Plasmonic temperature sensor using D-shaped photonic crystal fiber

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\textit{ARTICLE INFO}

Keywords:
Plasmonics
Photonic crystal fiber
Sensor

\textit{ABSTRACT}

Simple structure and high sensitivity with a broad detection range are highly desirable for temperature sensor. This work presents a highly sensitive plasmonic sensor based on D-shaped photonic crystal fiber (PCF) in the near infrared region (900–1900 nm) for temperature measurement. The proposed sensor is designed by finite element method (FEM) based simulation tool and sensing properties are investigated by means of wavelength interrogation method (WIM). To support the surface plasmon oscillation, 45 nm gold film is deposited on the flat portion of the D-shaped PCF which consists of pure silica. Benzene is used as the temperature sensitive material that offers large propagation loss (PL) peak shift. Simulation outcome shows that the maximum possible sensitivity of 110 nm/°C in the temperature range from 10 °C to 70 °C. To our knowledge, the achieved sensitivity is the highest for temperature sensing in the existing literature. In addition, the proposed sensor exhibits the maximum figure of merit (FOM) of 5.5/°C, resolution of $9.09 \times 10^{-4}$ °C, and excellent fitting characteristics of PL peak wavelengths. Moreover, low PL of the proposed sensor helps to extend the sensor length up to few centimeters. Such excellent results and wider temperature range make sure that the proposed sensor can be an appropriate choice for temperature measurement even in the remote sensing application.

\textit{Introduction}

In recent years, photonic crystal fiber (PCF) based temperature sensors have drawn plenty of interest owing to their excellent attributes like tiny size, light weight, ability to remote sensing and interference immunity of electromagnetic radiation [1]. To date, numerous methods have already existed for temperature measurement including fiber Bragg grating (FBG) [2], long period fiber grating (LPFG) [3], Sagnac interferometer (SI) [4,5] and surface plasmon resonance (SPR) [6]. For instance, M. Zaynetdinov et al. [2] demonstrated a FBG based multiplexible temperature sensor having measurement range from 2 K to 400 K. Isopropanol filled PCF long period grating based temperature sensor is proposed by C. Du et al. [3], which is applicable in the temperature range of 20–50 °C. However, FBG and LPFG based sensors are costly as they require high power lasers during fabrication. Besides that, the sensitivity of these sensors is not up to the mark as well. Q. Liu et al. [7] reported a sensor on the principle of coupling between liquid core and defect mode having a comparatively wider sensing range of 20–80 °C but the maximum sensitivity is as low as $-1.85$ nm/°C. Y. Peng et al. [8] achieved temperature sensitivity as high as $-5.5$ nm/°C using bandgap-like effect on a selective liquid filled PCF with a narrow temperature range of 20–28 °C. Chen et al. [9] studied on ultra-compact PCF based temperature sensor and reported maximum temperature sensitivity of 2.82 nm/°C. Avoided-crossing based selectively filled PCF temperature sensor is demonstrated by J. Zuo et al. [10]. This sensor exhibits maximum sensitivity of $-6.9$ nm/°C at 36.5 °C. Using SI phenomena G. Wang et al. [11] improved the sensitivity up to 16.55 nm/°C in the measurement range from 45 to 75 °C. Temperature sensor with polarization-insensitive liquid filled PCF was introduced by Abbasi et al. and shown uniform sensitivity of $-1.96$ nm/°C in both x
and y polarizations [12].

