KORESPONDENSI PUBLIKASI ARTIKEL PADA JURNAL NASIONAL TERAKREDITASI KEMENRISTEKDIKTI PERINGKAT 2

Judul : Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer
Jurnal : Jurnal Penelitian fisika dan aplikasinya (JPFA)
Volume :10
No : 1
Tahun : 2020
Penulis : **Ian Yulianti,** Ngurah Made Darma Putra, Fianti, Abu Sahmah Mohd Supa'at , Helvi Rumiana, Siti Maimanah, and Kukuh Eka Kurniansyah

No	Tanggal	Aktivitas
1.	16 Januari 2020	Pembuatan akun di JPFA dan submit manuskrip
2.	26 Januari 2020	Pemberitahuan untuk melengkapi berkas
3.	29 Januari 2020	Pengiriman berkas: Statement of Manuscript Authenticity dan Statement of Open Access
4.	17 Februari 2020	Pemberitahuan berkas telah diterima
5.	20 Februari 2020	Hasil review pertama
6.	6 Maret 2020	Pengiriman manuskrip yang telah direvisi dan self evaluation form
7.	23 Mei 2020	Pemberitahuan hasil review kedua: revisi minor dan tidak perlu ditelaah kembali
8.	3 Juni 2020	Pengiriman manuskrip revisi kedua
9.	4 Juli 2020	Pemberitahuan hasil review ketiga: revisi minor dan tidak perlu ditelaah kembali
10.	9 Juli 2020	Pengiriman manuskrip revisi ketiga
11.	14 Juli 2020	Keputusan Editor: Artikel diterima untuk publikasi
12.	21 September	Artikel in press
13.	29 September 2020	Artikel telah terbit pada volume 10, No. 1 tahun 2020

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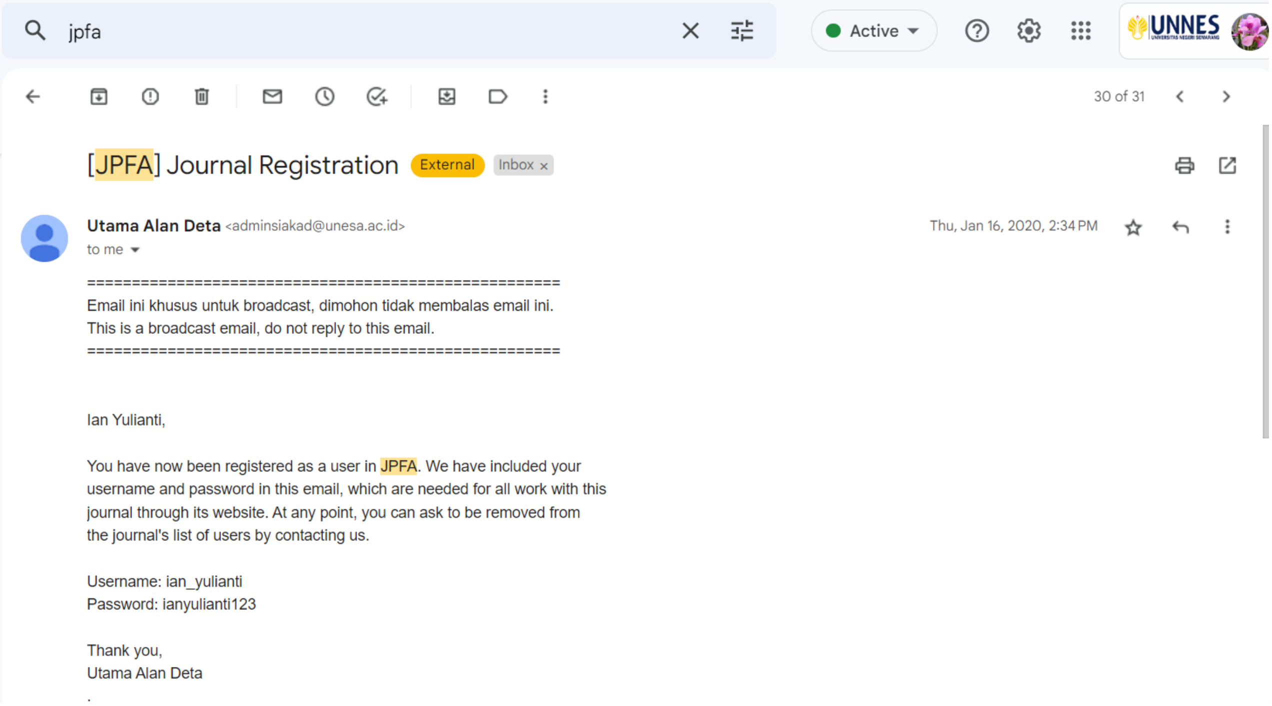

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Password: ianyulianti123

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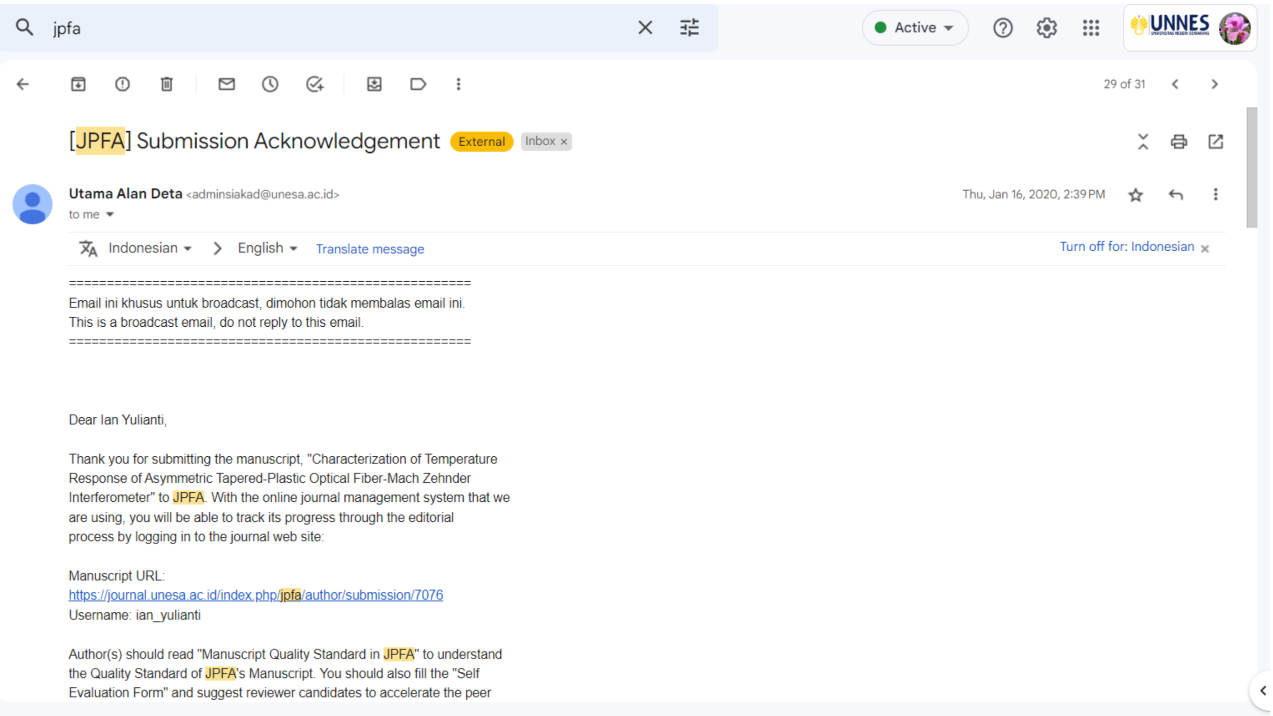

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Dear Ian Yulianti,

Thank you for submitting the manuscript, "Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer" to JPFA. With the online journal management system that we are using, you will be able to track its progress through the editorial process by logging in to the journal web site:

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https://journal.unesa.ac.id/index.php/jpfa/author/submission/7076
Username: ian_yulianti

Author(s) should read "Manuscript Quality Standard in JPFA" to understand the Quality Standard of JPFA's Manuscript. You should also fill the "Self Evaluation Form" and suggest reviewer candidates to accelerate the peer

