

Research Article

Important Effect of Defect Parameters on the Characteristics of Thue-Morse Photonic Crystal Filters

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Design and characterization of optical filters based on photonic crystal Thue-Morse structures are theoretically examined using transfer matrix method. It is shown that by introducing defect layer in the original structure of the proposed filter, main characteristics of it are changed. The main advantage of this defect in Thue-Morse structure is its capability for DWDM communication applications. In other words, achievement of DWDM filter through the Thue-Morse photonic crystal structure is much easier. The desired wavelengths can be achieved by changing the defect parameter. High efficiency of the proposed filter is one of its benefits. The transmission efficiency of this structure is about 96% and the quality factor is more than 77000.

1. Introduction

The advent of Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) technologies is an important step toward realizing all optical communication network [1, 2]. By use of these technologies one can optimize the capacity of optical fiber by launching multiple (4, 8, or more) optical channels at different wavelengths into one single fiber.

Optical filters are crucial devices for WDM and DWDM systems [3, 4]. Besides omitting the noise from channel information, optical filters are used for separating the undesired WDM and DWDM channels from desired channels. Other crucial applications of filters are in demultiplexing multiple channels in WDM and DWDM systems [5–7]. Since the discovery of photonic crystal in 1987 [8, 9], designing compact and highly selective optical filters has become possible. Thanks to these artificial periodic structures we can control the flow of light in ultrasmall scales [10]. Due to the simplicity of design and fabrication, 1D PhC based filters are the mass popular devices realized based on PhC. The key feature of PhCs is a wavelength region in which no optical wave is allowed to propagate inside the crystal;

this feature is called Photonic Band Gap (PBG) [11]. We can use the PBG property of 1D PhC to design optical reflector [12] and band reject filters [13]. Adding a defect layer to a 1D PhC creates a narrow band transmission filter [14]. Also if we replace the defect layer by a photonic quantum well [15] we will have a multichannel filter. By replacing dielectric layers by superconducting PhC we can realize a multichannel filter without using defect layer or quantum well [16]. In 1984 Shechtman [17] proposed a new class of crystals called quasi-periodic and aperiodic crystals. Fibonacci, Thue-Morse, and Rodin-Shapiro structures are some examples of nonperiodic photonic crystals. It has been shown that in Thue-Morse (ThM) structures increasing the order of system results in exponential increase in the density of resonance peaks [18]. Studying the propagation of light wave and localization properties of light in ThM multilayers showed that around the midgap frequencies the transmission is sensitive to optical thickness modulation [19]. Another advantage of ThM structure over ordinary periodic 1D PhCs has been proposed by Agarwal et al. [20] they found an enhancement in the number of PBG with a blue shift in reflectance peaks of ThM structure. Intrinsic asymmetry

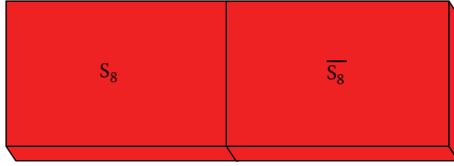


FIGURE 1: The schematic diagram of S_9 ThM structure without defect layer.

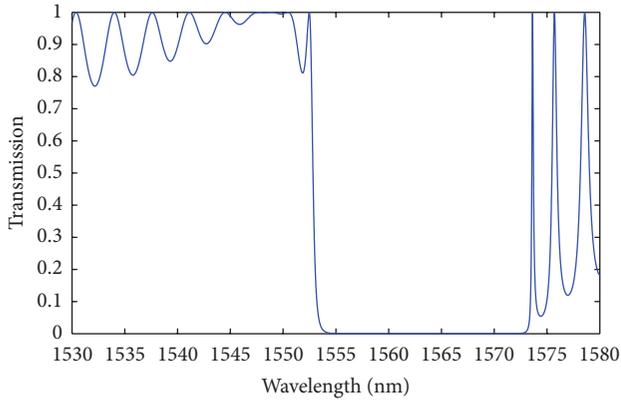


FIGURE 2: The transmission spectrum of S_9 structure shown in Figure 1.