On the other hand, surface plasmon resonance (SPR) based temperature sensors are more attractive because of their high sensitivity, convenient operation, and label-free measurement capabilities. The refractive index (RI) of the sensing medium has a significant impact on the SPR phenomenon. Therefore, noticeable shift occurs in the SPR spectrum due to the variation of RI by any physical factor. Temperature effect is one of these factors and the variation of RI of the sensing medium is directly proportional to the value of the thermo-optic coefficient of the medium. In 2012, Y. Peng et al. [13] demonstrated SPR based PCF sensor where PCF air hole is coated by metal film for SPR response and obtained maximum sensitivity of 720 pm/°C. Furthermore, several types of SPR based PCF temperature sensors have been proposed [1,6,14], where PCF air holes are coated with the metal film and then these entire holes are filled with temperature sensitive liquid. Metal film deposition surrounds the PCFs holes and filled them with temperature sensitive liquid is difficult due to the very small diameter of PCFs holes. A possible solution approach to this problem is to design the D-shape PCF sensor [15]. L. Hai et al. studied D-shape temperature sensor with ethanol as a sensing medium and their analysis revealed that maximum temperature sensitivity of ~1 nm/°C [16]. In this sensor, although ethanol has been placed on top of the flat portion but magnetic fluid (MF) material is filled into the cladding air-holes to measure the temperature and magnetic field based on the dependence of the MF refractive index on temperature and magnetic field. Hence, this type of structures can decrease the metal deposition complexity but not the liquid infiltration difficulty. However, J. Wu et al. improved the sensitivity of D-shape temperature sensor up to 36.86 nm/°C using index matching fluid having RI of 1.37 at 0 °C [17].

In this work, a D-shape PCF temperature sensor based on SPR is designed by the finite element method (FEM). The main motive is to attain improved sensitivity with high fabrication feasibility. The D-shape structure can reduce the metal deposition difficulty and can avoid infiltration of temperature sensitive liquid into the air holes. The gold layer on the polishing surface accomplishes the coupling between the fundamental and the plasmonic mode. Here, benzene is used as the temperature sensitive liquid to achieve higher sensitivity. Due to the large thermo-optic coefficient, the RI of the benzene is very sensitive to the temperature [6]. Besides that, the refractive index (RI) of benzene is very much close to the RI of fused silica in the detection range of the proposed sensor. Hence, any small temperature variation results in large shift of propagation loss (PL) peak that increases the sensitivity of the sensor tremendously. Moreover, the optimization of various structural parameters of D-shape PCF gives very high sensitivity that is competitive with the reported sensors.

Structure designed and theoretical analysis

The schematic cross-section of the proposed PCF based temperature sensor is depicted in Fig. 1 where air holes are arranged in triangular lattice. The center to center distance between any two neighboring air holes is considered as pitch (Λ). The fiber radius is r and side polished boundary height from the center of the fiber is h where the gold layer (t_b) is coated. Temperature sensitive liquid (benzene) of height t_b is taken placed on top of the gold-coated flat surface. Here, three different size of air holes with optimized diameter d, d_1, and d_2 are used to obtain consummate coupling between surface plasmon polariton (SPP) mode and core guided mode.

The fused silica is considered as a background material whose RI is calculated by the Sellmeier equation [17];

\[
\begin{align*}
n^2(\lambda, T) &= (1.31552 + 6.90754 \times 10^{-6}T) \\
&+ (0.78840 + 23.5835 \times 10^{-6}T)^2 \\
&+ (0.91316 + 0.548368 \times 10^{-6}T)^2 \\
&- (0.0110199 + 0.584758 \times 10^{-6}T) \\
&+ (1.31552 + 6.90754 \times 10^{-6}T) \\
&- 7.594 \times 10^{-4} \\
&+ (0.0110199 + 0.584758 \times 10^{-6}T) \\
&= \frac{1}{\lambda^2 - 100}
\end{align*}
\]

where \(\lambda\) (free-space wavelength) is in microns and \(T\) (temperature) is in degree Celsius (°C). The dielectric constant of the gold is calculated from the Drude-Lorentz formula [18]. In addition, RI of the benzene is determined as follows [17],

\[
n = n_{\text{liquid}} + \frac{dn}{dT}(T - 25)
\]