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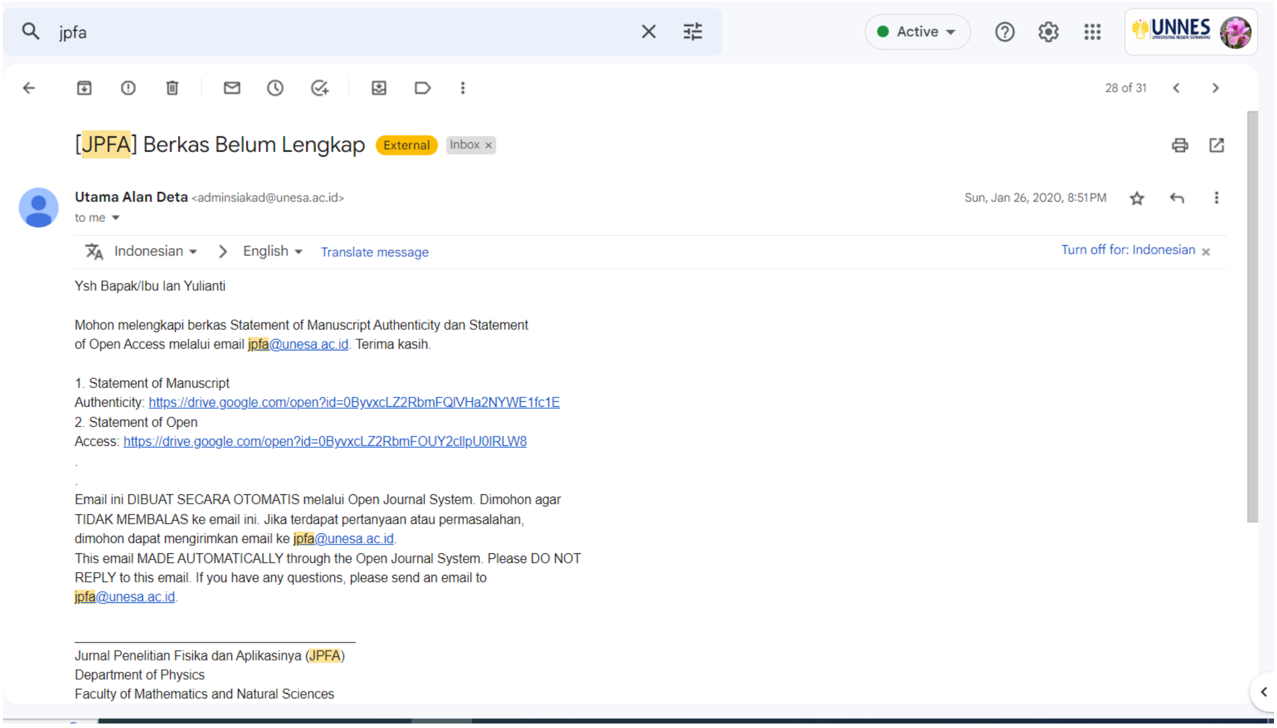
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Ysh Bapak/Ibu Ian Yulianti

Mohon melengkapi berkas Statement of Manuscript Authenticity dan Statement of Open Access melalui email jpfa@unesa.ac.id. Terima kasih.

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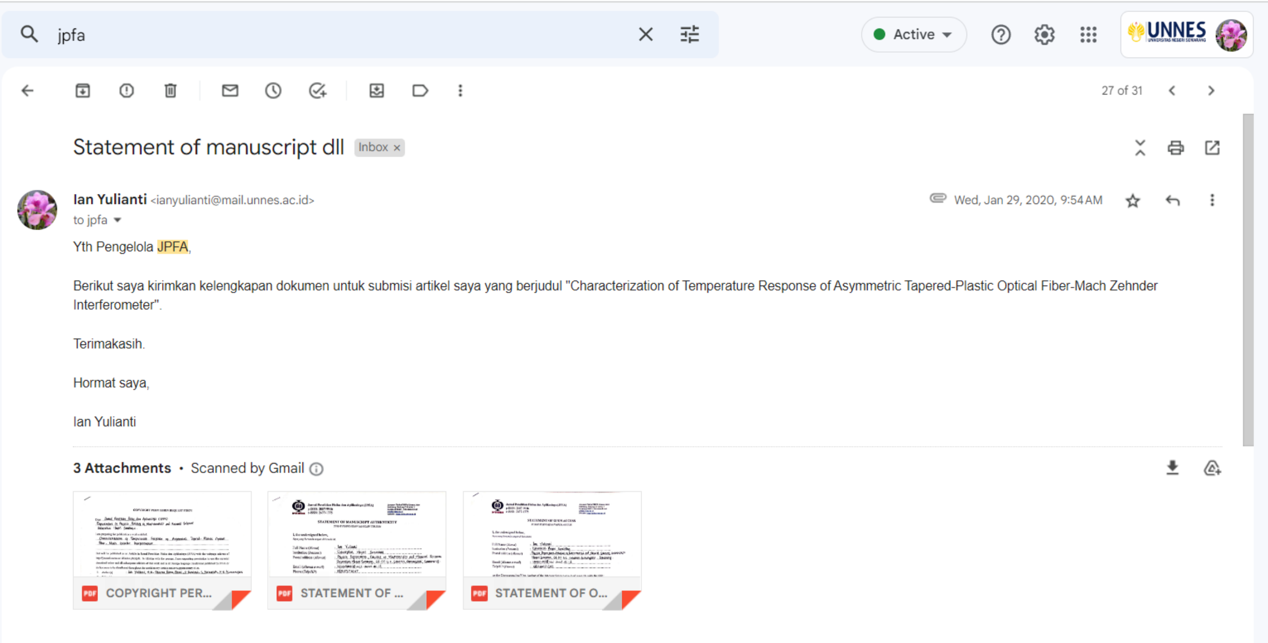
Statement of manuscript dll Inbox

Ian Yulianti <ianyulianti@mail.unnes.ac.id>
to jpfa

Wed, Jan 29, 2020, 9:54 AM

Yth Pengelola JPFA,

Berikut saya kirimkan kelengkapan dokumen untuk submisi artikel saya yang berjudul "Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer".

Terimakasih.

Hormat saya,

Ian Yulianti

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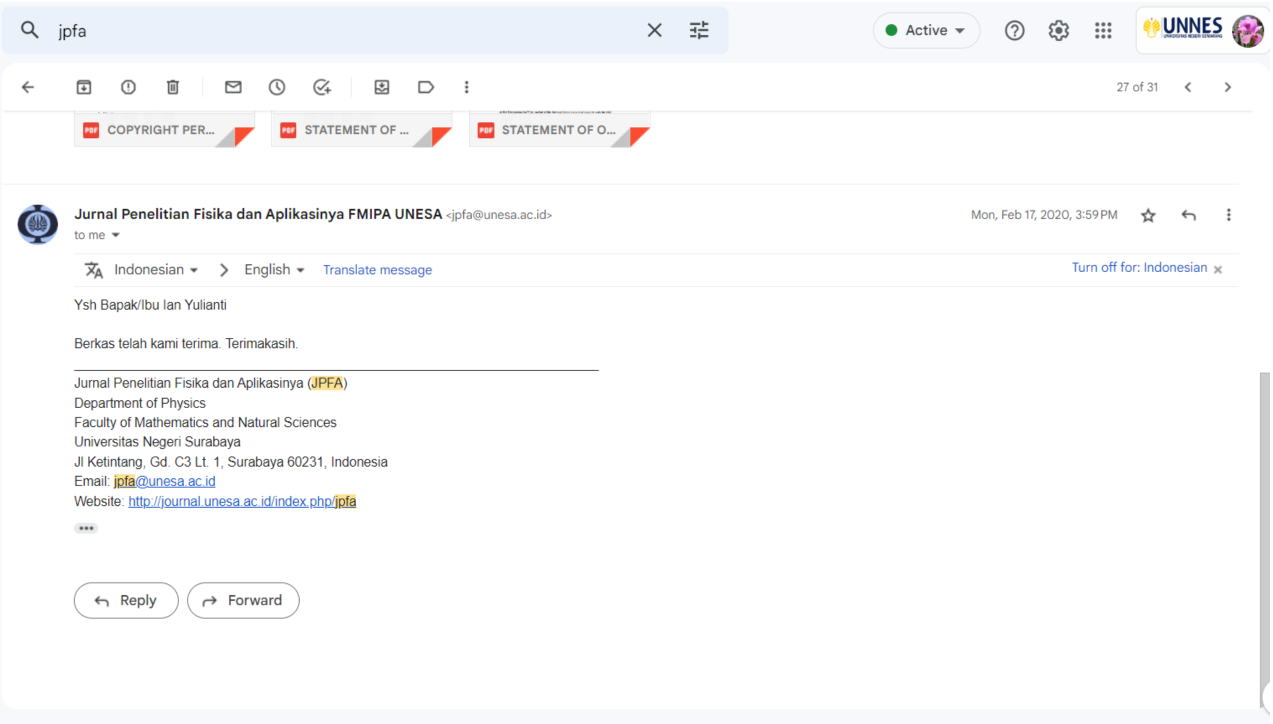
4. Pemberitahuan berkas telah diterima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Mon, Feb 17, 2020, 3:59 PM

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Ysh Bapak/Ibu Ian Yulianti

Berkas telah kami terima. Terimakasih.