of 1D ThM PhC in odd generation results in bistability, thresholds, that are structure to propagation direction so these structure can be used for designing all optical diode [21]. In Multicomponent Generalized TM (MCGTM) super lattices optical transmission has an interesting pseudo-constant characteristic at the central wavelength due to contra-set structure of these structures which can be used for designing complex optical devices [22]. A tunable filter based on TMPhC composed of single negative materials is proposed which is not sensitive to incident angle and polarization of light. It has been shown that bandwidth and frequency of this filter can be changed by adjusting the layer thicknesses and plasma frequency [23]. In 1D TM PhC composed of negative refractive index and positive refractive index materials there is an enlarged Omnidirectional Reflection Band (ORB) and the width and location of ORB are independent of TM order; the lower and higher edge of ORB depends only on TE and TM polarizations, respectively [24]. The most crucial advantages of ThM based PhC filters over periodic PhC filters are high transmission efficiency, small bandwidth, and high quality factor [25]. Other works have been done on ThM structures which have been devoted to the transmission and PBG properties of these structures [26–29].

In this work we are going to propose a new method for designing ThM based 1D PhC filter. In our work we introduced a defect layer inside the 9th order 1D ThMPhC structure. The significant characteristics of our filter are its very high transmission efficiency, very low bandwidth, and very high quality factor. The transmission efficiency of this structure is about 96% and the quality factor is more than 77000.

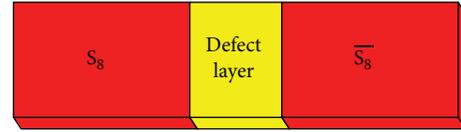


FIGURE 3: The final sketch of our proposed filter.

The rest of the paper is organized as follows. In Section 2 the design procedure of the filter has been proposed. In Section 3 we discussed the simulation process and the results and finally in Section 4 we concluded our work.

2. Filter Design

In this paper, we are going to propose a tunable filter based on defective 1D ThM structure. So first of all we are going to introduce ThM structure briefly.

2.1. Thue-Morse Structure. ThM is a binary sequence defined as follows:

$$S_n = S_{n-1}S_{n-1}^* \quad (1)$$

Some examples of ThM sequence are $S_1 = 10$, $S_2 = 1001$, $S_3 = 10010110$, and so on.

Now if one substitutes 1's and 0's with A and B layers, where A and B are dielectric layers with different refractive indices and thicknesses (n_A and n_B are the refractive index of A and B, resp., and h_A and h_B are the thicknesses of A and B, resp.).

So some example of ThM structure will be as follows: $S_0 = A$, $S_1 = AB$, $S_2 = ABBA$, $S_3 = ABBABAAB$, and so on.

In order to design proposed filter we used 9th order ThM structure; according to (1) 9th order ThM structure is as follows:

$$S_9 = S_8S_8^* \quad (2)$$

so

$$S_9 = ABBABAABBAABABBA \dots \quad (3)$$

In this structure the refractive index of A and B layers (e.g., n_A and n_B) are 3.17 and 2, respectively, and the thicknesses of these layers are $h_A = 235$ nm and $h_B = 798$ nm. Currently the best solution for studying the optical properties of 1D multilayer structure like 1D PhCs is Transfer Matrix Method (TMM). The fundamental structure used for designing our proposed filter is shown in Figure 1 and the transmission spectra of this structure with aforementioned values for n_A , n_B , h_A , and h_B are plotted in Figure 2. Figure 2 shows that we have a PBG in $1550 \text{ nm} < \lambda < 1570 \text{ nm}$ range. This PBG range is suitable for optical communication applications and WDM and DWDM technologies.

The next step in designing of the proposed filter is creating a transmission channel in the PBG region. As far as we know in ordinary periodic 1D PhCs, this will be done by introducing a defect layer into the structure. So in our filter

