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A biosensor based on one-dimensional photonic crystal for monitoring blood glycemia

A. Bouzidi[1], D. Bria[1], F. Falyouni [1,2], A. Akjouj[3], G. Lévêque[3], M. Azizi[1] and H. Berkhli[4]

[1]*Laboratoire de Dynamique et d'Optique des Matériaux, Département de Physique, Faculté des Sciences, Université Mohamed I, 60000, Oujda, Maroc.*
[2]*Faculté des sciences et techniques d'Al Hoceima, Université Mohamed I, 60000, Oujda, Maroc.*
[3]*Institut d'Electronique, de Micro-électronique et de Nanotechnologie(IEMN), Université de Lille1, 59655 Villeneuve d'Ascq Cedex, France*
[4]*Faculté de Médecine et de Pharmacie Université Mohamed I, 60000, Oujda, Maroc*

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afaf.bouzidi9@gmail.com

Abstract

In this work, we present a biosensor based on a one-dimensional photonic crystal for monitoring blood glucose. The one-dimensional photonic crystal is formed by alternating layers of two materials with an empty layer in the middle. This defect layer will be filled with blood. Numerical results show that the blood layer, leads to the appearance of electromagnetic modes within the photonic band gaps of the transmission spectrum, their frequency are depending on the concentration of glucose in blood.

1. Introduction

The proper functioning of the human organism is conditioned by the contribution of energy such as simple sugar compound called GLUCOSE which is carried throughout the body via the bloodstream [1]. The normal range of glucose concentration in blood is 70 mg / dl to 110mg / dl. It reaches the maximum rate (180 mg / dl), shortly after eating, but should return to normal within two to three hours. If the sugar takes more than three hours to return to normal for anybody, one can say that it potentially has diabetes. To ensure compliance with the acceptable range, the glucose level should be regularly monitored and measured three to six times a day [2, 3]. Self monitoring of blood glucose helps manage hypoglycemia or hyperglycemia.
An accurate and reliable detection device [4-15] allowing continuous and real-time monitoring of the concentration of glucose in blood, could have a considerable impact on the lives of diabetic patients by improving their glycemic control [16-18].
The objective of this study is to evaluate the feasibility of designing a sensor based on a one-dimensional photonic crystal for monitoring continuously and in real time the concentration of glucose in blood. We show that by using direct measurement of the coefficient of reflection on the photonic crystal containing blood, it is possible to detect low concentration levels of blood glucose.
The device is based on the introduction of a defect within the perfect one-dimensional photonic crystal [19], in order to create an electromagnetic cavity. This defect consists in exchanging one layer of the photonic crystal with another material, in our case; the blood of a diabetic patient. The objective is using this cavity as a glucose sensor.

2. Results and discussion

Figure 1 represents the proposed sensor made of stacked layers containing a cavity in the middle, of structure $(AB)_4$ C $(BA)_4$. The analyte to be sensed is introduced into the cavity. The electromagnetic wave emitted by the source is detected by a spectrometer after reflection. The periodic layers on each side of the

cavity, C, are made of two materials, A, with refractive index (RI), n_1 = 1.45 and thickness d_1, and B with refractive index, n_2 = 3.86 and thickness d_2.

