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Terahertz wave narrow bandpass filter based on photonic crystal

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ABSTRACT

We designed a narrow bandpass terahertz wave filter using photonic crystals with a line defect. An inserted linear defect in one-dimensional photonic crystal structures for a channeled filtering in the terahertz range are studied and designed theoretically. By using transfer matrix method, we examined the transmittance spectra for the proposed terahertz wave filter has a 3 dB transmission loss bandwidth of 20 MHz ranging from 0.29998 THz to 0.30001 THz. The simulated results show that a very narrow transmission band and high transmission (higher than 99.99%) centered at λ_0, and very sharp edges can be achieved.

1. Introduction

Terahertz (THz) wave, which refers to the frequencies from 0.1 THz to 10 THz, lie in the frequency gap between the infrared and microwave, have received considerable attention during the past decades. There are increasing demands for experiments in terahertz frequencies, in different areas such as biotechnology, nanotechnology, space science, security, terahertz wave communications, and plasma diagnostics [1,2]. For potential applications, the functional devices, such as beam polarizers, modulators and filters, are crucial components for a terahertz system. As a dispensable device for ultrafast information processing and interconnection of terahertz wave communication, terahertz wave filter has attracted considerable attention. Up to now, some kinds of terahertz wave filter based on photonic crystal, metamaterial and surface plasmon, have been reported. Libon et al. [3] demonstrated that a type-I/type-II GaAs/AlAs multiple quantum well sampled can be used as a THz filter which was optically controlled with a low power cw HeNe laser. Wu, et al. [4] demonstrated a THz plasmonic high pass filter. The subwavelength 2D cubic lattice of metallic wire arrays has a plasma frequency at 0.7 THz. A reflective frequency-selective surface has been used to design a filter with a passband at 300 GHz and a stopband at 450 GHz by Biber et al. [5]. Němec et al. [6] designed a thermally tunable filter with the transmission loss of −6 dB at 0.35 THz. A two-element tunable Lyot filter operating in the terahertz frequency range is demonstrated by Chen et al. [7]. The transmission bandwidth is 0.1 THz and the insertion loss of the present device is 8 dB due to the scattering of liquid crystal molecules in the thick LC cells. Melo et al. [8] have fabricated filters based on metal mesh structures centered at different frequencies between 0.4 and 10 THz, using photolithography and electroforming techniques. However, quantitative studies on terahertz wave filter are still very limited. Therefore, it is valuable to investigate the filter in the terahertz range.

Recently, photonic crystals have given rise to the new field of photonic bandgap. One of these features is that propagation of electromagnetic waves with the frequencies within the photonic bandgap is prohibited in the periodic photonic crystal structure. By introducing the defect in a perfect photonic crystal, the localized defect modes will appear in the photonic bandgap. These defect modes provide the function of filtering. In this paper, we design the terahertz wave filter structure based on an inserting linear defect in a dimensional periodic photonic crystal structure. The novel terahertz wave filter has been designed and calculated through transfer matrix method. The properties of bandpass filters such as centre frequency, bandwidth, and peak transmission are determined by the geometric parameters. The simulation results show that the designed filter exhibit excellent transmission performance such as high transmission (higher than 99.99%) at the central frequency, adjustable bandpass, sharp edges, and good rejection of the sideband frequencies.

2. Device design and analysis

A conventional perfect one-dimensional photonic crystal structures consists of identical alternating layers of high (n_1) and low (n_2) refractive indices. The configuration of the proposed terahertz wave filter using photonic crystal is shown in Fig. 1. It consists of a line defect layer inserted into a periodic structure of alternating layers of high/low index materials (the references of these structures fabrication sees Refs. [9,10]). To design a linear defect with specified defect states located at the pre-assigned frequencies, a quarter-wave layer n_2 is implanted in the perfect photonic crystal (i.e. a quarter-wave layer n_2 is inserted between the two groups $(n_1n_2)^N(n_1n_2)^N$, resulting in $(n_1n_2)^Nn_2(n_1n_2)^N$, where N represents the periodicity of the cross, $n_1$and n_2 are the refractive index of the dielectric materials, l_1 and l_2 are the dielectric

