Defected Photonic Crystal Array Using Porous GaN as Malaria Sensor

M.T. Tammam¹, Zaky A. Zaky*¹, Arvind Sharma², Z.S.Matar³, Arafa H. Aly¹, *, M.A. Mohaseb¹,³
¹TH-PPM Group, Physics Department, Faculty of Sciences, Beni-Suef University, Beni-Suef, Egypt
²Department of Physics, Government Dungar College, Bikaner, Rajasthan, India -334001
³Umm-Al-Qura University, Faculty of Applied Science, Department of Physics, Mecca, Saud Arabia
*Corresponding authors. E-mail: zaky.a.zaky@science.bsu.edu.eg (Zaky A. Zaky)
arafaaly@aucegypt.edu (Arafa H. Aly)

Abstract. A defective one-dimensional photonic crystal is investigated as a biosensor to detect malaria disease. The proposed photonic structure is air/(GaN/Porous GaN)N/Sample/(GaN/Porous GaN)N/Substrate. The red blood cells sample of the human being is used as a sample defect in the proposed optical device. The pioneer transfer matrix method is used to analyze the transmittance spectra. A change in sample refractive index highly affects the transmittance resonant peak and this shift in the peak plays a key role in the operation of the device. The relatively high figure of merit of 1022 RIU⁻¹ with a sensitivity of 1472 nm/RIU and quality factor of 1076 is detected. The proposed sensor is relatively better than others available to detect malaria disease.

Keywords: Photonic Crystal, Biosensor, Porous materials, Malaria Diagnosis

1. Introduction

In the last few decades, defected one dimensional photonic crystal (1D-PC) have attracted more attention in many potential applications such as biosensors [1-11], temperature sensors [12-16], solar cells [17-22], filters [23-30], air purifier [31], water desalination [32, 33] and others [34-36]. The most amazing feature of 1D-PC is the photonic bandgaps (PBG) originated due to multiple scattering at interfaces, and the incident waves are blocked to propagate within the PBGs [37, 38]. Because of the resonance of Fabry-Perot, a defect resonant peak appears within the PBG when a defect layer is introduced into 1D-PC [39]. As a result of the law of Bragg Snell’s, by changing the index of refraction of the defect layer, the resonant peak will be shifted. This dependence between the optical properties of the sample layer sample and the resonant peak is the principle of PC sensors.

Recently, Porous and two-dimensional layers have gained the attention of scholars in biosensing applications [40-42]. Defected 1D-PC of porous layers can sense different solutions based on their refractive indices change. Porous Gallium nitride (GaN) can be used as a multilayer PC with perfect lattice matching [43-45]. Porous GaN is more interesting than porous dielectrics because it can easily be incorporated with active electronics [42]. The optical properties of GaN can be adjusted by changing the
porosity [46]. Lheureux et al. [43] used standard photolithography to prepare the porous GaN utilizing the wet EC etching procedure.

Malaria is a serious disease that might kill 405,000 persons in 2018 according to WHO report [47]. Early diagnosis contributes to the high speed of achieving a cure for the disease. Malaria can be diagnosed using a variety of approaches, including quantitative buffy coat (QBC) method [48], microscopic diagnosis [49], rapid diagnostic tests (RDT) [50], indirect fluorescent antibody (IFA) [51], and others [52]. Most of these techniques have limitations such as not detect early stages effectively [48], take a large testing time [53], and not being cost-effective [54]. Human tissues are injected with a parasite during its sporozoite phase and cause malarial infection. This parasite moves through various stages (ring, trophozoite, and schizont) in red blood cells (RBCs). These phrases cause a change in the indices of refraction of the infected RBCs, as clear in Table 1. So, detecting the index of refraction of the RBCs is considered the key factor for malaria detection [55, 56].

Table 1: Average index of refraction values of different cells of RBCs [57]:

| Name                        | Average refractive index |
|-----------------------------|--------------------------|
| Normal RBC cells            | 1.402                    |
| Ring phase cells            | 1.395                    |
| Trophozoite phase cells     | 1.383                    |
| Schizont phase cells        | 1.373                    |

In this paper, we will try to overcome such limitations with defected 1D-PC malaria sensor using Porous GaN. The proposed structure has the potential to aid in the early detection of malaria.

