Design and Study of a Nanocavity-based One-dimensional Photonic Crystal for Potential Applications in Refractive Index Sensing

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Abstract—**Refractive index (RI) can be used to identify a particular substance and determine its purity and concentration. The RI of glucose solution with various concentrations can be determined using a distributed Bragg reflective (DBR) device containing a nanocavity. The optical property of the reflection spectrum produced by DBR is sensitive to the variation of the refractive index. In this study, a DBR with a cavity width of 220 nm, located in the middle of the device, is designed and used to sense the variation in the refractive index of glucose at different concentrations. The proposed design showed a sharp dip pattern within the reflection spectrum. The wavelength of the absorption peak was found to be sensitive to trivial variations in the refractive index of glucose solution. Results showed that the variation in the refractive index of glucose within the order of $\Delta n = 0.02$ has led to a noticeable shift in the absorption spectrum by $\Delta\lambda = 2.6$ nm. Furthermore, the sensitivity of the proposed device was found to be 130 nm/RIU which is considered high compared with those reported in the literature. Hence, the proposed structure can be a promising optical device for chemical ultrasensing applications.**

Index Terms—**Distributed Bragg Reflectors, Photonic crystal, Nanocavity, Refractive index, Sensor.**

I. Introduction

The refractive index (RI) is one of the most important physical properties to determine the composition of solutions (Singh, et al., 2013). Accurate determination of any solution concentration by measuring the RI is usually used in medicine (Elblbesy, 2020), food technology (Harrill, 1994), pollution measurements (Shi, et al., 2014) as well as chemical and physical studies (Reis, et al., 2010). Various studies have demonstrated to measure the refractive index of glucose at different concentrations. Glucose, as an optically active substance, an interferometer measurement system was used to provide a straightforward means of measuring the optical properties of chiral media (Lin and Su, 2003; Tan and Huang, 2015; Yeh, 2008). Furthermore, the minimum deviation of the prism technique was used to show the dependence RI of glucose solution on the variation of the source wavelength (Belay, 2018).

Distributed Bragg reflector (DBR) mirrors that consist of altered high and low refractive index staked layers show a high reflectivity phenomenon (Leem and Yu, 2013). The optical property of DBR depends on the stacked layers' thickness and their refractive index. Studies showed that introducing a nanocavity inside the DBR structure produced a sharp dip peak (that is, absorption spectrum) within the reflection spectrum. The peak position is highly sensitive to the refractive index of the introduced cavity and thickness (Shanmugan, et al., 2004; Kumar and Das, 2018). Kumar et al. introduced a refractive index sensor based on the cavity mode formed inside a (200–900) nm thin cavity layer sandwiched between multilayers of SiO_2/Ta_2O_5 and a 40 nm metal film. Their structure showed a relatively high sensitivity for different cavity thicknesses (Kumar and Das, 2018). However, their proposed structure is non-metal layer contained and consists of Si_3N_4/SiO_2 multilayer with nanocavity prepared by plasma-enhanced chemical vapor deposition.

In this study, a DBR structure with nanocavity is used to observe the shift of the absorption spectrum with the variation of the RI of glucose solution. Glucose, known as blood sugar, is an important composition which considered fuel for energy production, especially for the brain, muscles, and several other body organs and tissues. Results showed that the DBR structure containing nanocavity can be used as an ultrasensitive optical device to determine any small variations in the refractive index of solutions.

II. Structure Design and Simulation

The proposed nanocavity-based refractive index sensor is shown in Fig. 1a. The structure contains a 220 nm nanocavity sandwiched between the DBR layers which made up of Si_3N_4 and SiO_2. This structure is also known as one-dimensional photonic crystal (1D PC). The cavity of the DBR structure

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is located in the center as it forms the basis of the sensing mechanism. The refractive index of the medium in the cavity region dictates the absorption mode, and hence, any changes in the characteristics of the cavity region alter the absorption wavelength. The DBR is consisting of 14 bilayers of Si_3N_4/SiO_2 having thicknesses of 78 nm and 109 nm, respectively. The thicknesses of the stack layer were chosen to be in the order of quarter wavelength for a band gap centered at λ_o = 632.8 nm based on the following relations:

$$t_H = \frac{\lambda_0}{4n_H} \quad (1)$$

$$t_L = \frac{\lambda_0}{4n_L} \quad (2)$$

Where: t_H, t_L, n_H, and n_L are the thickness and refractive index (RI) of both the high Si_3N_4 (n_H = 2.028) and low SiO_2 (n_L = 1.45) refractive index material, respectively. The photonic band gap is in the visible region (566–718 nm) as shown in Fig. 1b.

