Polymer Optical Fibre Temperature Sensors - A Review

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Author’s contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/AJR2P/2020/v3i330121

Editor(s):
(1) Dr. Khalil Kassmi, Mohamed Premier University, Morocco.
(2) Dr. Jelena Purenovic, Kragujevac University, Serbia.
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Complete Peer review History: http://www.sdiarticle4.com/review-history/57711

Received 22 May 2020
Accepted 28 July 2020
Published 22 August 2020

ABSTRACT

Polymer optical fibre (POF) temperature sensors are rapidly replacing conventional temperature sensors owing to their unique and attractive features, such as small size, immunity to electromagnetic interference, multiplexing, and remote sensing capabilities. The recent developments in temperature sensing using polymer optical fibres are presented. Polymer optical fibre (POF) temperature sensors of various types: macro-bend fibre sensors, microfibre resonators, fibre Bragg grating, Fabry-Perot interferometers, and POF sensors coated with zinc oxide nanorods are discussed. This study also includes dual-parameter sensors to demonstrate intrinsic sensitivities of polymer fibres to temperature, relative humidity, and strain. The prospects and challenges of POF temperature sensors in the automotive industry, biomedical sector, chemical industry, and electrical power applications are also highlighted. This review aims to help researchers in this field identify areas of further work towards improving the accuracy and operating range of POF temperature sensors.

Keywords: Polymer optical fibre; temperature sensitivity; thermo-optic coefficient; thermal expansion coefficient; wavelength shift.

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1. INTRODUCTION

Polymer optical fibres (POFs) have continued to attract significant attention over silica optical fibres (SOFs) in sensing applications owing to the unique features of polymer over silica such as low Young's modulus, high elastic strain limits, high flexibility in bending, high fracture toughness and potential negative thermo-optic coefficients [1–6]. Apart from their immunity to electromagnetic interference, small size, and multiplexing capabilities – features jointly shared with SOFs – POFs are also easily handled without special care due to their toughness and durability [7]. Besides, POFs have excellent compatibility with organic materials, offering them great prospects in biomedical applications [6]. The possibility of using low precision connectors with POFs due to their large core diameters of typically 0.25 – 1 mm has effectively lowered the cost of a whole system [8].

Temperature sensors are necessary for the control of different processes in a wide range of sectors – the food industry, air-conditioning control, the automotive industry, and medical applications, amongst others [9]. The failure of conventional temperature sensors such as thermocouples, thermistors, and resistance temperature detectors, in satisfying specific requirements has spurred considerable interest in POF temperature sensors [10]. For instance, temperature measurement in the presence of electromagnetic disturbance would appropriately be carried out using POF due to its immunity to electromagnetic interference. Additionally, optical fibre-based temperature sensors are applicable in power plants or explosion-proof areas, and wherever measurement with electrical temperature sensors is not possible such as in high tension cable lines, electrical motors, airplanes, and spacecraft [11].

Several innovative techniques have been developed for temperature sensing using POF based on phase or amplitude changes of an electromagnetic wave traveling along an optical fibre produced by temperature variations [10]. The physical length and refractive index of a polymer-based fibre are intrinsically sensitive to environmental parameters such as temperature and humidity [12,13]. This feature and many others, such as light attenuation by both absorption and scattering [11], bending losses [10], and fibre Bragg grating wavelength shifts [14] have been exploited extensively by several researchers in adapting POF to temperature sensing. Simple, low-cost Fabry-Perot interferometers using polymer have also been proposed for temperature sensing [14]. The operating temperature limit for a POF temperature sensor varies between 80 and 100°C [8] but may be enhanced to 125–135°C by using a modified polyethylene or an elastomer with polyolefin coating [8].

Furthermore, polymethylmethacrylate (PMMA) fibres present humidity sensitivity due to their water absorption [15], which permits these types of POFs to act as intrinsic humidity sensors. Besides, PMMA POFs with a larger diameter (about 1 mm) are widely available commercially, and they may be employed with low-precision plastic connectors, which generally result in a lower-cost system [13]. Moreover, due to their higher numerical aperture, low-cost lasers, or light-emitting diodes (LEDs) [16] may also be used. Conventional technologies for humidity measurement include the use of materials that contract or expand with variations in humidity. However, the materials’ variations are slow and nonlinear [17]. This shortcoming can be solved by POF based sensors that offer a faster response and linear materials’ variation with humidity.

