Characterization of Temperature Response of Asymmetric Tapered-Plastic

by Ian Yulianti

Research Article

Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer

Ian Yulianti[1,*], N.M. Dharma Putra[1], Fianti[1], A.S. M. Supa'at[2], H. Rumiana[1], S. Maimanah[1], K.E. Kurniansyah[1]

[1]Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang
Gd. D7 lt.2, Sekaran, Gunungpati, Semarang, Central Java, Indonesia
[2]School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Johor Bahru, Malaysia

e-mail: ianyulianti@mail.unnes.ac.id

Abstract

Performance characterization of simple and low cost Mach Zehnder interferometer (MZI) using step index plastic optical fiber (SI-POF) to temperature variation is presented. The sensor consists of two tapers at several distance forming interferometer. The first taper was designed to be steep to allow excitation of cladding modes, while the second taper was gradual to supress power loss. Characterizations were done in terms of sensitivity, hysteresis and repeatability by analysing the output spectrums recorded by spectrometer at various environment temperature which are 35ºC to 85ºC with increment of 10ºC. The results showed that the sensor has sensitivity of 0.0431 nm/ºC and correlation coefficient of 0.9965. Hysteresis of 6.9×10^{-3} was observed. In terms of repeatability, the sensor shows maximum deviation of ±3ºC which was mainly resulted from fluctuation of oven temperature. Despite its high deviation, the sensor has advantages of simple fabrication process, low cost, robust and low power loss which make it as a good candidate for temperature sensor.

Keywords: *Mach-Zehnder interferometer; SI-POF; Temperatur measurement.*

Karakterisasi Respon Suhu Fiber Optik Plastik Taper Asimetri berbasis Mach-Zehnder Interferometer

Abstrak

Karakterisasi kinerja Mach-Zehnder Interferometer (MZI) menggunakan step index serat optik plastik (SI-POF) dengan fabrikasi sederhana dan biaya rendah untuk variasi suhu telah dilakukan. Sensor terdiri dari dua bagian lancip (taper) yang terpisah dan membentuk interferometer. Taper pertama dibuat agak curam untuk memungkinkan terjadinya eksitasi pada mode cladding, sedangkan kemiringan taper kedua dibuat lebih landai untuk menekan kehilangan daya. Karakterisasi dilakukan untuk memperoleh sensitivitas, histeresis, dan pengulangan dengan menganalisis spektrum keluaran yang direkam oleh spektrometer pada berbagai suhu lingkungan yaitu 35ºC hingga 85ºC dengan kenaikan 10ºC. Hasil penelitian menunjukkan bahwa sensor memiliki sensitivitas 0,0431 nm/ºC dengan koefisien korelasi 0,9965 dan histeresis sebesar $6,9 \times 10^{-3}$. Dalam hal pengulangan, sensor menunjukkan deviasi

maksimum ±3ºC yang dihasilkan dari fluktuasi suhu oven. Meskipun memiliki deviasi tinggi, sensor ini memiliki kelebihan yaitu proses fabrikasi sederhana, biaya rendah, kuat, dan rugi daya yang rendah menjadikannya sebagai kandidat yang baik untuk sensor suhu.

Kata Kunci: Mach-Zehnder interferometer; SI-POF; pengukuran suhu.

PACS: not more than 5 PACS codes, separated by semicolon (;)

I. INTRODUCTION

The importance of temperature measurement in various applications such as environmental monitoring, chemical industry and automotive industry has triggered the development of temperature sensors with various technology. 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 due to its advantages such as free from electromagnetic interference, suitable for hazardous environment and can be arranged in multiplexed array. 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. The wavelength based modulation technique is interesting since the measurement does not affected by power loss due to bending, fiber connection and light source fluctuation. However, complex fabrication process and high cost of PCF limits the sensors advantages.

