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Electro-optical Tunable Filter with Symmetric Generalized Fibonacci Photonic Crystal

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Abstract: A structure of symmetric generalized Fibonacci photonic crystal is proposed to design the electro-optical tunable filters based on the electro-optical effect of $LiNbO_3$ material. The characteristics of the tunable filter are theoretically investigated by the transfer matrix method. The numerical simulation results show that the channel wavelength of the filter can be modulated by the external electric field which is applied on the $LiNbO_3$ layers without changing the geometrical structure of the symmetric generalized Fibonacci photonic crystal, and the channel wavelength will linearly move to short wavelength as the increase of the external electric voltages. In addition, if the external electric voltage is fixed, the channel wavelength will move to short wavelength as the increase of the incident angle; if the incident angle is fixed, the channel wavelength will move to short wavelength for the increase of plus external electric voltage, while the channel wavelength will move to long wavelength for negative external electric voltage. Lastly, the characteristics of the tunable multi-channel filter with double external electric fields are discussed. It provides an important reference for design of novel photonic crystal devices.

Key words: Generalized Fibonacci sequence; Electro-optical effect; Photonic crystal; Tunable filter

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0 Introduction

Since the initial work of Yablonovitch[1] and John[2], photonic crystals have attracted much attention due to their peculiar characteristics of photonic band gaps (PBG) and photonic locations (PL), which have a wide applications in the areas of optoeletronics and optical communication. During the past decades, many efforts have been devoted to utilize the 1-D photonic crystals to implement various practical devices, e. g. optical filters[3-4], omnidirectional reflectors[5], optical switches[6], and optical buffers[7].

In recent years, many research works performed on 1-D photonic crystal have been gradually focused on aperiodic structures[8-10], for instance, Thue-Morse (TM) sequence structures, generalized Thue-Morse ones, Fibonacci ones, and generalized Fibonacci (GF) ones. These aperiodic structures exhibit unusual optical properties which differ from those of periodic and disordered structures. I. P. Coelho et. al. found the self-similar features of the transmission spectra and the optical fingerprints of the transmission coefficients by constructing the binary 1-D quasiperiodic structure with mirror symmetry[10]. P. W. Mauriz et. al. studied the self-similar transmission behavior through the symmetric Fibonacci (SF) photonic multilayers which made up of both positive and negative refractive index materials[11]. Zhang et. al. proposed a multi-component generalized Thue-Morse model which exhibits a pseudo-constant optical transmission characteristic[12]. The above research works demonstrate the aperiodic photonic structures can be applied to design optical filter. However, it is necessary to change their geometrical structures for designing the filters with different operation

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wavelengths，which will be an extremely tedious task in practical application.

In this work，a novel tunable filter based on the symmetric generalized Fibonacci （SGF） photonic crystal containing the electro-optical material $LiNbO_3$ is reported. By adjusting external electric field，the refractive index of $LiNbO_3$ can be changed，so the channel wavelength of filter can be modulated at the desired wavelength without changing its geometrical structure.

1 Tunable filter structure

The structure of designed electro-optical tunable filter is shown in Fig. 1，which is constituted by the aperiodic photonic multilayers and the metal electrodes. As shown in this schematic，the aperiodic photonic structure is composed of A/B multilayers，where A is an electro-optical material layer with the refractive index n_A and the thickness d_A，and B is the medium layer with the refractive index n_B and the thickness d_B，respectively. The A/B multilayers can be made by alternately depositing A layer and B layer with the megnetron sputtering method. The metal electrodes are made by tow steps：the metal layers are firstly deposited on the side faces of photonic multilayers by the electron-beam evaporation method，and then patterned the exact geometric widths by the lithography technology.

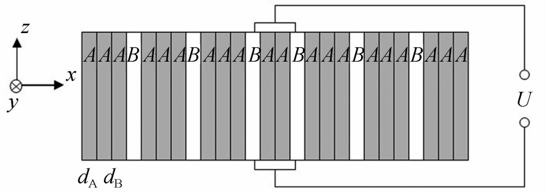


Fig. 1 The schematics of the tunable filter with SGF photonic multilayers for $m=3$，$n=1$，$j=3$ and $P=1$（A and B denote two kinds of materials，which indicated by grey region and white region，respectively）

In Fig. 1，Cartesian axes are chosen in such a way that the x-axis is normal to the plane of the layers，the y- and the z-axis parallel to the plane of the layers. Thus，the dielectric function of the multilayer structure is a constant in y and z directions but a generalized Fibonacci function along x-axis，besides the external electric field is applied on the electro-optical material along the z-axis.

