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A High Quality Factor Filter Based on Quasi-Periodic Photonic Structure

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***Abstract*—**We report the design and characterization of ultra high quality factor filter based on one-dimensional photonic-crystal Thue-Morse sequence structure. The behavior of aperiodic array of photonic crystal structure is numerically investigated and we show that by changing the angle of incident wave, desired wavelengths could be tuned and a tunable filter is realized. Also it is shown that high quality factor filter be achieved in the telecommunication window around 1550 nm, with a device based on Thue-Morse structure. Simulation results show that the proposed structure has a quality factor more than 100000 and it is suitable for DWDM communication applications.

***Keywords*—**Thue-Morse, filter, quality factor.

I. Introduction

IN today's information age we live in, beside air, food and shelter, information is another basic requirement of human being and exchanging huge amount of information and data in internet is an inseparable part of modern humankind daily life. This information exchange and the emergence of multimedia services have caused the enormous increase in information traffic all around the world. Due to this ever growing information traffic we have to improve the available bandwidth for worldwide internet users. Nowadays even several seconds delay in receiving breaking news or downloading a multimedia product is not tolerable anymore. Dense Wavelength Division Multiplexing (DWDM) technology, due to small channel spacing, high bit rates [1], compatibility with fiber optic infrastructure and its cost effectiveness [2] is a good candidate for responding to this bandwidth requirement. By DWDM technology we can transfer 2, 4 or more wavelength channels via one single optical fiber.

Tunable band pass filters are very important in DWDM systems. Beside this, tunable optical filters can be used in remote sensing [3], hyper spectral imaging [4], biomedical imaging [5], [6] and so etc.

Photonic Crystals (PhCs) proposed new possibilities for compact and highly tunable optical devices. These artificial structures are periodic arrays of dielectric materials with different refractive indices. As far as we know according to the periodicity of their refractive index distribution, PhCs are divided into 3 categories: a) 1D, b) 2D and c) 3D. The key feature of PhC, which makes them interesting for photonic designers, is their Photonic Band Gap (PBG). By definition PBG is a wavelength region in PhCs band structure in which no light wave is allowed to propagate inside these structures [7]. If we add a defect layer in a 1DPhC we can realize a narrow band transmission filter [8]. In these structures the pass band is located in the PBG region of 1D PhC. by replacing the defect layer by a photonic quantum well [9] we can have a multichannel filter. Another way of realizing multichannel filter based on 1DPhC is replacing dielectric layers by superconducting PhC, in these structures there is no defect layer [10]. It has been shown that by combining two defective 1DPhC, one with negative refractive index defect layer and the other with positive refractive index defect layer we will have a narrow band and narrow transmission angle filter [11]. Other kind of filters based on 1DPhCs is the reflection or band reject filters like anti-UVB filter [12].

Beside periodic multilayers, there are other kinds of 1D multilayer used as 1DPhCs named quasi-periodic and aperiodic 1D structure like Fibonacci, Thue-Morse and Rudin-Shapiro structures. Since the discovery of quasi crystals [13] much attention has been paid to the quasi-periodic and aperiodic structures. Among these much attention has been paid to Fibonacci and Thue-Morse structures. Light propagation properties in Fibonacci (Fc(1)) dielectric super lattices has been studied and it has been shown that transmission coefficient is a function of wavelength [14]. The characteristics of generalized Fibonacci (GF(m,n)) are better than those of Fc(1) [15]. Other kind of popular aperiodic structure is Thue-Morse crystals. High transmission efficiency, very small band width and high quality factor [16] are the most important features of Thue- Morse (TM) based PhC structures. In TM structures the density of resonance peaks increases exponentially by increasing the order of the system [17]. One of the pioneers in studying the optical properties of TM aperiodic structures was Liu [18], who had studied the propagation of light waves and localization properties of light in TM multilayers. He found that around the midgap frequencies the transmission is more sensitive to optical thickness modulation. After him many researchers investigated the different properties of light wave propagation in TM structure [19]-[22]. Recently, [23] studied the light propagation in polytype TM structures made of porous Si, and found an enhancement in the number of PBG with a blue shift in reflectance peaks compared with periodic structures. In Multi-Component Generalized TM (MCGTM) super lattice 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 [24]. Studying the nonlinear