Other wavelength based sensor is Mach Zhender interferometer (MZI) based optical sensor. MZI based sensors provide advantages such as high sensitivity, applicable for remote sensing and does not require other optical devices such as coupler or splitter [5]. MZI configuration has been demonstrated to measure physical and chemical parameters such as humidity [6,7], torsion [8], ammonia [8], refractive index [9,10] and strain [11]. For temperature measurement, MZI sensor has been realized by using various techniques such as SMF spliced with NCF and waist enlarged taper [5] and microstructured optical fiber (MOF) between two SMFs [12]. The sensors provide high sensitivity which is in the order of 10^{-1} nm/ºC. MZI using PCF for temperature measurement was reported which has sensitivity of 30.98 pm/°C at

wavelength range of 30–80°C [13]. The MZI consist of PCF spliced between two spherical SMF. Gong et al. [14] proposed MZI coated with polydimethylsiloxane (PDMS). The MZI structure was realized by forming mismatch three SMF segments through core-offset fusion splicing method. The PDMS coating was fabricated by using mold.   The sensor showed sensitivity of 0.101 nm/°C. To improve the sensitivity, Tong et al. [15] proposed the same MZI structure as proposed by Gong et al. [14], and cascaded it with FBG. The sensitivity was 10.389 nm/°C for temperature range of 10°C to 59.4°C. Although the above mentioned devices provide high sensitivity, the sensors structure are fragile due to the nature of silica fiber which limits their lifetime and durability.   Other disadvantage of the previous-mentioned sensors is that the fabrication process was complicated. Therefore, it is important to design MZI temperature sensor with high robustness with simple fabrication technique.

Robust optical sensor can be realized by using plastic optical fiber (POF) since it has high mechanical strength [16]. POF has been used for various sensor applications such as liquid level sensor [17], ammonia [18], biosensor [19], nitrite detection [20] and refractive index [21].   POF based MZI (POF-MZI) has been demonstrated for refractive index and strain measurement [22]. 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 coefficient of thermal expansion (CTE) of POF material [5][23], POF MZI can be adopted for temperature measurement.   Therefore, in this paper, characterization of inline MZI on POF for temperature measurement is presented.   The purpose of the study is to obtain temperature response of POF MZI which were sensor sensitivity, repeatability and hysteresis to temperature change.   Knowledge of temperature response of POF MZI is also important in optimizing MZI design for other applications such as refractive index and strain to avoid measurement error due to temperature variation.   Instead of using GI-POF, the proposed sensor used step index POF (SI-POF) since SI-POF provides higher dimension (about 1000μm).   Hence it sturdier than GI-POF.   Besides, SI-POF MZI has advantage of low cost interrogation systems since it uses low cost white LED as light source and VIS-NIR spectrometer as detector.   It also does not require coupling to SMF since the SI-POF can be connected directly to LED and spectrometer using SMA 905 connector.   Therefore, power loss can be reduced.   In addition, the proposed MZI has asymmetric tapers. The first taper was designed to be steep to allow excitation of cladding modes, while the second taper was gradual to provide adiabatic mode evolution so that it will reduce power loss.   From the author's best knowledge, characterization of SI-POF based MZI for temperature measurement has not been reported.

II. METHOD

The research methodology was carried out include sensor design, fabrication and sensor characterization at various temperatures. Through the characterization, sensitivity, hysteresis, and sensor repetition are obtained.

Design and Sensor Operation Principle

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 [23]. In this work, MZI was developed by using two tapers with different waist diameters (asymmetric taper) separated at several distance as shown in Figure 1.
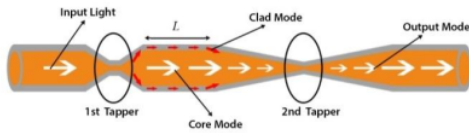
Figure 1. Schematic diagram of SI-POF MZI

Core modes that initially confined in fiber core excite cladding modes due to tapered structure at the first taper. The excited cladding modes then propagates across the interferometer region, L. At the second taper, light travels at core and cladding are then recombined and interference as output light. The transmission intensity of output light defined by [22]

