Remote Temperature Sensor Based on Tamm Resonance

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Abstract

A highly-sensitive remote temperature sensor based on Tamm resonance is proposed using a one-dimensional photonic crystal. The proposed structure is prism/Ag/Toluene/SiO₂/(PSi₁/PSi₂)^N/Si. The transfer matrix method is used to discuss the interaction between the structure and the S-polarization of the incident radiation waves. We optimized the structure by studying the effect of the incident angle, the thickness of the first and second layers of the photonic crystal unit cell, the porosity of them, and the thickness of the toluene layer. High sensitivity, high signal-to-noise ratio, and very low resolution are achieved due to the coupling between the porous silicon photonic crystal properties and Tamm resonance that makes it very distinguished compared to previous works.

Keywords Photonic crystal · Remote temperature sensor · Tamm resonance · Sensitivity

1 Introduction

Temperature sensing is probably the most important parameter in all branches of science. In daily life, temperature sensors are widely used in aerodynamics, metrology, climate and marine research, medicine, chemistry, biology, military technology, air conditioning, all heating and cooling devices, the storage of food, and others [1].

Optical thermometry has attracted great attention for remote temperature sensing. One method of optical thermometry is called luminescence temperature sensing (LTS) using a Gd₂O₃ host doped with rare-earth ions [2]. Even though Gd₂O₃ has a wide energy bandgap (5.6 eV), high refractive index (1.50–2.05), low phonon energy (600 cm⁻¹), excellent thermal and chemical stability, high mechanical strength, and high melting point, and Gd₂O₃ host doped with rare-earth ions was prepared by a simple and cost-effective process, the signal to noise ratio of these sensors need to be enhanced [1, 2].

Infectious substances testing is not nationally available in some countries so the specimens should be transported or stored. The correct handling of infectious substances during storage transportation is very important. Specimens that can be delivered to the laboratory promptly should be stored at 2–8 °C. If further delays are expected, Specimens shall be frozen to extremely low temperatures (from –20 °C to –70 °C) [3]. So, the presence of a remote sensor with high performance and covers this wide range of temperatures may help in the correct handling of infectious substances.

Since 1987, Yablonovitch [4] proposed an artificial periodic array with a new property that is called a photonic bandgap. He presented the first explanation about the photonic crystal. Then, this field attracted visual attention in different applications such as chemical sensors [5, 6], biosensors [7–9], filters [10, 11], optical lenses [12], solar cells [13], and other applications [14–21]. Recently, the main challenge is how to use Nanomaterials with a very small size to create smart structures that can be used as complex and sophisticated devices [22–24].

Photonic crystals are periodic refractive index structure arrays as a function of one-dimension, two-dimension, or all three-dimension space. At the interfaces between every two different layers, a portion of the incident wave is reflected. Due to the destructive interference between the incident waves and reflected waves, a standing wave is formed. So, a certain wavelength range is prevented from propagating through the photonic crystal [4]. Recently, photonic crystal sensors have attracted considerable support from researchers and organizations to overcome

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technological challenges. Researchers seek to minimize the size of the circuit to use it as integrated chip sensors. Moreover, they try to enhance the performance of sensors to be able to accurately measure and detect different biological and physical parameters [15].

Srivastava et al. [25] suggested a structure based on surface plasmon waveguide with a sensitivity of 70 pm/°C. Geng et al. [26] proposed a compact temperature fiber sensor based on photonic crystal and they obtained a sensitivity of 61 pm/°C. Chen et al. [27] designed a sensor based on a plasmonic resonant absorber and achieved a sensitivity of 0.27 nm/°C. Then, Rajasekar et al. [28] proposed a hexagonal photonic crystal ring resonator as a pressure and temperature sensor and recorded a sensitivity of 66.6 pm/°C. Kumar et al. [29] presented experimental temperature sensors using the Tamm plasmon resonance with a sensitivity of 7.8×10^{-4} /°C.

