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Special optical communication filter based on Thue–Morse photonic crystal structure

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In this paper we proposed a novel narrowband optical filter for wavelength division multiplexing applications. Due to their high transmission efficiency and very narrowband properties, we used the 5th generation Thue–Morse structure for designing our proposed filter. But novelty of our work is introducing another 1D photonic crystal structure as a defect structure into the Thue–Morse structure in order to create pass band inside the photonic band gap of the Thue–Morse structure. All of the simulations and calculations have been done using the transfer matrix method. The most interesting property of this filter is that by increasing the number of the periods of the ordinary 1D photonic crystal, the number of the pass bands increases.

Keywords: photonic crystal, Thue–Morse structure, optical filter, transfer matrix method (TMM).

1. Introduction

Insatiable desire of human being for learning and discovering new information and facts about his/her environment created so many breakthroughs in science and engineering. One example of most recent discoveries of researchers is photonic crystals (PhCs). As far as we know, PhCs are regular arrays of dielectric materials in which the distribution of the refractive index is periodic. This periodicity of the refractive index creates a wavelength reign in the band structure of the PhC, in which the propagation of electromagnetic waves including optical waves is forbidden. This wavelength region is called photonic band gap (PBG) [1–7]. The ability of controlling light in ultra-small dimensions makes them suitable candidates for designing all optical devices designed using photonic crystals.

Optical filters play a very important role in optical communication networks. The main task that an optical filter performs is simply passing the desired wavelength and stopping the undesirable ones. In wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) systems the optical filter can be used for separating optical channels from each other. Due to the simplicity of fabrication and analysis, 1D PhC-based filters are more popular than 2D and 3D PhC-based filters.

The PBG property of these structures can be used for designing optical reflectors [8] and band reject filters [9]. Adding a defect layer to 1D PhC results in a defect mode in the PBG of the 1D PhC, which can be used as a band pass filter [10]. It has been shown that by changing the optical thickness of the defect layer, one can tune the output wavelength of the filter [10]. Also by replacing the defect layer by a photonic quantum well we can have a multichannel filter [11].

Recently Thue–Morse (ThM) structures have attracted great amount of attention. In these structures, the dielectric layers are arranged following the ThM binary series. It has been shown that in these structures the density of resonant peaks increases exponentially by increasing the order of the structure [12], and around the mid-gap frequency the transmission is very sensitive to optical thickness [13]. Intrinsic asymmetry of odd generations of ThM PhC make them sensitive to propagation direction, so they can be used for designing all optical diodes [14]. By studying light propagation of ThM structures, Agarwal *et al.* [15] found an enhancement in the number of PBG with blue shift in reflectance peaks compared with periodic structures. By the way, very high transmission efficiency, ultra-narrow pass band and very high quality factor are the main characteristics of ThM-based photonic crystal filters [16].

In our previous work, by adding a defect layer to the ThM 1D photonic crystal, we proposed a tunable filter with high transmission efficiency and high quality factor [17]. In this work we proposed a quite new method, such that instead of one defect layer we add another photonic crystal to the ThM structure as a defect structure. This filter has very interesting characteristics. In this filter, by changing the number of periods of the defect photonic crystal, we can control the number of transmission bands. All the simulations and calculation of the transmission spectrum of the proposed structures have been done using the transfer matrix method (TMM) [18] by which we can study the behavior of electromagnetic waves inside multilayer structures.

The rest of the paper is organized as follows: in Section 2 we propose the design procedure of the proposed filter, in Section 3 the simulation process and the results are discussed and finally in Section 4 we conclude our work.

2. Filter design

As we discussed previously in Section 1, we used a quasi-periodic ThM structure for designing our proposed filter. So first of all we briefly introduce the ThM structure. ThM structures are composed of 2 dielectric layers, which we call A and B and whose refractive indices are different from each other. According to the definition of ThM series, we have:

$$S_{n+1} = S_n S_n^* \tag{1}$$

where S_n^* is the complement of S_n, that is for obtaining S_n^*, we should replace A with B and *vice versa*. Some examples of ThM structure are as follows:

$$S_0 = A \quad \text{and} \quad S_0^* = B \tag{2a}$$

$$S_1 = AB \quad \text{and} \quad S_1^* = BA \tag{2b}$$

$$S_2 = ABBA \quad \text{and} \quad S_2^* = BAAB \tag{2c}$$

and so on.