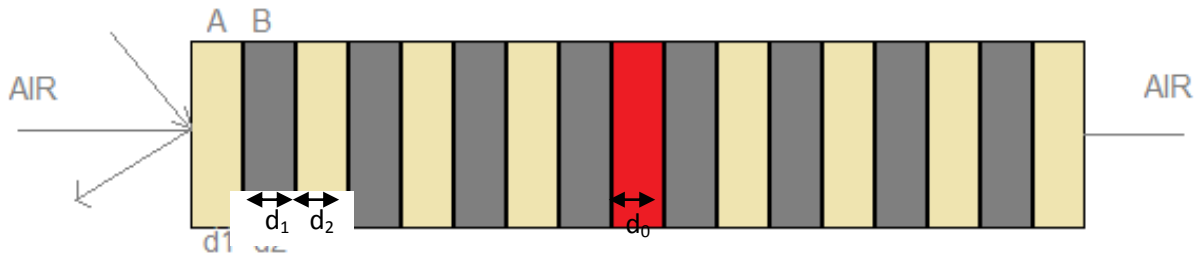

Figure1: Schematic representation of the photonic crystal sensor device

We define D = d_1 + d_2 as the period of the photonic crystal. The cavity defect layer will be filled with the analyte of complex permittivity ε0 and thickness d_0. The study of the propagation of electromagnetic waves through the photonic band gap structure is performed with the help of the interface response theory of continuous media. The objective of this theory is to calculate the Green's function of a composite system containing a large number of interfaces that separate different homogeneous media [20]. The results of this Green's function enable us to obtain different physical properties of the system such as the reflection and transmission coefficients of the waves. In order to use the structure of figure 1 for sensing purpose, the common methodology is to define specific features as peaks or dips within the reflection spectrum [21]. The introduction of a cavity inside a perfect photonic crystal leads to confined resonance modes whose frequencies depend on both the thickness and the content of the cavity [22].

We present in figure 2, the photonic reflection spectra at oblique incidence through (a) perfect photonic crystal, and (b) structure with a blood-filled cavity.

We can see that changing one layer of the perfect photonic crystal with a layer filled with blood, can lead to the occurrence of peaks inside the band gaps of the reflection curve called defect modes. These defect modes are sensitive to the thickness d_0 and the permittivity ε_0 of the blood in the defect layer. The choice of the parameter, d_0, is then a key parameter in the occurrence, tunability, sensitivity, and control of the cavity peak inside the band gap of the photonic crystal.

To give a deeper insight into the existence and behavior of the cavity modes as a function of d0, we have performed calculations on the evolution of the frequencies of reflection as a function of the relative length, d_0/D, for two different concentrations of glucose in blood [23] introduced into the cavity. The results are presented in figure 3 where the dots correspond to the minimum of the reflection. The white areas correspond to the photonic band gaps. One can see that two branches which correspond to the two glucose concentrations appear systematically in a band gap when blood is introduced into the cavity, the frequencies of these branches corresponding to the reflection peaks depend on the length d_0.

Figure 3b shows a zoom on the first gap: when the glucose concentration in the blood changes, the defect branch moves in the gap. The blood cavity thickness d_0 must be well chosen in order to have for each concentration a single peak in the gap, and this peak should be well defined and isolated. The thickness d_0 which verifies these conditions is d_0= 0.27D. We fix d_0 at this value (0.27D).

To see the effect of the variation of the glucose concentration in the blood, we present in the figure 4, the reflection spectra of the structure with the cavity filled with blood for various glucose concentrations in the case of a transverse magnetic (TM) polarization, (a), and transverse electric (TE) polarization (b). One can see that the change of the concentration of glucose in blood; involves a displacement of the reflection peak in the gap. In both case, when the concentration of glucose increases, the reflection peak moves to lower frequencies, which means that each concentration of glucose in the blood is determined by a specific frequency [23-26]. Thus, we can deduce that this 1D photonic crystal can be used as a sensor for monitoring in real time the concentration of glucose in blood.

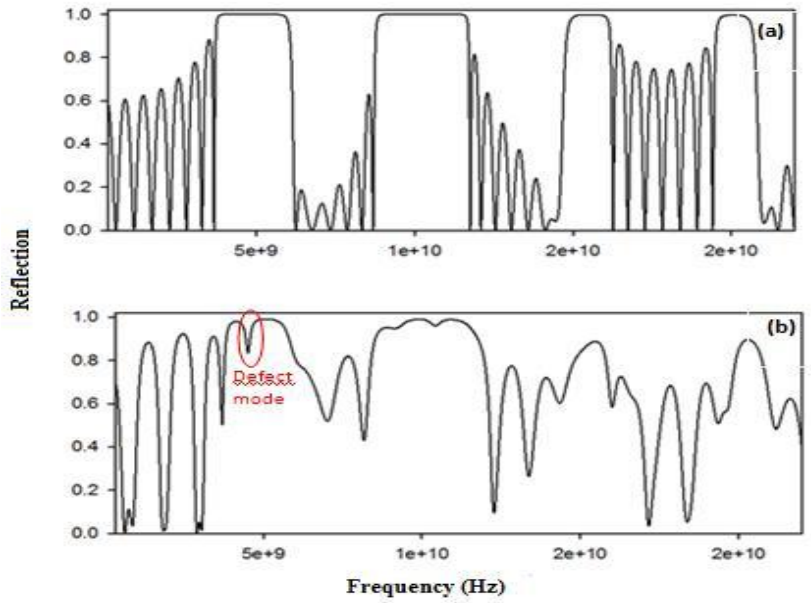

Figure 2: Photonic reflection-spectra through, (a) the perfect photonic crystal, (b) the photonic crystal with blood-filled cavity.