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

where $\Delta\phi$ is the phase difference between core modes and cladding modes which is defined by

$$\Delta\phi = \frac{2\pi}{\lambda}\int (n_{clad} - n_{core})dz \qquad (2)$$

I_1 and I_2 are the intensity of light propagates at core and cladding, respectively. λ is the wavelength of the light propagates along MZI, and n_{core} and n_{clad} is the effective refractive index of core modes and cladding modes, respectively. For SI-POF, refractive index along core and cladding remain constant, thus equation (2) can be written as

$$\Delta\phi = \left(\frac{2\pi}{\lambda}\right)\Delta N_{eff} L \qquad (3)$$

where $\Delta N_{eff} = n_{clad} - n_{core}$ and L is the optical route length of the interferometer. If the phase

difference satisfies $\Delta\phi = (2k+1)\pi$, where k is an integer, maximum transmission intensity occurs. Therefore, peak wavelength (λ_p) of transmission spectra occurs at

$$\lambda_p = 2\Delta N_{eff} L/(2k+1) \qquad (4)$$

Due to the thermal properties of POF material, which is Poly(methyl methacrylate) (PMMA), n_{core}, n_{clad} and L depend on temperature related by TOC and CTE of the fiber, respectively. For PMMA, the TOC and CTE are -1.2×10^{-4} and 0.68×10^{-4} /^{o}C, respectively [23]. Thus, any change of temperature of fiber and its surrounding will change the peak wavelength of the MZI transmission spectrums defined by

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

Fabrication and Characterization

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. Tapers were formed by heating the POF using solder at temperature of 80°C at two different points and then full it [22]. Prior to heating, the polyethylene jacket with diameter of 2.2 mm was removed at where the tapers to be located using fiber stripper and cleaned using alcohol. The tips of the POF were polished using fiber polishing kit to obtain smooth fiber tips and then SMA 905 connector (Industrial Fiber Optics, Inc) was coupled to one of the tips. While heated, the output spectrums were observed by connecting the tip with SMA 905 connector to VIS-NIR spectrometer (USB4000, Ocean Optics) and the other tip was connected to white LED. To measure the waist diameters and to observe the tapers shapes, the tapers were viewed using CCD-optical microscope.

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 connected to spectrometer and LED as shown in Figure 2. The temperature of the oven was increased from 35ºC to 85ºC with increment of 10ºC and was kept at each values for 1 minute before being further increased. The spectrum was recorded every 1 second. 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 times measurement.
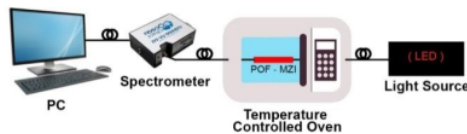


Figure 2. Characterization set up of the SI-POF MZI

III. RESULTS AND DISCUSSION

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. The normalized transmission spectrums of the sensor at room temperature is shown in Figure 4. As can be seen from the figure, there are three main peaks occurred over the spectral range of 450-650 nm. It also can be observed that the sensor provide low loss over the spectral range with maximum loss of < -7.5 dB at wavelength of 450 nm. As expected, the power loss is much lower than that of GI-POF [22]. Compared to SMF-based MZI sensor such as [14] and [15], the loss is lower up to 80%. The main power loss occurred due to connection between POF and

LED since the sensor tip was directly attached to LED without using connector. Low power loss is essential especially in multiplexed optical sensors to improve signal to noise ratio (SNR).
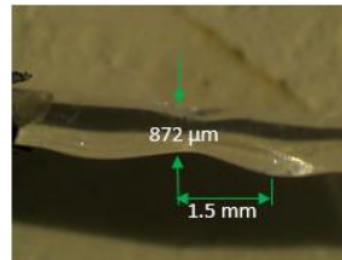
(a)
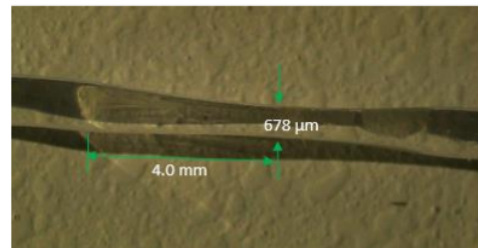
(b)

