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A Bent Fiber Optic with a D-Shaped Structure for Temperature Sensing

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Abstract

A simple and cost-effective plastic optical fiber temperature sensor is demonstrated in this paper. This paper presents the development of a bent fiber optic with a D-shaped structure. A D-shape region on the plastic optical fibre (POF) is created by side-polishing the surface of the POF until a curve D-region is formed, thereby exposing part of the fiber's core and cladding. This exposed region enables the surrounding temperature to directly interact with the propagating light within the POF, influencing its intensity. To enhance the sensitivity, the POF sensor is further bent to induce a macro bending effect. Based on the experimental results, the sensor exhibits a linear response to temperature ranging from 30 °C to 80 °C. In addition, the highest sensitivity value achieved is 1.5 x 10-3 $°C^{-1}$, obtained with a D-region of 1 cm at a wavelength of 778 nm. This proposed sensor demonstrates high sensitivity and linearity compared to previous developments.

1. Introduction

Historically, temperature sensors have employed various technological approaches, including magnetic, inductive, piezoelectric, and capacitive methods [1], [2], [3], [4]. In recent years, these techniques have gained popularity due to their use of low-cost sensing elements. Nevertheless, their performance is often limited by vulnerability to electromagnetic interference (EMI) [3]. Consequently, fiber optic temperature sensors—renowned for their inherent immunity to EMI—are increasingly being adopted as alternatives to conventional EMI-prone systems. These sensors also offer several other benefits, such as a compact form factor, low weight, high measurement precision, environmental durability, and the ability to support multiplexing [4]. As a result, the advancement of various types of fiber optic temperature sensors remains an active and ongoing area of research.

Optical fiber sensors measure physical quantities by inducing changes in either the light's intensity or its wavelength. Among wavelength-based sensing approaches, significant research has been devoted to fiber Bragg gratings [7], [8], [9], [10] tapered fiber structures [11], [12] and various interferometric designs [13], [14], [15]. Although this method offers high sensitivity, it increases system complexity due to the need for spectrum analyzers or interrogators for data extraction. In contrast, intensity-modulated temperature sensors operate based on variations in optical power and offer lower operational complexity.

Researchers have explored the use of both silica and plastic optical fibers (POFs) in the design of optical temperature sensors [16]. Nevertheless, intensity-modulated sensors based on POFs have garnered more attention than those using traditional silica fibers, primarily due to several inherent advantages [17], ~~[12]~~. In comparison to silica fibers, POFs feature a larger core diameter and lower Young's modulus, which contribute to improved mechanical flexibility, simplified handling, and lower maintenance requirements [18]. Although their thermal tolerance is lower than that of certain semiconducting materials, the multimode structure of POFs introduces distinct interactions with surrounding media that are important to consider in real-world applications [19].

Numerous sensing head structures have been reported by researchers, including straight fiber [20], balloon-shaped [21], macro-bend [16], [22], [23], [24], bundle configuration [25] and D-shaped configurations [26], [27]. These designs aim to enhance the interaction between the light traveling in the optical fiber and the surrounding medium [28]. Therefore, in this research, a bent POF coupled with a D-shaped surface for temperature sensing is proposed. This design has the potential to significantly improve sensitivity performance while offering a simple and cost-effective fabrication technique.

2. Method

The experimental setup used to investigate the sensor's response is shown in Fig.1. The setup comprises a spectrometer from Ocean Optics (HR4000), a deuterium halogen light source from Ocean Optics (DH-mini, UV-Vis-NIR), and a plastic optical fiber (POF) serving as the sensor head. The sensor head in this experiment utilized a POF with a 750 μm diameter polymethylmethacrylate (PMMA) core and a 20 μm thick cladding. The core and cladding had refractive indices of 1.492 and 1.417, respectively. For output monitoring, the spectrometer was connected to a computer running OceanView software. Detailed parameters of the components used in this experimental setup are tabulated in Table 1.

As illustrated in Fig.2(a), the D-shaped POF was prepared by first cutting 1.5 m of the fiber and fixing the middle section on 3D-printed optical fiber holders. To form the curved D-shaped surface on the fiber, a half-cylindrical metal block covered with sandpaper was used to polish the curved D-shaped area, as shown in Figures 2(c) and 2(d). In this work, three diameters of the curved D-shape were tested: 0.5 cm, 0.75 cm, and 1.0 cm. After polishing, the surface was cleaned using alcohol. The fabricated curved D-shaped POF before and after polishing is shown in Fig. 3.