One-dimensional photonic crystals (1D-PC) have generated attention because they are more affordable and easy to manufacture compared with the other two types [30]. A high refractive index contrast between used layers or their thicknesses is used to increase the PBG range. Also, we can use the Tamm plasmon resonance to increase the PBG range. Tamm plasmon is the appearance of resonant dip inside the PBG by adding a metallic layer in front of the one-dimensional photonic crystal [31]. On the contrary of surface plasmon resonance, Tamm plasmon can occur in both S and P polarization and at any incidence angle [32]. The resonant dip plays an important role in many applications of photonic crystals such as waveguides, high Q cavities, and optical filters [6, 33]. The dip position is shifted to a higher or lower wavelength with any change in the effective refractive index (n_{eff}) of the structure or the surrounding medium. In this case, the PBG appears as if it were a complete bandgap and gives the chance for the resonant dip to be shifted over a wide bandgap. Recently, porous silicon (PSi) is a very hot two-dimensional material to be used in photonic crystals [34–38]. It has a low mass and high surface area within a small volume. The optical properties of PSi can be controlled by varying the size of pores or their density and the type of filling material [35].

The novelty and creativity in this work are due to many reasons. Firstly, the proposed structure is simple and recorded high performance for remote temperature sensing due to the coupling between the porous silicon 1D-PC and Tamm plasmon resonance. Also, for the first time and in contrast to the ordinary [39, 40] according to the best of our knowledge, the increase of the incident angle has a negative effect on the sensitivity when the resonant dip approaches the edge of the PBG (Fig. 5). Finally, This sensor may help in the correct handling of infectious substances.

2 Sensor Design

In Fig. 1, the proposed structure is a binary one-dimensional photonic crystal composed of two porous silicon layers (PSi₁/PSi₂) with different porosity according to many previous experimental works [41–43]. The porosity of the first silicon layer is P_1 with thickness d_1 , and the second one is P_2 with a thickness d_2 . To achieve Tamm resonance, we deposited a metallic layer on a prism of glass ($n_0 = 1.5$) in front of the structure [44–46]. Due to the small absorption loss of Ag (imaginary part of the dielectric constant) compare with other metals, we used it with a thickness d_m [34].

Between the metallic layer and (PSi₁/PSi₂)^N/Si, we introduce toluene liquid as a very sensitive layer to temperature with thickness d_T [47]. To prevent toluene from entering the pores of silicon, we separate them by silicon dioxide layer with thickness d_c that can be done experimentally [48]. Different practical photonic crystals with hollow cores infiltrated with toluene had been published [47, 49–52].

To control the thickness of the toluene layer during the fabrication process, a certain material can be deposited during the fabrication, as clear in step 1 in Fig. 1(A). The structure is packaged using a good thermal conductive material, as clear in step 2. A small hall will be drilled in the center of the layer that will be filled with toluene, as clear in step 3. The material in this layer will be removed with a strong acid (etching), as clear in steps 4–5. The empty layer will be filled with toluene, as clear in step 6. The drilled hall will be closed, as clear in step 7. Therefore, the suggested bio-sensor consists of prism/Ag/T/C/(PSi₁/PSi₂)^N/Si.

3 Theoretical Model

The transfer matrix method (TMM) is used to discuss the interaction between the proposed structure and the incident radiation waves. As the evanescent fields produced with s-polarization are stronger than p-polarization [53], we used s-polarization in our simulations.

