



# Low Temperature Sensor Based on One-Dimensional Photonic Crystals

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**Abstract.** Based on the Green function method and by taking account of the thermal expansion effect and thermo optical effects, we theoretically investigate the transmittance spectra of a one dimensional photonic crystal (PC) with two defects layers designed as  $(AB)^6CBC(BA)^6$  made of Silicon dioxide ( $SiO_2$ ), Titanium dioxide ( $TiO_2$ ), and  $Bi_4Ge_3O_{12}$  (BGO). Numerical results show that the defect mode shifts toward the low frequencies region as the temperature of the structure increases and the central wavelength of defect modes changes linearly with temperature. The proposed structure may be used as a low temperature sensor.

**Keywords:** Photonic crystal · Low temperature sensor · Defect mode  
Green function

## 1 Introduction

A one-dimensional photonic crystal (1DPC) is an artificial microstructure consisting of media with different indices of refraction that are periodically arranged in the same dimension.

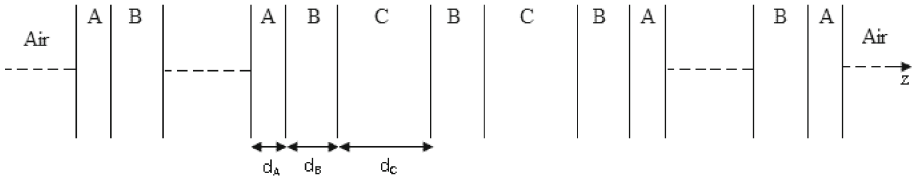
The most important feature of a photonic crystal is the photonic band gap (PBG) which consists of a range of frequencies where the photon can be controlled and manipulated effectively, this feature has led to the development of a wide range of optical devices for different applications.

When the periodicity of a PC is interrupted, by changing the thickness of a layer, or by adding a different medium in the perfect photonic crystal, some defective modes could be generated within the PBGs. The defect mode is a highly localized defect mode which, in general, can be seen in the transmission spectrum with a narrow resonant peak. With the presence of a resonance peak in the transmission spectrum, the structure can be used to function as a sensor [1–3].

In this article we propose a very sensitive photonic structure that can be used as a thermal sensor. The photonic structure is composed of an alternation of two layers, with low refractive index layer (Silicon dioxide  $SiO_2$ ), and high refractive index layer (Titanium dioxide  $TiO_2$ ), and with two defects layers of different thicknesses and different material.

## 2 Model and Method of Calculation

The proposed photonic structure is schematically shown in Fig. 1. It is made of stacked layers containing two defects layers [4, 5] with a different thicknesses, and different material. The light coming from the source goes through the photonic crystal and is transmitted in the outgoing medium. The one-dimensional photonic structure considered in this work can be expressed as  $(AB)^6CBC(BA)^6$ , where A and B stand for the different layers with high and low refractive index  $n_A$  and  $n_B$ , respectively, C is the defect layer. The defect layer consists of the  $Bi_4Ge_3O_{12}$  (BGO) of the thickness  $d_C$ . In our calculation, the material parameters of the dielectric material are taken from Ref. [6]. We assume the layers A of the thickness  $d_A$  to be Titanium dioxide ( $TiO_2$ ). The layers B of the thickness  $d_B$  are Silicon dioxide ( $SiO_2$ ). The period of the structure is  $D = d_A + d_B$ . The medium surrounding the PC is a vacuum. The materials constituting the layers A, B, and C of the structure are assumed homogeneous, and nonmagnetic.



**Fig. 1.** Schematic of PC  $(AB)^6CBC(BA)^6$  with the double defect layer

Serval researches have studied the propagation of optical waves through these composite systems using theoretical methods such as the transfer matrix, the plane-wave method, and so on. However, the plane-wave method is well suited to the study of the band diagram of an infinite superlattice, but it is not adapted to the study of periodicity defects.

In this work, to investigate the temperature dependent defect mode, we shall use the transmission spectrum which can be calculated by the Green function method. This method makes it possible to obtain the transmission coefficients in any type of composite system. The Green function is calculated by using the theory of interface response in composite materials. In this theory, the Green function  $g$  of a composite system can be written as

$$g(DD) = G(DD) + G(DM)[G - 1(MM)g(MM)G - 1(MM) - G - 1(MM)]G(MD) \quad (1)$$

where D and M are, respectively, the whole space and the space of the interfaces in the composite material. G is a block-diagonal matrix in which each block  $G_i$  corresponds to the bulk Green function of the subsystem i. In our case, the composite material is composed of a SL built out of alternating slabs of materials i ( $i = A, B$ ) with thickness

