement.

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