Moreover, POFs are suitable for measuring strain owing to their ductile behaviour coupled with both higher sensitivity and elastic strain limit compared to SOFs [6]. For instance, PMMA has an elastic limit of around 10%, as compared to 1–3% for silica [6]. The strain sensitivity of an optical fibre sensor can be defined as the phase change in a lightwave propagating through the optical fibre per unit length of elongation [6]. It is usually measured by subjecting the optical fibre to a pure axial strain [6]. The strain sensitivity of a PMMA POF has been theoretically predicted to be $132.6 \times 10^5$ rads m$^{-1}$ using the Pockel’s constants for bulk PMMA, which is 15% greater than that of bulk silica, $115 \times 10^5$ rads m$^{-1}$ [6]. Additionally, the thermal sensitivity of an optical fibre sensor can be defined as the phase shift in a lightwave propagating through the optical fibre per unit change in temperature per unit length of the fibre. For bulk PMMA, the thermal sensitivity has been estimated to be $-154.3$ rads m$^{-1}$ K$^{-1}$, which is both larger in magnitude than that of silica ($98.8$ rads m$^{-1}$ K$^{-1}$) and of the opposite sign. The negative thermo-optic coefficient, which is typical of some polymers, offer new possibilities for temperature compensation in strain sensors [6].
2. POF TEMPERATURE SENSORS

2.1 Macro-bend POF Temperature Sensors

The macro-bending loss resulting from the different thermo-optic coefficients of the cladding and core of a step-index POF has been demonstrated to be a vital technique for temperature sensing [10]. Compared with single-mode [18] and multi-mode silica optical fibre [19,20], POF macro-bend sensors possess a large core diameter and smaller Young modulus. This has made them less fragile and more comfortable to handle, which in turn has cut down development and maintenance costs [10].

In a macro-bend POF, the bending losses depend on the numerical aperture, which changes with temperature [10]. The macro-bend temperature sensor fabricated by Moraleda et al. [10] using a commercial step-index POF fibre with good tensile strength and flexing to provide excellent mechanical properties is shown in Fig. 1. The buffer coating was partially stripped from the middle section of the fibre length. The length of this stripped section was about 30 mm. The fibre sensor was formed by creating a single 180° loop (½ turn) with a concrete bend radius (Fig. 1). The local numerical aperture (NA) in the bent section of the fibre versus the temperature (T) can be expressed as [21]:

$$\text{NA}(T,R,\rho,\phi) = n_{\text{core}}(T) \left[ \frac{1 - n_{\text{cladding}}(T)}{n_{\text{core}}(T)} \left( \frac{R + \rho \cos \phi}{R - \rho \cos \phi} \right)^2 \right]^{1/2}$$

(1)

Where $R$ is the radius of curvature, $\rho_{\text{core}}$ is the fibre core radius, $\rho$ is the radial position in the core satisfying the relation $0 \leq \rho \leq \rho_{\text{core}}$, $\phi$ is the ray angle at the beginning of the bend, $n_{\text{core}}$ and $n_{\text{cladding}}$ are the core and cladding refractive indices, respectively. The temperature dependence of the core refractive index is given by [22]:

$$n_{\text{core}}(T) = n_{\text{core}}(0) - A \cdot T + B \cdot T^2$$

Where $n_{\text{core}}(0)$ is the core refractive index at a reference temperature, $A$ and $B$ are temperature coefficients.
Fig. 1. A macro-bend POF sensor (a) the schematic diagram (b) the photograph [10]

Fig. 2. The numerical aperture versus temperature for several radial positions in the core [10]

\[ n_{\text{core}}(T) = K_2 T^2 + K_1 T + n_0 \]  \hspace{1cm} (2)

where \( K_1 \) is the thermo-optic coefficient of the core measured in \(^\circ\text{C}^{-1} \), \( K_2 \) is the second-order temperature dependence term of the core measured in \(^\circ\text{C}^{-2} \), and \( n_0 \) is the core refractive index at 0 \(^\circ\text{C} \). The temperature dependence of the cladding refractive index is given by [23]:

\[ n_{\text{cladding}}(T) = n_{\text{cladding}}(T_0) + K_3 (T - T_0) \]  \hspace{1cm} (3)

where \( K_3 \) is the thermo-optic coefficient of the cladding, and \( n_{\text{cladding}}(T_0) \) is the cladding refractive index at the reference temperature (\( T_0 = 25 \, ^\circ\text{C} \)). Fig. 2 shows the numerical aperture versus temperature for several radial positions in the core with \( 2p_{\text{core}} = 980 \, \mu\text{m} \), \( R = 2.0 \, \text{mm} \) and \( \phi = 150^\circ \). The positive slope of the curves for each radial position shows that the local numerical aperture increases as the applied temperature increases.

The macro-bend POF sensor was tested in the temperature range from +27.2 \(^\circ\text{C} \) to +50.2 \(^\circ\text{C} \) by placing a hot plate (LTS350, Linkam, Surrey,
United Kingdom) at 1 mm from the sensor. An excellent linear response versus temperature was observed at the bend radii of 1.5 and 2.0 mm. Sensitivities of $1.81 \times 10^{-3}$ and $1.92 \times 10^{-3}$ $^\circ C^{-1}$ were recorded for bend radii of 1.5 and 2.0 mm, respectively. It was also observed that the sensitivity of the macro-bend POF sensor increases with an increase in the radius of curvature [10]. The sensor is suitable in a wide range of applications, such as the instrumentation process, automotive industry, air-conditioning control, chemical industry, biomedical sector, and detection of metal particles in contaminated fluids.

