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The design of a photonic crystal filter in the terahertz range*

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One-dimensional photonic crystal structures for multiple channeled filtering and polarization selective filtering in the terahertz (THz) range are studied theoretically. The design of aperiodic photonic quantum-well (APQW) structures for multiple channeled filtering and different polarization filtering at arbitrary preassigned frequencies are achieved by using the simulated annealing algorithm with a special merit function. The parameters of these filters can be expediently controlled and the transmission characters are polarization dependent. Numerical simulations show that the designed APQWs can meet the desired specification well.

Keywords: photonic crystal, filter, simulated annealing algorithm
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1. Introduction

Terahertz (THz) radiations, which refer to the frequencies from 100 GHz to 10 THz and lie in the frequency gap between the infrared and microwave, have attracted considerable attention during the past decades.[1−3] Due to their special properties, THz radiations have been applied in many fields such as biomedical diagnostics, quality control of packaged goods and moisture analysis for agriculture. The application of THz radiations in communications has also been proposed.[4,5] However, due to the lack of suitable devices, the development of THz communication is quite slow. The filter is an important device in optical communication for interconnection and ultrafast optical information processing. Therefore, it is valuable to investigate the design of a filter in the THz range.

Photonic crystals (PC) have been studied in one, two, and three dimensions because of their remarkable features.[6−10] One of these features is that the propagation of electromagnetic waves with the frequencies within the photonic bandgaps (PBGs) is prohibited in the periodic dielectric structure. The bandgap position is also different for incident waves with different polarization when the angle of incidence is not zero.[11] By introducing the defect into a perfect PC, the defect states will appear in the PBGs. These defect states provide a function of multiple channeled filtering. By inserting a short PC into another perfect PC, a new kind of photonic quantum well (PQW) structure can be achieved. The number of defect states can be tuned via altering the number of the PQWs.[12] The work on how to use the simulated anneal (SA) algorithm to conduct multiple channeled filtering at arbitrary preassigned frequencies lying in the visible light range has already been reported.[13] However, only the normally illuminating is considered in this work, thus the filter has the same characteristic for both the TE and TM incident waves. In this paper, we will first carry out the designs of the aperiodic PQW structures to achieve multiple channeled filtering and then for polarization selective filtering in the THz range by using the SA algorithm. The parameters of the filter can be easily controlled. The simulation results show that the designed filters can achieve the preset goal well.

2. Basic theory for design

The aperiodic PQWs (APQWs) are sandwiched in two finite-length ideal PCs, which consist of alter-

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nately stacked layers A and B with different dielectric constants of ϵ_{A} and ϵ_{B}, Their thicknesses are denoted by d_{A} and d_{B}, with $a = d_{\mathrm{A}} + d_{\mathrm{B}}$ being the lattice constant of the one-dimensional PC. The APQWs are composed of two different alternately stacked basic constituent layers C and D with dielectric constants of ϵ_{C} and ϵ_{D}, respectively. However, the thickness of each individual layer may not be equal and the individual layer thickness is determined by the merits of the desired filter. The transmission spectrum of designed APQW structures is calculated by using the transfer matrix method, and the transfer matrix in each individual layer can be obtained by solving Maxwell equations with a combination of boundary conditions. For the plane wave with TE or TM polarization and an arbitrary incident angle, the transfer-matrix for the l-th layer is given by

$$\boldsymbol{T}_l = \hat{\boldsymbol{D}}_{l+1}^{-1}\hat{\boldsymbol{D}}_l\hat{\boldsymbol{P}}_l^{-1}, \tag{1}$$

where $l \in \{1, 2, \ldots, N\}$ is the ordinary number of layers, and $\hat{D}_l$ is the transfer matrix. The propagation matrix $\hat{\boldsymbol{P}}_l^{-1}$ is

$$\hat{\boldsymbol{P}}_l^{-1} = \begin{pmatrix} \exp(\mathrm{i}k_{lz}d_l) & 0 \\ 0 & \exp(-\mathrm{i}k_{lz}d_l) \end{pmatrix} \tag{2}$$