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Faculty of Mathematics and Natural Sciences
Universitas Negeri Surabaya
Jl Ketintang, Gd. C3 Lt. 1, Surabaya 60231, Indonesia
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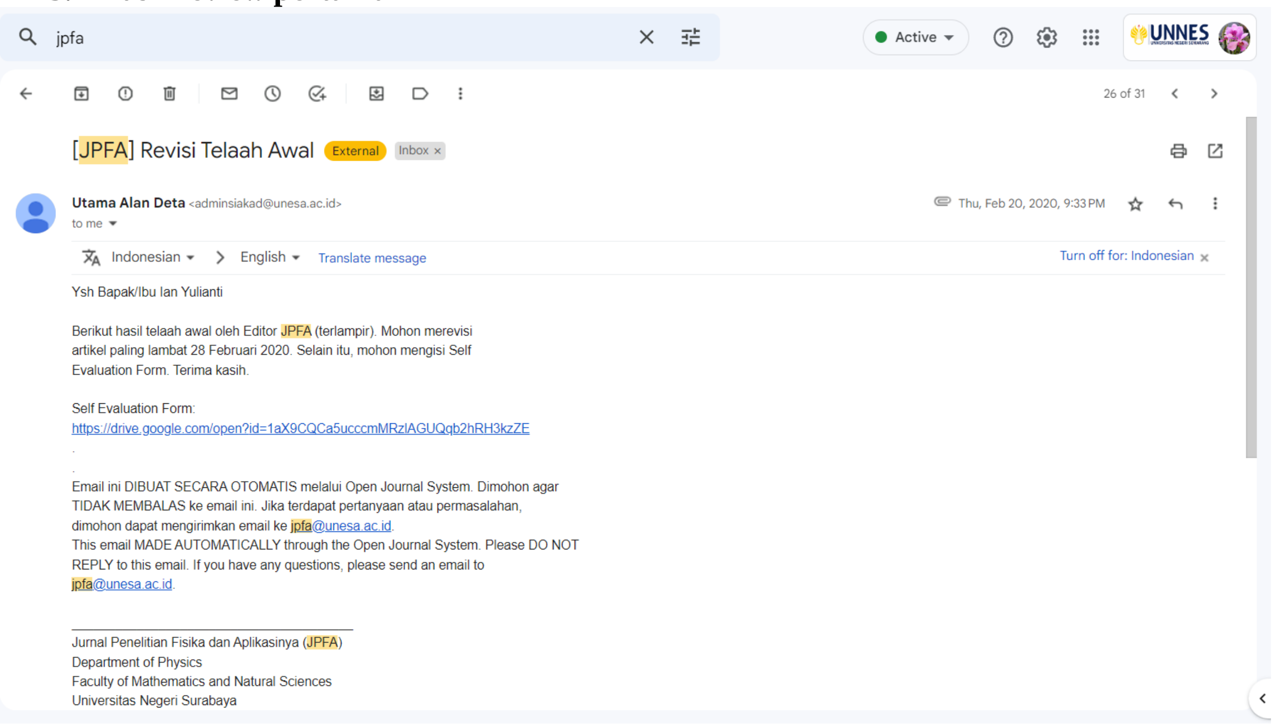
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Ysh Bapak/Ibu Ian Yulianti

Berikut hasil telaah awal oleh Editor JPFA (terlampir). Mohon merevisi artikel paling lambat 28 Februari 2020. Selain itu, mohon mengisi Self Evaluation Form. Terima kasih.

Self Evaluation Form:
https://drive.google.com/open?id=1aX9CQCa5ucccmMRzIAGUQqb2hRH3kzZE

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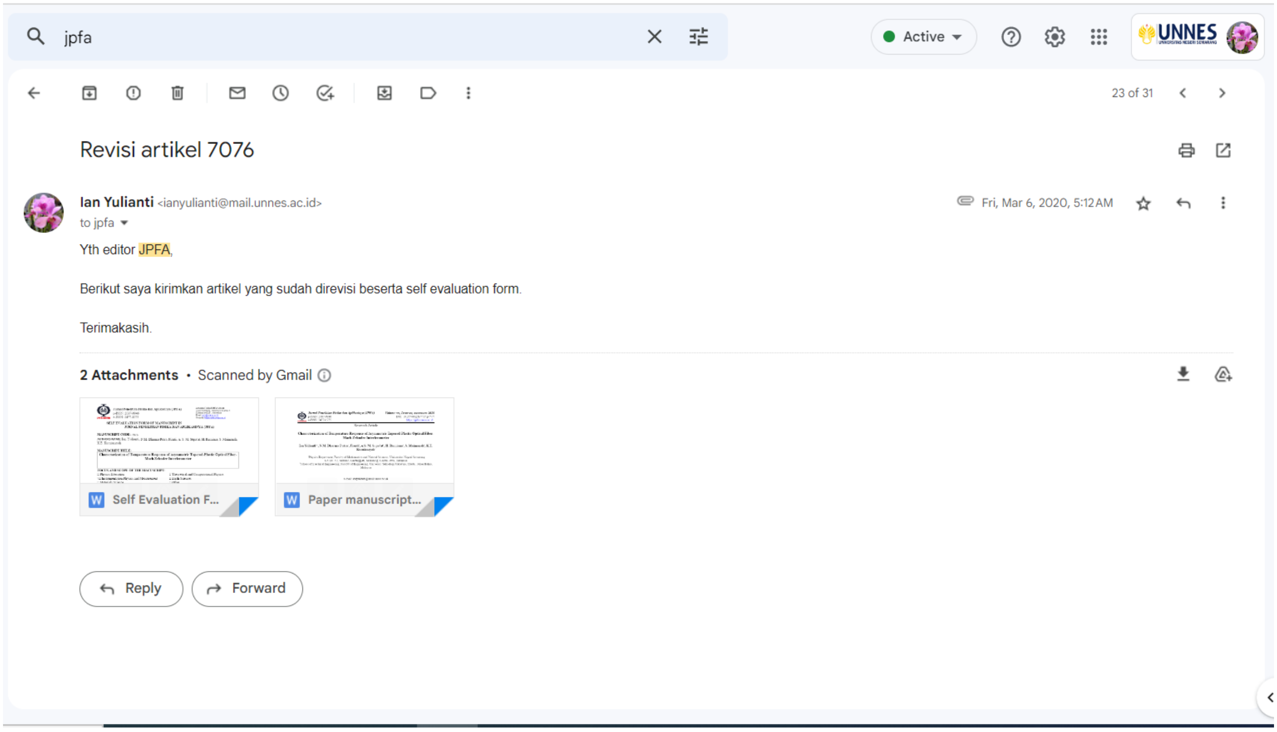
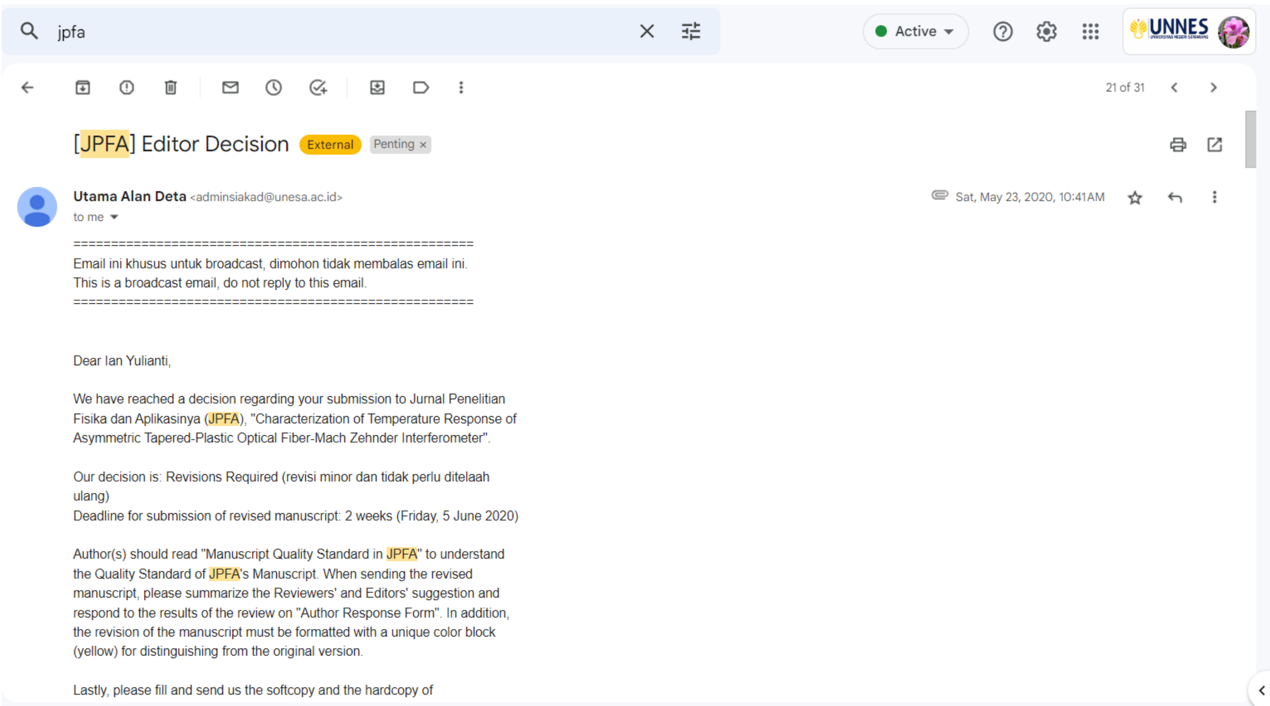
6. Pengiriman manuskrip yang telah direvisi dan self evaluation form



7. Pemberitahuan hasil review kedua: revisi minor dan tidak perlu ditelaah kembali



8. Pengiriman manuskrip revisi kedua

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Revisi Artikel 7076

Ian Yulianti <ianyulianti@mail.unnes.ac.id>
to jpfa

Wed, Jun 3, 2020, 9:25 AM

Yth Editor JPFA,

Berikut saya kirimkan artikel yang sudah direvisi dan Author response form. Untuk hard copy "Statement of Manuscript Authenticity" dan "Statement of Open Access"   sudah saya kirimkan ketika mengirimkan naskah. Berikut saya sertakan soft copy-nya. Terimakasih.