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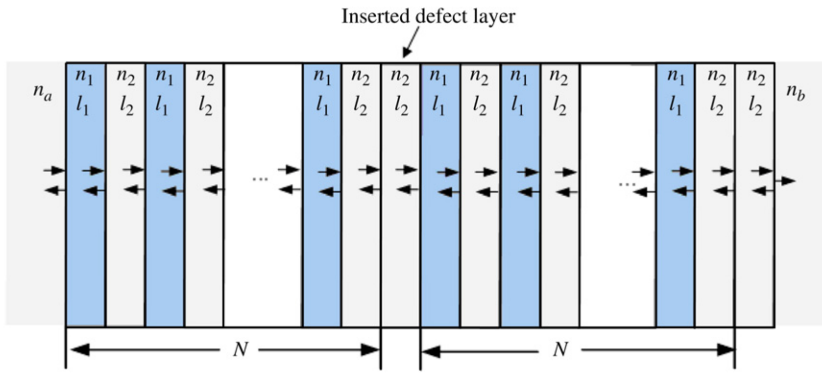

Fig. 1. Schematic diagram of the proposed terahertz wave filter.

materials length, respectively.). Adding another n_2-layer on the right, the structure $(n_1n_2)^Nn_2(n_1n_2)^Nn_2$ will act as $2n_2$, that is, a half-wave absentance layer at λ_0 (λ_0 is the operating wavelength.). If such a structure is sandwiched between the same substrate, then it will act as an absentance layer, opening up a narrow transmission window at λ_0, in the middle of its reflecting band. The reflection bands of a dielectric mirror arise from the *N*-fold periodic replication of high/low index layers of the type $(n_1n_2)^N$, where dielectric-layer (i.e. high and low refractive indices material) can have arbitrary lengths. The transfer matrix of the total electric and magnetic fields for *i*-th layer is given by

$$\begin{bmatrix} E_i \\ H_i \end{bmatrix} = M_i \begin{bmatrix} E_{i+1} \\ H_{i+1} \end{bmatrix}, \quad i = N, N-1, \ldots, 1 \tag{1}$$

Where $M_i = \begin{bmatrix} \cos k_il_i & j\eta_i \sin k_il_i \\ j\eta_i \sin k_il_i & \cos k_il_i \end{bmatrix}$ $k_il_i = 2\pi\frac{n_il_i}{\lambda}, \eta_i = \eta_0/n_i$, η_0 is the wave impedance.

Thus the total transfer matrix can be obtained by multiplying all individual transfer matrixes in sequence. It can be calculated from

$$M = (M_1M_2)^N = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{2}$$

Similarly the reflection responses and the transmission coefficient will satisfy the recursions:

$$\begin{cases} r = \dfrac{(M_{11} + M_{12}\eta_0)\eta_0 - (M_{21} + M_{22}\eta_0)}{(M_{11} + M_{12}\eta_0)\eta_0 + (M_{21} + M_{22}\eta_0)} \\ t = \dfrac{2\eta_0}{(M_{11} + M_{12}\eta_0)\eta_0 + (M_{21} + M_{22}\eta_0)} \end{cases} \tag{3}$$

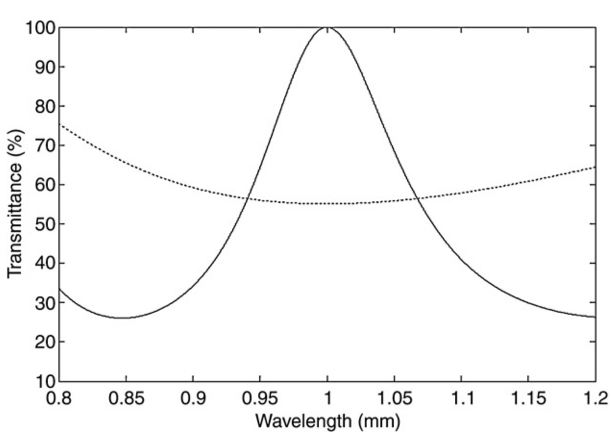

Fig. 2. The transmission spectrum of the designed filter at $\lambda_0 = 1$ mm for $N = 2$, unit (%).