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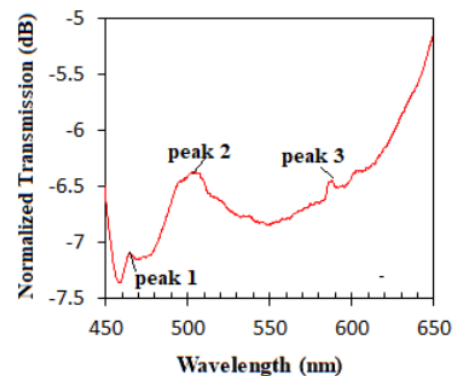

Figure 4. Transmission spectrums at room temperature of the fabricated POF-MZI

As the sensor subjected to temperature change, the peaks locations were red shifted. The results agree with other MZI-based temperature sensors [14], [15], [24]. Peak

analysis showed that peak 3 provides highest sensitivity and lowest data hysteresis. The sensor spectrum at various temperature values at wavelength ranging from 570 nm to 610 nm in which peak 3 is located are shown in Figure 5. The red-shift was occurred since, even though the refractive index of both core and cladding were decreased due to the negative TOC, the first term of Equation (5) is higher than the second term which results in positive wavelength change. It also can be observed from Figure 5 that power loss is decreased as temperature increased which is the effect of the decrease of POF Young's modulus which leads to reduction of stress on fiber and further results in reduction of power loss [16]. The decreased also due to the negative TOC of the POF and since the absolute TOC of core is smaller than that of cladding, then it results in the increase of the numerical aperture [25][26][27].
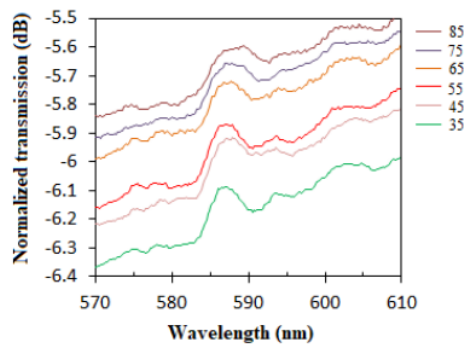

Figure 5. Transmission spectrums of POF-MZI at various temperature values

To obtain calibration curve of the sensor, the peak wavelengths corresponding to each temperature value obtained from three cycles measurement were averaged and then plotted against temperature. The averaged wavelength of peak 3 as function of temperature is shown in Figure 6. It is shown that the sensor provides sensitivity of 0.0431 nm/°C with correlation coefficient of 0.9965.

The linear regression equation is defined by

$$\lambda(nm) = 0.0431\,T + 585.65 \qquad (6)$$

Compared to SMF based-MZI temperature sensor [5][12], the sensor has one order lower sensitivity. However, compared to other wavelength based-temperature sensors, such as no-core fiber sensor [2], fiber Bragg grating sensor (FBG) [1], the proposed MZI provides higher sensitivity. Sensitivity can be further improved by applying coating material with high CTE and TOC to induce more thermal expansion and thermo-optic effect such as polydimethylsiloxane (PDMS) [28] and Molybdenum disulfide (MoS2) [29].
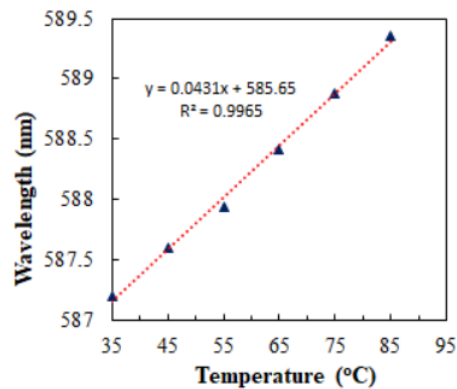

Figure 6. Calibration curve of POF-MZI sensor of peak 3

The wavelength shifts obtained from the increased and decreased temperature of the first cycle are plotted against temperature as shown in Figure 7. It is clearly seen that the sensor shows hysteresis behaviour as the peak wavelengths did not return to the same values when reversed measurements were conducted. Hysteresis of the sensor was evaluated by calculating the hysteresis value (H) of the first cycle which is defined by [11]

$$H = \frac{\max(I(i) - D(i))}{I(i)} \qquad (7)$$

where $I(i)$ and $D(i)$ is the increased and decreased measurement at temperature i, respectively. It was found that the sensor has hysteresis of 6.9×10^{-3}. The hysteresis