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properties of 1D TM structures showed that intrinsic asymmetry of 1DTM PhCs in odd generation's results in bistablity thresholds, which are sensitive to propagation direction, so these structures can be used for designing all optical diode [25]. A tunable filter based on TM PhC composed of single negative materials 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 [26]. In 1D TM PhC composed of negative refractive index and positive refractive index materials there is an enlarged Omni directional Reflection Band (ORB) and the width and location of ORB is independent of TM order; the lower and higher edge of ORB depends only on TE and TM polarizations respectively [27]. Therefore, in this paper we are going to propose a tunable filter with ultra-high quality factor based on TM PhCs. We will show that the output wavelength of our proposed filter is sensitive to incident angle, and we can use this property to tune it.

The rest of the paper is organized as follows. In Section II we discuss the theory and the method used for studying the properties of our filter also we will discuss the Thue-Morse sequence. In Section III we propose our results and final section consists of our paper conclusion.

II. Theory and Method

As we mentioned in this work we are going to use Thue-Morse sequence to design our proposed filter. As far as we know Thue-Morse sequence is a binary sequence defined as:

$$s_{n+1}=S_n\overline{S_n} \tag{1}$$

Some examples of Thue-Morse sequence are listed as:

$$\begin{gathered} s_0=1 \\ s_1=10 \\ s_2=1001 \\ s_3=10010110 \end{gathered} \tag{2}$$

and so on.

As we know 1DPhC based structures consist of 2 layers, namely A and B, with different refractive indices and different thicknesses. Now if we substitute 1 and 0 with A and B in Thue-Morse sequence we will have a Thue-Morse structure as:

$$\begin{gathered} s_0=\text{A} \\ s_1=\text{AB} \\ s_2=\text{ABBA} \\ s_3=\text{ABBABAAB} \end{gathered} \tag{3}$$

For designing our proposed filter we use 7 orders Thue-Morse structure as:

$$\begin{gathered} s_7=\text{ABBABAABBAABABBABAABABBAABBABAAB}\ldots \\ \ldots\ldots \end{gathered} \tag{4}$$

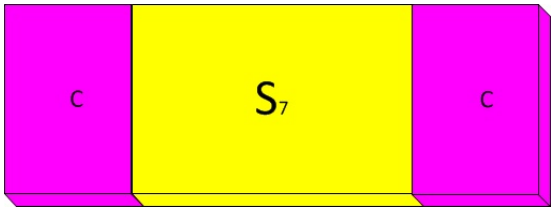


Fig. 1 The final schematic of our proposed filter

The final schematic of our proposed filter is shown in Fig. 1, which is composed of S_7Thue-Morse structure sandwiched between to C layers. Then we should study the behavior of light inside this structure. The best choice for studying1DPhC-based structures is Transfer Matrix Method (TMM), in this method we defined two different matrix for each layer: one dynamical matrix given by [28]:

$$D_m=\begin{cases}\begin{bmatrix}1 & 1\\ n_m\cos\theta_m & -\cos\theta_m\end{bmatrix} forTEwave\\ \begin{bmatrix}\cos\theta_m & -\cos\theta_m\\ n_m & -n_m\end{bmatrix} forTMwave\end{cases} \tag{5}$$

and a propagation matrix given by:

$$P_m=\begin{bmatrix}exp(ik_mh_m) & 0\\ 0 & exp(-ik_mh_m)\end{bmatrix} \tag{6}$$

where n_m is the refractive index of layers, h_m is the thickness of the layers, θ_m is the ray angle in each layer, and $k_m=\omega n_m\cos\theta_m/c$, in which m is the representative of layers C, A and B and $m_0=0$ is representative of air so that $n_0=1$ is the refractive index of air, D_0 is the dynamic matrix of air driven by:

$$D_0=\begin{cases}\begin{bmatrix}1 & 1\\ n_0\cos\theta_0 & -\cos\theta_0\end{bmatrix} forTEwave\\ \begin{bmatrix}\cos\theta_0 & -\cos\theta_0\\ n_0 & -n_0\end{bmatrix} forTMwave\end{cases} \tag{7}$$

and θ_0 is the incident angle of the incident ray of light. So according to TMM for every layer we have: $L_C=D_CP_CD_C^{-1}$, $L_A=D_AP_AD_A^{-1}$ and $L_B=D_BP_BD_B^{-1}$ now in (1) if we substitute each layer (i.e. A, B and C) with their corresponding matrix (L_C, L_A, and L_B for C, A and B respectively) the transfer matrix of our proposed filter will be obtained as:

$$M_F=m_Cm_{S7}m_C \tag{8}$$

where m_{S7} is the transfer matrix of 7th order Thue-Morse structure and final transfer matrix of the filter is:

$$\text{M}=D_0^{-1}M_FD_0=\begin{bmatrix}M_{11} & M_{21}\\ M_{21} & M_{22}\end{bmatrix} \tag{9}$$