where \(dn/dT = -7.594 \times 10^{-4}/°C\) is the thermo optical coefficient and \(n_{\text{liquid}} = 1.497866\) at 25 °C [19]. It should be mentioned that the dispersion of the benzene is not considered for the proposed design. The detection range (10 °C-70 °C) is chosen based on the boiling and melting point of the benzene. At the same time, the melting point of fused silica is about 1670 °C so the detection range doesn’t change the properties of the fiber as well. There is a significant positive correlation between the real effective refractive index (\(n_{\text{eff}}\)) of the fundamental mode and the plasmon mode. When they are coupling at a particular wavelength, then maximum energy is transferred from the core mode to the SPP mode in the way of generating surface plasmon waves (SPWs) due to the excitation of the free electrons of metal by the evanescent field. This particular wavelength is called phase matching point as well as resonance wavelength. As a result, a propagation loss (PL) peak is found at the phase matching wavelength. If the temperature changes then the \(n_{\text{eff}}\) of the SPP mode will be changed. Hence, a change in the resonance wavelength will be found. So, the temperature detection can be accomplished based on the resonance wavelength.

Fig. 2 shows the dispersion relation of the real \(n_{\text{eff}}\) of the y-polarized fundamental mode and the plasmon mode. According to the Fig. 1, the y-polarized fundamental mode can easily interact with the gold film than the x-polarized mode as the gold film is coated in the y-direction. Since the y-polarized light experienced stronger interaction with the SPP mode, the sensitivity will be high in this particular mode. So, y-polarized fundamental mode is considered for sensitivity investigation. According to the Fig. 2, it can be noticed that initially, the loss tends to upward, at 1.46 µm a PL peak is found and after that the loss tends to downward. The value of the PL at 1.46 µm is 0.004110 dB/cm which is maximum at the entire operating range for \(T = 50 °C\). It can be also seen that at 1.46 µm the real \(n_{\text{eff}}\) of the fundamental mode and the plasmon mode have coincided that leads to the maximum power transfer from the fundamental mode to the plasmon mode. As a result, the PL peak is found at that particular wavelength. An incomplete coupling indeed happens when the two coupling modes have equal real
parts of effective refractive indices but different imaginary parts \([20]\). Fig. 2 shows that at the coupling point, real part of the effective refractive index of the core guided and the SPP mode is same but the imaginary part is different. Therefore, the proposed structure has the phase matching and incomplete coupling. The electric field distributions of the fundamental and plasmon mode are shown in the inset.

The design and analysis of the proposed D-shaped temperature sensor have been accomplished by the FEM based COMSOL software. The finer meshing divided the entire mesh area (507.8 \(\mu m^2\)) into 18359 triangular elements including edge and vertex elements of 1722 and 103, respectively.

Results and discussions

The sensor performances are observed in terms of sensitivity, resolution, figure of merit (FOM), linearity of PL peak wavelengths and sensor length in the entire detection range.

PL characteristics and sensitivity

Herein, the PL and wavelength sensitivity are determined by using the equations (3) and (4) respectively \([18]\),

\[
\alpha = \frac{4.343 \times 4\pi}{10^{-4}} \times \lambda^{-1} \times \text{Im}(n_{eff})(\text{dB/cm})
\]

(3)

\[
S_i = \frac{\delta \lambda_{\text{peak}} \times (\partial T)^{-1}}{(\text{nm/RIU}^{-1})}
\]

(4)

where \(\text{Im}(n_{eff})\), \(\delta \lambda_{\text{peak}}\), and \(\partial T\) represent the complex imaginary part of the effective refractive index, resonance wavelength difference, and change of temperature in degree Celsius, respectively.

First of all, the PL is calculated using equation (3) in the whole detection range which is plotted in Fig. 3(a). According to the figure, PL peaks are found at 1860 nm, 1810 nm, 1770 nm, 1720 nm, 1670 nm, 1620 nm, 1560 nm, 1510 nm, 1460 nm, 1400 nm, 1360 nm, 1210 nm, and 970 nm, respectively, in the detection range from 10 °C to 70 °C with step size 5 °C. Basically, the PL peak (resonance) wavelength is extremely sensitive to the core-cladding index contrast. Due to the temperature variation, the RI of the temperature sensitive liquid changes. Therefore, any variation in the temperature changes the core-cladding index contrast which leads to the change in the resonance wavelength. At the same time, with the decrease of the temperature, the value of PL peak is increased significantly. That happens because at lower temperature the RI of benzene (which is placed outside the fiber structure) is much high than that of silica. So, the higher RI liquid outside the core region causes higher loss. Besides that, with the increase of the temperature, the RI of the benzene reduces that increases the light confinement significantly. As a result, the loss is reduced with the increase of the temperature. However, the maximum PL peak shift (240 nm) is found in the interval between 65 °C and 70 °C. After that, for the detection accuracy, the PL is calculated with a step size of 1 °C in that particular interval (65 °C and 70 °C) which plotted in Fig. 3(b). In that case, the maximum peak shift is observed of 110 nm in the interval between 68 °C and 69 °C. Therefore, according to the equation (4), the maximum sensitivities are 48 nm/°C and 110 nm/°C with a step size of 5 °C and 1 °C, respectively, which are much higher than previously reported sensitivity \([1-14,17]\).