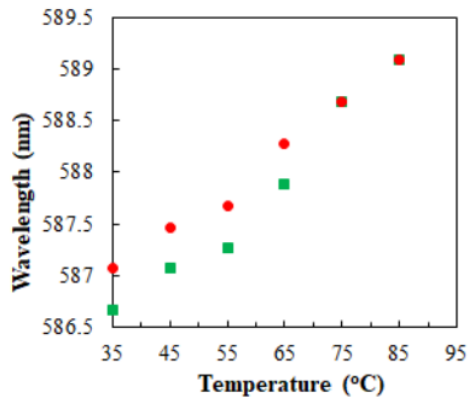occurred due to the fluctuation of the oven which was ±2ºC.

Figure 7. Hysteresis of the fabricated SI-POF MZI

The sensor repeatability was determined by evaluating the maximum difference between different measurements from the average of all measurement when the same experiment process is repeated under the same condition [30]. The peak wavelengths obtained from the measurements were first converted into temperature by using Equation (6). Maximum deviations of each temperature values are plotted against the actual temperatures measured by thermocouple as shown in Figure 8. The standard deviation of the data in the graph is 1.89ºC, meanwhile the maximum deviation is ±3ºC. The high deviation is mainly due to the fluctuation of the actual temperature during measurement which makes the measurement could not be repeated at the same temperature. By considering temperature fluctuation of the oven and deducing to the maximum deviation, then the sensor repeatability is ±1ºC. The

IV. CONCLUSION

SI-POF based MZI has been fabricated and the responses to temperature change in terms of sensitivity, hysteresis and repeatability have been characterized. The results showed that the sensor has comparable

result is comparable with other POF based temperature sensor which the measurement error is 1.48 ºC [16]. The wavelength resolution of spectrometer which is 0.1nm also limits the peak wavelength determination accuracy. More stable temperature chamber is required to investigate more accurate sensor repeatability.
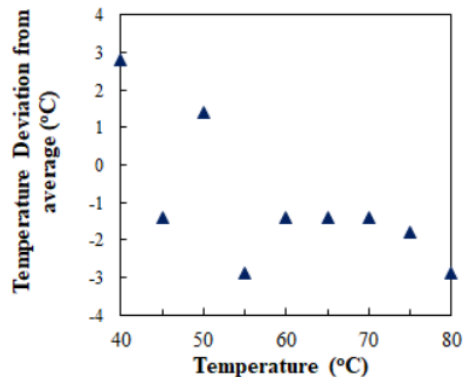

Figure 8. Repeatability of the SI-POF MZI

The obtained results confirm that MZI structure could be realized by forming two tapers at several distance in SI-POF. It also shows that the interference of light travelled in the cladding and core is affected by the surrounding temperature. Therefore, the structure could potentially apply for temperature sensor. On the contrary, if the structure is used for other sensor application such as refractive index and strain, its temperature dependence will affect the measurement accuracy. Therefore, it quires temperature compensation to reduce the temperature effect.

sensitivity to other wavelength-based sensor with good linearity. Despite its high deviation, the sensor has advantages of robust, simple fabrication process, low cost and low power loss. The sensitivity can be further improved by applying coating material with high CTE and TOC. It also can be concluded

that temperature variation might contribute to measurement error if the design is used for other application such as refractive index and strain. Therefore, temperature compensation technique should be optimized in designing SI-POF MZI for other application.

ACKNOWLEDGMENT

REFERENCES

[1]   Hsiao TC, et al. Metal-Coated Fiber Bragg Grating for Dynamic Temperature Sensor. *Optik*. 2016; **127**(22): 10740–10745. DOI:10.1016/j.ijleo.2016.08.110.

[2]   Ma L, Kang Z, Qi Y and Jian S. Fiber-Optic Temperature Sensor Based on a Thinner No-Core Fiber. *Optik*. 2015; **126**(9–10):1044–1046. DOI:10.1016/j.ijleo.2015.02.084.