Hormat saya,

Ian Yulianti

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> Dear Ian Yulianti,

9. Pemberitahuan hasil revisi ketiga

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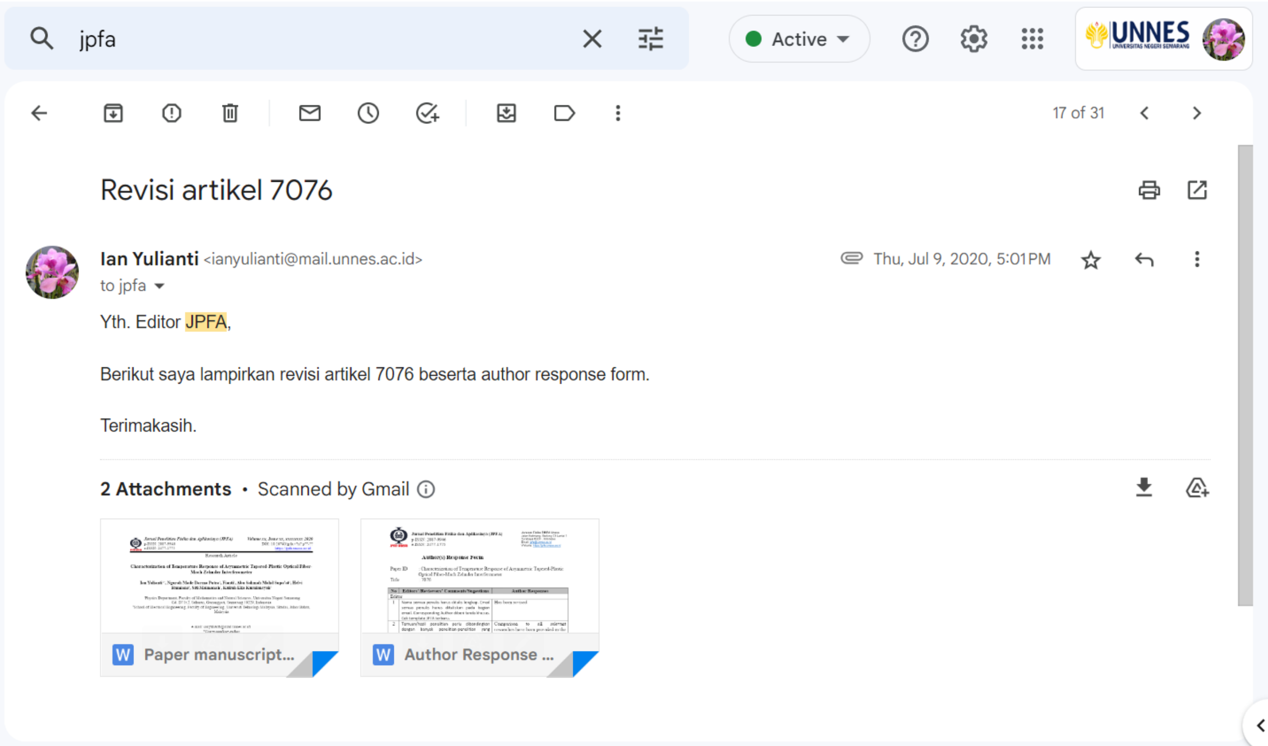
=== Pengumuman Pandemi Covid19 ===
Sehubungan dengan Pandemi Covid19 di Indonesia, kami memohon maaf atas keterlambatan kami untuk menerbitkan Edisi Juni 2020. Kami mengalami kesulitan koordinasi dengan Tim Editor dan Tim Reviewer. Selain itu, Tim Editor kemarin (29 dan 30 Juni 2020) fokus untuk Assesmen Lapangan Akreditasi Prodi kami. Demi kelancaran komunikasi dan mempercepat proses naskah, mohon Bapak/Ibu Penulis dapat bergabung di Telegram Grup dengan laman: https://t.me/JPFAUnesa
=== Pengumuman Pandemi Covid19 ===

Dear Ian Yulianti,

We have reached a decision regarding your submission to Jurnal Penelitian Fisika dan Aplikasinya (JPFA), "Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer".

Our decision is: Revisions Required (revisi minor dan tidak perlu ditelaah ulang)
Deadline for submission of revised manuscript: 1 weeks (Jumat, 10 Juli 2020)

10. Pengiriman manuskrip revisi ketiga



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Revisi artikel 7076

Ian Yulianti <ianyulianti@mail.unnes.ac.id>
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Thu, Jul 9, 2020, 5:01 PM

Yth. Editor JPFA,

Berikut saya lampirkan revisi artikel 7076 beserta author response form.

Terimakasih.

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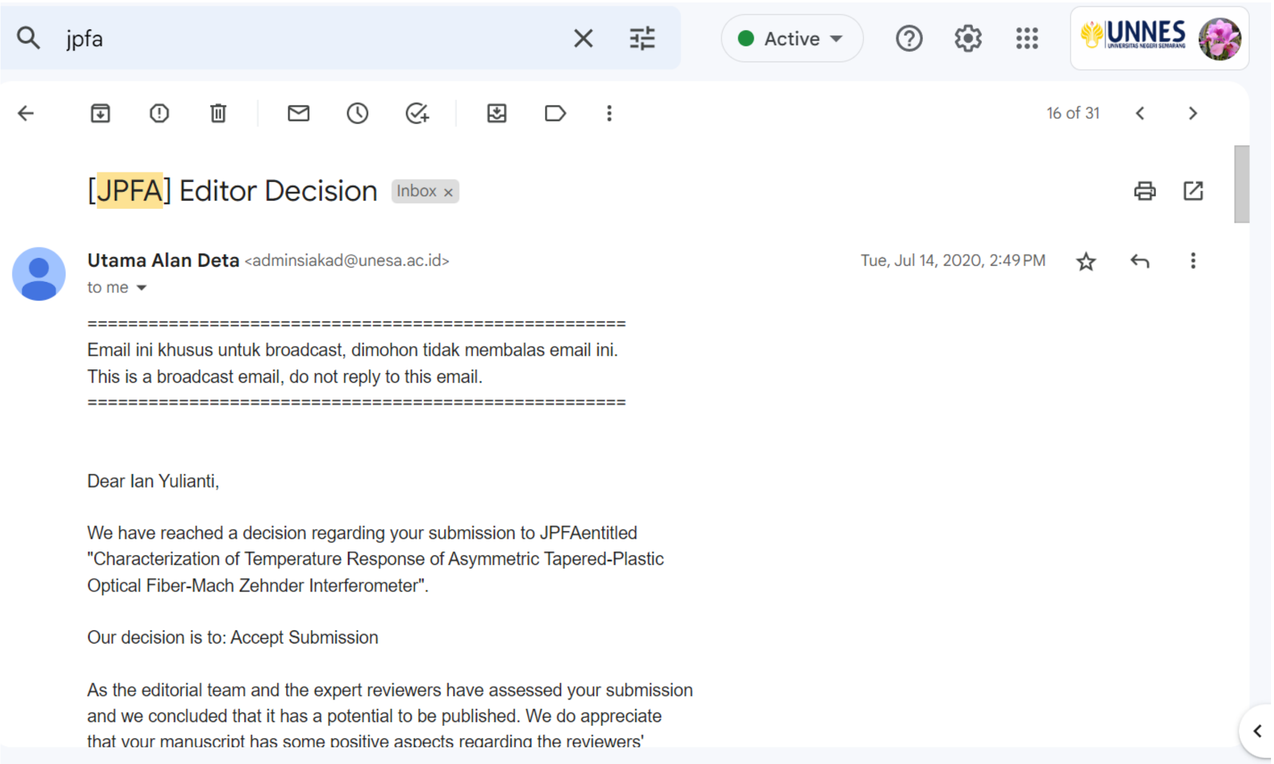
Author Response ...

11. Keputusan Editor: Artikel diterima untuk publikasi



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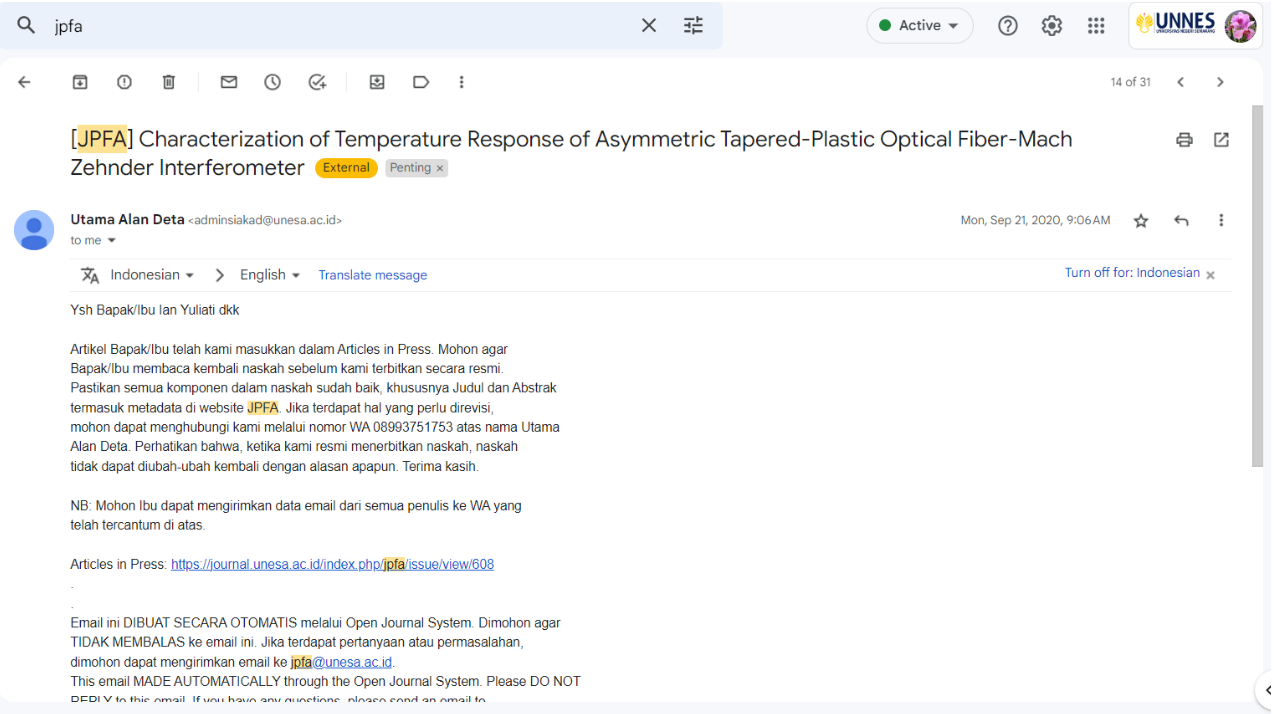
We have reached a decision regarding your submission to JPFAentitled "Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer".