Resolution and FOM

Resolution of a plasmonic temperature sensor can be expressed as \([13]\),

\[
S_i = \delta T \times \frac{\delta \lambda_{\text{peak}}}{\delta \lambda_{\text{min}}}
\]

(5)

where \(\delta \lambda_{\text{min}}\), \(\delta T\), and \(\delta \lambda_{\text{peak}}\) indicate minimum wavelength resolution, temperature difference and PL peak’s wavelength difference, respectively. Resolution of a temperature sensor describes how much smallest variation of the temperature can be detected by this sensor. From equation (5), maximum resolution are calculated of 2.08 \(\times\) \(10^{-3}\) °C and 9.09 \(\times\) \(10^{-4}\) °C with a step size of 5 °C and 1 °C, respectively. Therefore, the proposed sensor has the ability to response a small variation of temperature of the order of \(10^{-4}\) °C.

FOM is another important parameter of a sensor which is the ratio of sensitivity and full-width at half-maximum (FWHM) \([9]\),

\[
\text{FOM} = \frac{S}{\text{FWHM}} \text{ / °C}
\]

(6)

Sharp resonance response (lower FWHM) decreases spectral noise which leads to the higher signal to noise ratio (SNR) of the received signal. Therefore, higher sensitivity (higher PL peak shift) along with lower FWHM (sharp resonance response) is anticipated for detection accuracy. For the proposed sensor, maximum FOM of 2.4/°C and 5.5/°C are reported with a step size of 5 °C and 1 °C, respectively, that also an evidence of improved performance. Sensing performance in the temperature range from 10 °C to 70 °C with step size 5 °C and temperature range from 66 °C to 70 °C with step size 1 °C are summarized in Tables 1 and 2, respectively.

Linearity and sensor length

Polynomial fitting of the PL peak wavelengths in the temperature range from 10 °C to 70 °C with a step size of 5 °C is plotted in Fig. 4(a) which gives a satisfactory coefficient of determination \((R^2)\) of 0.9688. Polynomial fitting in the temperature range from 65 °C to 70 °C having \(R^2\) of 0.9814 with a step size of 1 °C is also shown in Fig. 4(b).

Higher PL will decrease the length of the sensor that will increase the fabrication complexity as the sensor length is inversely proportional with the PL which can express as \([21]\),

\[
S_i = \frac{1}{a(\lambda, T)}
\]

(7)

The maximum loss of the proposed sensor is obtained of 0.046 dB/cm at 10 °C. So, according to equation (7), the sensor’s length is extendable up to 21.74 cm that is another good sign for the proposed sensor. On the other hand, if the sensor length is higher than 21.74 cm, during light propagation through the optical fiber the optical signal will be attenuated before it reaches at the receiver. However, there is no effect of the length of the sensor on the sensitivity.

Optimization of the structural parameters

Initially the proposed temperature sensor has designed with consideration of \(\Lambda = 4 \mu m, h = 5.4 \mu m, d = 0.8 \times \Lambda, d_1 = 0.6 \times \Lambda, d_2 = 0.5 \times \Lambda, t_b = 2 \mu m, t_p = 45 \text{ nm and } r = 10 \mu m\). Then each of the
parameters are varied to attain the best possible performance from the suggested sensor.