In fact，the SGF photonic multilayers shiwn in Fig. 1 is arranged in a SGF fashion，which can be seen a superposition of two GF superlattices with mirror reflection at the center and constructed as follows：given m and n，the jth generation of GF sequence can be obtained by the recursive rule[13] $A\rightarrow A^mB^n$ and $B\rightarrow A$，where m and n are positive integers，written as S_j^L；and then，the manipulation of mirror image is applied to S_j^L，so that a SGF sequence is achieved which can be expressed as $S_j=S_j^L.S_j^R$，where S_j^R is generated by the recursive rule $A\rightarrow B^nA^m$ and $B\rightarrow A$，and the indices L and R mean left and right side，respectively. Assuming its generations start from B，i. e. $S_0^L=S_0^R=B$，the recursive relationship of SGF sequence is formulated as：$S_j=(S_{j-1}^L)^m(S_{j-2}^L)^n(S_{j-2}^R)^n(S_{j-1}^R)^m$，$(j\geqslant 2)$. Owing to its structural symmetry，a lot of unusual optical characteristics appear in our tunable filter which will be discussed detailedly later.

2 Numerical results and analysis

In order to design a SGF photonic crystal with a wide PBG range，electro-optical material $LiNbO_3$ and air are chosen as layer A and B，whose thicknesses are $d_A=175.24$ nm，$d_B=387.5$ nm，respectively. And the central wavelength of incident light is chosen as $\lambda_0=1.55$ μm. For electro-optical material $LiNbO_3$，its refractive indices of the ordinary and extraordinary ray are the functions as the incident wavelengthes （Fig. 2）. If the external electric voltage U is applied on electro-optical material $LiNbO_3$ along the z-axis （Fig. 1），the refractive index of ordinary ray of $LiNbO_3$ can be expressed as[14]

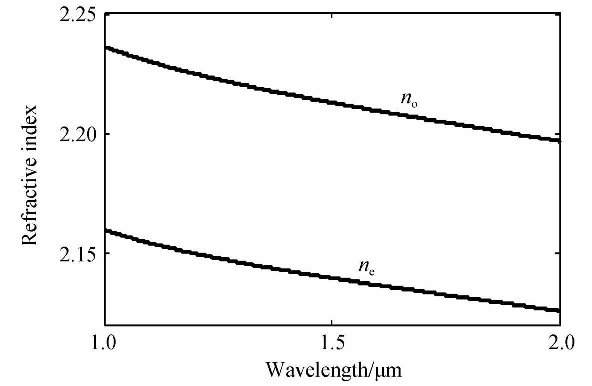
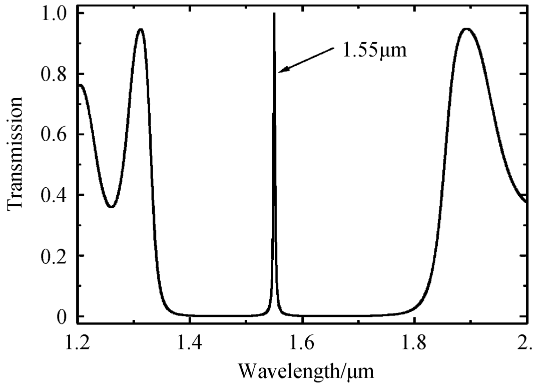


Fig. 2 The refractive index of $LiNbO_3$ as a function of incident wavelengthes

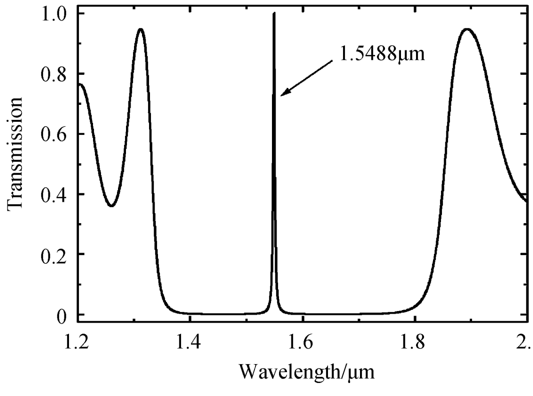
$$n_o'(\lambda,E)=n_o(\lambda)-\frac{1}{2}n_o^3(\lambda)\gamma_{13}E \qquad (1)$$

where $\gamma_{13}=9.6\times10^{-12}$ m/V is the electro-optical coefficient of $LiNbO_3$，and $E=U/h$ is the external electric field acting on $LiNbO_3$（where h is the height of media layer along z-axis，taken to be 0.4 mm[15-16]）. Here，especial notice is that the x_3-axis of $LiNbO_3$ parallels the z-axis of photonic crystal, the external electric field is applied on the electro-optical material along the z-axis, and the incident optical ray along the x-axis.