The transmission coefficient of the structure is $t=1/M_{11}$, so the transmission of the structure will be $T=|t^2|$. Now if we plot the T with respect to wavelength the transmission spectra of our proposed filter will be obtained.

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III. Simulation and Results

As we mentioned in previous section, we use S_7 Thue-Morse to design our proposed tunable filter. In our structure the refractive index of A and B are 1.7 and 3.78 respectively, and their thicknesses are 221.606 nm and 170 nm respectively. The transmission spectrum of this structure is shown in Fig. 2.

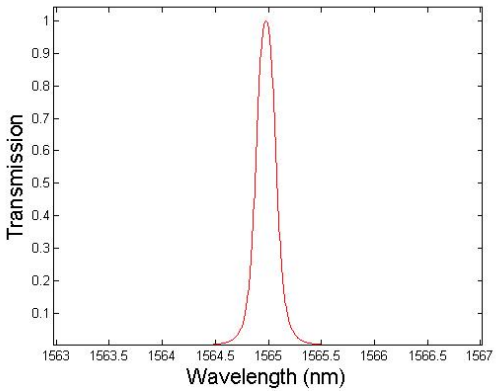


Fig. 2 Transmission spectrum of the filter without C layer

We observed that the quality factor ($Q = \lambda_0/\Delta\lambda$) of this structure is approximately 10000, in order to improve the quality factor we sandwich this structure between two C layer, the refractive index and the thickness of the C layer is 5.2 and 240 nm respectively. The transmission spectrum of this new structure is shown in Fig. 3.

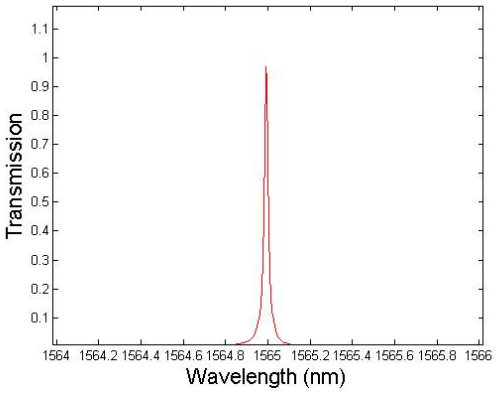
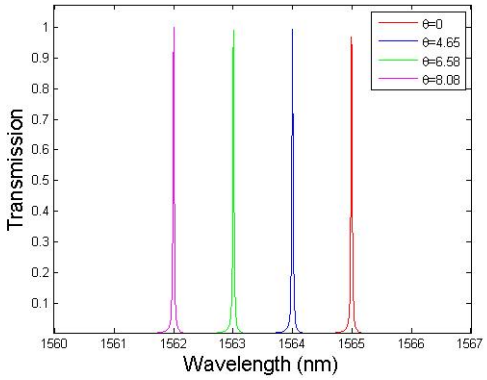
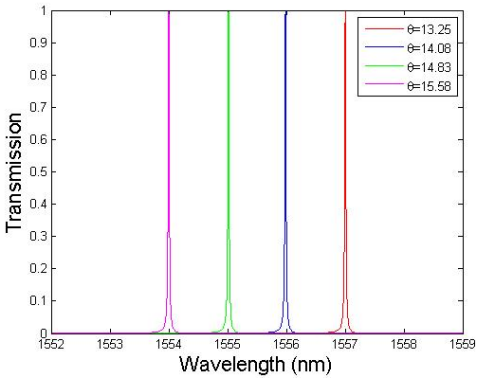