**Optimization of gold film thickness (t\textsubscript{f}) and benzene thickness (t\textsubscript{b})**

First of all, t\textsubscript{f} is varied from 30 nm to 50 nm with the step size of 5 nm and has gained propagation loss (PL) peak for temperature 50 °C and 55 °C which is depicted in Fig. 3(a). From Fig. 5(a), it can be seen that with the increase of t\textsubscript{f}, the value of PL peak is gradually decreased. This happens because thicker t\textsubscript{f} causes larger damping loss to the metal film. It can also be seen that PL peak gradually broadens with the increase of t\textsubscript{f} which happens due to the skin depth limitation of surface plasmon [18]. Along with the high sensitivity, sharp PL peak with lower value is desired for any plasmonic sensor. Low PL helps to increase the sensor length. On the other hand, sharp PL peak enhances the signal to noise ratio (SNR) that decreases the possibility of any false positive response [18]. It has also been observed that the same amount of PL peak shift is found for 30 nm, 35 nm, 40 nm, and 45 nm but it is decreased for 50 nm of t\textsubscript{f}. From Fig. 5(b), it can be seen that 45 nm of t\textsubscript{f} gives the best sensitivity with moderate PL. Therefore, gold film thickness is chosen to 45 nm as the trade-off between PL and the sensitivity.

On the other hand, propagation loss (PL) with the variation of benzene thickness (t\textsubscript{b}) for temperature 50 °C and 55 °C is plotted in Fig. 3(a). From Fig. 5(a), it can be seen that the value of PL peak gradually increases for thickness of 50 nm of benzene, which happens due to the skin depth limitation of surface plasmon [18]. It has also been observed that the same amount of PL peak shift is found for 30 nm, 35 nm, 40 nm, and 45 nm but it is decreased for 50 nm of t\textsubscript{b}. From Fig. 5(b), it can be seen that 45 nm of t\textsubscript{b} gives the best sensitivity with moderate PL. Therefore, t\textsubscript{b} is optimized to 45 nm as optimum with consideration of high sensitivity and moderate PL.

**Optimization of pitch (Λ) and the distance from center to flat portion (h)**

The gap between two adjacent air holes (Λ) is also optimized. Fig. 9(a) illustrated the PL resonance characteristics of the proposed sensor with a variation of Λ from 3.8 μm to 4.2 μm. According to Fig. 9(b), it can be seen that the PL peak is gradually increased with the increase of Λ. At the same time, it can be found the equal sensitivity for 4 μm to 4.2 μm of Λ but the value of pitch less than 4 μm results lower sensitivity. Therefore, the pitch (Λ) is selected to 4 μm as optimum