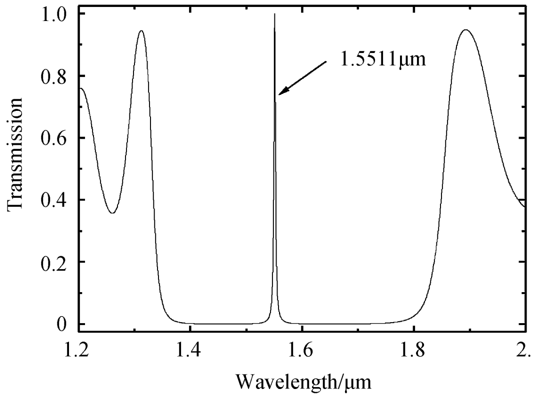
Depending on the structural factors $m=3$, $n=1$ and $j=3$, the SGF photonic crystal can be written as $\{AAABAAABAAABAABAAABAAABAAA\}^P$, where P is the stack period. As shown in Fig. 3, the calculated transmission spectrum is plotted as a function of incident wavelength for three different external voltages. In Fig. 3(a), it is found that there is an extremely sharp peak emerging at the wavelength $\lambda_p=1.55$ μm when the applied voltage is zero. The shape of this transmission peak is similar to a delta function which allows only a single-frequency channel to pass. So this delta-function-like peak can be used to design a precisely single channel tunable filter device. The channel wavelength λ_p is slightly shorter when a positive voltage is applied (Fig. 3(b)), whereas it becomes longer when a negative voltage is applied (Fig. 3(c)). The relationship between the channel wavelength λ_p and applied voltage U is almost linear with a negative slope, illustrated in Fig. 4, which can be written as $\lambda_p=-3.84066\times10^{-5}U+1.54998$ μm.



(a) 0kV



(b) +30kV



(c) -30kV

Fig. 3　Transmission spectrum for $P=1$ at different external electric voltages

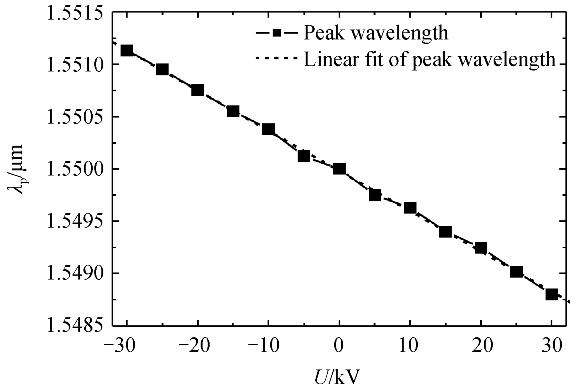


Fig. 4　Dependence of channel wavelength on the applied voltages

The influence of the incident angle θ of light beam on the channel wavelength of the SGF filter is also investigated and shown in Fig. 5. It has indicated that the channel wavelength is gradually shortened with increasing incident angle when the external electric field is fixed. For the case of a fixed incident angle, as shown in the inset in Fig. 5, the channel wavelength is shortened with an increasing voltage if the voltage is positive whereas the channel wavelength is elongated with an increasing absolute value of applied voltage if the voltage is negative.

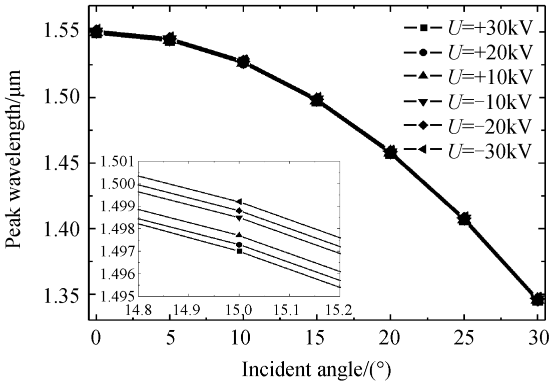


Fig. 5　The channel wavelength as a function of the incident angle at different external electric voltages

In addition, the characteristics of multi-channel SGF filter are also discussed. According to the SGF fashion, the filter is composed of the SGF photonic crystal with 52 layers and the metal electrodes with two control voltages, which is shown in Fig. 6. And, the other structural parameters are considered as the same as the former structure. It is clear in Fig. 7 that three filter channels emerge around 1. 55 μm in the photonic band gap which shift to shorter wavelength with an increasing positive external voltage U_2, and to longer wavelength with the increasing absolute value of negative external voltage U_2 when U_1 is fixed on + 30 kV. Moreover, the filter channels possess quite high quality in regardless of the external voltage U_1 and U_2 are chosen as positive or negative value. For example, when the external electric field is chosen as $U_1=+30$ kV, $U_2=+20$ kV (the dash-dot-dot line shown in Fig. 7), there are three 100% extreme narrow-band filter channels whose center wavelength are 1. 529 μm, 1. 549 μm and 1. 570 μm, respectively.