However, the DBRs reflectivity calculation is based on the transfer matrix method. Formulation of the boundary conditions at the multilayers' interfaces was derived from both Fresnel and Maxwell's equations for the dielectric medium (Mohammed, 2019).

III. Results and Discussion

First of all, the optical resonance of 1D PC containing a nonocavity was optimized by manipulating the cavity width and position. To study the effect of cavity position in the DBR structure for 0% glucose concentration solution with n = 1.3264 and cavity width of 220 nm, the cavity position was changed from 10th to 20th single layer. Calculations indicated that the cavity at the middle of the DBR structure (14 bilayers) shows the highest dip in the reflection spectra (Fig. 2a) and the narrowest width (that is, full width at half maximum [FWHM]) as shown in Fig. 2b.

Second, the cavity thickness was varied from 210 to 240 nm with a step size of ±5 nm, to observe the absorption wavelength spectrum for each cavity thickness, as shown in Fig. 3a. For the initial refractive index (n = 1.3264), it was observed that the absorption wavelengths have undergone a red shift from 612 to 635 nm within the broad reflection band (Fig. 3b). The intensities of absorption wavelengths and their width were varied due to tuning of the resonance wavelength of the cavity modes with the variation in the cavity thickness. Calculations showed that the cavity of 220 nm supports the highest reflection dip spectrum and the narrowest spectrum width, as shown in Fig 3c.

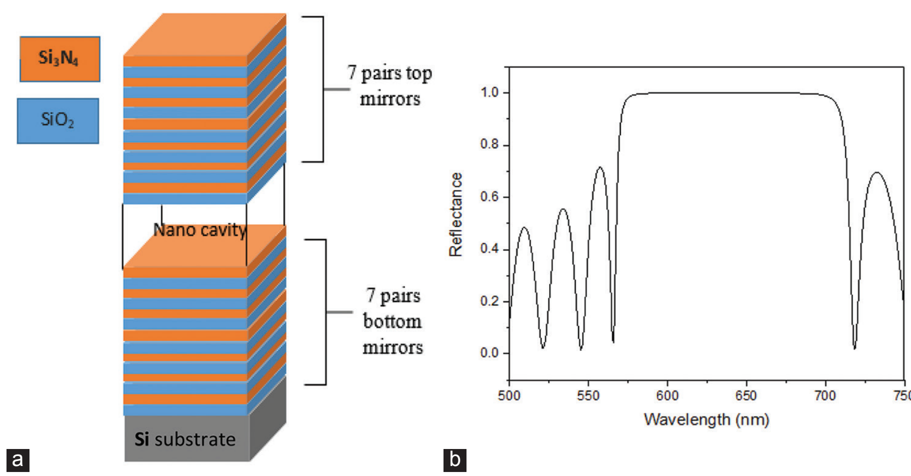

Fig. 1. (a) Fixed nanocavity distributed Bragg reflectors structure (1D PC) between 14 pairs of highly reflecting mirrors on a Si substrate and (b) reflectance spectrum of 14 pair of Si_3N_4/SiO_2 layers.

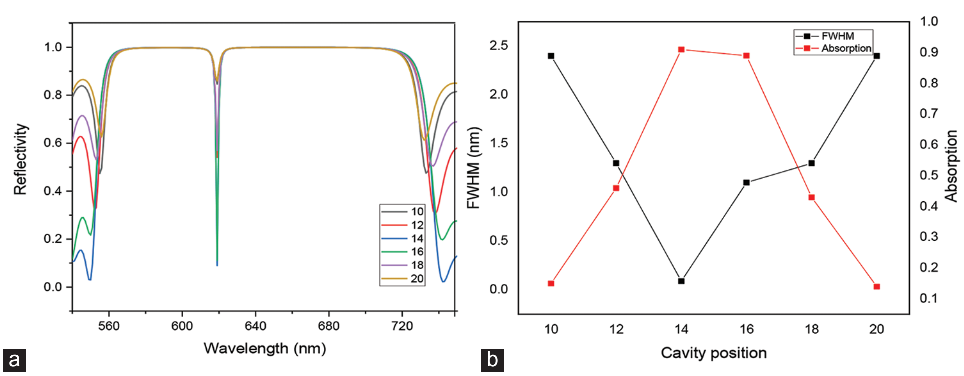

Fig. 2. (a) Absorption spectrum at different position of the nanocavity in the distributed Bragg reflector structure. (b) Absorption and full width at half maximum of produced spectrum versus cavity position.