Thus the total transmittance can be achieved as

$$T = t \cdot t^* \tag{4}$$

3. Simulation results

Here, we employ the structure (see Fig. 1) to design a bandpass filter in a terahertz range. The optical thicknesses are typically chosen to be quarter-wavelength long, that is, $n_1l_1 = n_2l_2 = \lambda_0/4$ at operating wavelength λ_0. The standard arrangement is to have a high index layer being the first and last layer (i.e. n_a and n_b). We will assume that they are quarter-wavelength layers at the design wavelength λ_0. The proposed bandpass filter in the terahertz range was simulated by using the transfer

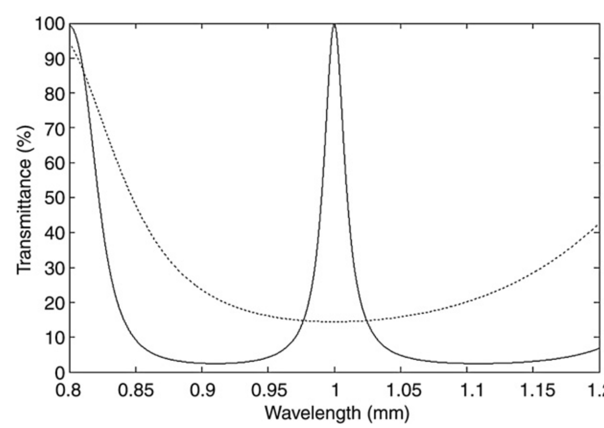

Fig. 3. The transmission spectrum of the designed filter at $\lambda_0 = 1$ mm for $N = 4$, unit (%).

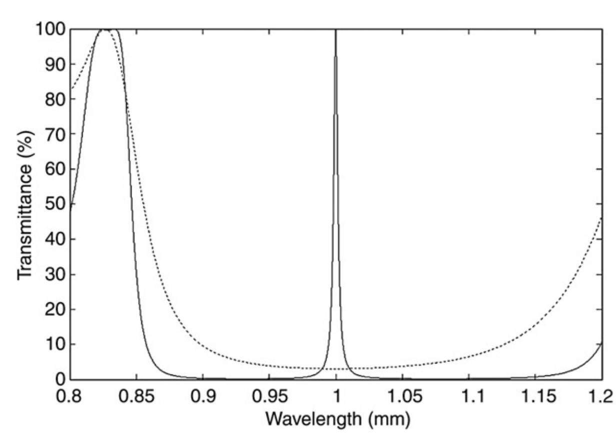

Fig. 4. The transmission spectrum of the designed filter at $\lambda_0 = 1$ mm for $N = 6$, unit (%).