2. Materials and method

The proposed structure of the malaria sensor is air/(GaN/Porous GaN)N/Sample/(GaN/Porous GaN)N/Substrate as clear in Fig.1. At the center of the structure, a defect layer is inserted between two identical 1D-PC of (GaN/Porous GaN)N. N is the total number of layers of 1D-PC. A transverse electric (TE) polarization will fall on the structure. The thicknesses of the first and second layers are \(d_1 = 163\) nm and \(d_2 = 208\) nm, with refractive indices as in Eq. 1 and Eq. 2. This porosity of porous GaN will be 53% [43]. Experimentally and theoretically, a multilayer of GaN/Porous GaN was studied [43, 45, 58]. As clear in Fig. 1, by injecting the sample at the top of the structure, the pores will be infiltrated with the analyte sample. The index of refraction of the porous GaN (\(n_2\)) is calculated by using volume average theory [46]:

\[
n_2 = \sqrt{(1 - P) n_1^2 + P n_{sam}^2},
\]

where \(P\), \(n_{sam}\), and \(n_1\), are the porosity ratio, the index of refraction of the analyte that is infiltrated inside the pores (index of the RBCs sample), and the index of refraction of GaN. The index of refraction of GaN as a function of wavelength (\(\lambda\)) is calculated as [59]:

\[
n_1 = \sqrt{3.6 + \frac{1.75\lambda^2}{\lambda^2 - 0.256^2} + \frac{4.1\lambda^2}{\lambda^2 - 17.86^2}}.
\]
Figure 1. The structure of the proposed 1D-PC sensor.

Multilayer structure problems can be solved and analyzed by the famous transfer matrix method (TMM). The TMM is explained by several authors [60-63]. The transmittance of the proposed device is calculated using TMM. Here we are considering the interaction between incident transverse electromagnetic (TE) waves with normal incidence. It is given by the overall matrix as follows:

\[
C = \begin{bmatrix}
C_{11} & C_{12} \\
C_{21} & C_{22}
\end{bmatrix} = (c_1 c_2)^N c_{sam}(c_1 c_2)^N,
\]

where \(C_{11}, C_{12}, C_{21}, \) and \(C_{22}\) are elements of the transfer matrix. Here \(c_1, c_2\) and \(c_{sam}\) are characteristic matrix corresponding to GaN, porous GaN, and sample which are as follows:

\[
c_k = \begin{pmatrix}
\cos \phi_k & -i \frac{p_E}{\lambda} \sin \phi_k \\
-i p_E \sin \phi_k & \cos \phi_k
\end{pmatrix},
\]

where \(k = 1, 2, \) and \(sam\). The \(\phi_k\) is phase difference at each layer and it is denoted by:

\[
\phi_k = \frac{2\pi n_k d_k \cos \theta_k}{\lambda}.
\]

The values of \(p_k\) for the TE(S) polarisation is given by \(p_k = n_k \cos(\theta_k)\).

The incident angle \(\theta_0, \theta_1, \theta_2, \theta_{sam}\), and \(\theta_s\) are at the surfaces of air, GaN, porous GaN, sample, and substrate. Here angle \(\theta_0\) represents the angle of incidence of the incident light from the air to the proposed device and satisfying the Snells law as follows:

\[
n_0 \sin(\theta_0) = n_1 \sin(\theta_1) = n_2 \sin(\theta_2) = n_{sam} \sin(\theta_{sam}) = n_s \sin(\theta_s).
\]

The matrix \((c_1 c_2)^N\) can be calculated by using the Chebyshev polynomials of the second kind. The transmission coefficient \(t\) using the above equations is given below[48-50]:

\[
t = \frac{2p_s}{(C_{11} + C_{12}p_0)p_s - (C_{21} + C_{22}p_0)}
\]

Hence, the transmittance \(T\) of the proposed device is given by,

\[
T(\%) = 100 \times \frac{p_0}{p_s} |t|^2.
\]
3. Results and discussions

The proposed structure of the malaria sensor is as air/(GaN/Porous GaN)$^N$/Sample/(GaN/Porous GaN)$^N$/Substrate. At the middle of the structure, a defect red blood cell sample is inserted between two identical 1D-PC of (GaN/Porous GaN)$^N$. A transverse electric (TE) polarization will be incident on the structure. The transmittance of the proposed sensor without defect layer (black line), and with defect layer (red line) at $n_{sam}=1.731$ is depicted in Fig. 2. Without defect layer resonant peak non exists but using the defect layer of refractive index 1.731 a clear sharp resonant peak of 100% and large photonic bandgap exist.