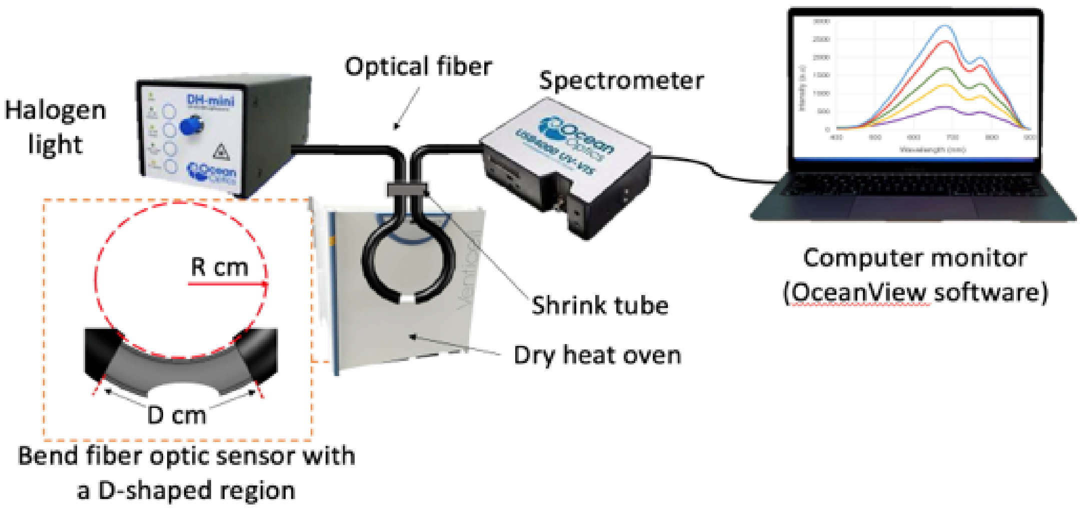


Fig. 1 *Experimental setup for characterization the POF temperature sensor*

Table 1 *Important parameter components for D-shaped with bend structure characterization process*

Components	Value	Model
Halogen Light source	Wavelength: 400 nm to 1600 nm	Ocean Optics DH-mini
Spectrometer	Wavelength: 200 nm to 1100 nm	Ocean Optics HR 4000- CG-UV-NIR
Dry Heat Oven	Temperature range: 30°C to 80°C	Venticell 55
Plastic Optical Fiber (POF)	RI Core : 1.492 RI Cladding : 1.417	
Sensor Head Bending Diameter (mm)	0.5 cm, 0.75 cm, and 1.0 cm	