Our decision is to: Accept Submission

As the editorial team and the expert reviewers have assessed your submission and we concluded that it has a potential to be published. We do appreciate that your manuscript has some positive aspects regarding the reviewers'

12. Artikel in press



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[JPFA] Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer External Penting ×

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Mon, Sep 21, 2020, 9:06 AM

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Ysh Bapak/Ibu Ian Yuliati dkk

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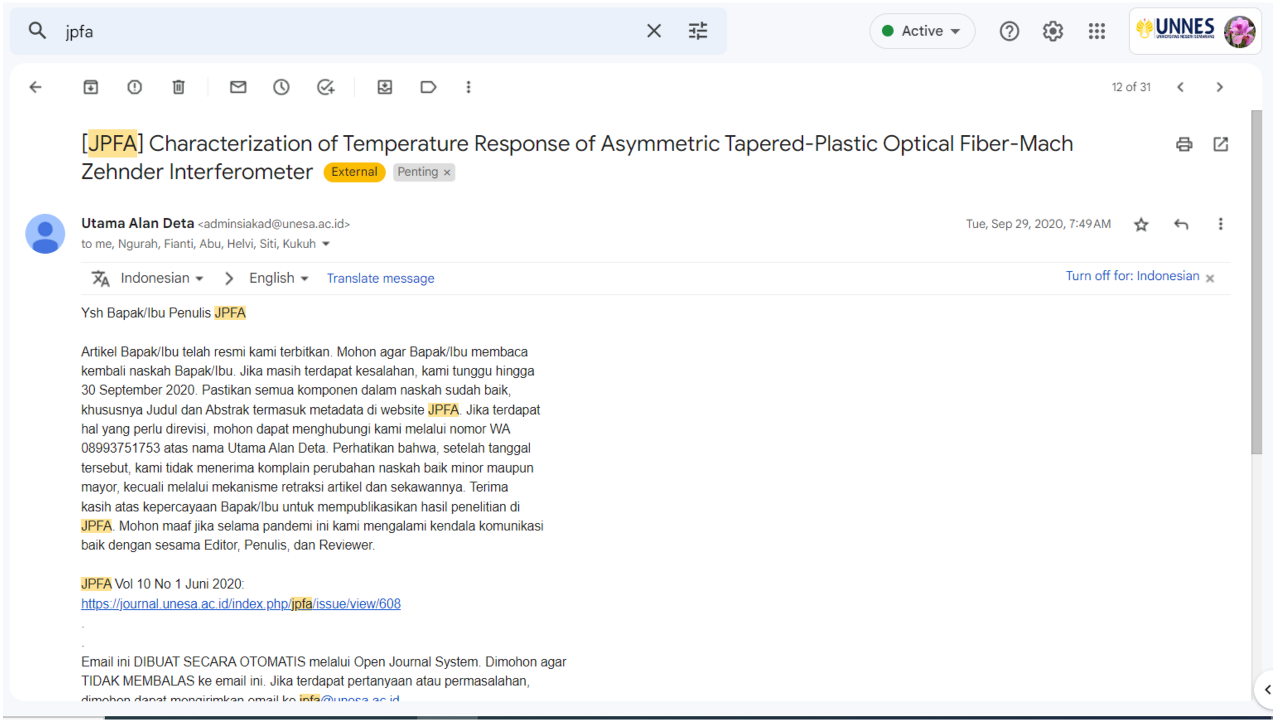

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[JPFA] Characterization of Temperature Response of Asymmetric Tapered-Plastic Optical Fiber-Mach Zehnder Interferometer External Penting ×

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Tue, Sep 29, 2020, 7:49 AM

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JPFA Vol 10 No 1 Juni 2020:
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Select and fill in the appropriate section.

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MANUSCRIPT TITLE:

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MANUSCRIPT'S TYPE: ☐ **Research Article** ☐ Review Article

A. GENERAL EVALUATION OF THE MANUSCRIPT

No	Review	Criteria	
		Yes	No
1	**Focus and Scope** Does the manuscript fit the JPFA's Scope and Topic?	V	
2	**Similarity Check** The percentage of similarity checked in *Turnitin* ………… % . Is it less than 25%? Please attach the checking result.		
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4	**Originality** Is the research theme or topic considerably new or currently discussed among researchers?	V	
5	**Novelty** Is the research offer any novelty?	V	
6	**Scientific Impact** Is the scientific impact of this research good enough?		V
7	**Abstract** Does the abstract contain **short introduction** (1-2 sentendces), **research objectives**, **brief methods**, **research findings**, and **conclusions**? Explain the reason in part B if you choose No.	V	
8	**Introduction** Does the introduction contain **state of the art**, **gap analysis**, and **research objectives**? Explain the reason in part B if you choose No.	V	
9	**Method** Is the method **clear**, **detailed**, and **reproducible** for other researchers? Explain the reason in part B if you choose No.	V	
10	**Results and Discussion** Have the results **summarized the research findings**? Explain the reason in part B if you choose No.	V	

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11	**Results and Discussion** Does the discussion **answer the research questions**, **interpret the results** of the study, **compare the results** of the research with other relevant research, **construct new theories**, and/or **modify previous theories**? Explain the reason in part B if you choose No.		V
12	**Result and Discussion** Have the **implications of the research finding** been written in the last paragraph of discussion? Explain the reason in part B if you choose No.		V
13	**Conclusion** Does the conclusion **answer** the research objective/research question? Have the conclusions been **concise** and **clear**? Explain the reason in point 19 if you choose no.	V	
14	**Number of Pages** Does the number of pages of the manuscript comply with JPFA's Author Guidelines? (6-15 pages)	V	
15	**Manuscript Format** Does the manuscript format comply with JPFA's Author Guidelines JPFA?	V	
16	**Primary References** A minimal of 30 references, with 80 % of references come from primary sources		V
17	**Updated References** A minimal of 30 references, with 80 % up-to-dated references (less than 10 years)		V
18	**Supplementary Files** Has the author attached "Statement of Manuscript Authenticity" and "Statement of Open Access"?		
19	**Notes in the manuscript** Is there any notes or comments in the manuscript's file?		V

B. SUGGESTION FOR IMPROVEMENT

State the reason or suggestion (based on the initial review) if the manuscript needs to be improved or rejected:

1. Abstrak berisi pendahuluan singkat, tujuan penelitian, metode singkat, temuan penelitian dan kesimpulan
2. Pada pendahuluan, state of the art masih kurang. Perlu dijelaskan hasil penelitian-penelitian relevan yang telah ada. Selain itu, gap analysis dan tujuan penelitian kurang nampak.
3. Pada pembahasan, peneliti perlu membandingkan hasil/temuan penelitian dengan penelitian-penelitian sebelumnya. Perlu banyak sitasi dalam bagian ini. Selain itu, pada paragraph akhir, perlu dijelaskan implikasi temuan penelitian di bidang optik.
4. Kesimpulan sebaiknya tidak menuliskan kembali data.
5. Cek penulisan referensi.
6. Referensi perlu ditambah, minimal 30 rujukan yang berasal dari artikel di Jurnal Nasional Terakreditasi (minimal Sinta 2) dan/atau Jurnal Internasional Berreputasi (terindeks Scopus dan/atau Web of Science) yang terbaru (5 tahun terakhir) minimal 80 % dari total Referensi.
7. Sebaiknya penulis berkolaborasi dengan penulis dari luar negeri agar diversitas penulis lebih baik.

C. RECOMMENDATION (CHOOSE ONE)

a. The manuscript is not suitable to be published in JPFA.
b. The manuscript needs to be improved by Authors.
c. The manuscript can be directly processed to the Peer-Review Process.

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D. DOUBLE BLIND PEER-REVIEW

The author's name, institution, and identity in the manuscript (found at the beginning of the manuscript and in the Acknowledgments section) should be replaced by a period (.).

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   Email : ……………………………..
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   Email : ……………………………..
   Scopus ID: ……………………………
9. Name : ……………………………...
   Affiliation: …………………………...
   Email : ……………………………..
   Scopus ID: ……………………………
10. Name : ……………………………...
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Give a sign (in bold or check) to 2-3 (two-three) recommended Peer Reviewers to review this manuscript.