Furthermore, Tapetado et al. [24] designed and characterised a self-reference, low-cost, intensity macro-bend temperature sensor based on POF. The sensor system was based on the ratio of the output transmittances at two different wavelengths in a single macro-bend sensor to avoid possible errors related to undesired optical power fluctuations [25]. In this intensity sensor, the losses depend on the NA change with the core and cladding refractive index variations [24]. The refractive indexes, in turn, are dependent on the temperature and the wavelength [24]. Also, at a given temperature, the local NA decreases as the wavelength increases. In addition, the local NA increases with the temperature since an optical ray that is unguided at the reference temperature becomes guided at higher temperatures. Conversely, the NA temperature sensitivity increases when a bend is applied to the optical fibre. The optical fibre used by the authors comprised a step-index POF [26] with PMMA 980 μm core diameter and 1mm cladding diameter of fluorinated polymer. The schematic of the experimental setup for characterizing the POF temperature sensor is shown in Fig. 3. The sensor can operate in a temperature range from -55 to 70°C. Temperature sensitivity and linear regression coefficient of $8.95 \times 10^{-4}$ nm/°C and 99.5%, respectively, were obtained for the measured calibration curve from 27 to 70°C. The proposed temperature sensor is a top candidate for biomedical applications. Besides, it is well suited for monitoring the temperature of an electrical power transformer where the use of traditional sensors is restricted by the presence of electromagnetic interferences [27]. Hence, the use of a macro-bend temperature sensor could mitigate the breakdown and explosion of electrical power transformers due to overheating during hot climatic conditions. A significant challenge limiting the accuracy of this device is the significant contribution of the spectrometer to the system error. This can be overcome by utilising a spectrometer that offers more excellent intensity resolution coupled with higher sensitivity [24].

Tian et al. [28] developed a temperature sensor with high sensitivity using a balloon-shaped bent single-mode (BSBS) fibre structure. The BSBS fibre structure comprised a length of unstripped single-mode fibre (SMF), and a capillary tube was used in bending the length of SMF into a balloon shape. The proposed sensor outperformed the uncoated BSBS fibre structure in terms of temperature sensing due to the high thermo-optical coefficient (TOC) and thermal expansion coefficient (TEC) of the polymer coating. The temperature sensitivity of the BSBS fibre structure was significantly improved to over 2465 pm°C$^{-1}$. A resolution of 0.008°C over the temperature range of 20.7–31.7°C was recorded for the proposed device, which was the best resolution compared with the ones reported in literatures [29–34]. The BSBS fibre structure is highly suitable for accurate temperature measurement founded on its high sensitivity, excellent repeatability, ultra-low-cost, and straightforward fabrication process.

Fig. 3. Schematic of the experimental setup for characterizing the POF temperature sensor [24]
2.2 Microfibre Resonator Temperature Sensors

Microfibre resonators have demonstrated great potential in temperature sensing [35] because of their high sensitivity, extensive coupling capability, and compact size [36]. It has been reported that evanescent wave propagating through the fibre surface of microfibre resonators interact effectively with the adjacent environment [37]. Therefore, the transmission spectrum of the resonance light is subject to variations in the outer environment [37]. This unique feature of microfibre resonators can be exploited for sensing applications. The microfibre ring normally splits the light into two parts and produces the resonance enhancement effect [38]. One part of light resonates in the ring fibre and builds a harmonic electromagnetic field, while the other part transmits along the bus fibre directly and couples with the resonating light [38].

The resonance frequency is determined by the condition [38]:

\[ m\lambda_m = 2\pi Rn_{\text{eff}} \]  \hspace{1cm} (4)

where \( m \) is the resonant mode number, \( \lambda_m \) is the resonant wavelength, \( R \) is the radius of the microfibre ring, and \( n_{\text{eff}} \) is the effective index of the microfibre. The free spectral range (FSR), also known as resonant wavelength spacing, is given by [38]:

\[ \text{FSR} \approx \frac{\lambda^2}{2\pi R n_{\text{eff}}} \approx \frac{\lambda^2}{n_g L}, \]  \hspace{1cm} (5)

where \( \lambda \) is the wavelength, \( n_g \) is the mode propagating index in the microfibre, and \( L \) is the loop length. When the external temperature changes, the loop length \( L \) and mode propagating index \( n_g \) vary accordingly, results in the peak shift of resonant wavelength. The relative variation can be expressed as [38]:

\[ \frac{\Delta \lambda}{\lambda} = \frac{\Delta L}{L} + \frac{\Delta n_g}{n_g} + \alpha_s + \frac{1}{n_g} \frac{\Delta n_p}{n_p} \frac{\Delta T}{T}, \]  \hspace{1cm} (6)

where \( \alpha_s \) and \( \alpha_p \) are the thermal expansion coefficients of microfibre and polydimethylsiloxane (PDMS) respectively. Here, \( \alpha_s \) can be ignored because \( \alpha_s \) and \( \alpha_p \) are \( \sim 5.5 \times 10^{-7} \) and \( \sim 3 \times 10^{-5} \), respectively; \( \frac{\Delta n_g}{n_g} \frac{\Delta T}{T} \) and \( \frac{\Delta n_p}{n_p} \frac{\Delta T}{T} \) are the thermo-optic coefficients of microfibre and PDMS, which are \( \sim 1.1 \times 10^{-5} \) \( ^\circ \text{C}^{-1} \) and \( \sim 5 \times 10^{-4} \) \( ^\circ \text{C}^{-1} \), respectively.