[3]   Villalba A and Martín JC. Interferometric Temperature Sensor Based on a Water-Filled Suspended-Core Fiber. *Optical Fiber Technology*. 2017; **33**: 36–38. DOI:10.1016/j.yofte.2016.11.006.

[4]   Abbasi M, Soroosh M and Namjoo E. Polarization-Insensitive Temperature Sensor Based on Liquid Filled Photonic Crystal Fiber. *Optik*. 2018; **168**: 342–347. DOI:10.1016/J.IJLEO.2018.04.116.

[5]   Hsu JM, et al. Temperature Fiber Sensors Based on Mach-Zehnder Interferometer With Sturdy Structure. *IEEE Sensors Journal*. 2015; **15**(12): 6995–7000. DOI:10.1109/JSEN.2015.2469670.

[6]   Ma Q, Ni K and Huang R. A Carboxy-Methyl Cellulose Coated Humidity Sensor Based on Mach-Zehnder Interferometer with Waist-Enlarged Bi-Tapers. *Optical Fiber Technology*. 2017;**33**:60–63. DOI:10.1016/j.yofte.2016.11.002.

[7]   Ni K, et al. A Chitosan-Coated Humidity Sensor Based on Mach-Zehnder Interferometer with Waist-Enlarged Fusion Bitapers. *Optical Fiber Technology*. 2017; **33**: 56–59. DOI:10.1016/j.yofte.2016.11.005.

[8]   Huerta-Mascotte E, et al. A Core-Offset Mach Zehnder Interferometer Based on a Non-Zero Dispersion-Shifted Fiber and Its Torsion Sensing Application. *Sensors (Switzerland)*. 2016; **16**(6). DOI:10.3390/s16060856.

[9]   Wang Q, et al. High Sensitivity Refractive Index Sensor Based on Splicing Points Tapered SMF-PCF-SMF Structure Mach-Zehnder Mode Interferometer. *Sensors and Actuators, B: Chemical*. 2016; **225**:213–220. DOI:10.1016/j.snb.2015.11.047.

[10]   Melo L, Burton G, Kubik P and Wild P. Refractive Index Sensor Based on Inline Mach-Zehnder Interferometer Coated with Hafnium Oxide by Atomic Layer Deposition. *Sensors and Actuators, B: Chemical*. 2016; **236**: 537–545. DOI:10.1016/j.snb.2016.06.030.

[11]   Avila-Garcia MS, et al. High Sensitivity Strain Sensors Based on Single-Mode-Fiber Core-Offset Mach-Zehnder Interferometers. *Optics and Lasers in Engineering*. 2018; **107**: 202–206. DOI: 10.1016/J.OPTLASENG.2018.02.008.

[12]   Deng M, et al. Highly Sensitive Temperature Sensor Based on an Ultra-Compact Mach–Zehnder Interferometer with Side-Opened Channels. *Optics Letters*. 2017; **42**(18): 3549. DOI:10.1364/OL.42.003549.

[13]   Zhao L, et al. Photonic Crystal All-Fiber Mach-Zehnder Interferometer Sensor Based on Phase Demodulation. *Optical Fiber Technology*. 2019; **53**: 102059. DOI: https://doi.org/10.1016/j.yofte.2019.10205

9.

[14] Gong J, et al. High Sensitivity Fiber Temperature Sensor Based PDMS Film on Mach-Zehnder Interferometer. *Optical Fiber Technology*. 2019; **53**: 102029. DOI: https://doi.org/10.1016/j.yofte.2019.102029.

[15] Tong R, Zhao Y, Hu H and Qu J. Large Measurement Range and High Sensitivity Temperature Sensor with FBG Cascaded Mach-Zehnder Interferometer. *Optics & Laser Technology*. 2020; **125**: 106034. DOI: https://doi.org/10.1016/j.optlastec.2019.106034.

[16] Leal-Junior A, Frizera-Netoc A, Marques C and Pontes M. A Polymer Optical Fiber Temperature Sensor Based on Material Features. *Sensors*. 2018; **18**(1): 301. DOI:10.3390/s18010301.