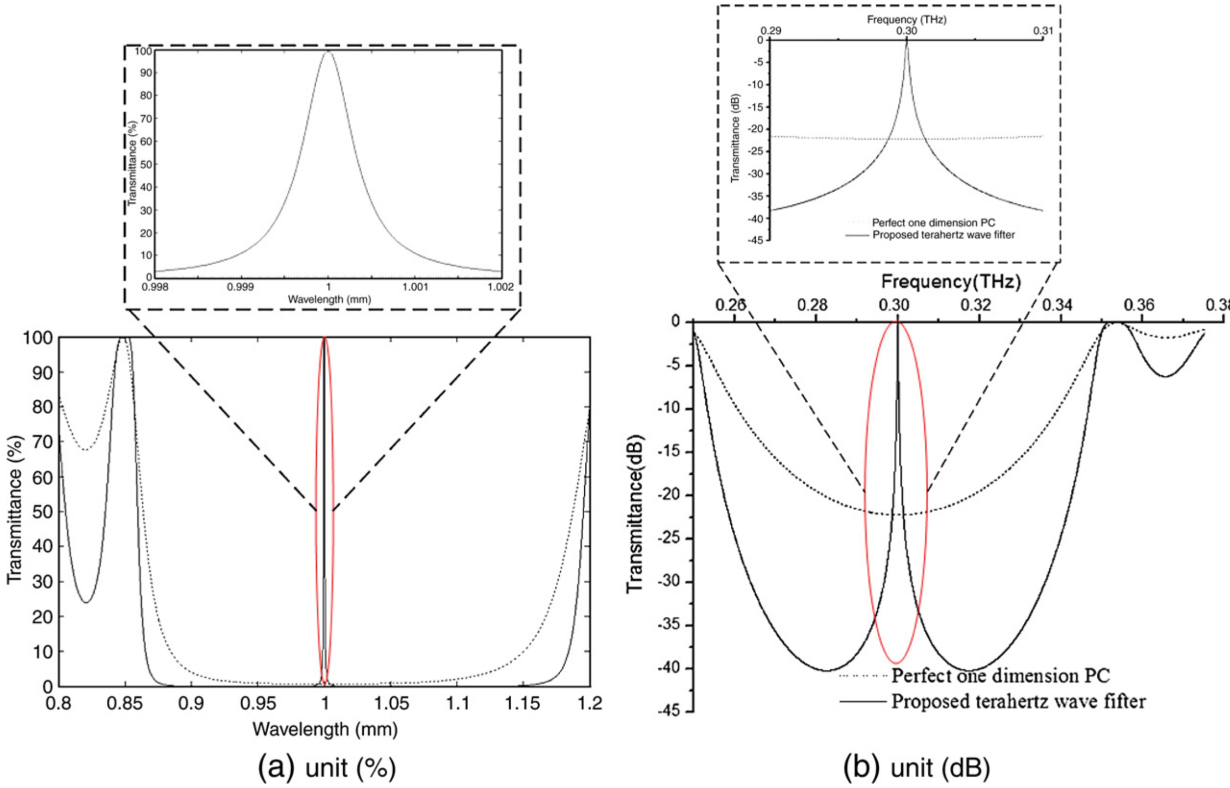

Fig. 5. The transmission spectrum of the designed filter at $\lambda_0 = 1$ mm for $N = 8$.