High-performance temperature sensors with sensing mechanism based on the dependence of the resonant wavelength on the temperature of the MKR have been reported. Li et al. [38] designed a high sensitivity temperature sensor based on MKR encapsulated by PDMS film. The excellent performance of the device was attributed to the high thermo-optic and thermal expansion coefficients of PDMS, which shifted the resonant wavelength in response to the variation in temperature [38]. The experiment results obtained indicated that the PDMS-packaged MKR structure exhibited excellent linearity and high sensitivity of 1.408 nm/°C in the range of 24–38°C. The proposed temperature sensor has excellent potential for observing the air condition stability and organism owing to its outstanding performance and simple fabrication process [38]. However, a sharp decrease in linearity and a relatively lower sensitivity of 0.973 nm/°C was observed at a higher temperature range of 40–54 °C caused by the thermal expansion effect of PDMS. This challenge can be overcome by coating another transition film on the PDMS with excellent thermal expansion properties, such as graphene [37], to increase the operating range [38].

Furthermore, Fan et al. [39] reported a temperature sensor fabricated using MKR packaged by PDMS with high sensitivity and excellent stability. The MKR structure was sandwiched by two glass slides and encapsulated by PDMS, whose thickness was controlled as 0.66 mm by two Teflon tubes. In the range of 20–70°C, the temperature sensor recorded a high sensitivity of 1.67 nm/°C, which is more than nine times that of bare MKR (183 pm/ °C). Hence, the PDMS film enhanced the temperature sensitivity of silica MKR structure. It also supports the fragile MKR to improve its stability and extend its service life [39]. The proposed sensor is applicable for precisely monitoring temperature fluctuation owing to its high sensitivity and miniature slice structure [39].

Moreover, several researchers have demonstrated that the sensitivity of optical fibre temperature sensors can be upgraded by coating the fibres with thermally-sensitive materials: graphene, titanium dioxide (TiO2), and reduced graphene oxide (rGO) [40–42]. However, the temperature sensitivities reported for these coated-fibre sensors were relatively low due to poor contact made by the thermally sensitive materials. This problem was investigated by Wang et al. [43] through the fabrication of a
highly efficient temperature sensor using MKR bundled by PDMS-graphene pliable composite film (PGF). The PDMS enabled close contact between the thermally sensitive material and the fibre, thereby enhancing the sensor sensitivity [43]. Fig. 4a shows a schematic of the sensor system. The MKR was sandwiched between two PGFs with both ends of the MKR fixed on the MgF$_2$ coated silicon substrate. Fig. 4b shows a photographic image of the fabricated device. Fig. 4c shows an enlarged picture of the MKR carefully enfolded by two pieces of PGF, producing a compact and stable sandwich structure with a diameter of $\sim$0.185 mm.

The experimental results obtained showed that the extinction ratio (ER) decreased from 8.3 to 3.05 dB as the temperature rises from 30 to 60 °C (Fig. 5a), producing a high-temperature sensitivity of $-0.174$ dB °C$^{-1}$. Besides, the optical loss increases as the MKR diameter decreases [43]. Hence, the critical coupling condition can be achieved by reducing the diameter of MKR during the production process [43]. Additionally, the experimental results in Fig. 5b display a shift of resonant wavelength to shorter wavelength region because of the temperature variation in three experiments. The resonant wavelength shifted from 1547.8 to 1531.8 nm when the temperature rises from 30 to 60 °C, giving a high-temperature sensitivity of $-0.533$ nm °C$^{-1}$. The blue shift of resonant wavelength was attributed to the large and negative thermo-optic coefficients of PDMS [43,44].

The sensing device exhibited a high sensitivity of 0.544 dB °C$^{-1}$ over the temperature range of 30–60°C. This outstanding performance was credited to the exceptional thermal properties of graphene and PDMS. Besides, the extinction ratio (ER) displayed a greater temperature sensitivity ($>0.174$ dB °C$^{-1}$) compared to the previous result (0.043 dB °C$^{-1}$) reported [43]. Some of the merits of this novel temperature sensor include ultra-compactness, high sensitivity, corrosion resistance, robustness, and good stability, which offer it a great potential for data centre temperature detection [43].

Fig. 4. (a) Schematic of the PGF-filled MKR structure. (b) Picture of the fabricated device. (c) A magnified image of the MKR enclosed by two pieces of PGF [37]

Fig. 5 (a) The ER of transmission spectra with different temperatures. (b) The wavelength of transmission spectra at different temperatures [43]
spectral evolution of transmitted light, as the LP11 (1554.0 nm) modes. Fig. 6a displays the corresponding to the LP01 (1558.5 nm) mode fibre with two transmission dips simulated using FEM. The simulated results were dispersion, and PW modal properties were fabricated in the SMF to calibrate PW material resonance in the transmission spectrum. A silica tube spliced between two single laser power produced an obvious Bragg ced an obvious Bragg grating (FBGs), which ced an obvious Bragg grating (FBGs), which ced an obvious Bragg grating (FBGs), which Fig. 6a displayed the spectral evolution of transmitted light, as the ambient temperature increased from 24°C to 40°C. The blue shift in the Bragg resonant wavelength was evident in this process. The attenuation of the sensor system rapidly grew higher which can be attributed to the reduced refractive index of polymer as temperature rises. A linear POFBG thermal response was achieved with a high sensitivity of -220 pm/°C over a temperature range of 24°C to 40°C as shown in Fig. 6b. This is 20 times higher than that of pure silica FBG and higher than previous reports on POFBGs [45].

