Modeling of Multichannel Filter Using Defective Nano Photonic Crystal with Thue-Morse Structure

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Abstract—In this work, we study a multichannel filter by using one-dimensional photonic crystal (1DPC) based on Thue-Morse sequence (TMS). We use a dielectric defect layer between binary sequence cells with a TMS structure. First, we show transmission in terms of wavelength for the structure without defect layers. Then, we plot transmission in terms of wavelength for a different number of defect layer periods \( N \) in normal incidence. The analysis shows that there are two photonic bang gaps (PBG) in visible and infrared regions and two defect modes in each one for \( N = 1 \). Moreover, the number of defect modes is increased by increasing \( N \). So, by tuning them, this structure can be used as a multi-channel filter within an optical wavelength range.

1. INTRODUCTION

When a light source includes light emitted in one direction to 1DPC, it causes transmission and reflection from layers. Optical filters are devices that selectively transmit light of different wavelengths, while blocking the remainder which is called PBG. PBGs have many applications in optical communications, optoelectronics and optical devices [1–3]. A binary PC is a periodic structure including dielectric elements with different refractive indices. There are a lot of researches in using dielectric and metals in PC [4–15].

In this paper, we use transfer matrix method (TMM) to study the behavior of electromagnetic waves inside PC [16–19]. We use this method to 1DPC containing dielectric materials with different refractive indices.

In TMS, the dielectric layers are arranged in THS binary series. The THS structures are well known for their high transmission efficiency which is useful for modeling a multi-channel filter. In this structure by changing the number of defect layers, we can increase the number of resonant peaks very much. Also, the structure of TMS with a defect layer leads to two BGs in both visible and infrared regions, and more defect modes appear in both ranges [20].

2. THEORETICAL ANALYSIS

We use TMS for modeling our proposed filter. TMS is composed of dielectric layers (A and B) with thicknesses \( d_1, d_2 \), and their indices of refraction are \( n_1 \) and \( n_2 \), respectively.

In TMS, we have series as follows

\[ S_{n+1} = S_n S_n^* \]  

where \( S_n^* \) is the complement of \( S_n \). Thus, for calculating \( S_n^* \), we should replace \( A \) with \( B \) and vice versa. So we have

\[ S_1 = AB, \quad S_1^* = BA \]  

\[ S_2 = ABBA, \quad S_2^* = BAAB \]  

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And in this way we have,

\[ S_5 = (ABBABAABBAABBABAABBBABAABABABA) \]

\[ S_5^* = (BAABABBAABBABAABBBABAABBBABA) \]  

According formula (1), for modeling filter with 6th generation of TMS we have,

\[ S_6 = S_5 S_5^* \]  

(2)

The defect PC is \( D^N \), where \( D \) is dielectric defect layers and \( N \) the number of defect layers. According to formula (2) \( S_6 \) of TMS is composed of \( S_5 \) and \( S_5^* \), and in order to have a multi-channel filter, we add the defect PC between two parts,

\[ M_T = S_5 D^N S_5^* \]  

(3)

So the total characteristic matrix of the PC is given by [10, 21–27]

\[ M_T = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^N = S_5 D^N S_5^*. \]

(4)

Then the transmission coefficient \( t \) is given by

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

where \( p_0 = n_c \cos \theta_0 \). We can calculate the transmission [21–27].

\[ T = |t|^2 \]  

(6)

Also, the transmission coefficient \( r \) by using Equation (4) is given by

\[ r = \frac{(m_{11} + m_{12}p_0)p_0 - (m_{21} + m_{22}p_0)}{(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22}p_0)} \]  

(7)

So, we can calculate the reflection \( R = |r|^2 \).

3. RESULTS AND DISCUSSION

In this paper, layers A and B are InP and Si\textsubscript{3}N\textsubscript{4}, and their refractive indices and thicknesses are \( n_1 = 3.16, d_1 = 200 \) nm and \( n_2 = 2, d_2 = 400 \) nm. The substrate is assumed to be GaSb with refractive index \( n_C = 3.9 \). Also, the defect layer is taken to be GaSb whose index of refraction and thickness are \( n_D = 3.9 \) and \( d_D = 600 \) nm, respectively. This structure is depicted in Figure 1.

![Figure 1. The structure of ternary PC with TMS.](image)

In Figure 2, we show transmission in terms of wavelength in normal incidence without adding a defect layer (Equation (3)). We see that there are two BGs without defect mode for \( N = 0 \) in visible (between 50 nm to 520 nm) and infrared regions (between 70 nm and 730 nm). So, for modeling a multi-channeled filter, we need to add defect layer D to the structure.
Figure 2. Transmission in terms of wavelength for $S_6$ (Equation (3)) in normal incidence for (a) visible and (b) infrared region.
Figure 3. Transmission in terms of wavelength for different $N$ from 1 to 6 in normal incidence in visible range.

Figure 4. Transmission in terms of wavelength for (a) $N = 10$, (b) $N = 20$ in visible range.

Table 1. The number of defect modes and their wavelengths in 1DPC with THS structure $(C/S_5D^NS_5/C)$ in both visible and infrared regions.

| $N$ | No. of defect modes | Wavelengths (~ nm) in visible region | Wavelengths (~ nm) in infrared region |
|-----|---------------------|------------------------------------|-------------------------------------|
| 1   | 2                   | 507                                | 721                                 |
| 2   | 2                   | 509                                | 708                                 |
| 3   | 2                   | 510                                | 720                                 |
| 4   | 3                   | 505                                | 712–727                             |
| 5   | 3                   | 507                                | 706–720                             |
| 6   | 3                   | 508                                | 714–726                             |
| 10  | 4                   | 507                                | 707–716–724                         |
| 20  | 9                   | 505–508–510                        | 703–708–713–717–722–727            |
In Figure 3, we plot transmission in terms of wavelength for PC with a TMS structure (ABC) and for different numbers of $D$ (Equation (4)). We see that there is one defect mode in visible range, and the number of defect modes is increased by increasing $N$. We give the wavelength of the defect modes for different $N$ in visible range in Table 1.

In Figure 4, we show transmission in terms of wavelength for higher $N$. As we see, the number of defect modes increases a lot.

We show transmission in terms of wavelength for different $N$ in infrared region in Figure 5. We see that for the TMS structure in PC we have the other BG in infrared region whose defect modes increase with increasing $N$. We give the wavelength of the defect modes for different $N$ in infrared range in Table 1.

![Figure 5](image_url)

**Figure 5.** Transmission in terms of wavelength for different $N$ in infrared range.
In Figure 6, we show transmission in terms of wavelength for higher $N$ in infra-red region. As we see, the number of defect modes increases a lot.

4. CONCLUSIONS

In this paper, we have shown that 1DPC with dielectric defect layers based on a TMS structure can act as a multi-channel filter. First, we plot transmission in terms of wavelength for the structure without defect layer ($D$) and show that there are two PBGs without defect mode. Then, we show transmission in terms of wavelength for different numbers of defect layers ($N$) in both visible and infrared regions, and we see that there are two defect modes for $N = 1$ in both regions. Also, the number of defect modes increases by increasing $N$. So, we have more transmission peaks by increasing $N$. Our analysis shows that 1DPC with TMS structure can be used as a multi-channel filter with high transmission and can be tuned by increasing $N$.

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