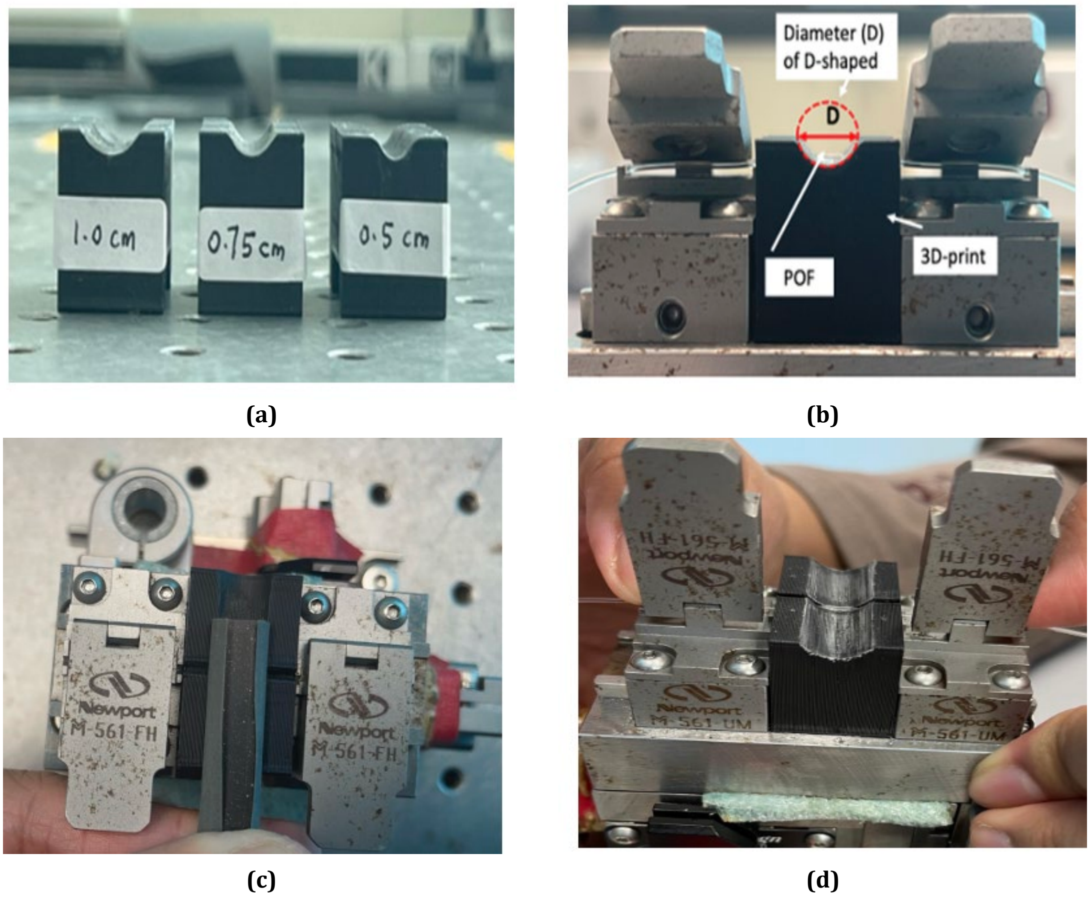
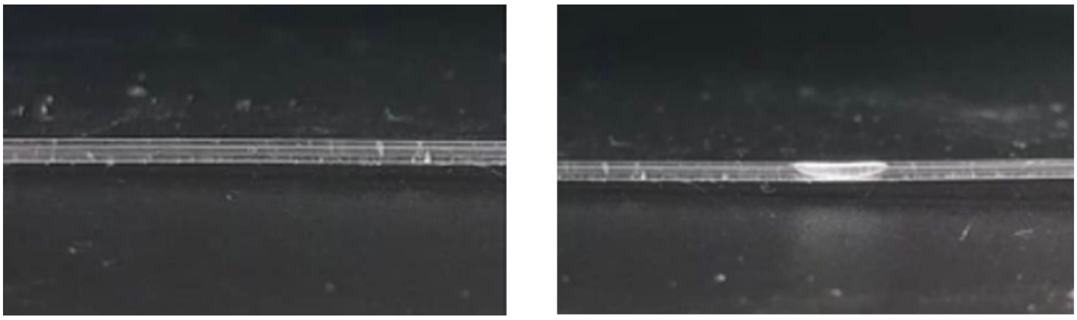


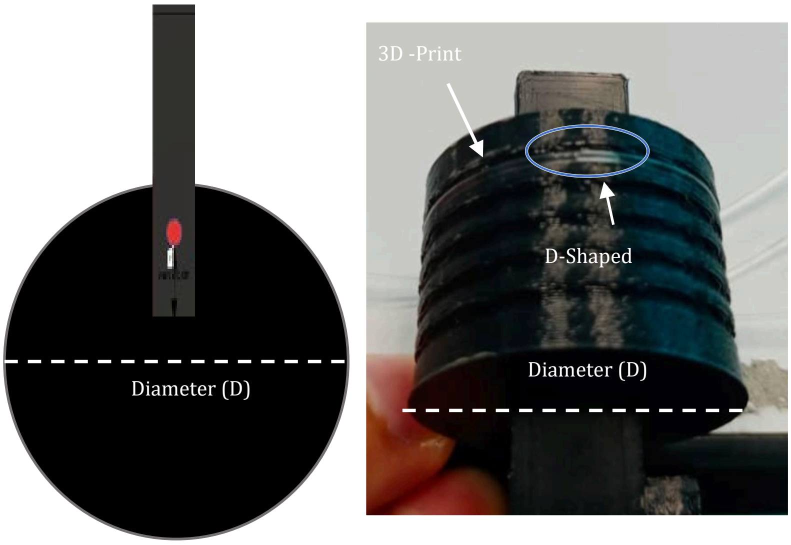
Fig. 2 *Illustration of (a) 3D-printed for D-shaped (Diameter: 0.5 cm, 0.75 cm, and 1.0 cm); (b) Polishing setup; (c) A half-cylindrical metal block covered with sandpaper; (d) Curved D- shaped surface*



(a) **(b)**

Fig. 3 *Image of the D-shaped POF (a) Before; and (b) After polish*

After forming the curved D-shape on the fiber surface, the sensing region was bent. The bent sensor structure was created by fixing the fiber at a specific diameter using a 3D-printed object, as presented in Fig. 4(a). The bending diameter was defined as D = 3 cm. The effect of bending on the sensor was analyzed, as illustrated in Fig. 4(b). For further analysis, sensors with different D-shaped diameters (0.5 cm, 0.75 cm, and 1.0 cm) were evaluated. This analysis was conducted to determine the optimal D-shape configuration, in combination with bending, that provides high sensitivity along with good linearity and resolution performance.