TMM details were mentioned in lists of articles [54, 55]. By using the following matrices the suggested structure will be characterized:

$$J = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} = (j_m)(j_T)(j_c)(j_1 j_2)^N, \quad (1)$$

where J_{11} , J_{12} , J_{21} and J_{22} are the elements of the transfer matrix for the structure. j_m , j_T , j_c , j_1 , and j_2 are the characteristic matrix for the metallic layer, toluene layer, SiO₂ layer, PSi₁, and PSi₂:

Fig. 1 (A) Steps of toluene layer fabrication (B) Schematic diagram of the suggested temperature sensor

$$\begin{aligned}
 j_m &= \begin{pmatrix} \cos \beta_m & -\frac{i \sin \beta_m}{p_m} \\ -ip_m \sin \beta_m & \cos \beta_m \end{pmatrix}, \\
 j_T &= \begin{pmatrix} \cos \beta_T & -\frac{i \sin \beta_T}{p_T} \\ -ip_T \sin \beta_T & \cos \beta_T \end{pmatrix}, \\
 j_c &= \begin{pmatrix} \cos \beta_c & -\frac{i \sin \beta_c}{p_c} \\ -ip_c \sin \beta_c & \cos \beta_c \end{pmatrix}, \\
 j_1 &= \begin{pmatrix} \cos \beta_1 & -\frac{i \sin \beta_1}{p_1} \\ -ip_1 \sin \beta_1 & \cos \beta_1 \end{pmatrix}, \\
 j_2 &= \begin{pmatrix} \cos \beta_2 & -\frac{i \sin \beta_2}{p_2} \\ -ip_2 \sin \beta_2 & \cos \beta_2 \end{pmatrix}
 \end{aligned} \quad (2)$$

where the phase differences (β) is given by;

$$\beta_i = \frac{2\pi n_i d_i \cos \alpha_i}{\lambda}, \quad i = m, T, c, 1, \text{ and } 2 \quad (3)$$

Also, p for the s-polarized (TE) wave is given by $p_i = n_i \cos \alpha_i$. The angles of incidence α_m , α_T , α_c , α_1 , and α_2 on the Ag, toluene, SiO₂, PSi₁, and PSi₂ layers satisfy Snell's law:

$$\begin{aligned}
 n_0 \sin \alpha_0 &= n_m \sin \alpha_m = n_T \sin \alpha_T = n_c \sin \alpha_c = n_1 \sin \alpha_1 \\
 &= n_2 \sin \alpha_2,
 \end{aligned} \quad (4)$$

($j_1 j_2$) will be repeated for N periods based on the Chebyshev polynomials of the second kind. The coefficient of reflection is computed according to the following equation:

$$r = \frac{(J_{11} + J_{12} p_s) p_0 - (J_{21} + J_{22} p_s)}{(J_{11} + J_{12} p_s) p_0 + (J_{21} + J_{22} p_s)}, \quad (5)$$

where $p_0 = n_0 \cos \alpha_0$ (for prism) and $p_s = n_s \cos \alpha_s$ (for substrate). Besides, α_0 is referring to the incident angle of the radiation waves on the Ag/T/C/(PSi₁/PSi₂)^N/Si structure. Finally, the reflectance of the suggested design is [56]:

$$R = 100 * |r|^2, \quad (6)$$

4 Results and Discussions

Firstly, the refractive index of the metallic layer (n_m), the toluene layer (n_T), SiO₂ layer (n_C), PSi₁ (n_1), and PSi₂ (n_2) will be calculated as a function of wavelength (infra-red

range) and temperature (from -80°C to 80°C) both. Then, we will study the effect of the angle of the incident radiation, the thickness of the first and second layers of the photonic crystal unit cell (d_1 and d_2), the porosity of them (P_1 and P_2), and the effect of the toluene layer thickness on the designed sensor performance. Finally, the analysis of the sensor will be discussed.

4.1 Refractive Index of Ag

The increase in temperature causes an increase in the collision frequency of electrons (ω_c). Consequently, the metal absorption increases with the temperature increase. On the other hand, plasma frequency ω_p will be considered as a constant value over the temperature range [57]. The refractive index of Ag-metal is calculated by using the Drude model [58]:

$$n_m = \sqrt{1 - \frac{\omega_p^2}{\omega(\omega - i\omega_c)}}, \quad (7)$$

where $\omega_p = 8.28 \text{ eV}$, $\omega_c(T) = \left(\frac{\omega_c(T=300)}{300^{\frac{1}{3}}}\right)T^{1/3}$, and $\omega_c(T=300) = 0.048 \text{ eV}$ [58, 59].