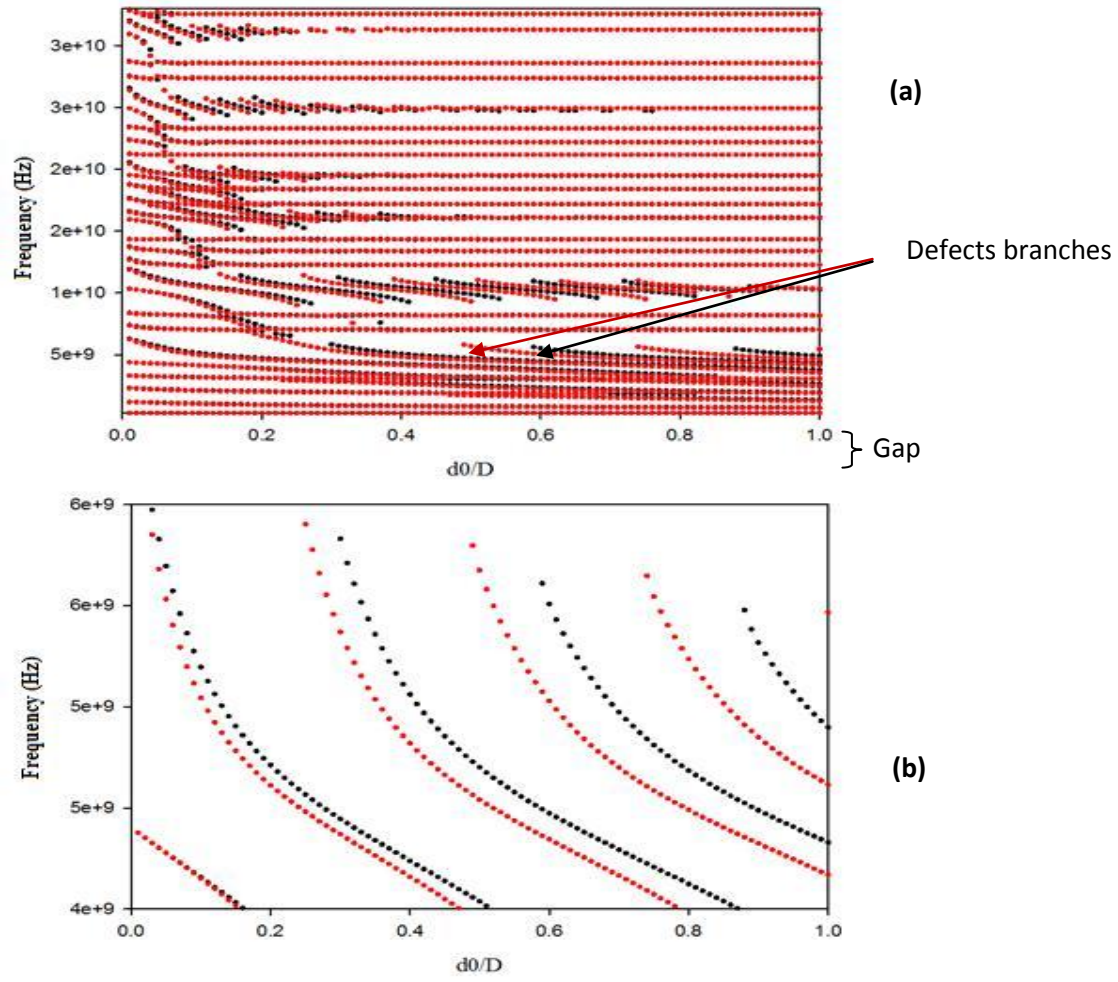

Figure 3: (a) Variation of the reduced frequency of the reflection minima versus d_0/D for two glucose concentrations in blood, 140mg / dl (black dots) and 540mg / dl (red dots). (b) Zoom on the first gap.