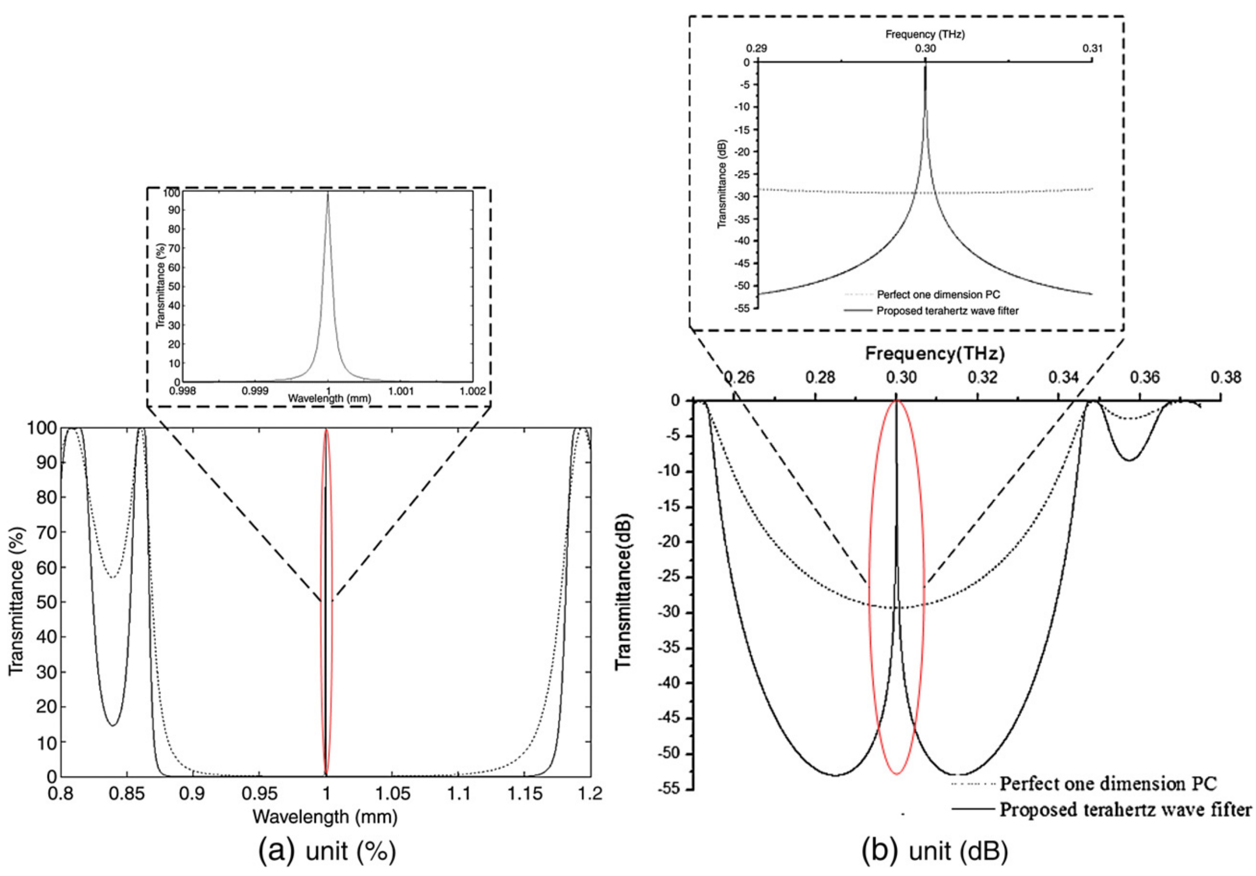

Fig. 6. The transmission spectrum of the designed filter at $\lambda_0 = 1$ mm for $N = 10$.

matrix method. The refractive indices of the layers are selected as $n_a = n_b = 1.52$, $n_1 = 2.1$ (zirconium oxide) and $n_2 = 1.4$ (magnesium fluoride). Their absorptions in THz band are 0.3 cm^{-1} and 0.0001 cm^{-1}, respectively. The terahertz frequencies were selected for the terahertz wave wireless communication applications. The terahertz frequency is 0.3 THz, corresponding to the less atmospheric loss windows. The design wavelength at which the layers are quarter-wavelength is taken to be $\lambda_0 = 1$ mm. We have compared the design case of using one-dimensional photonic crystal structures and one-dimensional photonic crystal with a line defect structure. Figs. 2–6 show the transmission spectrums of the designed filter when the periodicity of the cross N are equal to 2, 4, 6, 8, and 10, respectively. From these figures, one sees that the device based on a perfect one-dimensional photonic crystal is not a filter (dot line). The magnitude of the transmittance is very low and it is around 0.1%, which means there is high reflection in a perfect one-dimensional photonic crystal structure at the centre frequency of λ_0. However, the proposed bandpass filter based on a one-dimensional photonic crystal structure with a line defect can achieve the desired specification characteristic (dash line). But the transmission bandwidth becomes narrower as N increases. From Fig. 5, it can be noted that the magnitude of transmittance peak becomes quite high, and it is about 100%. The 3 dB transmission loss bandwidth is 210 MHz ranging from 0.29989 to 0.3001 THz. From Fig. 6, one sees that the 3 dB transmission loss bandwidth is 20 MHz ranging from 0.29998 to 0.30001 THz. That means the number of periods have not more significance to enhance the transmittance at the centre frequency for the filter. But the number of periods has great influence on the bandwidth for the proposed filter.