4.2 Refractive Index of Toluene

The refractive index of toluene (n_T) is calculated as a function of both wavelength and temperature as the following equation [47]:

$$n_T(\lambda, T_c) = 1.474775 + \frac{6990.31}{\lambda^2} + \frac{2.776 \times 10^8}{\lambda^4} - \partial(T_c - 20.15), \quad (8)$$

where λ is in nm, T_c is in $^{\circ}\text{C}$ and ∂ is the thermo-optic coefficient of toluene, $\partial = 3.94 \times 10^{-4} / ^{\circ}\text{C}$. Where the toluene is very thermo-sensitive, its refractive index decreases sharply with increasing temperature. Also, it slightly decreases with increasing wavelength as clear in Fig. 2(A) Where, the melting point of toluene is -94.9°C and the boiling point is 110.6°C , the range of calculations is between -80 to 80°C . Because the thermo-optic coefficient becomes unstable when the temperature of a given material is near the melting or boiling points [47].

4.3 Refractive Index of SiO_2 and Prism

For SiO_2 , the refractive index at 25°C (n_r) equals 1.46. Due to the change of temperature, the refractive index of it will be changed by [60, 61]:

$$n_c(T) = n_r + \Delta n, \quad (9)$$

$$\Delta n = \gamma n_r (\Delta T),$$

where γ is the thermo-optic coefficient ($6.8 \times 10^{-6} / ^{\circ}\text{C}$), and ΔT is the change in temperature [60]. Figure 2(B) shows the variation of the refractive index of SiO_2 with temperature. The thermal expansion coefficient for the silicon will be neglected because it is very small. The refractive index of the used prism is 1.5 [62].

4.4 Refractive Index of Porous Silicon n_{Psi}

The refractive index of Silicon (n_{Si}) in the ranges 1.2 to $14 \mu\text{m}$ and 20 – 1600 K is calculated as [63, 64]:

$$n_{\text{Si}}^2(\lambda, T_K) = \varepsilon(T_K) + \frac{e^{-3\left(\frac{\Delta L(T_K)}{L_{293}}\right)}}{\lambda^2} \times (0.8948 + (4.3977 \times 10^{-4} T_K) + (7.3835 \times 10^{-8} T_K^2)), \quad (10)$$

where λ in μm , T_K in K, $\varepsilon(T_K) = 11.4445 + (2.7739 \times 10^{-4} T_K) + (1.7050 \times 10^{-6} T_K^2) - (8.1347 \times 10^{-10} T_K^3)$, $\frac{\Delta L(T_K)}{L_{293}} = -0.071 + (1.887 \times 10^{-6} T_K) + (1.934 \times 10^{-9} T_K^2) - (4.554 \times 10^{-13} T_K^3)$ for $293 \text{ K} \leq T_K \leq 1600 \text{ K}$, $\frac{\Delta L(T_K)}{L_{293}} = -0.021 - (4.149 \times 10^{-7} T_K) - (4.620 \times 10^{-10} T_K^2) + (1.482 \times 10^{-11} T_K^3)$ for $20 \text{ K} \leq T_K \leq 293 \text{ K}$.

As cleared in Fig. 2(C), by increasing the wavelength (λ), the refractive index of Si decreases at a constant temperature. On the contrary, by increasing the temperature, the refractive index of Si increases at a constant wavelength.