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Manuscript Editor

(………………………………)

Jurnal Penelitian Fisika dan Aplikasinya (JPFA) **Volume xx, Issue xx, xxxxxxxx 2020**
p-ISSN: 2087-9946 DOI: 10.26740/jpfa.v?n?.p??-??
e-ISSN: 2477-1775 https://jpfa.unesa.ac.id

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

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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 35°C to 85°C with increment of 10°C. The results showed that the sensor has sensitivity of 0.0431 nm/°C and correlation coefficient of 0.9965. Hysteresis of $6.9\times10^{-3}$was observed. In terms of repeatability, the sensor shows maximum deviation of ±3°C 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 35°C hingga 85°C dengan kenaikan 10°C. Hasil penelitian menunjukkan bahwa sensor memiliki sensitivitas 0,0431 nm/°C dengan koefisien korelasi 0,9965 dan histeresis sebesar $6,9\times10^{-3}$. Dalam hal pengulangan, sensor menunjukkan deviasi *maksimum ±3°C 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 (;)

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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/°C. 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.

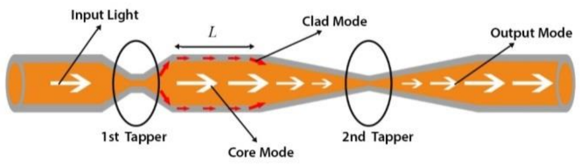


Figure 1. Schematic diagram of SI-POF MZI

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

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

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

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

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} /ºC, 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 80ºC 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 35°C to 85°C with increment of 10°C 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.

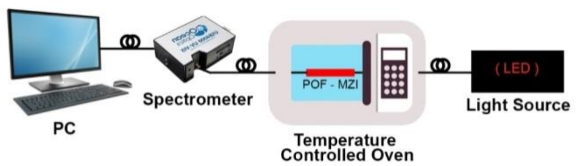
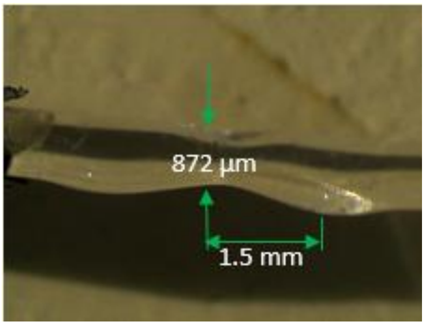


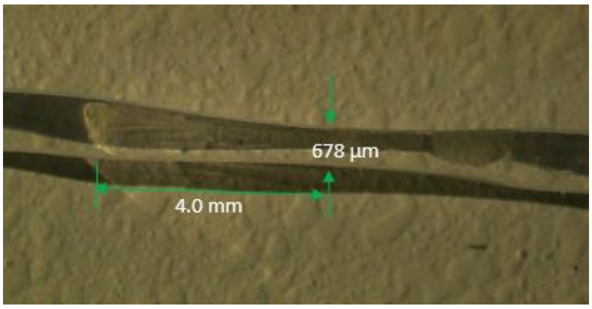
Figure 2. Characterization set up of the SI-POF MZI

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

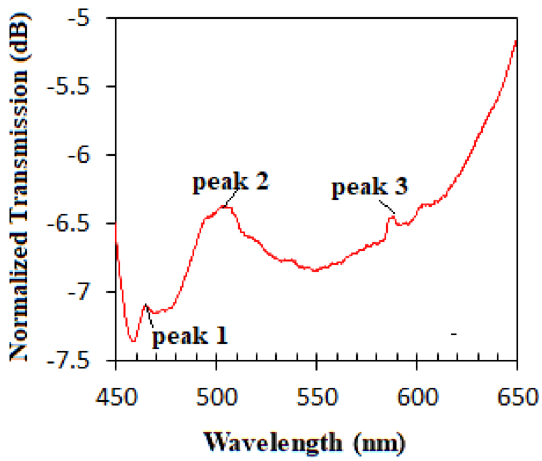


Figure 4. Transmission spectrums at room temperature of the fabricated POF-MZI

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].

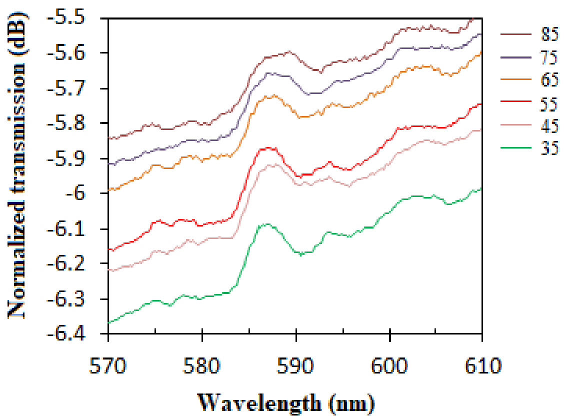


Figure 5. Transmission spectrums of POF-MZI at various temperature values

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

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

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 (MoS_2) [29].

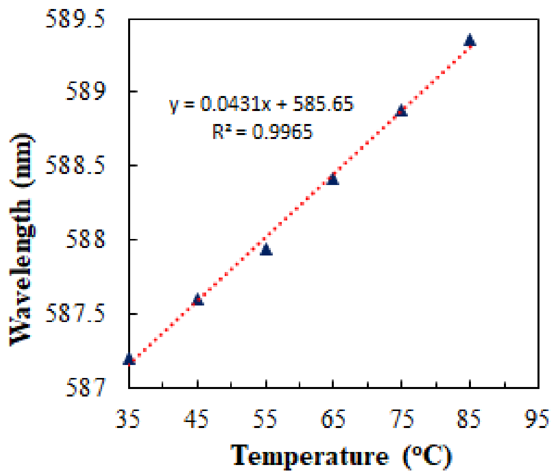


Figure 6. Calibration curve of POF-MZI sensor of peak 3

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]

$$H = \frac{\max\left(I(i) - D(i)\right)}{I(i)} \quad (7)$$

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 ±2°C.

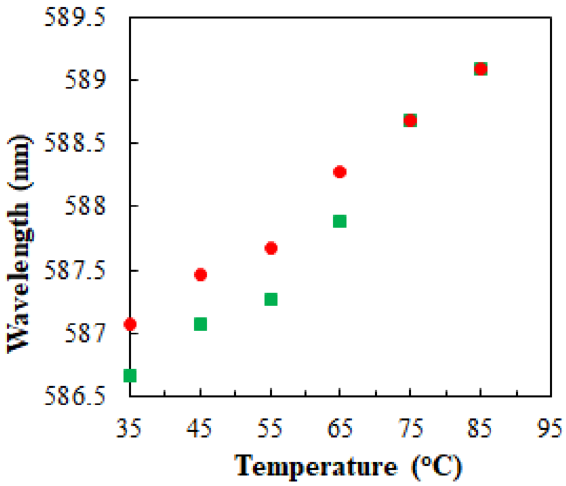


Figure 7. Hysteresis of the fabricated SI-POF MZI

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 1.89°C, meanwhile the maximum deviation is ±3°C. 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 ±1°C. The result is comparable with other POF based temperature sensor which the measurement error is 1.48 °C [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.

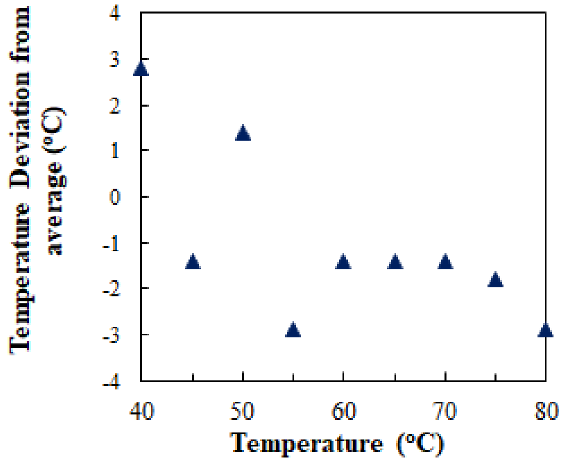


Figure 8. Repeatability of the SI-POF MZI

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.

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 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.

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

MANUSCRIPT'S TYPE (MUST BE COMPLETED): ☐ **Research Article** ☐ Review Article

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4	**Accuracy and Correctness** Considering the Methodology and Results and Discussion.					
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8	**Introduction** Introduction shows clarity in defining the research problem, the relationship with previous or existing research, and the theories used. It explains **state of the art** of the research, **gap analysis**, and **research objectives/questions**.			
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10	**Ethics of Writing (*Optional)*** The manuscript adheres the research ethics as well as the principles in the care and use of laboratory, animal, and/or human subjects, including ethics when using personal information or images from patients, research subjects, and/or other individuals.			
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☐ Informative and complementary
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Research Article

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

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Abstract

Temperature measurement is important in various applications, therefore various temperature sensors have been developed. Due to its advantages, many optical fiber-based temperature sensors have been proposed. Wavelength modulation-based optical sensor is interesting due to high accuracy. However, complex fabrication process and high cost limits the sensors advantages. Therefore, we proposed a simple and low cost Mach Zehnder interferometer (MZI) sensor using step index plastic optical fiber (SI-POF). Performance characterization of the sensor 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 35°C to 85°C with increment of 10°C. The results showed that the sensor has sensitivity of 0.0431 nm/°C and correlation coefficient of 0.9965. Hysteresis of 6.9×10^{-3} was observed. In terms of repeatability, the sensor shows maximum deviation of ±3°C 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

Pengukuran suhu merupakan hal yang penting dalam berbagai aplikasi, oleh karena itu berbagai sensor suhu telah dikembangkan. Sensor suhu berbasis serat optik telah banyak dikembangkan karena sensor berbasis serat optik memiliki banyak keunggulan. Diantara jenis sensor optik yang ada, sensor optik berbasis modulasi panjang gelombang menarik karena memiliki akurasi yang tinggi. Namun, sensor jenis ini memiliki kelemahan berupa proses fabrikasi yang kompleks dan biaya tinggi. Oleh karena itu, *dalam penelitian ini digunakan sensor Mach Zehnder interferometer (MZI) yang sederhana dan murah menggunakan step index plastic optical fiber (SI-POF). 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 35°C hingga 85°C dengan kenaikan 10°C. Hasil penelitian menunjukkan bahwa sensor memiliki sensitivitas 0,0431 nm/°C dengan koefisien korelasi 0,9965 dan histeresis sebesar 6,9 ×10^{-3} . Dalam hal pengulangan, sensor menunjukkan deviasi maksimum ±3°C 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.*

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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/°C. 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.