![Figure 2](image)

**Figure 2.** The transmittance of the proposed sensor without defect layer (black line), and with defect layer (red line) at $n_{sam}=1.731$.

The sensitivity (S) of any sensor, figure of merit (FoM), and Q factor can be calculated as [64-66]:

\[
S = \frac{\Delta \lambda_R}{\Delta n_{sam}}
\]

(9)

\[
FoM = \frac{S}{FWHM'}
\]

(10)

\[
Q = \frac{\lambda_R}{FWHM}
\]

(11)

![Fig. 3](image)

**Fig. 3:** The sensitivity and FoM at different thicknesses of the sample layer.
The performance parameters of the investigated sensor at different thicknesses of the sample layer are clear in Fig. 3. The rise in the defect layer of the sample analyte thickness raises the sensitivity of the photonic sensor. The rise in defect of the sample analyte layer thickness from 3000 nm to 15000 nm raises sensitivity value from 652.3 nm/RIU to 1472.2 nm/RIU. Initially, the rise in sensitivity value is sharper. If defect layer thickness increases onwards 11000 nm, the sensitivity is approximately constant. The variation in the position of resonance mode is that it depends upon the total index of refraction of all structures and thickness of periodic PC. The standing wave formation due to defect at the resonant wavelength obey the condition [4, 67]

\[ O = z\lambda = n_{\text{eff}}g, \]  

(12)

where \( O \) is the optical path length, \( z \) is a scalar bomber, \( \lambda \) is the incident wavelength, \( n_{\text{eff}} \) is the refractive index of the whole device and \( g \) is the path length. Here, we are increasing \( g \) but \( z \) and \( n_{\text{eff}} \) remain constant hence the resonant wavelength shift towards a longer wavelength. The FoM increases approximately linearly from 152.3 RIU to 1022.6 RIU with a rise from 3000 nm to 15000 nm in the sample layer thickness, respectively. It is clear from the investigation that the optimum value of sample layer thickness obtained was 15000 nm for different RBCs. The human tissues are injected with a parasite with a mosquito bite during its sporozoite phase and cause malarial infection. This parasite goes through different phases in RBCs. These phrases cause a change in the indices of refraction of the infected RBCs, as clear in Table 1. The transmittance of the proposed sensor with an optimum sample layer thickness of 15000 nm for different phases in RBCs is depicted in Fig. 4. For the phases normal RBC, ring, trophozoite, and schizont in red blood cells (RBCs) the refractive index is decreasing. For the phases ring, trophozoite, and schizont in red blood cells (RBCs) concerning normal RBC, the resonant peak shifted towards lower wavelength (blue shift) due to decreasing values of refractive index.

![Figure 4](image.png)

**Figure 4.** The transmittance of the investigated sensor with a sample layer thickness of 15000 nm for different RBCs.

The performance comparison of our work is represented in the following table 2. The relatively high sensitivity of 1472 nm/RIU with a figure of merit of 1022 RIU and quality factor 1076 is detected.
Table 2: Performance comparison (NC= not be calculated).

| Reference     | S (nm / RIU) | FoM (RIU⁻¹) | Q-factor  |
|---------------|--------------|--------------|-----------|
| 2017, [68]    | 17           | 233          | 3*10⁴     |
| 2019, [6]     | 1000         | ----         | 35 517    |
| 2020, [2]     | 1400         | 6*10⁶        | 3.5*10⁶   |
| 2020, [69]    | 777          | ----         | 2576      |
| 2020, [70]    | 656          | 1.13         | 2719      |
| 2020, [43]    | 10           | 15.1         | 300       |
| 2021, [52]    | 496          | ----         | 203000    |
| **This work** | **1472**     | **1022**     | **1076**  |

4. Conclusion

A GaN and porous GaN-based one-dimensional defective photonic crystal is investigated as an optical sensor to detect malaria disease. The red blood cells sample of the human being is used as a sample defect in the proposed optical sensor. The notable change in sample refractive index affects the transmission resonant peak and the shift in the peak plays a vital role in the operation of the photonic sensor. The relatively high sensitivity of 1472 nm/RIU with a figure of merit 1022 RIU⁻¹ and quality factor 1076 was detected. The proposed optical sensor is relatively better than others available to detect malaria disease.

Conflicts of interest/Competing interests

The authors declare no conflicts of interest.

ORCID IDs

https://orcid.org/0000-0003-0795-378X (A. H. Aly)
https://orcid.org/0000-0002-8300-7755 (Z. A. Zaky)

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