for the l-th layer in the sample. $\hat{\boldsymbol{D}}_l$ has different forms for the TE and TM waves:

$$\hat{\boldsymbol{D}}_l = \begin{pmatrix} 1 & 1 \\ \gamma_l & -\gamma_l \end{pmatrix} \tag{3}$$

for the TE wave and

$$\hat{\boldsymbol{D}}_l = \begin{pmatrix} \alpha_l & \alpha_l \\ \beta_l & -\beta_l \end{pmatrix} \tag{4}$$

for the TM wave, where $\alpha_l = k_{lz}/k_l$, $\beta_l = n_l/\mu_l$, $\gamma_l = \alpha_l\beta_l$, $k_l = 2\pi n_l/\lambda$, and $k_{lz} = \frac{2\pi}{\lambda}n_l\sqrt{1-\left(\frac{n_1\sin\theta_1}{n_l}\right)^2}$; θ_1 is the incident angle. Thus the total transfer matrix can be obtained by multiplying all individual transfer matrixes in sequence. It can be calculated as follows:

$$\begin{pmatrix} t_N \\ r_N \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} t_1 \\ r_1 \end{pmatrix}, \tag{5}$$

with

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \hat{T}_N\hat{T}_{N-1}\ldots\hat{T}_2\hat{T}_1. \tag{6}$$

Thus the total transmission can be achieved as

$$\frac{n_N}{n_1}\left|\frac{t_N}{t_1}\right|^2. \tag{7}$$

To design the APQWs with specified defect states located at the preassigned frequencies $\omega_{p,q}^{(0)}$ for different polarizations within a given range of $[\omega_a, \omega_b]$, a perfect PC must be initially chosen to serve as the prototype PC, into which the APQW, is sandwiched, as shown in Fig.1. It requires that the chosen prototype PC

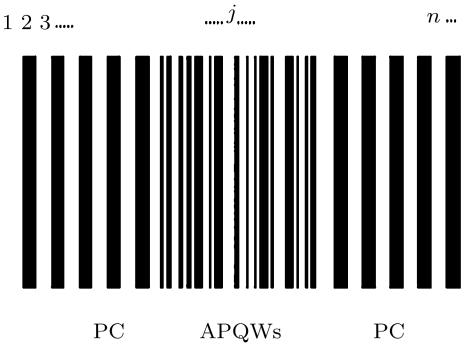


Fig.1. Schematic diagram of the APQW structure.

should have an appropriate PBG located in this frequency range and a certain width, not narrower than the range of $[\omega_a, \omega_b]$ for both TE and TM polarizations while the incident angle is not zero. After determining this prototype PC, the APQWs can be designed by using the SA algorithm. Here a non-traditional merit function, more appropriate to our designs and completely different from that used in Ref.[14] is defined as

$$O = \sum_p \sum_q \sum_s |\omega_{p,q}^{(0)} - \omega_{p,q}^{(s)}|, \quad \omega_{p.q}^{(0)}, \quad \omega_{p,q}^{(s)} \in [\omega_{p,q-1}, \omega_{p,q}], \quad p = 1, 2, \quad q = 1, 2, 3, \ldots .$$
$$\omega_0(=\omega_a) < \omega_{p,1}^{(0)} < \omega_{p,1} < \ldots < \omega_{p,\alpha-1} < \omega_{p,\alpha}^{(0)} < \omega_{p,q}(=\omega_b), \tag{8}$$

where $\omega_{p,q}^{(s)}$ denote the frequencies of the defect states appearing in $[\omega_a, \omega_b]$ for different polarization p, which are generated in every routed configuration of the APQWs during the SA routine; $\omega_{p,q}^{(0)}$ denotes the preassigned

