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A tunable terahertz photonic crystal narrow-band filter

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***Abstract*—We theoretically propose and investigate a magnetically tunable narrow-band terahertz filter based on a triangular lattice silicon photonic crystal with a point and two line defects. The optical properties of the filter have been analyzed in detail. It is found that a single resonant peak with the central frequency of around 1 THz is existed in the transmission spectrum, which has a narrow full width at half maximum (FWHM) of less than 2 GHz. Moreover, under the control of an external magnetic field, transmission frequency and width of passband are adjustable, which reveals that the two-dimensional silicon photonic crystal waveguide with point and line defects can serve as a continuously tunable bandpass filter at the terahertz wave band.**

***Index Terms*—terahertz, narrow-band filter, photonic crystal.**

I. INTRODUCTION

Terahertz (THz) waves, typically defined in the frequency range from 0.1 THz to 10 THz, are finding growing applications in various important fields such as space science, communications, and security screening [1-3]. Besides sources and detectors, development of THz technologies also requires devices to guide and manipulate THz waves. Therefore, the demand for high performance quasi-optic components such as frequency filters [4], attenuators [5], splitters [6], and polarizers [7] is increasing. High-resolution THz imaging applications need high-efficient narrowband THz filters to improve image quality for the reason that the dynamic range of existing THz detectors could be increased if high-quality prefiltering is used to dramatically reduce the noise band-width [8].

Photonic crystals (PCs) are periodic structures of dielectrics with different refractive index. They are characterized by photonic bandgaps (PBGs) in which the propagation of electromagnetic waves is strongly forbidden [9]. When the periodicity is broken, defects in the periodic PCs cause highly localized defect modes with high quality factor which can be utilized for construction of filters with an exceptionally narrow transmission band. Thus, the use of PCs with defects for high-quality frequency filtering is a straightforward and potentially very promising method. A THz plasmonic high pass filter which consisting of high-aspect-ratio micron-sized wire arrays was reported by Wu *et al* [10]. Timothy D. Drysdale *et al*. proposed a metallic photonic crystal filter, which could be tuned over the range of 365 - 386 GHz by a relative lateral shift of 140 μm between two micromachined metallic photonic crystal plates [11]. By use of $SrTiO_3$ as a defect material, Nemec *et al*. tuned a single defect mode in the one-dimensional photonic crystal from 185 GHz at 300 K down to 100 GHz at 100 K [12]. Voltage controlled wavelength selection at microwave frequencies was also achieved by Yang and Sambles using a structure of metallic slat gratings with the thin grooves between the metallic slats filled with nematic liquid crystal (NLC) [13]. Yong Sung Kim *et al*. fabricated a tunable terahertz filter based on a defect mode of a metallic photonic crystal, central frequency could be tuned from 1.43 THz to 1.577 THz [14]. All these studies are significant in THz frequency range. However, researches about THz filters with central frequency of about 1 THz are rare, which equals to THz wave generated by optical methods such as difference frequency generation and optical rectification.

In this paper, we propose a tunable narrowband THz filter using the defect modes of a two-dimensional photonic crystal composed of silicon (Si) and magnetically controlled liquid crystal (LC). It is found that the central bandpass frequency of the filter is around 1 THz and could be tuned from 1.126 THz to 1.193 THz, which is highly matched to the central frequency of THz waves generated by optical methods such as difference frequency generation and optical rectification. Furthermore, the full width at half maximum (FWHM) of the passband is less than 2 GHz.

II. DESIGN OF THZ NARROW-BAND FILTER

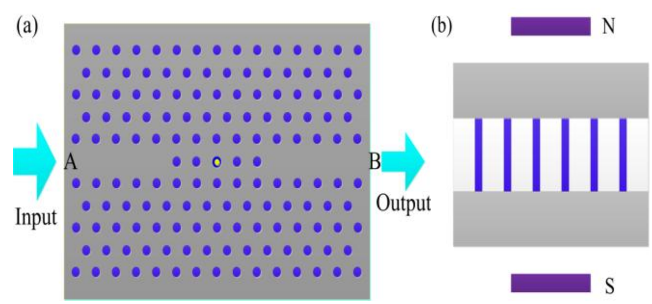

Fig. 1. (a) and (b) illustrate the structures of THz narrowband filter. Blue and yellow circles represent the silicon rods and liquid crystal defect, respectively. Gray sections are the substrates.