The maximum operating temperature of the device was experimentally determined to be 80°C since the $T_g$ of the used resin was $\sim$100°C. This enhanced temperature sensitivity was attributed to the high TOC of the utilised polymer and fully suspended polymer structure [44]. Moreover, this all-in-fibre POFBG exhibited excellent mechanical strength, exceptional temperature sensitivity, and ultra-high integration, making it suitable for biosensing applications [44]. However, the proposed POFBG exhibited cross-sensitivity to humidity (-36 pm / % RH) which can be overcome by using a glass tube package.

Furthermore, owing to their strong affinity to water, PMMA based POFBGs are used for developing humidity sensors as the absorption or desorption of moisture leads to a change in refractive index and size of the fibre, both of which contribute to a change in Bragg wavelength [1]. However, PMMA based POFBGs suffer from strong cross-sensitivity to humidity when they are used to develop strain and temperature sensors. To avoid such cross-sensitivity to humidity, POFBGs made from a different class of polymers called cyclo-olefin copolymers, such as Topas grade 8007, and
5013, have been used as they have very low affinity to water [1]. Besides, cyclo-olefin copolymers have good chemical inertness to bases and acids, and many polar solvents as compared to the conventional PMMA based POFs [1]. Woyessa et al. [1] fabricated and characterised a Zeonex microstructured POF (mPOF) for high-temperature measurement using humidity insensitive Bragg grating. The mPOF was fabricated from cyclo-olefin homopolymer Zeonex grade 480R with a markedly high glass transition temperature $T_g$ of 138°C and insensitivity to humidity. The benefits offered by Zeonex fibres over humidity insensitive Topas core fibres include higher temperature sensitivity, better transmittance, ease of manufacturing, and better mechanical stability at high temperatures. Fibre Bragg gratings (FBGs) were also inscribed and characterised in Zeonex mPOFs in the low loss 850 nm spectral band. The temperature sensor possessed a sensitivity of 24.01±0.1 pm/°C over the temperature range of 20–100°C. Zeonex mPOFBG showed better temperature sensitivity compared to TOPAS 5013 mPOFBG [46]. The fibre Bragg gratings inscribed in Zeonex mPOFs are applicable in the automotive and composite materials, which require mechanical stability at high temperatures and very low moisture absorption.

2.4 Fabry-Perot Interferometer Temperature Sensors

Fibre sensors in a Fabry-Perot configuration are the simplest and easiest to fabricate [47]. The implementation of Fabry-Perot cavities (FPCs) on the tip of an optical fibre, for sensing temperature for example, is appealing since they combine low cost fabrication, microscopic size, and high sensitivity [14]. The thermo-optic properties of the cavity are usually exploited in FP interferometer temperature sensors – temperature induces a shift of the interference pattern. However, in most FPCs, a large temperature change is required to produce a measurable interference pattern shift owing to their small TOC (6.3x10$^{-4}$/°C) [48]. The low thermal sensitivity makes FPCs unattractive for biological applications where temperature range of interest is 20 – 60°C [14]. This limitation can be overcome by utilising polymers with large TOCs resulting in high sensitivities such as PDMS, NOA 61 (Norland optical adhesive 61), and NOA 65 whose TOCs are −4.66x10$^{-4}$/°C [49], −1.7x10$^{-4}$/°C [50], and −1.83x10$^{-3}$/°C [51], respectively.

Hernandez-Romano et al. [14] proposed a simple, cost-effective, and highly accurate temperature sensor using a single-mode fibre Fabry-Perot microcavity coated with PDMS polymer. The Fabry-Perot microcavity was fabricated by an internal mirror produced from a thin titanium dioxide (TiO$_2$) film. The reflectance of the interface between the fibre core and the PDMS varied strongly with temperature caused by the high TOC of PDMS polymer. The sensor exhibited a high-temperature sensitivity of 0.13 dB/°C over the range of 20–65°C. The proposed microscopic device is applicable for monitoring temperature in biological and microchannel structures [52]. A significant drawback of the device is the inaccurate monitoring of the extinction ratio, which depends on the selection of peaks and dips. However, a more accurate method suggested by the authors is to analyze the interference patterns using the Fast Fourier Transform to obtain information on the phase, frequency, and amplitude of the interference patterns.