Bruggeman's effective medium approximation (BEMA) is used to calculate the refractive index of the PSi layer (n_{Psi}) filled air as following [34, 65, 66]:

$$n_{\text{Psi}} = 0.5 \sqrt{B + \sqrt{B^2 + 8 n_{\text{Si}}^2 n_{\text{Air}}^2}},$$

$$B = 3 P (n_{\text{Air}}^2 - n_{\text{Si}}^2) + (2 n_{\text{Si}}^2 - n_{\text{Air}}^2), \quad (11)$$

where P , n_{Air} , n_{Si} , and n_{Psi} are the porosity ratio, the refractive index of air pores, silicon, and PSi, respectively. The refractive index of air is independent of temperature and wavelength. Figure 2(D, E) shows the refractive index of PSi as a function of temperature and wavelength at porosity 25% and 85%. Compared with the toluene, the thermal expansion coefficient for the silicon will be neglected because it is very small [63]. As clear in Fig. 2(F), the effective refractive index of the whole structure decreases with the increase of both temperature and wavelength.

4.5 Reflectance Spectra of Structure

The structure is prism/Ag/T/C/(PSi₁/PSi₂)^N/Si. The thicknesses and porosities of the layers will be assumed as $d_T =$

Fig. 2 Refractive index variation of (A) Toluene, (B) SiO₂, (C) Si, (D) PSi(25%), (E) PSi(85%), and (F) n_{eff} of the structure at $d_T = 1000$ nm, $d_1 = 800$ nm, $d_2 = 200$ nm, $P_1 = 25\%$, and $P_2 = 85\%$ as a function of temperature and wavelength

1000 nm, $d_1 = 800$ nm, $d_2 = 200$ nm, $P_1 = 25\%$, and $P_2 = 85\%$, then they will be optimized.

The thickness of the Ag layer affects only the reflectance of resonant dip, as we reported in [6]. The thickness of 30 nm was selected because the resonant dips have near-zero reflectance at this thickness (Fig. 3). The thickness of the SiO₂ layer was selected to be small thickness (40 nm) because the more increase in SiO₂ thickness causes a redshift in the resonant dip. As the thermo-optic coefficient of SiO₂ is very small [60], the more increase in SiO₂ thickness does not affect sensitivity.

Figure 3 (black curve) is the reflectance spectra as a function of the wavelength of the prism/T/C/(PSi₁/PSi₂)^N/Si structure at a normal incident angle and $N = 10$. N does not affect sensitivity as we reported in [6], but the full width at half maximum of the resonance dip (FWHM) decreases from $N = 5$ to $N = 10$. With more increase in N , the FWHM seems to be constant. The number of unit cells was selected to be $N = 10$.

By adding an Ag layer with a thickness of 30 nm in front of the structure, Tamm resonance appears and makes the PBG

Fig. 2 (continued)

look like a complete PBG (red curve in Fig. 3). The incident light is confined between the 1D-PC (inside the bandgap region) and the metallic layer due to their high reflectance, and a strong localization occurs inside the 1D-PC [67].

Over a wavelength range, Tamm resonant dip appeared at $\lambda_R = 1671$ nm inside the PBG as a direct result of the confinement of electromagnetic waves between the Ag metal surface and the 1D-PC Bragg reflector [32, 34, 68].

4.5.1 Effect of Temperature

As the temperature increases, the refractive index of PSi_1 and PSi_2 increases, and the position of the PBG is redshifted because the position of the PBG depends only on the optical

properties of the unit cell layers ($\text{PSi}_1/\text{PSi}_2$) as cleared in Fig. 4(A).

The increase of temperature causes a sufficiently large decrease in the effective refractive index (n_{eff}) of the periodic structure as clear in Fig. 2(F). Consequently, the resonant dip is blue-shifted to a lower wavelength as clear in Fig. 4(B) according to Bragg–Snell law [69, 70]:

$$u\lambda_R = 2\| \sqrt{n_{\text{eff}}^2 - \sin^2 \alpha_0}, \quad (12)$$

where u is the diffraction order, λ_R is the wavelength, $\|$ is the interplanar spacing, α_0 is the incident angle, and n_{eff} is the effective index of refraction of the whole

Fig. 3: The reflectance spectra for prism/ $\text{T}/\text{SiO}_2/\text{PSi}$ -1DPC and prism/ $\text{Ag}/\text{T}/\text{SiO}_2/\text{PSi}$ -1DPC as a function of the wavelength at $T=0$ °C, $d_T=1000$ nm, $d_1=800$ nm, $d_2=200$ nm, $P1=25\%$, and $P2=85\%$