The structure of the tunable narrowband THz filter is shown in Fig. 1, which is composed by high-resistivity (ρ>10^4 Ωcm) silicon rods (with dielectric constant 11.7 and absorption loss of $0.23cm^{-1}$ at the THz wave band) [15] with hexagonal lattice arrayed in air host. Two line defects are existed in it, which are significant for narrowband filters. The input and output ports of the structure are labeled A and B, respectively. THz waves are coupled in and out of the waveguide by using two solid immersion lens also made of high resistivity silicon. The structural parameters of a and r are the lattice constant and the radius of the Si pillar, respectively. Appropriate fill factors related to the ratio of r/a are needed, therefore, in our paper the relationship between lattice constant a and radius of the Si pillar under study is $r = 0.2\ a$, r equals 20 μm.

Silicon is an excellent material for the construction of photonic crystals because it has extremely low loss in THz frequency range and silicon processing technology is well developed. The central point defect is filled with liquid crystal (LC) (E7, Merck) which is magnetic birefringent and has small losses (κ<0.05) at the THz wave band [16]. It was confined in a silicon container with thickness of 500 nm. The ordinary refractive index n_o and the extraordinary refractive index n_e of E7 are 1.57 and 1.75 at around 1 THz, respectively [17]. The effective refractive index $n(\theta)$ of E7 depends on the orientation of the LC molecules where θ is the angle between the THz propagation direction and the magnetic field. Therefore, the effective refractive index of the LC can be changed from 1.57 to 1.75 when the magnetic field is applied. The threshold magnetic field required to reorient LC molecules with the magnetic field perpendicular to the alignment direction is less than 0.001 T. Therefore, the lengths of the silicon and LC rods are set to 1.5 mm, which could ensure the tunable range of its effective refractive index [17].

III. TRANSMISSION PROPERTIES OF THE THZ NARROW-BAND FILTER

Photonic crystal composed of Si with hexagonal lattices were adopted in our paper, thus, PBGs for hexagonal lattices photonic crystal without any defects were calculated by using the plane wave expansion (PWE) method as described in detail by Ho *et al*. [18]. Waves with frequencies in the PBG of the PC will be reflected or leaked by the PC, so they cannot propagate through the PC. However, if a waveguide formed by a line defect in the PC is considered, only the waves with frequency in the PBG of the PC can be guided and transmitted through the waveguide.

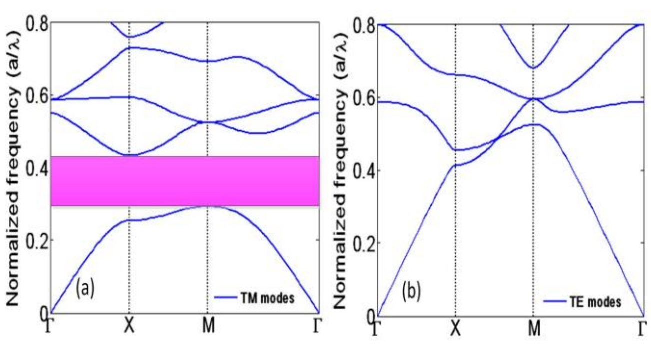

Fig.2. Band gap diagrams for the two models: (a) for TM model, (b) for TE mode.

Figure 2 shows the band gaps of the TM and TE modes obtained by using PWE method. It is found that a relatively large band gap exists within 0.315-0.416 in normalized frequency (a/λ) equivalent to 0.95 THz to 1.25 THz with TM polarization, which means that transmission of THz waves in this frequency range is forbidden, therefore, it could be used to construct THz narrow-band filters when line and point defects are existed in it. However, photonic bandgaps that existed in TM polarized mode is not appeared with TE polarized mode.

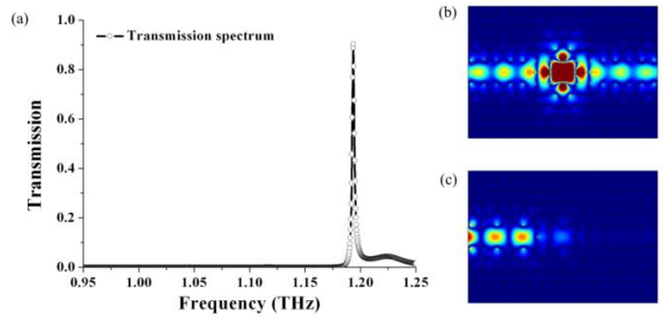

Fig.3. (a) Transmission spectrum of THz wave through filter. (b) and (c) illustrate the electric field distributions for incident TM wave at 1.1935 THz and 0.98 THz, respectively.