[17] Jing N, et al. A Liquid Level Sensor Based on a Race-Track Helical Plastic Optical Fiber. *IEEE Photonics Technology Letters*. 2017; **29**(1): 158–160. DOI:10.1109/LPT.2016.2630730.

[18] Rithesh Raj D, Prasanth S, Vineeshkumar T V and Sudarsanakumar C. Ammonia Sensing Properties of Tapered Plastic Optical Fiber Coated with Silver Nanoparticles/PVP/PVA Hybrid. *Optics Communications*. 2015; **340**: 86–92. DOI: https://doi.org/10.1016/j.optcom.2014.11.092.

[19] Cennamo N, et al. An Innovative Plastic Optical Fiber-Based Biosensor for New Bio/Applications. The Case of Celiac Disease. *Sensors and Actuators B: Chemical*. 2013; **176**: 1008–1014. DOI: https://doi.org/10.1016/j.snb.2012.10.055.

[20] Elias SN, Arsad N and Abubakar S. Nitrite Detection Using Plastic Optical Fiber (POF); an Early Stage Investigation towards the Development of Oral Cancer Sensor Using POF. *Optik*. 2015; **126**(21): 2908–2911.DOI:

https://doi.org/10.1016/j.ijleo.2015.07.038

[21] Gowri A and Sai VVR. Development of LSPR Based U-Bent Plastic Optical Fiber Sensors. *Sensors and Actuators B: Chemical*. 2016; **230**: 536–543. DOI:10.1016/J.SNB.2016.02.074.

[22] Jasim AA, et al. Refractive Index and Strain Sensing Using Inline Mach-Zehnder Interferometer Comprising Perfluorinated Graded-Index Plastic Optical Fiber. *Sensors and Actuators, A: Physical*. 2014; **219**: 94–99. DOI:10.1016/j.sna.2014.07.018.

[23] Luo Y, et al. Fabrication of Polymer Optical Fibre (POF) Gratings. *Sensors (Switzerland)*. 2017; **17**(3). DOI:10.3390/s17030511.

[24] Li C, et al. Liquid Level and Temperature Sensor Based on an Asymmetrical Fiber Mach–Zehnder Interferometer Combined with a Fiber Bragg Grating. *Optics Communications*. 2016; **372**: 196–200. DOI:https://doi.org/10.1016/j.optcom.2016.04.025.

[25] Jing N, et al. Optical Fiber Technology Temperature Dependence of Light Power Propagation in Bending Plastic Optical Fiber. *Optical Fiber Technology*. 2016; **31**: 20–22. DOI:10.1016/j.yofte.2016.05.006.

[26] Moraleda AT, García CV, Zaballa JZ and Arrue J. A Temperature Sensor Based on a Polymer Optical Fiber Macro-Bend. *Sensors (Basel, Switzerland)*. 2013; **13**(10): 13076–13089. DOI:10.3390/s131013076.

[27] Tapetado A, Pinzón PJ, Zubia J and Vázquez C. Polymer Optical Fiber Temperature Sensor With Dual-Wavelength Compensation of Power Fluctuations. *Journal of Lightwave Technology*. 2015; **33**(13): 2716–2723. DOI:10.1109/JLT.2015.2408368.

[28] Li J, Gai L, Li H and Hu H. A High Sensitivity Temperature Sensor Based on Packaged Microfibre Knot Resonator. *Sensors and Actuators, A: Physical*. 2017;

263:369–372.
DOI:10.1016/j.sna.2017.06.031.

[29] Mohanraj J, Velmurugan V, Sathiyan S and Sivabalan S. All Fiber-Optic Ultra-Sensitive Temperature Sensor Using Few-Layer MoS2 Coated D-Shaped Fiber. *Optics Communications*. 2018; **406**: 139–144.

DOI:10.1016/J.OPTCOM.2017.06.011.

[30] Wang Z. Intrinsic Fabry-Perot Interferometric Fiber Sensor Based on Ultra-Short Bragg Gratings for Quasi-Distributed Strain and Temperature Measurements, Virginia Polytechnic Institute and State University, 2006.

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Characterization of Temperature Response of Asymmetric Tapered-Plastic

FINAL GRADE

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GENERAL COMMENTS

Instructor