confined states appearing in the bandgap for different polarizations. In the SA routine, more than one defect states may occur in the subregion, thus, s may be larger than 1, and the sum over s should be taken into account. The optimal design of the APQWs corresponds to a search for the minimum of merit function. The sandwiched part in the sample is divided into N unit blocks with thickness of δd; the dielectric constant of each individual block is chosen to be one of the binary values of $\epsilon_{\rm C}$ and $\epsilon_{\rm D}$ decided by the SA algorithm. At the beginning of the SA routine, the initial temperature $T_{\rm e}$ and dropping rate $\Delta T_{\rm e}$ are selected, next a random constructed APQW is used to compute the initial merit function O_0. Then a new merit function O_1 is calculated with changing the dielectric constant of a unit block and the difference of the merit functions $\Delta O = O_0 - O_1$ is obtained. A random number P $(0 \leq P \leq 1)$ is generated by the computer. If P satisfies $P < \exp(-\Delta O/T_{\rm e})$, this change will be accepted and O_0 will be replaced by O_1, or the dielectric constant of this unit block will be retired and O_0 does not change. After testing all of the blocks, this procedure will be repeated with a new temperature $T_{\rm e} = T_{\rm e} \times \Delta T_{\rm e}$ until no dielectric constant changes in the APQWs. Thus, the favourable arrangement of the APQWs can be completely determined.

3. Simulated results

Firstly, the APQW for achieving two channeled filtering in a given range of $[0.69, 0.98]$ THz is designed. The incident angle is zero, thus the PC has the same bandgap for both TE and TM waves. Therefore, $p = 1, q = 2$ is selected in Eq.(8). The dielectric constants are selected to be $n_{\rm A} = n_{\rm B} = 3.377$ and $n_{\rm C} = n_{\rm D} = 1.0$, corresponding media are high resistance silicon and air. The thicknesses of the constituent layers A and B in the prototype PC are set to $d_{\rm A} = 122.46$ μm and $d_{\rm B} = 1761.54$ μm, thus, the second PBG of the prototype PC is located just in $[0.69, 0.98]$ THz. Five AB layers $(\rm AB)_5$ are employed on either side of the APQWs. The sandwiched part is divided into $N = 100$ blocks and the thickness of the basic block is $\delta d = 37.68$ μm. Two filtering frequencies are preassigned as $\omega_{1,1}^{(0)} = 0.80$ THz and $\omega_{1,2}^{(0)} = 0.93$ THz. The transmission spectrum of the designed sample is displayed in Fig.2. The diagram of the designed APQW is shown in Fig.2(a) and the transmission spectrum is shown in Fig.2(b). The frequencies of the defect states accord exactly with the preset values. Their transmittances are 0.99 and 0.94 for 0.80 and 0.93 THz, respectively.

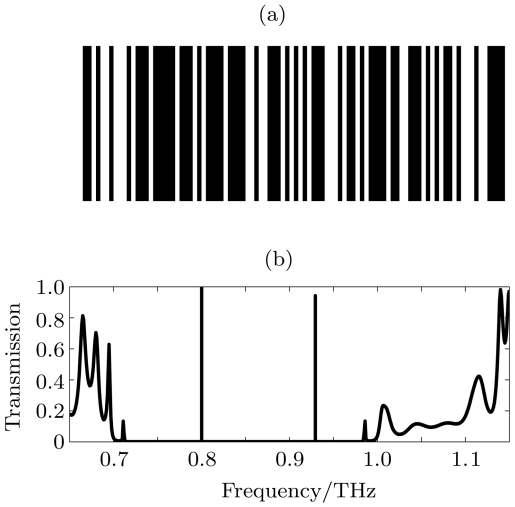


Fig.2. Results of APQWs designed for two-channel filtering. (a) Diagram of the designed APQWs and (b) the transmission spectrum.

Then the APQWs used for achieving polarization selective filtering in a given range of $[1.4, 1.55]$ THz is designed. Two filtering frequencies are preassigned to be $\omega_{1,1}^{(0)} = 1.43$ THz for the TE wave and $\omega_{2,1}^{(0)} = 1.46$ THz for the TM wave. The thicknesses of the constituent layers A and B in the prototype PC are set to $d_{\rm A} = 847.80$ μm and $d_{\rm B} = 1036.2$ μm, thus the second PBG of the prototype PC is located in $[1.4, 1.55]$ THz. The sandwiched part is also divided into $N = 100$ blocks and the thickness of the basic block is $\delta d = 37.68$ μm. The transmission spectra of the designed sample are displayed in Fig.3. The diagram of the designed APQWs is shown in Fig.3(a). The transmission spectra for TE and TM waves are shown in Figs.3(b) and 3(c), respectively. The frequencies of the defect states accord exactly with the preset values. The transmittances are 0.97 and 0.91 for $\omega_{1,1}^{(0)} = 1.43$ THz and $\omega_{2,1}^{(0)} = 1.46$ THz, respectively.