Fig. 4 The reflectance spectra for (A) prism/T/SiO₂/PSi-1DPC as a function of the wavelength and temperature, and (B) prism/Ag/T/SiO₂/PSi-1DPC as a function of the wavelength and temperature at a normal angle of incidence, $N = 10$, $d_C = 40$ nm, and $d_m = 30$ nm, $d_T = 1000$ nm, $d_1 = 800$ nm, $d_2 = 200$ nm, $P_1 = 25\%$, and $P_2 = 85\%$

structure. By increasing the temperature, Tamm resonant dip is blue-shifted to lower wavelengths.

4.5.2 The Effect of the Incident Angle

According to Bragg–Snell law (Eq. 12), increasing the incident angle causes a blue shift to both PBG and resonant dip at a constant temperature as clear in Fig. 5 (A). In Fig. 5(B), by increasing the incident angle, the resonant dips at different temperatures go out from the PBG to lower wavelengths gradually and look like a negative effect on the sensitivity with the increase of the incident angle.

For the first time and in contrast to the ordinary according to the best of our knowledge [6, 39, 40], the increase of the incident angle has a negative effect on the sensitivity of this design. This negative effect of the incident angle on the sensitivity is because the resonant dip has the highest value at the center of the PBG [71], and decreases dramatically with the approach of the resonant dip to the edge of the PBG as clear in Fig. 5 (B). Where the angle 0° recorded the highest resonant dip shift in the wavelength range of concern, we will consider it as the optimum angle, and we will use it in the following study.

4.5.3 The Effect of the Porosities of the Unit Cell Layers (P_1 and P_2)

The insets of Fig. 6 elucidate the reflectance spectra as a function of both wavelength and porosities. Figure 6 (A) elucidates the reflectance spectra of the first layer (PSi₁) of the PC-unit

cell as a function of both wavelength and porosities with $N = 10$, $P_2 = 85\%$, $d_T = 1000$ nm, $d_C = 40$ nm, and $d_m = 30$ nm at $T = -80^\circ\text{C}$ (green line), $T = 0^\circ\text{C}$ (black line), and $T = 80^\circ\text{C}$ (blue line). By increasing the value of P_1 , the width of the PBG decreases, and the resonant dip shift recorded the highest value at $P_1 = 28\%$ at the center of the PBG. So, $P_1 = 28\%$ will be considered the optimum porosity for the PSi₁ layer and will be used in the following calculations. The PBG disappeared when the porosity of the PSi₁ approach to the value of the porosity of PSi₂ (85%) because there is no refractive index contrast at this condition.

For P_2 , Fig. 6(B) show the reflectance spectra as a function of both wavelength and porosities of PSi₁ layer with $N = 10$, $P_1 = 28\%$, $d_T = 1000$ nm, $d_C = 40$ nm, and $d_m = 30$ nm at $T = -80^\circ\text{C}$ (green line), $T = 0^\circ\text{C}$ (black line), and $T = 80^\circ\text{C}$ (blue line). At low values of P_2 (approach to the value of the porosity of PSi₁ = 28%), there is no PBG because there is no refractive index contrast at this condition. By increasing the value of P_2 , the width of the PBG increases due to the increase of the refractive index contrast between the PSi₁ and PSi₂ layers. Besides, the resonant dip shift increased gradually from 50% to 85%, then the shift seems to be constant. So, $P_2 = 85\%$ will be considered the optimum porosity for the PSi₂ layer and will be used in the following calculations.