However, it was found that increment in the solution concentration has led to increase in the refractive index (Tan and Huang, 2015). The DBR mirrors with nanocavity tested as a refractive index sensor device for various concentrations of aqueous glucose solutions in the range of 0–50 mg/mL. The achieved data are illustrated in Table I.

The variation of absorption mode in the reflection spectra as a function of different glucose refractive indices is shown in Fig. 4a. For all guided wavelengths, the absorption spectra were linearly red shifted with the increase in the refractive index, as can be seen in Fig. 4b. By applying a curve fitting technique, the linear correlation between the refractive index of glucose and absorption spectrum dip wavelength was found, which can be expressed as below:

$$\lambda = 130.08n + 445.59 \tag{3}$$

Where n is the glucose refractive index. Eq. (3) indicates that the average difference of refractive index (Δn= 0.02) caused a $\Delta\lambda$= 2.6 nm shift in the absorption peak spectrum. The absorption peak spectrum was found to be comparable to their average FWHM which was around 1.2 nm. Interestingly, the sensitivity for our device which is defined as $S = \frac{\Delta\lambda}{\Delta n}$ (Shaban, et al., 2017; Zaky, et al., 2022) was found to be $130\frac{nm}{RIU}$. This result showed a high sensitivity for the proposed structure in comparison with the previously reported ones $20\frac{nm}{RIU}$ (Yeh, 2008) and $48\frac{nm}{RIU}$ (Shaban, et al., 2017). The nm/RIU is typically refers to a change in the refractive index of the region probed by the resonant mode causing a corresponding wavelength shift of the optical resonance of the sensor (White and Fan, 2008).