In this work we used the 6th generation of ThM structure for designing our proposed filter. According to (1) 6th generation ThM structure is

$$S_5 = S_5 S_5^* \tag{3}$$

By substituting the equivalents of S_5 and S_5^*, we will have

$$S_5 = (ABBABAABBAABABBABAABABBAABBABAAB) \times \\ \times (BAABABBAABBABAABABBABAABBAABABBA) \tag{4}$$

where the first parenthesis is S_5 and the second one is S_5^*; the approximate schematic diagram of structure S_6 is shown in Fig. 1.

Figure 1 shows that our primary structure is composed of two sections (S_5 and S_5^*). The refractive indices of *A* and *B* layers are 3.16 and 2, respectively, and the thicknesses of them are 190 and 860 nm, respectively. The material used for *A* layers is InP whose absorption and excitation coefficients are 0 cm^{-1} and 0, respectively. And the material used for layer *B* is Si_3N_4 whose absorption and excitation coefficients are 2.4 cm^{-1}

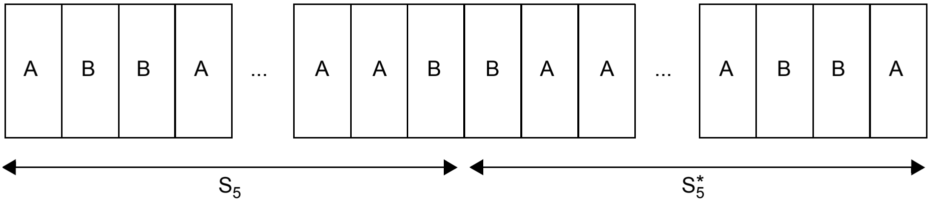

Fig. 1. The schematic diagram of structure S_6.

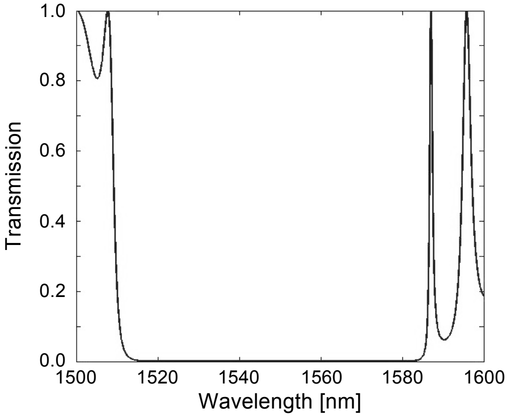

Fig. 2. Transmission spectrum of structure S_6.

and 0, respectively. Considering the aforementioned values for n_A, n_B, h_A and h_B (n_A and n_B are the refractive indices and h_A and h_B are the thicknesses of A and B layers, respectively), the transmission spectrum of the 5th generation of ThM structure is shown in Fig. 2.

Figure 2 shows that our structure has a photonic band gap between 1510 to 1590 nm. After creating a PBG region in the transmission spectrum of the structure, we have to create a pass band inside this PBG region, in order to have a narrow band pass filter. In previous works this job had been done by adding a single defect layer or a photonic quantum well to the periodic structure of 1D photonic crystal and in our previous work we did this by adding a single defect layer to the ThM structure. But in this paper we used a quite new method and instead of one single defect layer we added a 1D photonic crystal to the 5th generation ThM structure. The defect photonic crystal is as follows:

$$D = (EF)^N \tag{5}$$

where E and F are representatives of two dielectric materials with different refractive indices and N is the number of periods of the defect PhC. The schematic diagram of the defect PhC structure is shown in Fig. 3.

The corresponding values for the refractive index and thickness of E and F layers are as follows: $n_E = 3.4$, $n_F = 3.9$, $h_E = 799$ nm and $h_F = 235$ nm. The material used for layers E is Si whose absorption and excitation coefficients are 3.2×10^{-8} cm^{-1} and 0, respectively. And the material used for layers F is GaSb whose absorption and excitation coefficients are 10134 cm^{-1} and 0, respectively. According to (3), our S_6 structure consists of two parts S_5 and S_5^*. In order to create the pass band inside PBG region, we introduce the defect PhC (D) structure exactly between these two parts, so we will have:

$$T = S_5(EF)^N S_5^* \tag{6}$$

and finally we put the T structure between two C layers, whose refractive indices and thicknesses are $n_C = 3.52$ and $h_C = 261$ nm. The final structure of our proposed filter will be as in Fig. 4.