(a) **(b)**

Fig. 4 *(a) Bend structure with a bending diameter D; (b) 3-D print object with D-shaped structure*

3. Results and Discussion

The ideal diameters of the curved D-shape in the bent fiber optic were determined through analysis of the performance parameters: sensitivity, linearity, and output intensity. The curved D-shaped POF diameters used in this experiment were 0.5 cm, 0.75 cm, and 1.0 cm. Each fiber with a different curved diameter was tested in an oven at temperatures ranging from 30 °C to 80 °C. Fig. 5 shows the optical intensity for different curved D-shaped diameters with a fixed bending region at a temperature of 30 °C. The results indicate that increasing the diameter of the curved region leads to greater intensity losses. For further analysis, the sensitivity and linearity performance of the sensor were evaluated at the three curved diameters: 0.5 cm, 0.75 cm, and 1.0 cm.

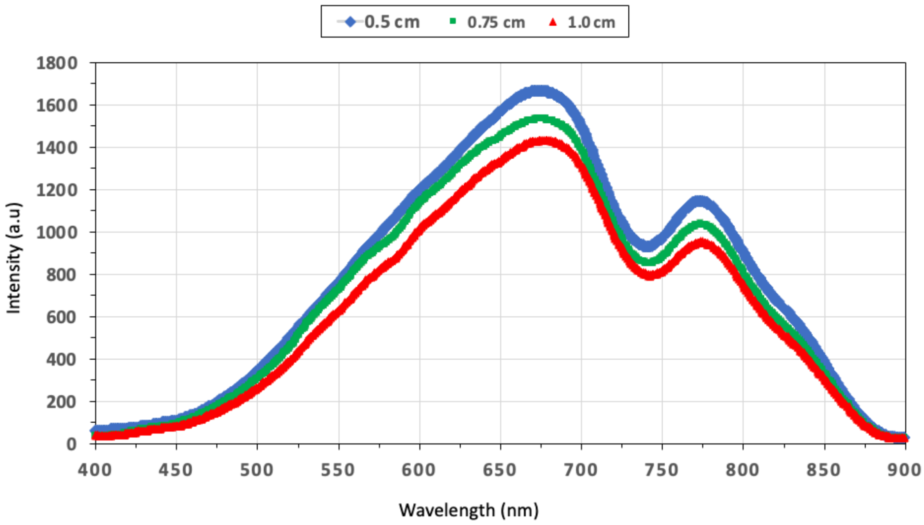
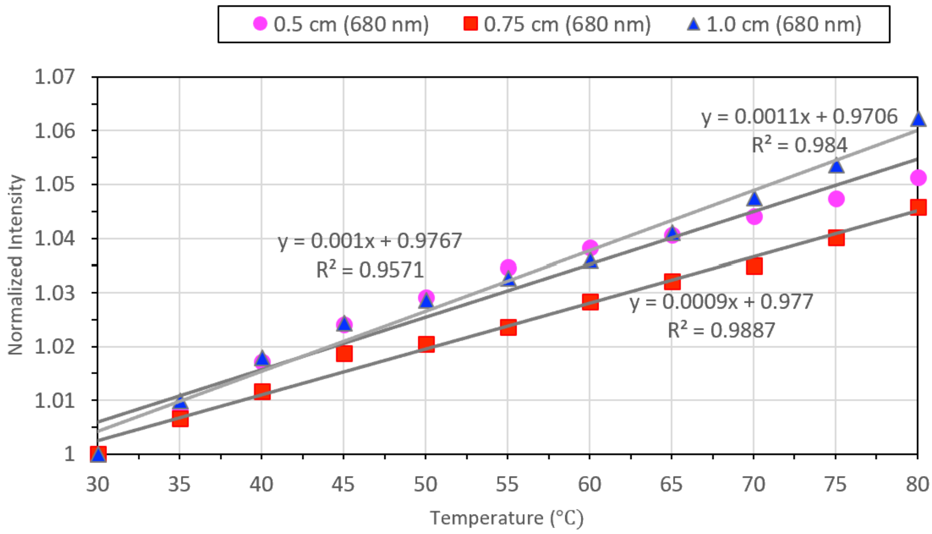
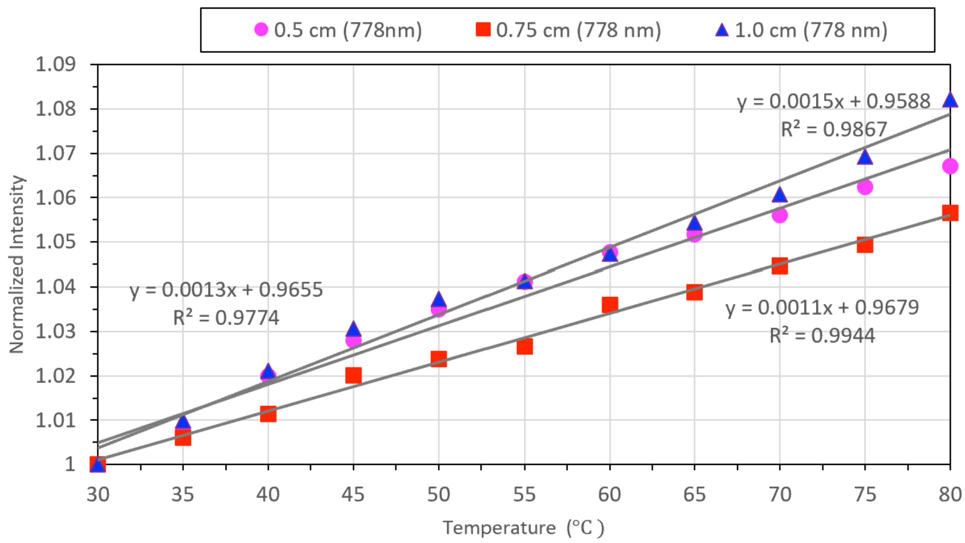