4.5.4 The Effect of the Thicknesses (d_1 and d_2)

As clear in Fig. 7, the resonant dip has the highest shift at the center of the PBG. Figure 7(A) shows that the optimum

Fig. 5 The reflectance spectra as a function of the wavelength for (A) prism/T/SiO₂/PSi-1DPC at T = 0 °C, and (B) prism/Ag/T/SiO₂/PSi-1DPC at N = 10, d_T = 1000 nm, d_C = 40 nm, d_m = 30 nm, for three different values of temperature −80 °C, 0 °C, and 80 °C

thickness of d₁ is 185 nm that achieves $\Delta\lambda = 66.18$ nm at d₂ = 200 nm, PSi₁ = 28%, and PSi₂ = 85%. Then, the optimum thickness of d₂ is 270 nm that achieves $\Delta\lambda = 67.74$ nm using previous optimum conditions (d₁ = 185 nm, PSi₁ = 28%, and PSi₂ = 85%) as clear in Fig. 7(B).

4.5.5 The Effect of the Toluene Layer Thickness

The increase of the toluene layer thickness does not influence the PBG as cleared in Fig. 8(A) because the toluene layer is outside the periodic structure. By contrast, in the presence of

Fig. 6 The reflectance spectra as a function of both wavelength and porosities (P₁ and P₂) of prism/T/SiO₂/PSi-1DPC with N = 10, d_T = 1000 nm, d_C = 40 nm, d_m = 30 nm at T = −80 °C (green line), T = 0 °C (black line), and T = 80 °C (blue line) (A) P₁ with assuming P₂ = 85%, and (B) P₂ with using the optimum value of P₁ = 28%

Fig. 7 The reflectance spectra as a function of both wavelength and thickness (d_1 and d_2) of prism/T/SiO₂/PSi-1DPC with $N = 10$, $d_T = 1000$ nm, $d_C = 40$ nm, $d_m = 30$ nm at $T = -80$ °C (green line), $T = 0$ °C (black line), and $T = 80$ °C (blue line) (A) d_1 with assuming $d_2 = 200$ nm, and (B) d_2 with using the optimum value of $d_1 = 185$ nm

the Ag layer, changing the toluene layer causes a drastic change in the Tamm resonance conditions, and increases the radiation confinement, which makes it very sensitive to temperature. Figure 8(B) shows that the resonant dip shift increases with the increase of the wavelength and the increase of toluene layer thickness due to the increase of the optical path through the toluene with the increase of its thickness. High confinement of electromagnetic waves occurs with the increase of the optical path length. We will consider the thickness of 10,795 nm as the optimum toluene thickness because the resonant dips will overlap with each other at thicknesses higher than 10,795 nm.

4.6 Sensor Analysis at the Optimum Conditions

The optimum conditions of the proposed sensor are $\alpha_0 = 0^\circ$, $N = 10$, $d_T = 10,795$ nm, $d_C = 40$ nm, and $d_m = 30$ nm, $d_1 = 185$ nm, $d_2 = 270$ nm, $PSi_1 = 28\%$ and $PSi_2 = 85\%$. As clear in Fig. 8(C), the resonant dip is blue-shifted from 2193.6 nm to 2082.3 nm with the increase of temperature from -80 °C to 80 °C.

To assess the performance of the proposed sensor, different parameters will be calculated such as sensitivity, signal-to-noise (SNR), resolution (RS), Q-factor, and detection limit (LOD). The sensitivity is calculated as the following [72]:

$$S = \frac{\Delta\lambda_R}{\Delta T}, \quad (13)$$

where $\Delta\lambda_R$ is the resonance wavelength shift ($\Delta\lambda_R = \lambda_{T2} - \lambda_{T1}$), and ΔT is the Temperature difference ($\Delta T = T_2 -$

T_1). The second parameter is signal-to-noise (SNR) that is calculated by [40]:

$$SNR = \frac{\Delta\lambda_R}{FWHM}. \quad (14)$$

The third parameter is the resolution (RS) of the suggested sensor which reflects the smallest change in the resonant dip that can be measured accurately by [40]:

$$RS = \frac{2(FWHM)}{3(SNR)^{1/4}}. \quad (15)$$

The quality factor of the proposed sensor is calculated as:

$$Q = \frac{\lambda_R}{FWHM}. \quad (16)$$

This proposed sensor showed a significantly lower detection limit ($DL = 10^{-1}$) that can be calculated by [73, 74]:

$$LOD = \frac{\lambda_R}{20 S Q}. \quad (17)$$

Table 1 shows that the proposed sensor has high sensitivity (0.7 nm/°C), high SNR (~ 30), and very low RS (~ 0.25) which makes it very distinguished compared to previous works as cleared in Table 2. Figure 6(C) shows the reflectance spectra of the sensor at optimum conditions for different values of temperatures.