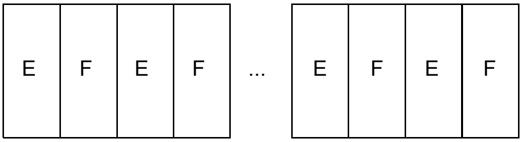

Fig. 3. The schematic diagram of defect PhC (D) structure.

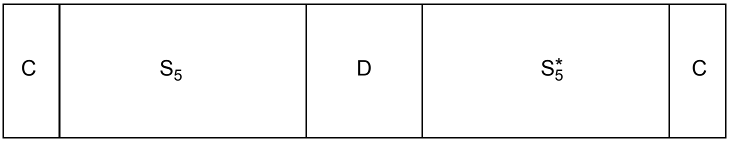

Fig. 4. The final structure of the filter.

3. Simulation and results

After finalizing the design process of our proposed filter, we are going to investigate the optical properties of this structure. In this work we mainly focus on the effect of N (number of the periods of defect PhC (D)) on the optical behavior of the proposed filter. First, we assume $N = 1$, which means that our D structure is composed of one period of E and F layers, and the output spectrum of the filter for $N = 1$ is shown in Fig. 5. The incident optical waves are perpendicular to the structure and are at TE mode.

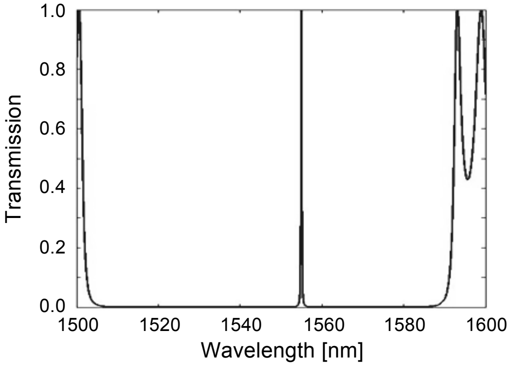

Fig. 5. Transmission spectrum of the filter for $N = 1$.

According to Fig. 5, the filter has one pass band at $\lambda = 1555$ nm, whose bandwidth is $\Delta\lambda = 0.089$ so the quality factor will be $Q = \lambda/\Delta\lambda = 17400$. The transmission efficiency is 100%. Then we assume $N = 6$; for this case the output spectrum of the filter is shown in Fig. 6. According to this figure for $N = 6$ we have two pass bands at $\lambda_1 =$ $= 1523$ nm and $\lambda_2 = 1571$ nm. In this case, the bandwidths of the pass bands are 0.15 and 0.08 nm, respectively, so the corresponding quality factors are 10153 and 19637. In both pass bands, the transmission efficiency is approximately 100%. The unique

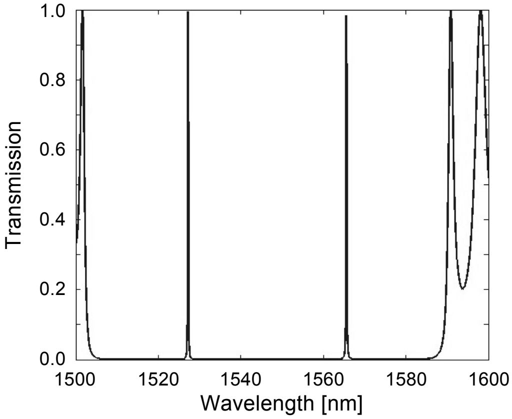

Fig. 6. Transmission spectrum of the filter for $N = 6$.