**Table 1**

Sensing performance in the temperature range from 10 °C to 70 °C with a step size of 5 °C.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Peak loss (dB/cm)</th>
<th>Reso. peak wave. (nm)</th>
<th>∂λ\textsubscript{peak} (nm)</th>
<th>Sensitivity (nm/°C)</th>
<th>Resolution (°C)</th>
<th>FWHM (nm)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.046263</td>
<td>1860</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>30</td>
<td>0.33</td>
</tr>
<tr>
<td>15</td>
<td>0.038603</td>
<td>1810</td>
<td>40</td>
<td>10</td>
<td>1.25 × 10\textsuperscript{-2}</td>
<td>20</td>
<td>0.40</td>
</tr>
<tr>
<td>20</td>
<td>0.032696</td>
<td>1770</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>30</td>
<td>0.33</td>
</tr>
<tr>
<td>25</td>
<td>0.025564</td>
<td>1720</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>20</td>
<td>0.50</td>
</tr>
<tr>
<td>30</td>
<td>0.018805</td>
<td>1670</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>20</td>
<td>0.50</td>
</tr>
<tr>
<td>35</td>
<td>0.014146</td>
<td>1620</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>30</td>
<td>0.33</td>
</tr>
<tr>
<td>40</td>
<td>0.009536</td>
<td>1570</td>
<td>60</td>
<td>12</td>
<td>8.33 × 10\textsuperscript{-3}</td>
<td>30</td>
<td>0.40</td>
</tr>
<tr>
<td>45</td>
<td>0.006869</td>
<td>1510</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>30</td>
<td>0.33</td>
</tr>
<tr>
<td>50</td>
<td>0.004110</td>
<td>1460</td>
<td>60</td>
<td>12</td>
<td>8.33 × 10\textsuperscript{-3}</td>
<td>50</td>
<td>0.24</td>
</tr>
<tr>
<td>55</td>
<td>0.002388</td>
<td>1400</td>
<td>50</td>
<td>10</td>
<td>1.00 × 10\textsuperscript{-2}</td>
<td>70</td>
<td>0.14</td>
</tr>
<tr>
<td>60</td>
<td>0.001838</td>
<td>1350</td>
<td>140</td>
<td>28</td>
<td>3.57 × 10\textsuperscript{-3}</td>
<td>60</td>
<td>0.47</td>
</tr>
<tr>
<td>65</td>
<td>0.001562</td>
<td>1210</td>
<td>240</td>
<td>48</td>
<td>2.08 × 10\textsuperscript{-3}</td>
<td>20</td>
<td>2.40</td>
</tr>
<tr>
<td>70</td>
<td>0.000502</td>
<td>970</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>30</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Fig. 3. PL as a function of wavelength in the temperature range (a) from 10 °C to 70 °C with step 5 °C (b) from 66 °C to 70 °C with step 1 °C.
Moreover, the distance from center to the flat portion of the PCF ($h$) is optimized based on PL characteristics which is shown in Fig. 10(a). According to the Fig. 10(b), it can be seen that decreasing of $h$ from 5.4 µm to 5.2 µm does not affect the sensitivity, but increases the PL. On the other hand, increasing of $h$ from 5.4 µm to 5.6 µm reduces both the sensitivity and the PL. Finally, side-polished distance is selected to $h = 5.4$ µm as optimum.

### Table 2
Sensing performance in the temperature range from 66 °C to 70 °C with a step size of 1 °C.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Peak loss (dB/cm)</th>
<th>Reso. peak wave. (nm)</th>
<th>$\delta_{\lambda_{\text{peak}}}$ (nm)</th>
<th>Sensitivity (nm/°C)</th>
<th>Resolution (°C)</th>
<th>FWHM (nm)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>0.001578</td>
<td>1200</td>
<td>20</td>
<td>20</td>
<td>$5.00 \times 10^{-3}$</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>67</td>
<td>0.001505</td>
<td>1180</td>
<td>20</td>
<td>20</td>
<td>$5.00 \times 10^{-3}$</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>68</td>
<td>0.001384</td>
<td>1160</td>
<td>110</td>
<td>110</td>
<td>$9.09 \times 10^{-4}$</td>
<td>20</td>
<td>5.5</td>
</tr>
<tr>
<td>69</td>
<td>0.000688</td>
<td>1050</td>
<td>80</td>
<td>80</td>
<td>$1.25 \times 10^{-3}$</td>
<td>50</td>
<td>1.6</td>
</tr>
<tr>
<td>70</td>
<td>0.000502</td>
<td>970</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>30</td>
<td>N/A</td>
</tr>
</tbody>
</table>

![Fig. 4. Polynomial fitting of the PL peak wavelengths in the temperature range (a) from 10 °C to 70° C and (b) from 66 °C to 70° C.](image)

![Fig. 5. (a) PL characteristics and (b) maximum PL and sensitivity at temperature 50 °C and 55 °C with different value of $t_g$.](image)

![Fig. 6. (a) PL characteristics and (b) maximum PL and sensitivity at temperature 50 °C and 55 °C with different value of $t_b$.](image)
Sensitivity comparison of the proposed sensor with three different liquids (benzene, toluene, and CS2)