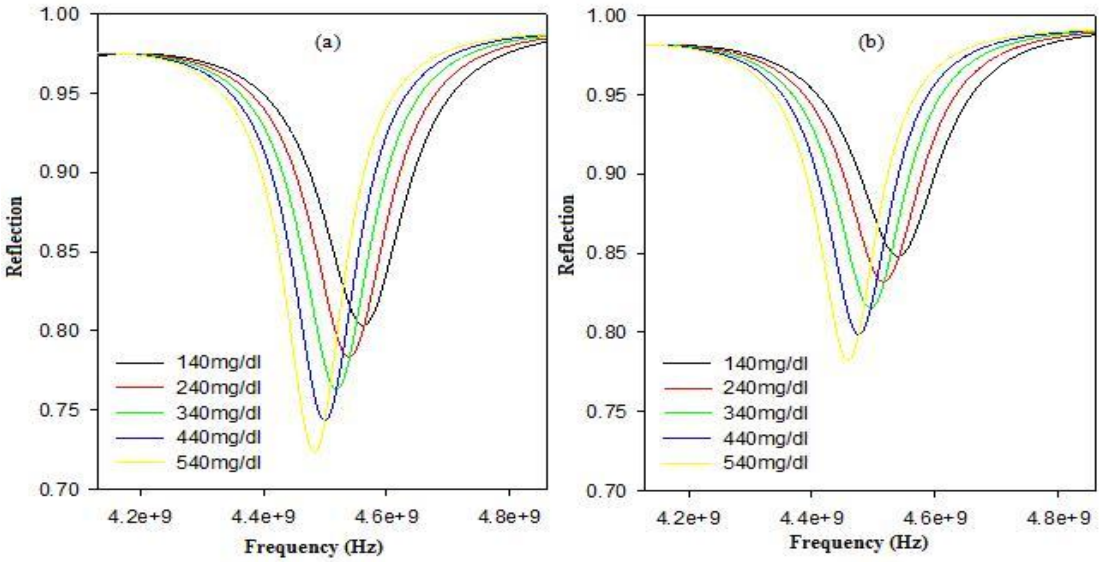

Figure 4: Reflection corresponding to different blood glucose concentration for TM polarization (a) and TE polarization (b)

The variation of the wavelength depends on the glucose concentration in the blood. The relationship between the concentrations and the wavelength is plotted in Figure 5. As shown in this figure, it is observed that the wavelength λ increases with increasing of concentrations of glucose in the blood. The most common way to estimate the efficiency of a sensor is to calculate sensitivity. The sensitivity is given by the following expression: $S = \Delta\lambda/\Delta C$.

With this detection device, the measured sensitivity is S = 2563nm / (mg / dl).

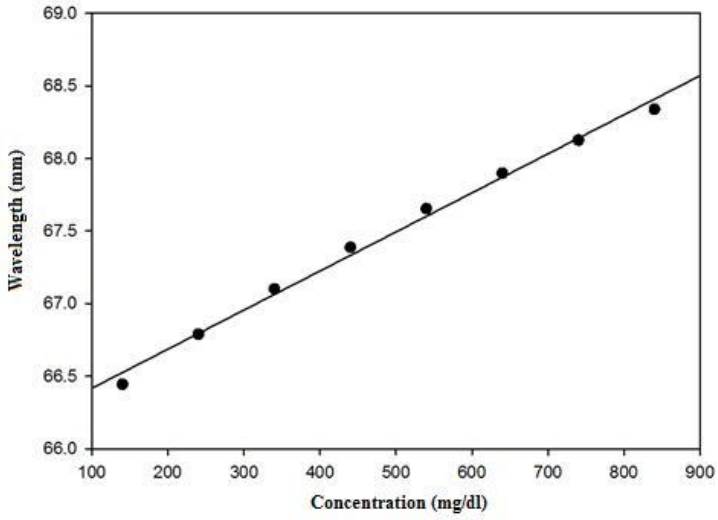

Figure 5: The wavelength of the reflection peak as a function of the concentration of glucose in blood.

Conclusion

We demonstrated detection capability using the peak reflection in conditions that can easily be satisfied in experimental configurations. The position of the reflection peak has been found to be very sensitive to the concentration of glucose in blood. The wavelength shift is a function of glucose concentration in blood which shows that; the photonic crystal sensor can be operated as a sensor for monitoring the glucose concentration in blood.

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