Furthermore, Li et al. [53] designed a high sensitivity, miniature Fabry-Perot temperature probe comprising a microfibre and SMF tip in one cut of hollow-core fibre (HCF), both encapsulated by temperature-sensitive PDMS. The microfibre tip and a common SMF end served as the two reflectors of the Fabry-Perot interferometer. Fig. 7 shows the schematic of the microfibre and PDMS-based Fabry-Perot interferometer temperature sensor. An amplified stimulated emission (ASE) produced the light, which was launched into the Fabry-Perot interferometer temperature probe through a coupler. The reflected optical signal was collected by an optical spectrum analyser (OSA). The temperature probe was placed in a thermostat (25–250°C, resolution 0.1°C). Temperature sensitivity of higher than 10 nm/°C over the range 43–50°C was experimentally obtained from the device with the microfibre diameter of ~63 nm and cavity length of ~34 nm. A reduction in the cavity length to ~31 nm yielded the highest sensitivity of 11.86 nm/°C with excellent repeatability and stability. The authors compared the sensitivity of the proposed optical fibre temperature sensor to other fibre temperature sensors reported in recent years and discovered that the sensitivity of the proposed temperature sensor was higher than most other temperature sensors. The fabricated Fabry-Perot temperature sensor has excellent potentials for accurate monitoring of temperature fluctuations in food...
storage, industrial production, and biochemical reaction processes [53].

2.5 POF Temperature Sensor with Zinc Oxide Nanorod Coating

Most optical sensing applications operate with laser light source by launching light from one end of the optical fibre and output signal is collected from other end [54]. This is more complex and often expensive due to the need of coupling the light in the optical fibre to align the laser beam [11]. To overcome this challenge, Rahim et al. [11] proposed a POF temperature sensor fabricated by light side coupling through spirally patterned zinc oxide (ZnO) nanorods coated directly on POF. The POF based temperature sensor can utilize ambient light coupled through the nanorods into the fibres for sensing. The spirally patterned ZnO nanorod coating compared to unpatterned POF’s had an increased coupling of the light source due to the higher interfacial ZnO regions on the POF [55]. A linear relationship has been reported between the absorptivity of ZnO and temperature [56]. Likewise, the refractive index of ZnO coating layer was observed to change with temperature [57]. The sensing mechanism of the temperature sensor was based on the attenuation of light by scattering and absorption as it navigates through the ZnO nanorods, as shown in Fig. 8. A relative reduction in the light scattering was observed as the temperature and light absorption in the ZnO nanorods coating were increased. Thus, the intensity of guided light inside the POF decreased owing to lower light coupling.

Fig. 7. Schematic of the microfibre and PDMS-based Fabry-Perot interferometer temperature sensor [53]

Fig. 8. The temperature sensing mechanism (a) before illumination (b) upon illumination and (c) aluminium rod near ZnO nanorods coating layer (adapted from [11], copyright (2017), with permission from Elsevier)
The real-time responses of the spirally patterned and unpatterned ZnO nanorods coated POFs to temperature variation from 20°C to 100°C under visible light illumination were examined. The output voltage of the two coated POFs varied with the temperature. However, a higher sensitivity of 0.0623 mV/°C was recorded for the spirally patterned coated POF. In comparison, the sensitivity of the unpatterned coated POF decreased to 0.0484 mV/°C. The higher sensitivity of the spirally patterned POF is traceable to the contribution by the uncoated polymer regions to optical loss and which is temperature-dependent [11,58,59]. Based on the sensitivity results, the use of the spirally patterned coatings improved the sensitivity of the temperature sensor by a factor of 1.3 compared to POFs with continuous coating. These temperature sensors are suitable for environmental and biomedical applications [60,61] due to their simple fabrication process and sensitive detection of temperature changes using a visible light source.

3. DUAL-PARAMETER POF BASED SENSORS

Several dual-parameter POF sensors for the simultaneous measurement of temperature and other parameters such as RH and strain have been developed.

3.1 Temperature and Humidity POF Sensors

Temperature and humidity monitoring are essential in applications such as structural health monitoring (SHM) and pharmaceutical, medical, and food processing and storage [62]. For instance, in wearable robotics, the measurement of temperature and humidity is applied to monitor the microclimate conditions between human skin and the robotic device [62]. Leal-Junior et al. [62] developed a low-cost system capable of measuring temperature and RH using POF sensors. The sensing mechanism was based on the variations of the Young's and shear moduli of the POF with variations in temperature and RH. The system comprised two POFs, each with predefined torsion stress that resulted in a variation in the fibre refractive index due to the stress-optic effect [63]. The variation in the refractive index leads to a variation in the POF's output power. The commercial POFs employed for the sensor system comprised a PMMA core with a diameter of 0.98 mm, a cladding of 20 µm thickness made of a fluorinated polymer, and a polyethylene coating with a diameter of 2.2 mm that is also characterized by the temperature dependency of its mechanical properties [64]. The experimental setup presented in Fig. 9 was positioned inside a climatic chamber with a closed-loop temperature controller for the temperature characterization of the POF sensors. Different torques were applied to the fibre to characterise their influence on the POF's output power and to enhance the fibre's sensitivity to temperature and RH variations. The torque was applied by rotating the fibre in a predefined torsion angle in the directions shown in Fig. 9.