The impact of temperature sensitive liquid on sensitivity is also investigated with three different liquids (benzene, toluene, and CS2) which is plotted in Fig. 11. From Fig. 11, it is clear that benzene exhibits better sensitivity as the temperature sensing material than toluene and CS2. The RI variation of fused silica with temperature is shown in Fig. 12(a) and (b) shows the change of RI of benzene, toluene, and CS2 with temperature in the measurement range from 10 °C to 70 °C. From Fig. 12(a), it can be seen that temperature changes resulting very little change in the RI of fused silica. So, if the temperature sensitive liquid is highly sensitive to temperature then any small variation in the temperature will result a large variation in the core-cladding index contrast. As a result, the shift of the PL peak will be higher. From Fig. 12(b), it can be seen that the value of slope of the benzene (0.0008) line is higher than that of toluene (0.0005) that implies benzene is much more temperature sensitive than toluene. That’s why benzene represents better sensitivity than toluene. On the other hand, despite the same slope of benzene and CS2 line, benzene shows better sensitivity than CS2. The reason behind that resonance condition requires equating the $n_{\text{eff}}$ of the fundamental mode and the plasmon mode. So, to attain better performance $n_{\text{eff}}$ of the two modes should be closer. Basically, the $n_{\text{eff}}$ of the fundamental mode and the plasmon mode depends on the temperature
sensitive liquid and the material in contact with metal (fused silica), respectively. Therefore, higher RI difference between fused silica and CS\textsubscript{2} causes poor performance. From Fig. 11 it can be also seen that benzene shows tremendous performance in the temperature range from 55 °C to 65 °C. This happens because in that particular range the RI of benzene is very much close to the RI of fused silica.

Performance comparison and generalized measurement setup

A comparative analysis of sensing properties among proposed and existing temperature sensor stated in the literature is shown in Table 3. According to the table, it is clear that the suggested sensor reveals better performance in terms of sensitivity, resolution, and FOM. Besides that, the temperature range is also comparable with other reported temperature sensor. The gold film near the core of the D-shaped PCF facilitates electron excitation. In addition, benzene is extremely sensitive to temperature variation. As a result, the proposed temperature sensor shows better sensing properties than other configurations.

A generalized temperature measurement setup [22] using our recommended fiber is shown in Fig. 13. Commercially available laser light can be used to generate optic power which is then introduced into the proposed fiber through a single mode fiber (SMF). When light passes through the proposed fiber, it interacts with the gold and causes surface plasmon excitation. As a result, a PL peak is found in the whole measurement range which can be observed in the optical spectrum analyzer (OSA). The OSA is connected with the proposed PCF by another SMF. It should be included that the proposed PCF needs to be placed in a temperature control chamber. If temperature changes then RI of the benzene will be changed. Therefore, a shift of the PL peak will be observed at the OSA. Moreover, the temperature measurement process is accomplished by observing these PL peak wavelengths. The IN and OUT port of the benzene flow channel can be controlled by a pump.

The D-shaped PCF based SPR sensor with triangular lattice air hole has been fabricated by polishing the endless single mode (ESM)-12 PCF for RI sensing and investigated the sensing performance experimentally with 45 nm gold layer [23]. ESM-12 PCFs have adequate mechanical strength. Hence, the air holes of the PCF maintain their original shape even after polishing. On the other hand, gold deposition can be accomplished by using commercially available magnetron sputtering device. So, the proposed D-shaped PCF can be implemented for temperature measurement experimentally.
sensing properties than other configurations.

**Conclusion**

A highly sensitive plasmonic temperature sensor based on D-shaped PCF has been proposed in this paper. The operating wavelength of the proposed sensor in the near-infrared region makes it inexpensive as the low-cost laser sources are commercially available in that region. The D-shape structure facilitates metal deposition as well as eliminates the complexity of liquid infiltration which make the sensing procedure more feasible. The pair of gold (plasmonic metal) and benzene (temperature sensing liquid) gives sensitivity as high as 110 nm/°C in the temperature interval between 68 °C and 69 °C which is better than any PCF based temperature sensor. In addition, the FOM of 5.5/°C, resolution of 9.09 × 10^{-4} °C, and excellent fitting characteristic are obtained for the proposed sensor. Moreover, benzene shows better sensitivity than other liquid in the whole measurement range from 10 °C to 70 °C. Due to such promising outcomes, we believe that benzene will draw much more attention to the researcher in the upcoming days as a temperature sensitive liquid.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**References**