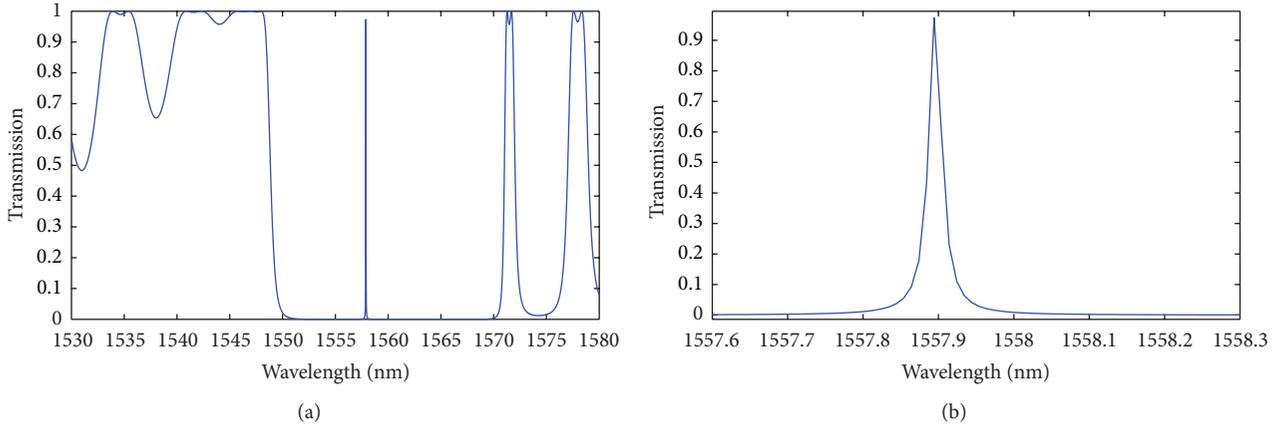


FIGURE 4: The output spectrum of our proposed filter: (a) normal view and (b) zoomed in view.

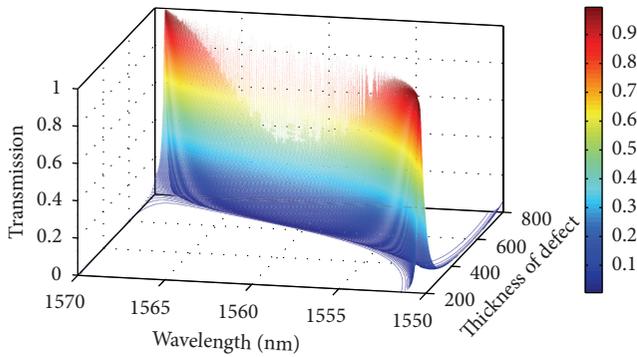


FIGURE 5: The 3D plot of the output spectra of the filter for different values of h_D .

we introduce a defect layer in to the ThM structure, so the final sketch of our filter will be like Figure 3.

We call the refractive index and thickness of defect layer n_D and h_D , respectively. In this filter n_D and h_D are 1 and 554 nm, respectively. The transmission spectrum for the defective structure (final sketch of filter) is shown in Figure 4.

As we observe from Figure 4 we have a transmission channel at $\lambda = 1557.9$ nm. This proves that the effect of defect layer in ordinary 1D PhC is true for ThM based multilayers, too. The transmission efficiency of the proposed structure is about 96%.

3. Simulation and Results

As we mentioned in the previous section, we use defective mode of 9th order ThM structure for designing our filter; the final structure of our filter will be as follows: $F = S_8 D S_8^*$ which is shown schematically in Figure 3. After finalizing the design procedure of filter, we are going to investigate the effect of h_D —the thickness of the defect layer—on the filtering behavior of the proposed structure. The transmission spectra of the proposed filter for different values of h_D are

shown in Figures 5, 6, and 7. Figure 5 is a 3D plot of the output spectrum of the filter, which shows the transmission efficiency and output wavelength of the proposed filter for various values of h_D . The obvious point we obtain from Figure 5 is that our filter is tunable. This figure shows that by changing the thickness of the defect layer from 400 nm to 800 nm the output wavelength will change from 1550 nm to 1570 nm. It means that by increasing the thickness of the defect layer the output wavelength will shift towards upper wavelengths.

Figure 6 is the top view of Figure 5. In this figure, the vertical and horizontal axes are representative of wavelength and the thickness of the defect layer and the transmission efficiency is shown by the color scale, which is shown next to the figure. The white region in Figure 6(a) is the PBG region and the multi-color curve inside the white region is the defect mode that has been created by inserting a defect layer into the ThM structure. We observe that by increasing the thickness of the defect layer (h_D) the multi-color curve shifts towards higher wavelengths. Figure 6(b) is the zoomed in form of Figure 6(a) in which we zoomed in around the central wavelength of one channel according to the color scale and we see that the peak of the output spectrum for $h_D = 554.6$ nm and $\lambda = 1557.96$ nm whose transmission efficiency is about 96%.