In the letter, we supported that a 2% manufacturing tolerances were made for the length of the line defect layer inserted into a periodic structure and the length of alternating high/low index materials, and the simulated transmission spectrum of the designed filter is shown in Fig. 7. From the figure, one sees that the centre frequency (λ_0) of the designed narrow bandpass filter is 1 mm (dark line, see Fig. 7), if the dielectric material length has no manufacturing tolerances. When only the length of the inserted defect layer has the 2% manufacturing tolerances, the centre frequency (λ_0) of the designed narrow bandpass filter becomes 0.94 mm (blue line, see Fig. 7). For the case of the 2% manufacturing tolerances for all length of the high/low index materials, the centre frequency (λ_0) of the designed narrow bandpass filter becomes 0.9 mm (dot line, see Fig. 7). The centre frequency (λ_0) of the proposed bandpass filter changes as the high/low index materials length changes. It should be pointed out that the frequency line width of the filtering channel is very narrow with high isolation. The frequency line width of filtering is quite narrow due to the confined state effect. By repeating N several times and using possibly different lengths, it is possible to design a very narrow transmission band centered at λ_0 having a flat passband and very sharp edges.

4. Conclusion

A line defect layer inserted into a periodic structure of alternating layers of high/low index materials, a defect mode over the entire lowest forbidden band in terahertz region was obtained. We design a narrow bandpass filter based on one-dimensional photonic crystals with a line defect. By changing the length of dielectric material, we tuned a defect mode over the entire lowest forbidden band. Simulation results demonstrate that the obtained terahertz wave filter can achieve a narrow transmission band and high transmission (higher than 99.99%) centered at λ_0, having a flat passband at the central frequency, and sharp edges. The design of this filter is easy and is fully flexible in controlling fractional bandwidth.

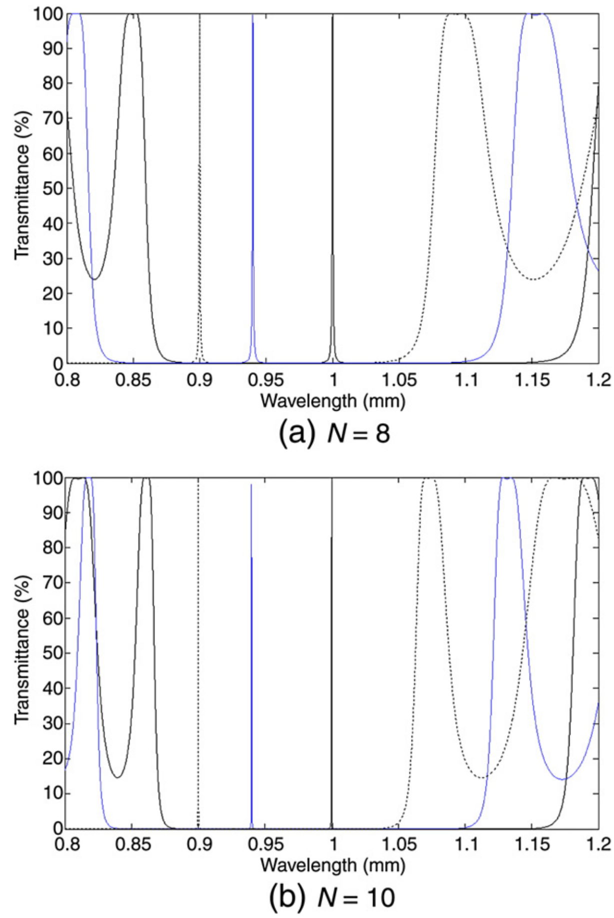

Fig. 7. The transmission spectrum of the designed filter (a) $N = 8$, (b) $N = 10$, without manufacturing tolerances (dark line), only the length of the inserted defect layer has the 2% manufacturing tolerances (blue line), 2% manufacturing tolerances for all length of the high/low index materials (dot line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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