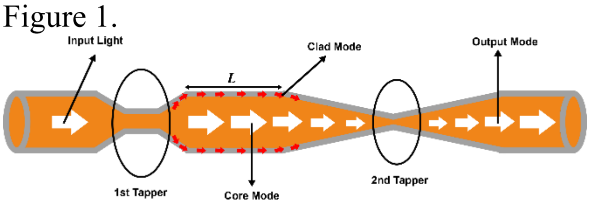


Figure 1. Schematic diagram of SI-POF MZI

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

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

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

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

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} /°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

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

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 35°C to 85°C with increment of 10°C 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.

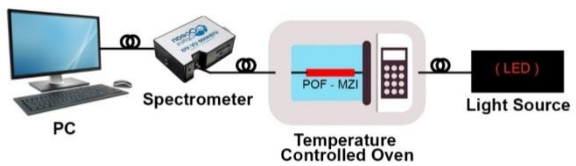
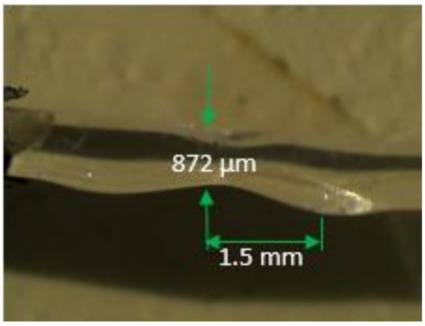


Figure 2. Characterization set up of the SI-POF MZI

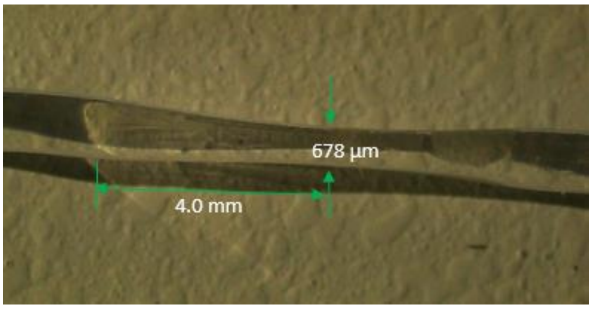
III. RESULTS AND DISCUSSION

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

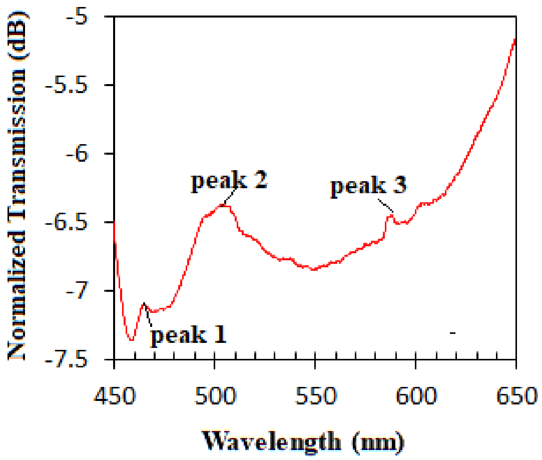


Figure 4. Transmission spectrums at room temperature of the fabricated POF-MZI

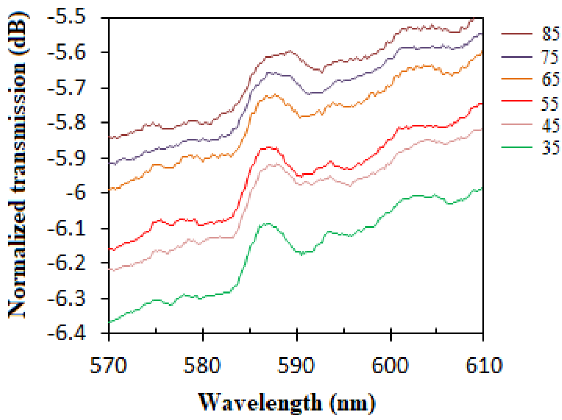


Figure 5. Transmission spectrums of POF-MZI at various temperature values

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].

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

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

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 (MoS_2) [29].

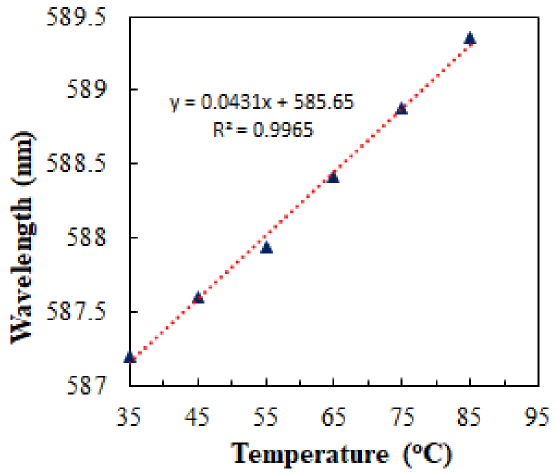


Figure 6. Calibration curve of POF-MZI sensor of peak 3

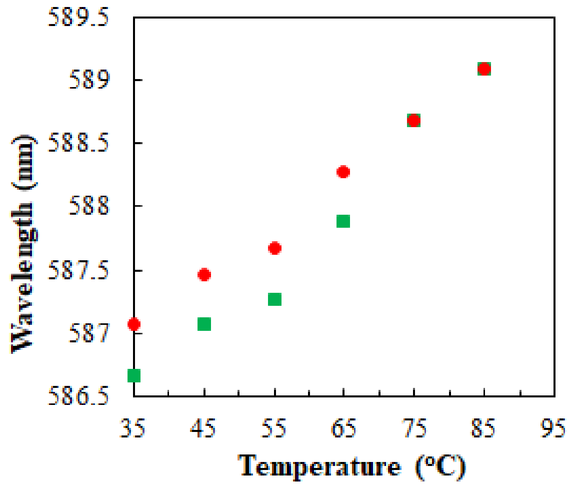


Figure 7. Hysteresis of the fabricated SI-POF MZI

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]

$$H = \max\left(I(i) - D(i)\right) / I(i) \tag{7}$$

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 ±2°C.

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 1.89°C, meanwhile the maximum deviation is ±3°C. 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 ±1°C. The result is comparable with other POF based temperature sensor which the measurement error is 1.48 °C [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.

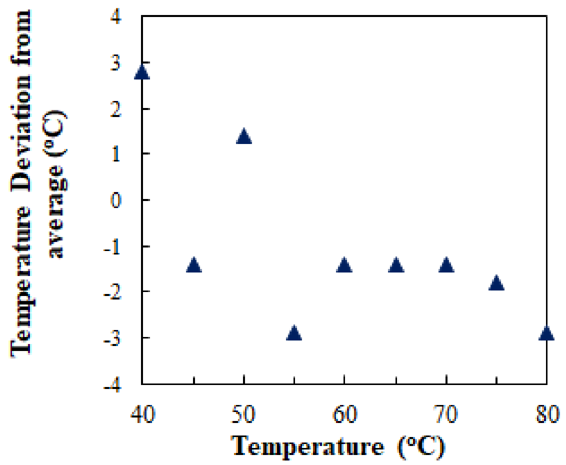


Figure 8. Repeatability of the SI-POF MZI

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.

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 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.

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Research Article

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

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Abstract

Temperature measurement is important in various applications, therefore various temperature sensors have been developed. Due to its advantages, many optical fiber-based temperature sensors have been proposed. Wavelength modulation-based optical sensor is interesting due to high accuracy. However, complex fabrication process and high cost limits the sensors advantages. Therefore, we proposed a simple and low cost Mach Zehnder interferometer (MZI) sensor using step index plastic optical fiber (SI-POF). Performance characterization of the sensor 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 35°C to 85°C with increment of 10°C. The results showed that the sensor has sensitivity of 0.0431 nm/°C and correlation coefficient of 0.9965. Hysteresis of $6.9\times10^{-3}$was observed. In terms of repeatability, the sensor shows maximum deviation of ±3°C 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

Pengukuran suhu merupakan hal yang penting dalam berbagai aplikasi, oleh karena itu berbagai sensor suhu telah dikembangkan. Sensor suhu berbasis serat optik telah banyak dikembangkan karena sensor berbasis serat optik memiliki banyak keunggulan. Diantara jenis sensor optik yang ada, sensor optik berbasis modulasi panjang gelombang menarik karena memiliki akurasi yang tinggi. Namun, sensor *jenis ini memiliki kelemahan berupa proses fabrikasi yang kompleks dan biaya tinggi. Oleh karena itu, dalam penelitian ini digunakan sensor Mach Zehnder interferometer (MZI) yang sederhana dan murah menggunakan step index plastic optical fiber (SI-POF). 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 35°C hingga 85°C dengan kenaikan 10°C. Hasil penelitian menunjukkan bahwa sensor memiliki sensitivitas 0,0431 nm/°C dengan koefisien korelasi 0,9965 dan histeresis sebesar 6,9 ×10*$^{-3}$ *. Dalam hal pengulangan, sensor menunjukkan deviasi maksimum ±3°C 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.*

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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/°C. 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.