We also observe that the bandwidth of the transmission channel is very small and the output spectrum is very sharp so the quality factor of our proposed filter is very high.

The bandwidth is less than 0.02 nm and the quality factor is more than 70000. Finally the output wavelength of the filter for different values of h_D is shown in Figure 7. This figure shows the high transmission efficiency and narrow band properties of the proposed filter.

4. Conclusion

We have proposed the design of a compact optical filter in a Thue-Morse structure with photonic crystals. Since the filter does not involve either additional materials or other complexities, it might realize the tough fabrication

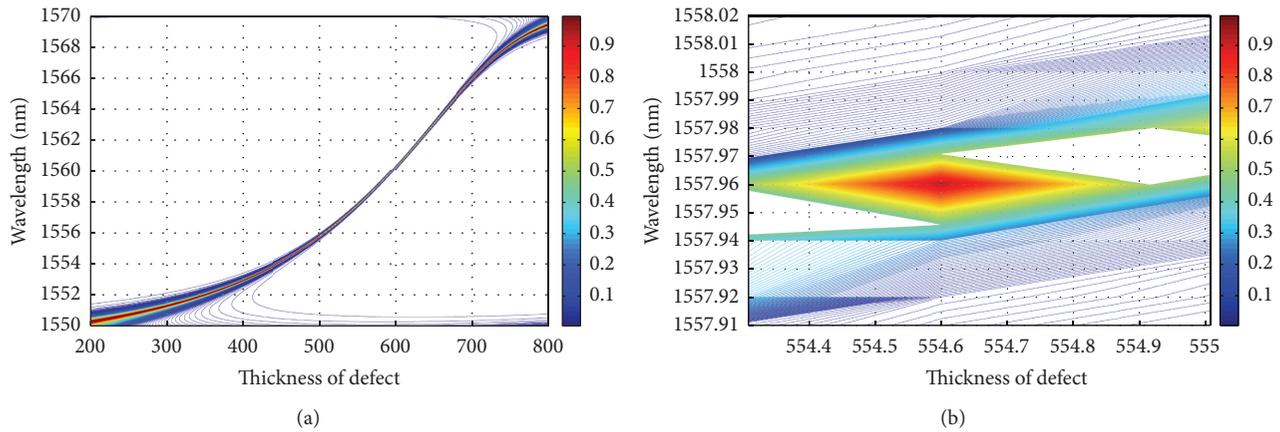


FIGURE 6: The top view of Figure 5. The variation of output wavelength versus h_D : (a) normal view, (b) zoomed in view.

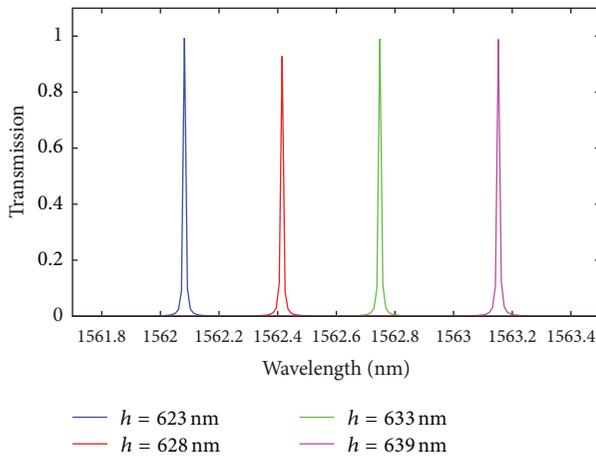


FIGURE 7: The output spectra of our proposed filter for different values of h_D .

requirements. By introducing defect layer between the Thue-Morse structure layers, dependency of the proposed filter to the defect layer is shown. The efficiency of the designed filter is very good and is about 96%. The proposed filter is suitable for WDM and DWDM communication applications due to its narrow band transmission spectra.

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