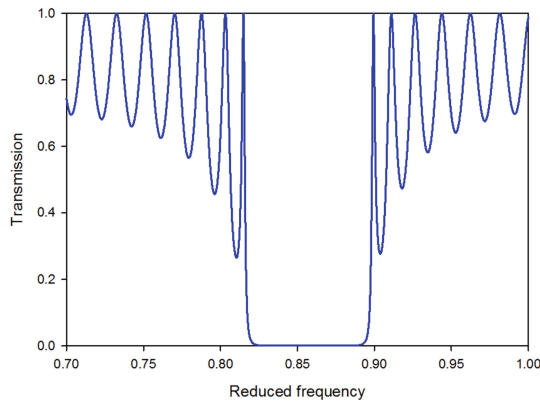
di. In Eq. (1) the calculation of  $g(DD)$  requires, besides  $G_i$ , knowledge of  $g(M M)$ . In practice, the latter is obtained by inverting the matrix  $g^{-1}(M M)$ , which can be simply built from a juxtaposition of the matrices  $g_{si}^{-1}(M M)$ , where  $g_{si}^{-1}(M M)$  is the interface Green's function of the slabs  $i$  ( $i = A, B$ ) and of the substrate alone.

Within this theory, the reflected and transmitted waves  $u(D)$ , resulting from a uniform plane wave  $U(D)$  incident upon a plane boundary between two different media, are given by

$$u(D) = U(D) + G(DM) \{ [G(MM)] - 1 g(MM) [G(MM)] - 1 - [G(MM)] - 1 \} U(M) \quad (2)$$

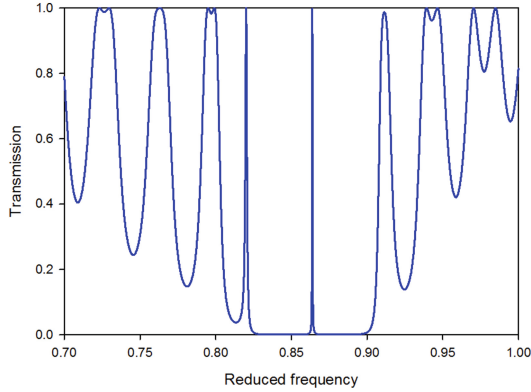
### 3 Discussion and Numerical Results

It can be seen from Fig. 2 that there is a PBG in the range of reduced frequency 0.81–0.89. Our aim is to engineer this PBG to producing a defect mode, which can be tuned by the temperature.



**Fig. 2.** The transmittance for an ideal PC

In order to see the effect of the defect layers, we now replace the central layers of  $TiO_2$  by  $Bi_4Ge_3O_{12}$ . The defective PC has a structure of  $(AB)^6CBC(BA)^6$  embedded in the air, as shown in Fig. 1. The calculated transmittance of this structure at a fixed temperature of 20 °C is shown in Fig. 3. It can be seen that a transmittance peak is produced within the PBG. This transmittance peak is referred as a defect mode. With the appearance of this peak, the structure is used to function as a sensor. In what follows, we shall investigate how this defect mode can be shifted by the temperature change.



**Fig. 3.** The defect mode in the PBG of  $(AB)^6CBC(BA)^6$

The temperature dependence of defect mode arises from two factors. One factor is due to the thermal expansion which will cause the thicknesses of the constituent layers to be a function of the temperature. The other one is the so-called thermal–optical effect, that is, the index of refraction of the layer can be varied as the temperature changes. Both factors will be simultaneously considered in the following study. For the thermal expansion, the thickness  $d$  of each layer changes in the following manner,

$$d(T) = d_0(1 + \alpha\Delta T) \tag{3}$$

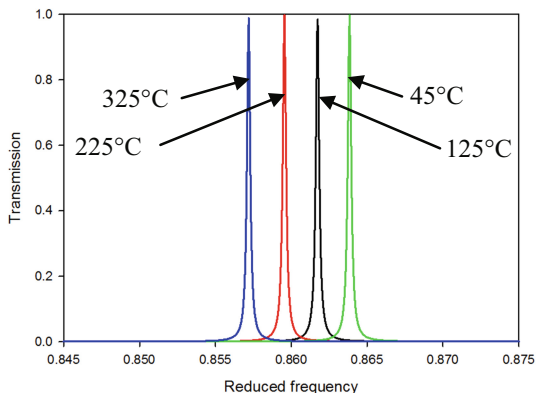
In Eq. (3),  $\alpha$  is the thermal expansion coefficient, and  $\Delta T$  is the temperature variation. The thermal expansion coefficients of  $TiO_2$  and  $SiO_2$  are  $8 \times 10^{-6}/^\circ C$  and  $5.5 \times 10^{-7}/^\circ C$  [7], respectively. As for thermal-optical effect, the temperature dependence of index of refraction  $n$  of each layer is written by,

$$n(T) = n_0(1 + \beta\Delta T) \tag{4}$$

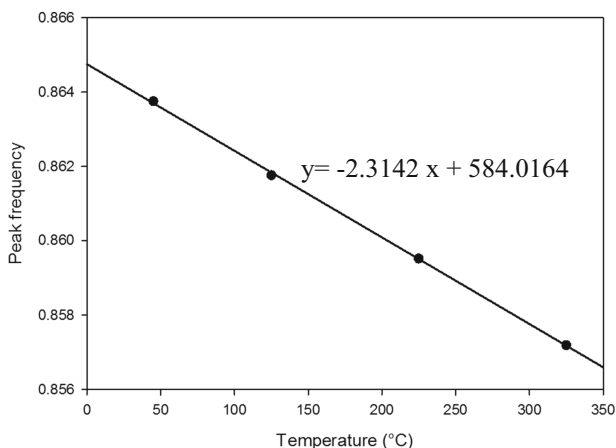
In Eq. (4),  $\beta$  is the thermo-optic coefficient. The thermo-optic coefficients of  $TiO_2$  and  $SiO_2$  are  $2.31 \times 10^{-5}/^\circ C$  [8], and  $1 \times 10^{-5}/^\circ C$  [9], respectively.