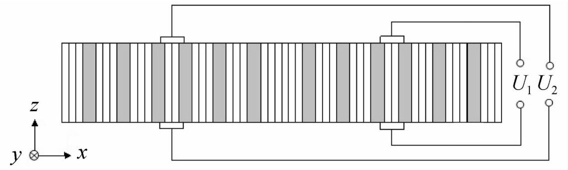


Fig. 6 The schematics of the tunable filter with SGF photonic multilayers for $m=3$, $n=1$, $j=3$ and $P=2$

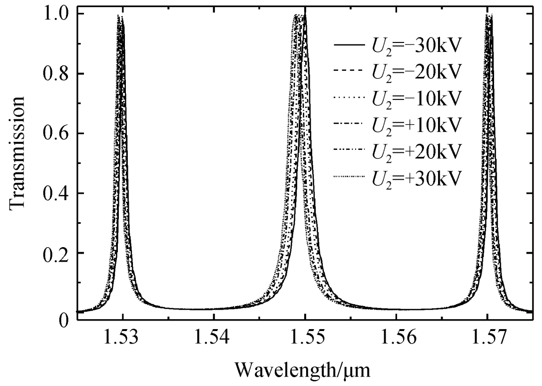


Fig. 7 The dependence of tunable multi-channel filter on the external voltage U_2 when U_1 is fixed on +30 kV

Based on $P=2$, $m=3$, $n=1$, $j=3$, and $U_1=+30$ kV, $U_2=+20$ kV for different incident angle θ, the transmission spectrum of SGF photonic crystal is shown in Fig. 8. When $\theta=10°$, it is noted that the third channel wavelength is 1. 55 μm, which agrees with the window of optical communication. With the increase of the incident angle, the filter channels move to the shorter wavelength which can be used to design the angle-dependent tunable filters.

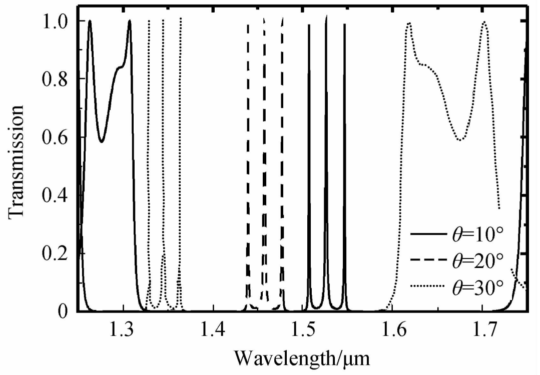


Fig. 8 The dependence of filter channels on incident angle when the external electric fields are $U_1=+30$ kV and $U_2=+20$ kV

3 Conclusion

In summary, the characteristics of the SGF tunable filter containing electro-optical material $LiNbO_3$ have been investigated. Compared with the conventional photonic crystals, the channel wavelength of our SGF structures can be modulated by altering the external electric voltage without changing their geometrical structure. These SGF filters exhibit good performances which open a door for the implementation of tunable filters with the other aperiodic structures.

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基于对称广义 Fibonacci 光子晶体结构的电光可调谐滤波器

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摘　要：本文构建了含有电光材料 $LiNbO_3$ 的一维对称广义 Fibonacci 光子晶体结构，提出并设计了一种基于该结构的可调谐滤波器，并利用传输矩阵法对设计的滤波器的可调谐滤波特性进行了理论研究. 数据模拟结果表明：保持对称广义 Fibonacci 光子晶体的几何结构不变，通过改变电极所在处施加在电光介质（$LiNbO_3$）层上的外加电场，即可实现滤波器的滤波通道波长的调节，滤波通道波长的改变与外加电压呈线性关系，随着外加电压的增加，滤波通道波长向短波长方向移动. 此外，电压一定时，通道波长随光的入射角的增加向短波长方向移动；光的入射角一定时，外加正电压下，通道波长随电压增加发生蓝移，而外加负电压下，通道波长随反向电压的增加发生红移. 最后，讨论了双电场作用下的多通道波长滤波器的结构极其特性. 以上结果对于新型光子晶体器件的设计具有重要的参考价值.

关键词：广义 Fibonacci 序列；电光效应；光子晶体；可调谐滤波器