The experimental results showed the output power (measured in volt) increased with temperature for both sensors. The results of the characterization for both POF sensors and the linear regression of their responses for the temperature and relative humidity tests (in the range of 24–44°C and 10–70%, respectively) are displayed in Fig. 10. The sensitivities of Sensor 2 to the humidity and temperature variations were about 70% and 54% higher than those of Sensor 1. The higher temperature sensitivity of Sensor 2 could be traced to its higher lateral section depth, which caused an increase in the stress-optic effect variation due to the temperature effects on the POF's material properties. A key challenge of this sensor system is the significant variations in the sensors' torques, which can cause changes in the sensors' performance. Nonetheless, the variations can be minimised by protecting the sensing regions of the fibres with a metal coating.

Chen et al. [65] demonstrated agarose coated macro-bend fibre (AC-MBF) sensor for temperature and RH measurement at 2 µm wavelength region. It has been reported that agarose gel outperformed other hygroscopic materials in response time and a wide dynamic range of RH [66,67]. The proposed sensor exploited the strong light absorption of agarose [68] and the weaker optical field confinement of the waveguide at 2 µm. Additionally, the existence of a robust humidity-based wavelength shift at 2 µm region was also utilised to enhance RH sensing capability of the AC-MBF sensor. The experimental results obtained showed that the AC-MBF sensor possessed a nearly linear response to both temperature and RH with maximum sensitivities of 5.37 nm/°C for temperature varying between 20 and 50°C, and 314 pm/%RH for humidity in the range of 40–95%, which are much higher than other sensors.
at 1.5 μm. Besides, the AC-MBF sensor recorded fast response time and recovery time of ~300 ms and 600 ms, respectively. The response time for the sensor is more rapid than those reported in previous publications, such as 5 s in [69], and 0.63 s in [70]. Additionally, the proposed sensor was demonstrated to be applicable for continuous human breath measurement. The intensity-modulated sensor is a low-cost device with a simple structure. However, it is susceptible to power fluctuations of the light source [65].

![Experimental setup for POF temperature and humidity sensor tests](image)

**Fig. 9.** Experimental setup for POF temperature and humidity sensor tests [62]

![Relative humidity and temperature characterizations](image)

**Fig. 10.** (a) Relative humidity and (b) temperature characterizations of stress-induced optical effect POF sensors [62]
Moreover, Oliveira et al. [71] fabricated a dual fibre sensor consisting of a Fabry–Perot (FP) cavity made of NOA 78 and a POFBG for measuring temperature and humidity simultaneously. The FP cavity was produced using a revised version of the light-induced self-written waveguide technology [72,73], by adopting a no-core fibre as a UV light transporting fibre. This fabrication technique enabled the formation of an FP cavity with specific dimensions, thereby solving the reproducibility problems associated with FP sensors. The POFBG was written in a specially designed flat sides PMMA mPOF to decrease the humidity response time of the sensor. The temperature and humidity resolutions of the sensing scheme were below 0.2°C and 0.2% RH, respectively, which are below those of other optical fibre sensors reported in literatures [74–79]. However, the response time of the proposed sensors for increasing and decreasing humidity was much higher than those reported in literatures [74–79] due to the large amount of polymer material used for the construction of the FP cavity. The proposed sensor is well suited for the simultaneous measurement of temperature and humidity with high resolution.

### 3.2 Temperature and Strain POF Sensors

The concept of sensitivity differentiation – a solution to the technical issue of cross-sensitivity in FBG sensors – has been utilised in diverse configurations for the simultaneous measurements of strain and temperature [80]. Bhowmik et al. [80] demonstrated a novel sensing configuration for measuring temperature and strain simultaneously with enhanced intrinsic sensitivity based on a fibre Bragg grating pair, with one grating in the etched and the other in un-etched region of polymer fibre. A PMMA-based single-mode polymer fibre was etched to different diameters to alter the material properties of the fibre – Young's modulus and TOC [80]. The temperature and strain responses of the FBGs written on etched fibre are different from those of FBG on unetched fibre due to different Young’s modulus of the fibres. Thus, strain and temperature change were measured by utilising the characterisation matrix given by:

$$\left[ \frac{\Delta \epsilon}{\Delta T} \right] = \frac{1}{K_{e1}K_{ST} - K_{e2}K_{IT}} \begin{bmatrix} K_{ST} & -K_{IT} \\ -K_{e2} & K_{e1} \end{bmatrix} \begin{bmatrix} \Delta \lambda_1 \\ \Delta \lambda_2 \end{bmatrix}$$

(10)

where $\Delta \lambda_1$ and $\Delta \lambda_2$ are the net wavelength shift and $K_{e1}$, $K_{IT}$ and $K_{e2}$, $K_{ST}$ are the strain and temperature sensitivities of the un-etched and etched POFBG, respectively. Hence, by exploiting their different strain and temperature sensitivities and using this simple configuration, the strain and temperature were simultaneously measured with very high sensitivity.