Fig. 5 *Light intensity output spectrum across varying fiber diameters*

Figs. 6(a) and 6(b) present the analysis results of the output intensity at wavelengths of 680 nm and 778 nm, respectively, for different curved diameters of the D-shaped regions over a temperature range of 30 °C to 80 °C. According to Fig. 6(a), the highest sensitivity of 0.0011 $°C^{-1}$ was achieved at a diameter of 1.0 cm, while the highest linearity (R^2 = 0.9887) was observed at 0.75 cm. In contrast, the 778 nm wavelength in Fig. 6(b) shows the highest sensitivity of 0.0015 $°C^{-1}$ at a 1.0 cm diameter, with the highest linearity (R^2 = 0.9944) found at 0.75 cm. The best sensitivity performance at both 680 nm and 778 nm wavelengths was obtained with the 1.0 cm diameter. Additionally, the sensor exhibited slightly higher sensitivity at 778 nm compared to 680 nm. Notably, the linearity at both wavelengths was excellent, with R-squared values of 0.9840 at 680 nm wavelength and 0.9867 at 778 nm wavelength. These high R^2 values, above 0.98, confirm a strong linear correlation between the output light intensity and the measured temperature.



(a)



(b)

Fig. 6 *Normalized output intensity versus temperature for multiple diameters at (a) 680 nm wavelength; and (b) 778 nm wavelength*

Fig. 7 and Fig. 8 present the analysis of sensor performance based on sensitivity and linearity, respectively, at different diameters of 0.5 cm, 0.75 cm, and 1.0 cm. The sensor exhibited a sensitivity of 0.0011 $°C^{-1}$ at a wavelength of 680 nm, while the measured sensitivity at 778 nm was slightly higher at 0.0015 $°C^{-1}$. Both tests demonstrated that a bent optical fiber with a D-shaped POF of 1.0 cm diameter provided optimal sensitivity performance.