A more complex design is carried out. The bandgap range is $[1.4, 1.55]$ THz. Two wavelengths $\omega_{1,1}^{(0)} = 1.45$ THz and $\omega_{1,2}^{(0)} = 1.53$ THz are expected for the TE wave and $\omega_{2,1}^{(0)} = 1.43$ THz and $\omega_{2,2}^{(0)} = 1.51$ THz are expected for the TM wave. The sandwiched part is also divided into $N = 200$ blocks and the thickness of the basic block is $\delta d = 18.84$ μm.

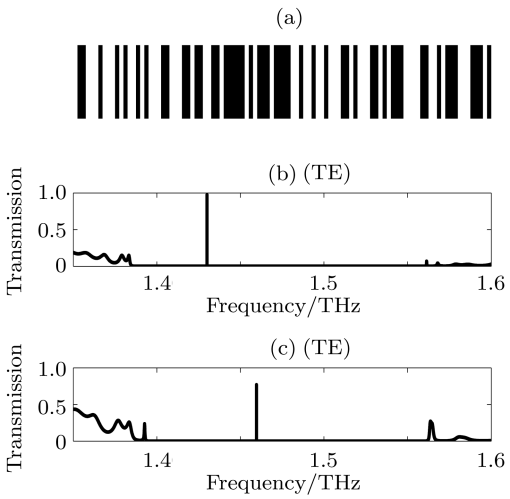


Fig.3. Results of APQWs designed for polarization selective filtering. (a) Diagram of the designed APQWs, (b) the transmission spectrum for the TE wave and (c) that for the TM wave.

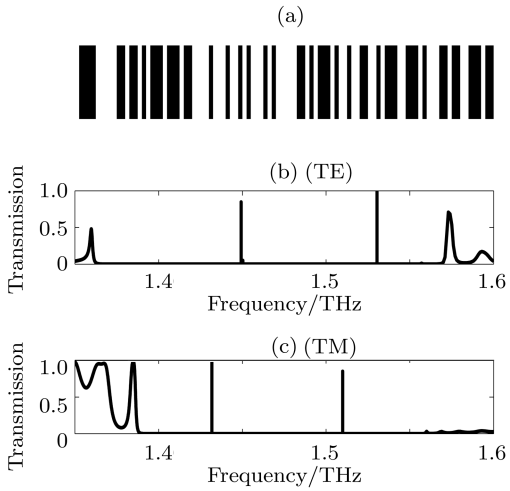


Fig.4. Results of designed APQWs for multi-wavelength polarization selective filtering. (a) Diagram of the designed APQWs, (b) the transmission spectrum for the TE wave and (c) that for the TM wave.

The data of the design are shown in Fig.4. The frequencies of the defect states accord exactly with the preset values. The transmittances are 0.85, 0.97, 0.92, and 0.85 for $\omega_{1,1}^{(0)} = 1.45$ THz, $\omega_{1,2}^{(0)} = 1.53$ THz, $\omega_{2,1}^{(0)} = 1.46$ THz, and $\omega_{2,2}^{(0)} = 1.51$ THz, respectively. These results illustrate that the three design examples can achieve the desired specification well. It should be pointed out that the frequency linewidth of each filtering channel is narrower than 20 GHz with high isolation.

4. Conclusion

In conclusion, the SA algorithm with a new merit function has been employed to design the APQWs for achieving multiple-channel filtering and polarization selective filtering at arbitrary preassigned frequencies in the THz region. Simulated results demonstrate that the obtained APQWs can achieve the desired specification well. The frequency linewidth of each filtering channel is quite narrow due to the confined state effect.

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