Fig. 8 The reflectance spectra at $\alpha_0 = 0^\circ$, $N = 10$, $d_C = 40$ nm, $d_m = 30$ nm, $d_1 = 185$ nm, $d_2 = 270$ nm, $PSi_1 = 28\%$ and $PSi_2 = 85\%$ for (A) prism/T/SiO₂/PSi-1DPC as a function of the wavelength and toluene layer thickness at $T = -80^\circ\text{C}$, (B) prism/Ag/T/SiO₂/PSi-1DPC as a function of the wavelength and toluene layer thickness at $T = -80^\circ\text{C}$ (green line), $T = 0^\circ\text{C}$ (black line), and $T = 80^\circ\text{C}$ (blue line), and (C) prism/Ag/T/SiO₂/PSi-1DPC as a function of the wavelength, at $d_T = 10,795$ nm

5 Conclusion

In summary, we suggested a high-sensitivity temperature sensor based on Tamm resonance in a silver-coated multilayer of mesoporous Si. The optimization process showed a negative effect on the increase of the incident angle and a positive effect on the increase of the thickness of the toluene layer on the

performance of the proposed sensor. It recorded high sensitivity ($0.7 \text{ nm}/^\circ\text{C}$), high SNR (~ 30), and very low resolution (~ 0.25) for temperature sensing that makes it very distinguished compared to previous works. The proposed design may help in the correct handling of infectious substances and can be used as a narrow-band filter under temperature effects.

Table 1 Sensor parameters for different values of temperature at the optimum conditions

T ($^\circ\text{C}$)	λ_R (nm)	$\Delta\lambda_R$ (nm)	S (nm/ $^\circ\text{C}$)	FWHM (nm)	SNR	RS	Q-factor	LOD
80	2082.3	—	—	1.133	—	—	1837.9	—
40	2110.8	28.5	0.713	1.024	27.8	0.3	2061.3	0.07
0	2138.8	28.0	0.7	0.919	30.5	0.3	2327.3	0.07
-40	2166.6	27.8	0.695	0.836	33.3	0.2	2591.6	0.06
-80	2193.6	27.0	0.675	0.811	33.3	0.2	2706.5	0.06

Table 2 Comparison of sensitivity and the dynamic range of the proposed structure with other temperature sensors in the literature (NC = not counted)

Reference	S (nm/°C)	SNR	RS	LOD	operating range (°C)
[75], 2012	0.07	NC	NC	NC	20 to 70
[25], 2013	0.07	NC	NC	NC	0 to 527
[26], 2018	0.06	NC	NC	NC	25 to 170
[27], 2019	0.27	NC	NC	NC	−40 to 40
[28], 2019	0.06	NC	NC	NC	5 to 540
[76], 2019	0.24	NC	NC	0.004 to 0.006	20 to 60
This work	0.70	~30	~0.25	0.06 to 0.07	−80 to 80

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Author Contributions Z.A. Zaky invented the original idea for the study, implemented the computer code, performed the numerical simulations, analyzed the data, and wrote the main manuscript text. A.M. Ahmed discussed the data. A.H. Aly discussed the results and supervised this work. All Authors developed the final manuscript.

Data Availability Requests for materials or code should be addressed to Z.A.Z.

Declarations

Ethics Declarations This article does not contain any studies involving animals or human participants performed by any of the authors.

Consent to Participate Not Applicable.

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