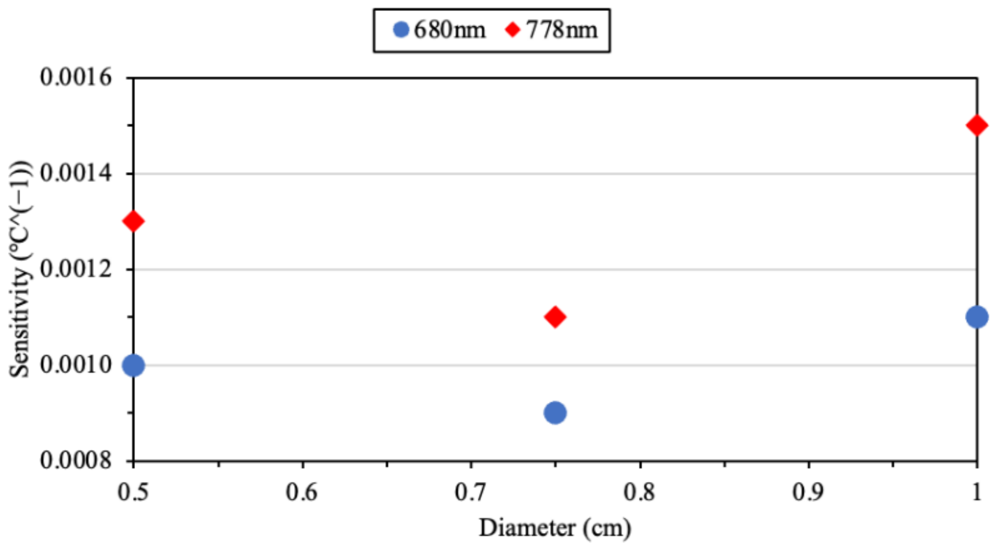


Fig. 7 *Performance analysis for sensitivity at wavelengths of 680 nm and 778 nm*

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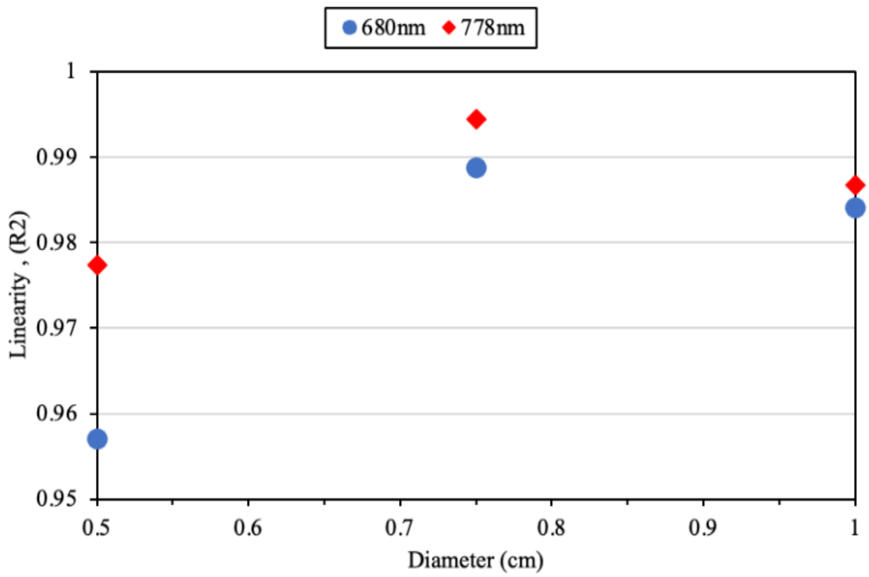

Fig. 8 *Analysis of linearity performance at wavelengths of 680 nm and 778 nm*

Prior to the earlier investigation result, a wavelength of 778nm is used in the subsequent investigations of sensor performance due to its lower optical loss and better sensitivity compared to 680 nm. In this research work, the sensor achieved a resolution of 6.67 °C, calculated using mathematical formula as follows [29];

$$Resolution = \frac{N}{Sensitivity} \quad (1)$$

where the smallest scale of the spectrometer is represented by N, 0.01, and sensitivity is attained from the earlier analysis presented in Fig.6(a) and (b). Fig.9 shows the output resolution at different diameters of D-curved for wavelength 680nm and 778nm. In accordance with the formula, higher sensitivity leads to a lower resolution value. Since, the resolution of a sensor implies the smallest change in temperature it can reliably measure, hence it is best to obtain a lower (better) resolution value. Performances of the sensor for each diameter is tabulated in Table 2.