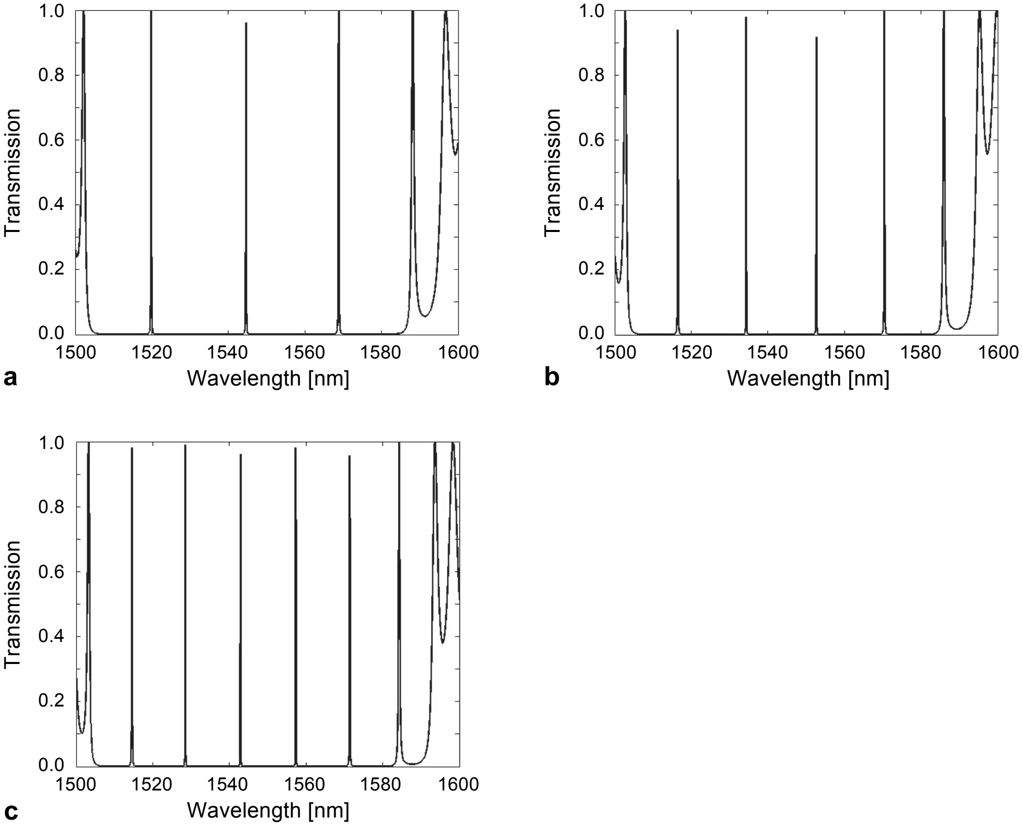

Fig. 7. Transmission spectrum of the filter for $N = 11$ (**a**), $N = 16$ (**b**), and $N = 21$ (**c**).

characteristic of this structure is that the number of output pass bands is tunable by changing the number of the defect PhC periods.

The output spectrum of the filter for different values of N ($N = 11$, 16 and 21) is depicted in Fig. 7. Also detailed information about the optical properties of the proposed structure for different values of N is presented in Table 1. The results show that

Table 1. Major parameters of the filter for different values of N.

N	Number of pass bands	Mean Q- factor	Space between pass bands [nm]	Minimum transmission efficiency [%]
1	1	17400	–	100
6	2	14895	38	98
11	3	30880	24	95
16	4	52600	18	92
21	5	70772	15	94
26	6	71350	12	86
31	7	52000	10	70

by every 5 unit increase in the number of the defect PhC structure periods, the number of pass bands increases by 1. By increasing the value of *N*, the wavelength space between the pass bands reduces. But increasing the number of the pass bands has a negative effect on the transmission efficiency of the pass bands, and as we observe from Table 1 by increasing the number of pass bands, the transmission efficiency reduces.

4. Conclusion

In this paper, by combining 1D ThM structure with an ordinary 1D PhC structure, we proposed a new optical pass band filter suitable for WDM applications. The ThM structures are well-known for their high transmission efficiency and very narrow pass bands, which results in a very high quality factor. Therefore we used the 5th generation ThM structure as our basic structure which has a PBG in 1510 to 1590 nm wavelength range. Then, by introducing a 1D PhC structure as our defect structure inside the ThM structure, we created pass bands inside the aforementioned PBG region. The number of pass bands directly depends on the number of the periods of the 1D defect PhC structure and by every 5 unit increase in the number of the periods, the number of pass bands increases by 1.

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