The experimental results showed that the etched 105 μm polymer FBG recorded a higher temperature sensitivity of $-133$ pm/°C than a 185 μm un-etched polymer FBG with a temperature sensitivity of $-92$ pm/°C [80]. The higher temperature sensitivity of the etched fibre was caused by the decrease in its Young's modulus, which increased its TOC. Similarly, the Bragg grating inscribed on etched fibre with a diameter of 105 μm displayed an enhanced strain sensitivity of 1.65 pm/με, while a Bragg grating written on un-etched fibre with diameter 185 μm presented a strain sensitivity of 1.24 pm/με. Therefore, the experimental results confirmed that the etched fibre exhibited higher intrinsic sensitivity than un-etched fibres in measuring temperature and strain. Amongst the advantages offered by the proposed sensor configuration over previously reported techniques are high intrinsic sensitivity, low cost, and ease in fabrication. Thus, the device is well suited for applications involving simultaneous measurements. The downside of this device is the degradation of the sensor's accuracy by the error in matrix coefficient [80]. This can be prevented by ensuring the acceptable accuracy of temperature and strain values through the accurate measurements of individual sensitivity values [80].

Marques et al. [81] reported the first phase-shifted polymer optical fibre Bragg grating (PS-POFBG) sensor inscribed with only one krypton fluoride laser pulse at 850 nm region with high quality for temperature and strain measurements. The device was written in a single-mode PMMA optical fibre, with a core doped with benzyl dimethyl ketal (BDK) for photosensitivity enhancement [81]. The PS-POFBGs were characterised to temperature and strain to demonstrate the spectral dependence of the Bragg peak under different external conditions. In the range of 22 – 52°C, a higher temperature sensitivity ($\sim 57.0\pm4.1$ pm/°C ) than that of silica PS-FBG was obtained [81]. The fabricated sensor also possessed a slightly larger strain sensitivity (0.76±0.01 pm/με) than that of silica PS-FBG (0.7 pm/με) [82]. The optical characteristics of the fabricated PS-POFBGs displayed promising results in applications that require high-precision measurements, such as ultrasonic detection [81].
Kavungal et al. [83] designed a novel an inline cascade of optical micro-resonators (ICOMRs) coupled to multiple tapered sections along with a single optical fibre. The multiple micro-resonators are suitable for sensing several parameters or a single parameter at various locations simultaneously. Simultaneous measurements of temperature and strain were carried out for an ICOMR formed by POF-based and PDMS-coated silica cylindrical micro-resonators. Fig. 11a shows the strain response of the POF based cylindrical micro-resonator, while Fig. 11b displays the temperature response of the PDMS-coated silica cylindrical micro-resonator. High temperature sensitivity of 330 ± 18 pm/°C and axial tensile strain sensitivity of 1.4 ± 0.04 pm/με were recorded. The high-temperature sensitivity can be attributed to the significant negative thermo-optical coefficient of the PDMS material (−1.8 x 10^{-4}°C^{-1}) [78]. The operating range of the temperature sensor was limited to −50 °C to 200 °C. The authors claimed that the proposed inline resonator structure is promising for many photonic applications such as distributed sensing, cross-sensitivity studies, lab-on-a fibre technology, optical coding, and optical logic gates [83].

Table 1 shows that the Fabry-Perot interferometer consisting of microfibre and SMF tip, both coated with temperature-sensitive PDMS, displayed the highest temperature sensitivity of 10.67 nm/°C and closely followed by the agarose coated macro-bend temperature.
sensor with 5.37 nm/°C. Zeonex mPOF Bragg grating and ZnO nanorods coated POF possessed the most comprehensive temperature range of 20–100°C.

4. CONCLUSION

The recent advances in POF temperature sensors have been reviewed in this study with a focus on low-cost and easy to fabricate sensors such as macro-bend fibre sensors, microfibre resonators, Fabry-Perot interferometers, fibre Bragg grating, and POF sensors coated with zinc oxide nanorods. The macro-bend temperature sensor is well suited for monitoring the temperature of an electrical power transformer where the presence of electromagnetic interference restricts the use of conventional sensors. Hence, this could mitigate the breakdown of electrical power transformers due to overheating during hot climatic conditions, mostly experienced in tropical regions of the world. The Fabry-Perot interferometer with both microfibre and SMF tip coated with PDMS displayed the highest temperature sensitivity of 10.67 nm/°C. Zeonex mPOF Bragg grating and ZnO nanorods coated POF possessed the most extensive temperature range of 20–100°C. Additionally, a dual fibre sensor consisting of a Fabry–Perot cavity made of NOA 78 and a polymer fibre Bragg grating is suitable for the simultaneous measurement of temperature and humidity with high resolution. Experimental results confirmed that the etched fibre exhibited higher intrinsic sensitivity than un-etched fibres in measuring temperature and strain. An ICOMF formed by POF-based and PDMS-coated silica cylindrical micro-resonators demonstrated both high temperature micro-axial and axial tensile strain sensitivities of 330 ± 18 pm/°C and 1.4 ± 0.04 pm/με, respectively. The multiple micro-resonators are promising for many photonic applications such as distributed sensing, cross-sensitivity studies, lab-on-a fibre technology, optical coding, and optical logic gates. The various sensors discussed in this study presented a diverse range of applications of POF in the automotive industry, air-conditioning control, food storage, biomedical sector, electrical power sector, and environmental monitoring. POF temperature sensors are on course to replace SOF in several applications owing to the rapid improvement in their accuracy, sensitivity, and operating range.

COMPETING INTERESTS

The author has declared that no competing interests exist.

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Peer-review history:
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