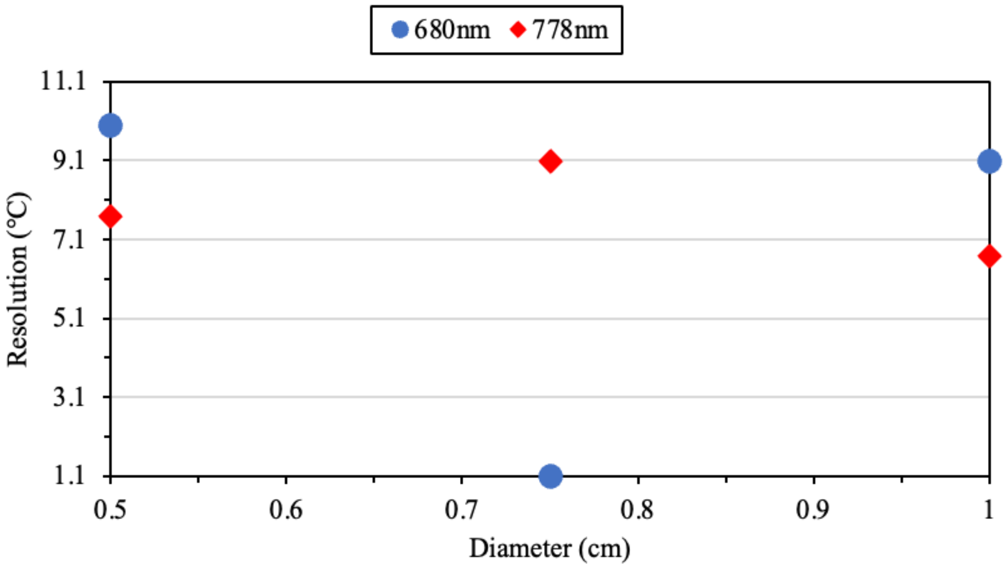

Fig. 9 *Output resolution with various diameter*

Table 2 *Sensor performance at 680 nm and 778 nm operating wavelength*

Wavelength (nm)	Diameter (cm)	Sensitivity $(^oC)^{-1}$	Linearity, R^2	Resolution (^{o}C)
680	0.5	0.001	0.9571	10
	0.75	0.0009	0.9887	1.1
	1.0	0.0011	0.984	9.09
778	0.5	0.0013	0.9774	7.69
	0.75	0.0011	0.9944	9.09
	1.0	0.0015	0.9867	6.67

This study includes three separate repetitions of the experiment, labeled as Experiment 1 (Exp 1), Experiment 2 (Exp 2), and Experiment 3 (Exp 3). Each repetition produces a corresponding dataset representing the first, second, and third trials. The results from these trials are illustrated in the graph presented in Fig. 10. Furthermore, the Relative Standard Deviation (RSD) is determined based on the data from the repeated experiments and is displayed in Fig. 11. RSD is calculated as the ratio between the standard deviation (σ) and the mean (μ), as defined by the equation shown in Equation (2).

$$RSD = \frac{Standard\ deviation, \sigma}{Mean, \mu} \text{ x } 100 \quad (2)$$

According to the results obtained, the minimum RSD value is 0.29%, while the maximum RSD value is 0.37%, observed at 40 °C and 65 °C, respectively. This results in a difference of 0.08% between the maximum and minimum RSD values. Based on the RSD analysis, it can be concluded that this research provides precise measurement data, as indicated by the low RSD values, which reflect minimal data dispersion [30].

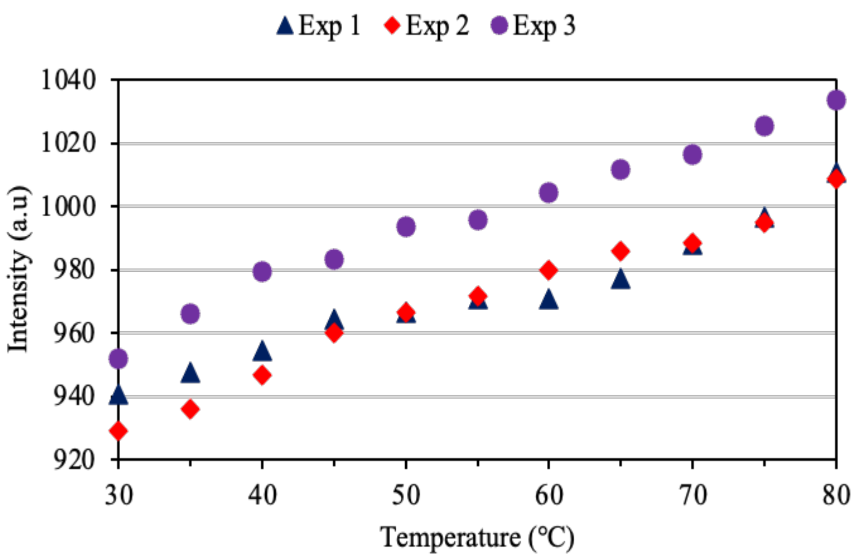

Fig. 10 *Output intensity against temperature variation for sensor with 1.0 cm diameter operating at 778nm wavelength*