Fig. 3 Transmission spectrum of the filter with C layer

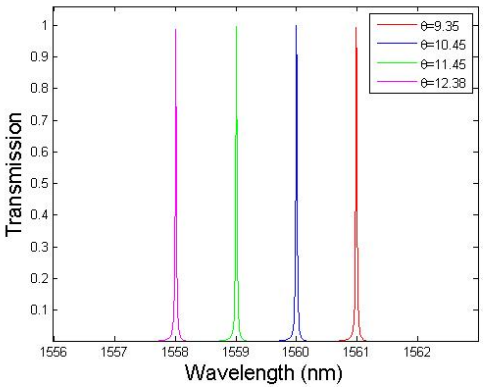
We observed that the quality factor for this new structure is more than 100000. So we have great improvement in quality factor. The central wavelength of this filter for θ_0=0^0 is 1565 nm. Our simulation shows that by changing the incident angle we can tune the output wavelength of the filter. If we change the incident angle to $4.65^0$the output wavelength will be 1564 nm. We observed that by increasing the incident angle our wavelength shifts toward lower wavelengths. So by increasing the incident angle from 0^o to 18.25^o we created 16 channel between 1565-1550nm. The channel spacing between every two adjacent channels is 1nm. The Q factor is more than 100000. The transmission spectra of different output wavelengths are shown in Figs. 4 (a)-(e).



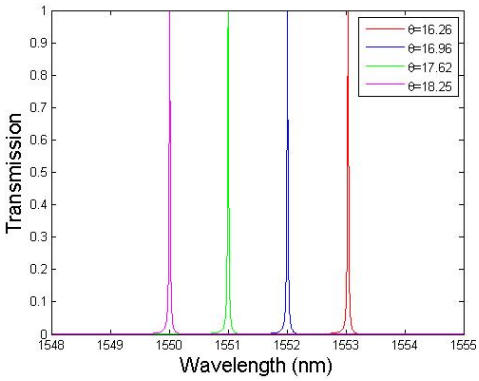
(a)



(b)

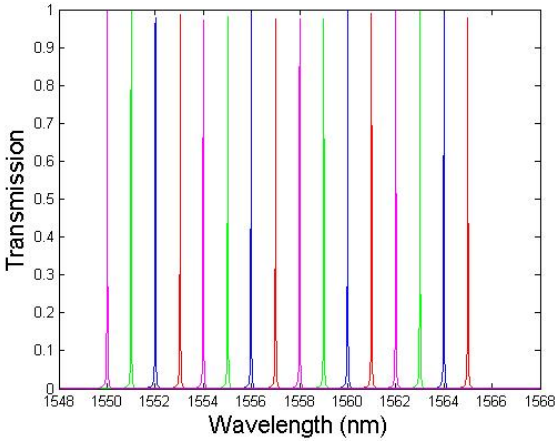


(c)



(d)

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(e)

Fig. 4 Transmission spectra of the filter with C layer for different incident angles

In addition the complete specification of the channels like incident angle, output wavelength A and B width and Q-factor are listed in Table I. As we observed from Fig. 4, in 1550-1565 nm we have 16 different channels, where channel-spacing is 1 nm, so this filter is suitable for DWDM communication applications.

TABLE I
THE CHARACTERISTICS OF THE FILTER FOR DIFFERENT INCIDENT ANGLES

incident angle	λ_0	$\Delta\lambda$	Q
0	1565 nm	0.015 nm	104333
4.65	1564 nm	0.015 nm	104266
6.58	1563 nm	0.015 nm	104200
8.08	1562 nm	0.015 nm	104133
9.35	1561 nm	0.015 nm	104066
10.45	1560 nm	0.015 nm	104000
11.45	1559 nm	0.015 nm	103933
12.38	1558 nm	0.015 nm	103866
13.25	1557 nm	0.015 nm	103800
14.08	1556 nm	0.015 nm	103733
14.83	1555 nm	0.015 nm	103666
15.58	1554 nm	0.015 nm	103600
16.26	1553 nm	0.015 nm	103533
16.96	1552 nm	0.015 nm	103466
17.62	1551 nm	0.015 nm	103400
18.25	1550 nm	0.015 nm	103333

IV. CONCLUSION

In this paper we proposed and designed ultra high quality tunable filter based on Thue-Morse sequence structure. In order to have high quality factor we used seventh orders Thue-Morse structure and by sandwiching the S_7 structure between two C layers we improved our Q-factor. We showed that by changing the incident angle we can tune this filter. Also, the channel spacing between adjacent channels of this filter is 1 nm and the Q factor this filter is more than 100000, so this filter is suitable for DWDM applications.

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