The index of refraction of BGO is  $n_{BGO} = 2.13$ ; the thermal expansion coefficient is  $\alpha_{BGO} = 6.3 \times 10^{-6}/^\circ C$ ; and its thermo-optic coefficient is  $\beta_{BGO} = 3.9 \times 10^{-5}/^\circ C$ . We chose the BGO as a defect layer because our photonic structure with this material allowed to reach a high sensitivity.

With the inclusion of Eqs. (3) and (4), the calculated transmittance spectra at four different temperatures 45, 125, 225, and 325 °C are plotted in Fig. 4 and the variation of the corresponding transmittance peaks with temperature is shown in Fig. 5. It is seen that as the temperature of the structure increases, the defect mode shifts toward the low frequencies region. The dependence of defect modes on temperature is due to two factors. First one is the thermal expansion effect and the second one due to the dependence of refractive index on temperature. The shifting behavior can be explained as well. When the thickness  $d$  and index of refraction  $n$  of each layer increase, the



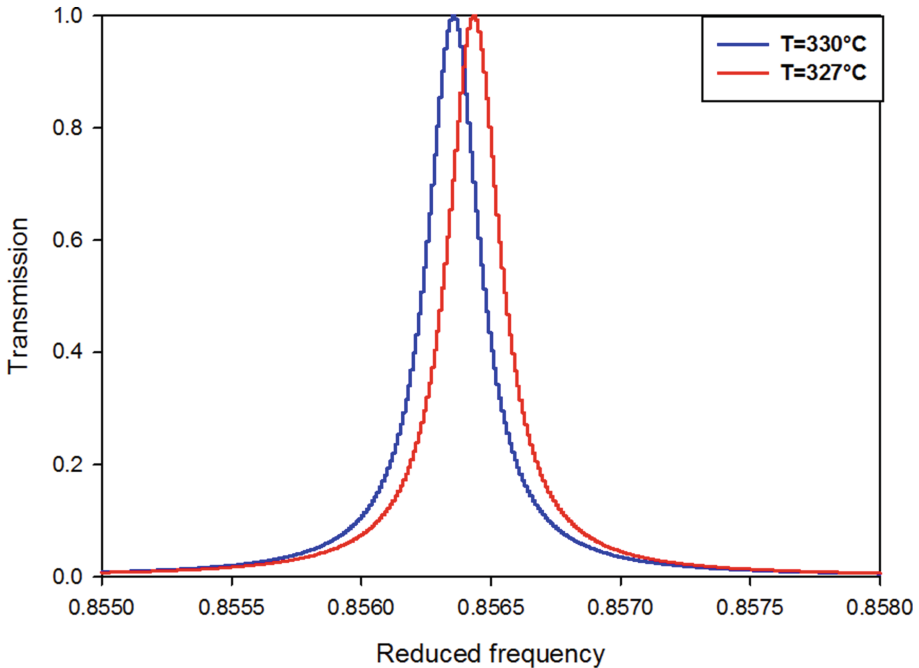
**Fig. 4.** The defect state of  $(AB)^6CBC(BA)^6$  at different temperatures.



**Fig. 5.** The variation of the central frequency of defect mode with temperature for PC structure  $(AB)^6CBC(BA)^6$ .

wavelength  $\lambda$  must increase accordingly to keep the phase  $\phi$  unchanged. It is also found (Fig. 5.) that the central wavelength of defect modes changes linearly with temperature.

The frequency of transmittance peak at low temperature variations are shown in Fig. 6. for 327 °C the peak is at the reduced frequency 0.85646, and for 330 °C the peak is at the reduced frequency 0.85632. A temperature variation of 3 °C induces a shift of 0.00014. Therefore the limit of detection of the temperature is 3 °C.



**Fig. 6.** The defect state of  $(AB)^6CBC(BA)^6$  for very small temperature variation.

## 4 Conclusion

The phenomenon of the transmission optical waveguide through a photonic crystal structure having a defect mode can be advantageously used for temperature detection. The effect of the temperature on the defect mode in a one-dimensional dielectric PC with two defects layers has been investigated by simultaneously considering thermal expansion effect and thermal–optical effect. It is found that the defect mode shifts toward the low frequencies region as the temperature of the structure increases.

We have shown also that the proposed structure is very sensitive to temperature variation. A variation of 3 °C is clearly visible.

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