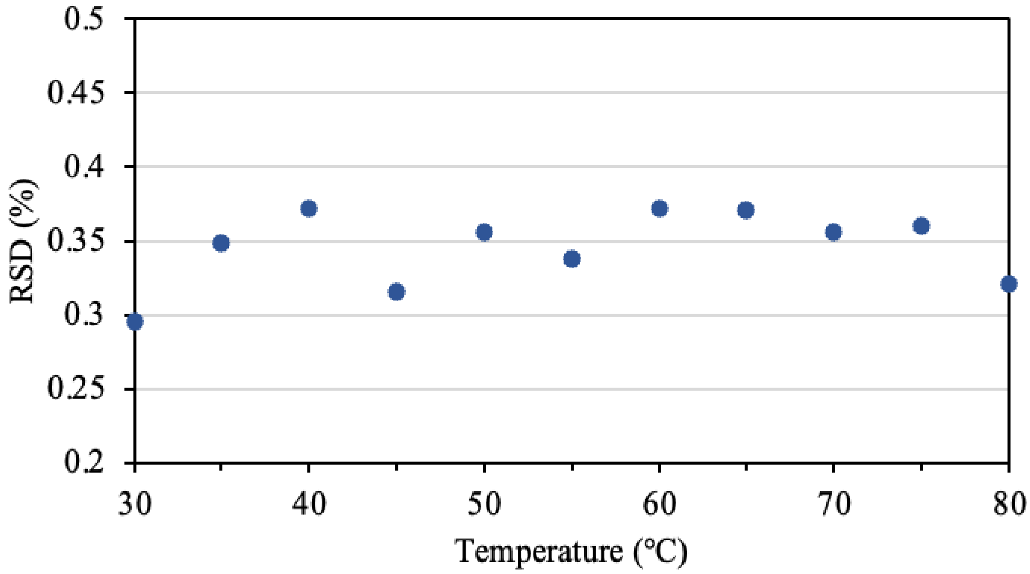

Fig. 11 *Calculated RSD for sensor with 1.0 cm diameter operating at 778 nm wavelength*

In addition, a comparison of the sensor's performance parameters with those reported in previous studies is presented in Table 3. Based on the results, this work demonstrates a good balance of sensitivity, temperature range, and reliability. Although some designs exhibit higher sensitivity, the proposed sensor covers a broad temperature range from 30 to 80 °C, shows strong linearity with an R^2 value of 0.9867, and achieves a resolution of 6.67 °C. It also ensures reliable and repeatable measurements, as indicated by a low relative standard deviation of 0.37%. Overall, the proposed sensor provides a practical and stable solution for temperature sensing, making it a strong alternative to existing methods.

Table 3 *Comparison of sensor performances with previous studies*

Reference	Sensitivity (°C)$^{-1}$	Temp range (°C)	Linearity, R^2	Resolution (°C)	RSD (%)
Balloon-bent [21]	22.2×10^{-3}	40 - 80	0.9900	0.45	-
Macro bend [16]	1.92×10^{-3}	27.2 - 50.2	0.9940	< 0.3	-
Macro bend [22]	0.895×10^{-3}	-55 - 70	0.9950	-	-
Macro bend [23]	7.3×10^{-3}	35 - 50	0.9925	-	-
Loop [24]	27.3×10^{-3}	33 - 55	0.9956	-	-
Bundle [25]	6.4×10^{-3}	40 -75	0.9500	1.56	-
D-shape with U-bend [27]	1.04×10^{-3}	25- 100	0.9940	-	-
D-shape with Balloon-like bend [This work]	1.5×10^{-3}	30 - 80	0.9867	6.67	0.37

4. Conclusion

In conclusion, the use of a bent fiber optic with a D-shaped structure for temperature measurement has been demonstrated as an effective approach. In this study, sensors with D-shaped region diameters of 0.5 cm, 0.75 cm, and 1.0 cm were tested at temperatures ranging from 30 °C to 80 °C. The sensor exhibited a sensitivity of 0.0011 $°C^{-1}$ at a wavelength of 680 nm, while the sensitivity at 778 nm was slightly higher at 0.0015 $°C^{-1}$. Both tests revealed that a bent optical fiber with a 1.0 cm D-shaped POF provided optimal performance, with sensitivity and linearity greater than 0.98, indicating a strong linear correlation between output light intensity and temperature. The bent D-shaped POF sensor offers several advantages, including ease of fabrication, low cost, and structural simplicity. Experimental results without coating have demonstrated its potential as a reliable and sensitive device for temperature measurement. For future work, additional coatings will be applied to the sensor head to further enhance performance, particularly in terms of sensitivity. The coated sensor will also be evaluated using a dual-wavelength operating method to improve accuracy in temperature detection.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nazrah Ilyana Sulaiman, Nor Hafizah Ngajikin, Noran Azizan Cholan;* ***data collection:*** *Nazrah Ilyana Sulaiman, Nurfatihah Che Abd Rashid;* ***analysis and interpretation of results:*** *Muhammad Zakir Md Yassin, Siti Hajar Aminah Ali, Maslina Yaacob;* ***draft manuscript preparation:*** *Nazrah Ilyana Sulaiman. All authors reviewed the results and approved the final version of the manuscript.*

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