We first analyze the properties of the THz filter by using finite element method (FEM) without central LC material as a defect which is composed of an air point defect and two line defects. Transmission spectrum of this filter is illustrated in Fig. 3 (a). It is found that only a single narrow-band transmission peak exists in a broadband frequency range from 0.95 THz to 1.25 THz. The frequency of the transmission peak of the spectrum is 1.1935 THz and FWHM of the passband is 1.92 GHz. Figure 3 (b) and (c) show the electromagnetic field distributions in the PC filter for an incident TM polarized THz wave at 1.1935 THz and 0.98 THz. It is found that THz wave can propagate along the waveguide at 1.1935 THz with low energy loss and high efficiency (output efficiency is about 92%). The central point defect constitutes a cavity, which has high quality factor and acts as Lorentzian filter with a single sharp resonance. On the contrary, transmission of THz wave with frequency of 0.98 THz is forbidden in the filter, because most of the energy are reflected or leaked out from the waveguide.

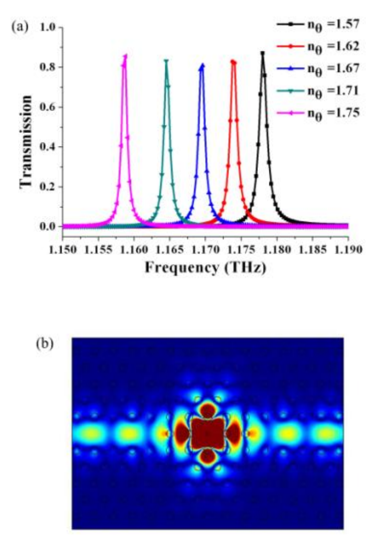

Fig. 4. (a) Transmission spectra of THz wave through filter with different effective refractive index of LC material. (b) Illustrates the electric field distribution for incident TM wave at 1.1581 THz.

In order to analyze the tunable properties of the filter, we fill the middle point defeat with LC material with fixed radius of 10 μm whose effective refractive index could be controlled via applied magnetic field. The corresponding transmission spectra with different effective refractive index of LC material are plotted in Fig. 4 (a). It is found that the central frequencies of the transmission spectra are decreasing with increment of the effective refractive index of LC material. This phenomenon could be explained by the fact that when the effective refractive index of LC changes, effective refractive index of the cavity mode changes accordingly, which leads to a variation of the coupling between the cavity and the waveguide, as well as the resonant frequency. The FWHM of the passband is also about 2 GHz with output efficiency of about 85%. Therefore, we could tune the central frequency of transmission spectrum from 1.1581 THz to 1.1791 THz through controlling the direction of magnetic field. The electric field distribution for incident TM wave at 1.1851 THz is shown in Fig. 4 (b), it is obvious that the THz wave can propagate along the waveguide at 1.1581 THz with low energy loss and high efficiency.

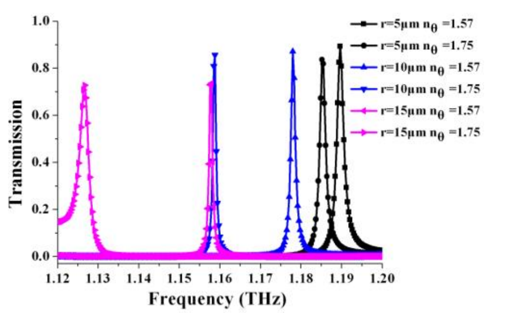

Fig. 5. Transmission spectra of THz wave through filter with different effective refractive index and radius of LC material.

For the purpose of analyzing the influences of LC defect on the transmission properties further, we have changed the radius of the LC defects from 5 μm to 15 μm. Transmission spectra with different radius of LC material and effective refractive index are plotted in Fig. 5. When the radiuses of the LC defects are fixed, it is found that the central frequencies of the transmission spectra are decreasing with the increment of effective refractive index of LC material. Furthermore, the central frequencies of the transmission spectra also decrease with the increasing of the radiuses of LC material with the same effective refractive index. However, we can also find that when the radius of LC defect is increase, the central frequency difference between two transmission spectra with the same radius is increase, which means that the tunable range is larger. Neverthelessly, due to the absorption of LC, peak output efficiency decrease with increasing of its radius.

IV. Conclusions

In this letter, we bring forward a tunable narrow-band terahertz filter based on a silicon photonic crystal with a point defect and two line defects. It is found that the central bandpass frequency of the filter is around 1 THz and could be tuned from 1.126 THz to 1.193 THz under the control of an external magnetic field, which is highly matched to the central frequency of THz waves generated by optical methods such as difference frequency generation and optical rectification. Moreover, the FWHM of the passband is less than 2 GHz. Therefore, this high efficient and narrow-band THz filter is a promise candidate for THz high-quality prefiltering, which is important for reducing the noise band-width and improving image quality.

Acknowledgment

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