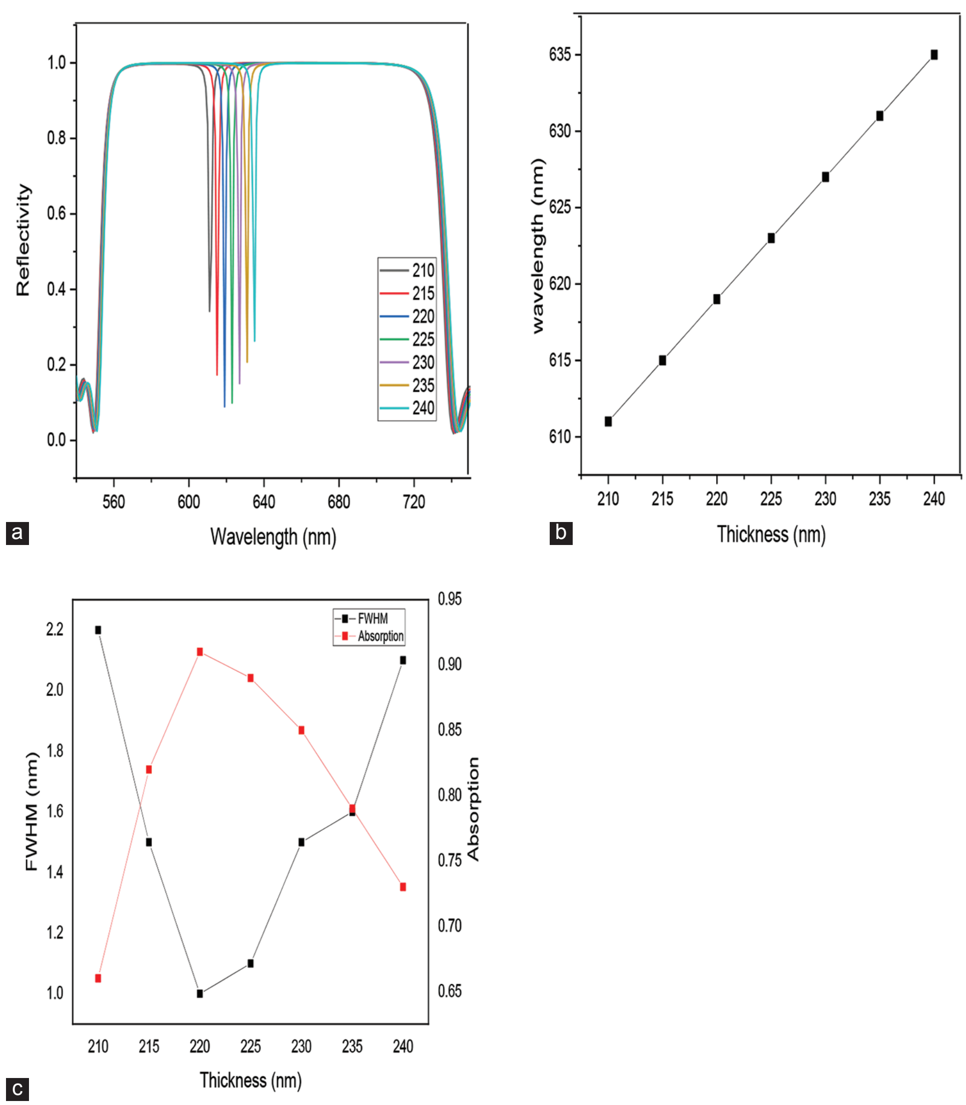

Fig. 3. (a) Absorption spectrum versus different cavity thicknesses. (b) Red shift of absorption spectrum as the cavity thickness increase. (c) Relation between absorption and full width at half maximum spectrum with the cavity thickness.

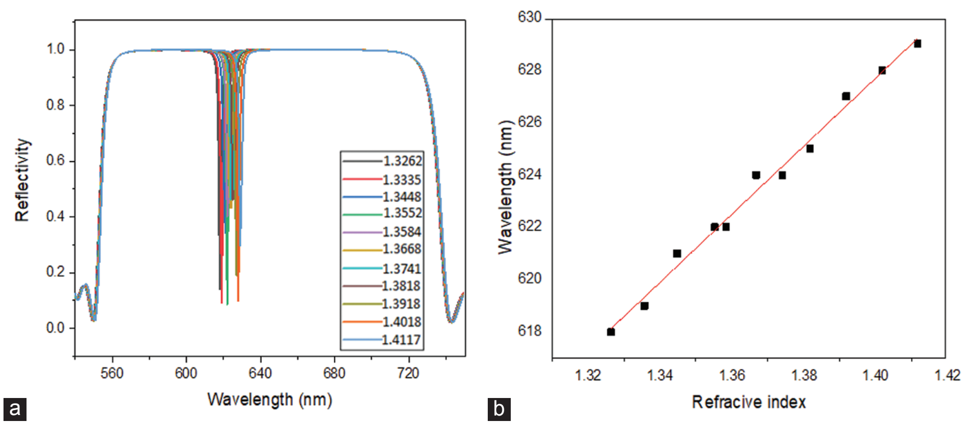

Fig. 4. (a) Absorption spectrum versus variation of glucose refractive index (RI) and (b) Red shift of absorption spectrum as the RI of glucose solution increase.

TABLE I
Simulation Results for Refractive Index of Samples of Glucose Concentrations in the Range 0–50 mg/mL. The Refractive Index Value Extracted from (Belay, 2018)

Concentration % (mg/mL)	RI	Wavelength λ_{abs} (nm)
0	1.3264	618
5	1.3357	619
10	1.3448	621
15	1.3552	622
20	1.3584	622
25	1.3668	624
30	1.3741	624
35	1.3818	625
40	1.3918	627
45	1.4018	628
50	1.4117	629

IV. Conclusions

The DBR device containing a nanocavity, which is used to detect colugos concentration by means of the variation in the refractive index of the samples, is designed and investigated. This study elucidates that there is a linear relation between the absorption wavelength and the refractive index of glucose solution by which an empirical expression was established. Besides, the cavity widths and positions were changed to optimize the performance of the proposed DBR structure. The results manifest that this design can sense the change of refractive index by Δn = 0.02 which in turn produced a 2.6 nm shift in the absorption spectrum. It was concluded that the sensitivity of the device was superior in comparison with those reported in the literature. Thus, these findings can help to improve the fundamental understanding of using DBR stacked layers as a sensitive chemical sensor.

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