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

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

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

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

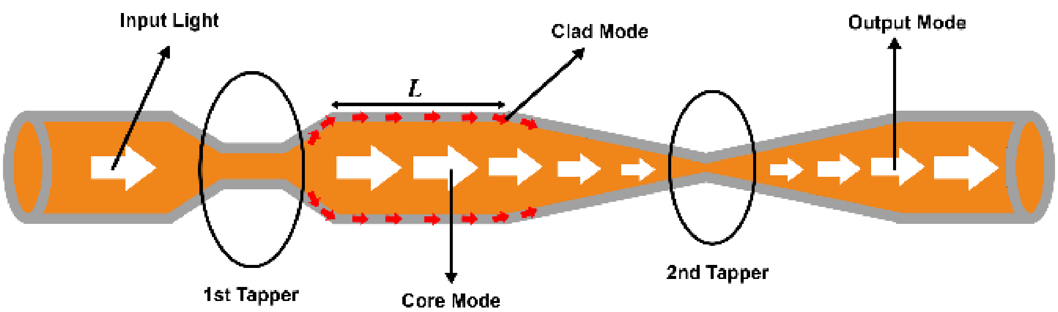


Figure 1. Schematic diagram of SI-POF MZI

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} /ºC, respectively [23]. Thus, any change of temperature of fiber and its surrounding will change the peak wavelength of the MZI transmission spectrums defined by

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

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 80ºC 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.

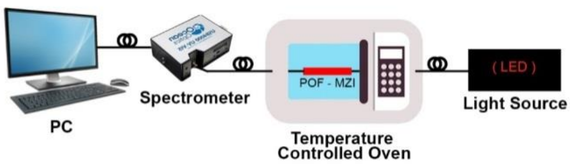
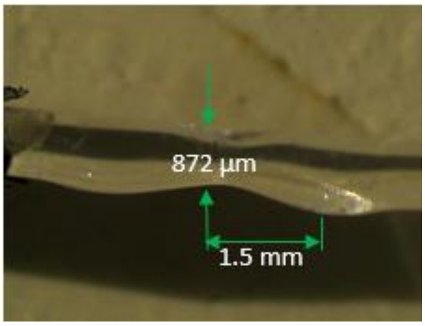


Figure 2. Characterization set up of the SI-POF MZI

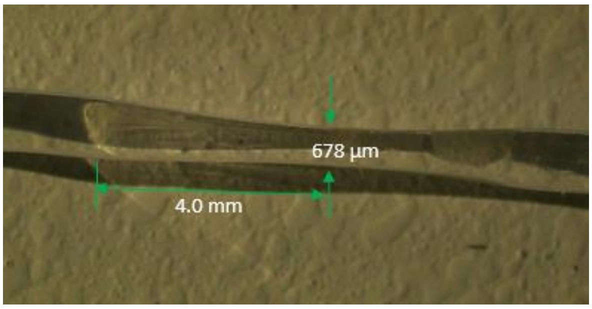
III. RESULTS AND DISCUSSION

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

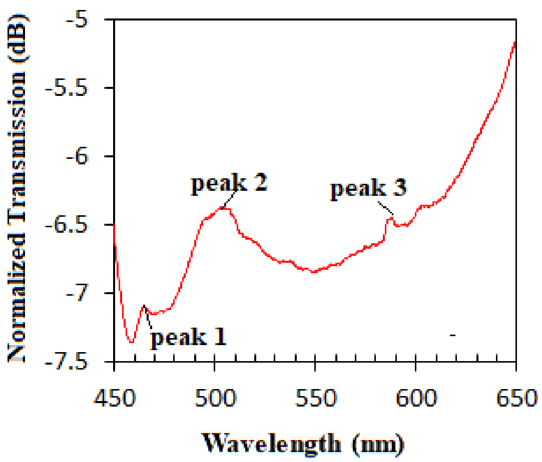


Figure 4. Transmission spectrums at room temperature of the fabricated POF-MZI

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].

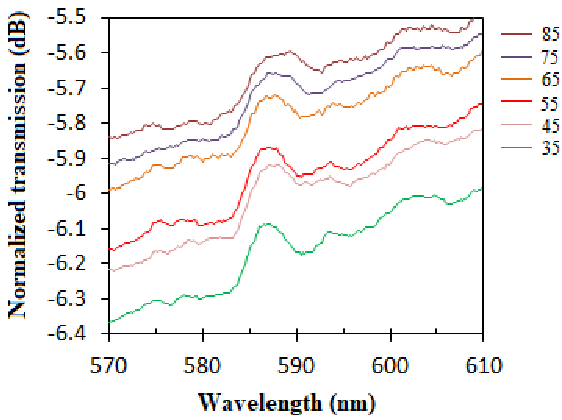


Figure 5. Transmission spectrums of POF-MZI at various temperature values

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

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

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].

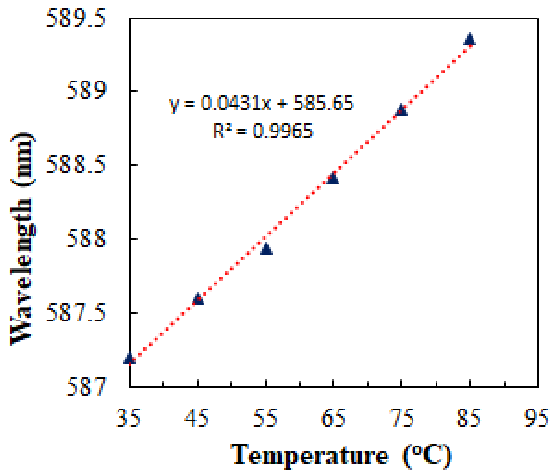


Figure 6. Calibration curve of POF-MZI sensor of peak 3

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]

$$H = \max\left(I(i) - D(i)\right) / I(i) \qquad (7)$$

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 ±2°C.

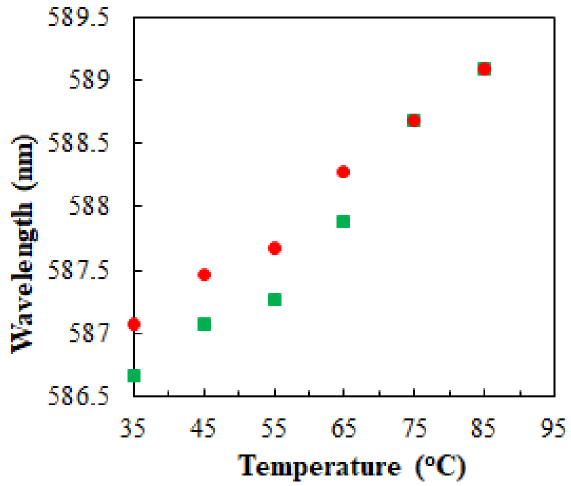


Figure 7. Hysteresis of the fabricated SI-POF MZI

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 1.89°C, meanwhile the maximum deviation is ±3°C. 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 ±1°C. The result is comparable with other POF based temperature sensor which the measurement error is 1.48 °C [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.

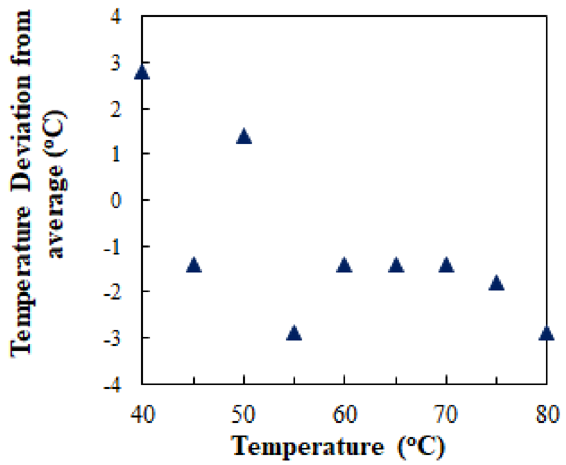


Figure 8. Repeatability of the SI-POF MZI

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 be applied 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.

IV. CONCLUSION

Based on the results, it can be concluded that the sensor has comparable sensitivity to other wavelength-based sensor with good linearity. However, the sensor has high deviation. Other sensor advantages are 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.

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3	Ditambahkan satu paragraph di akhir bab hasil dan diskusi yang menjelaskan implikasi hasil penelitian di bidang Fisika Instrumentasi dan Pengukuran.	The implication has already been provided in the previous manuscript in the last paragraph: "Therefore, the structure could potentially be applied 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."
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5	Ucapan terima kasih diberikan nama hibah yang diterima.	Has been revised.

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