Design and Performance Analysis of a Multi Wavelength Terahertz Modulator Based on Triple-Lattice Photonic Crystals

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Terahertz (THz) communication has important applications in high-speed and ultra broadband wireless access networks. The THz modulator is one of the key devices in a THz communications system. Wavelength division multiplexing (WDM) can expand the capacity of THz communications systems, so research on multi wavelength THz modulators has significant value. By combining photonic-crystal and THz technology, a novel type of multi wavelength THz modulator based on a triple-lattice photonic crystal is proposed in this paper. Compared to a compound-lattice photonic crystal, a triple-lattice photonic crystal has a larger gap width of 0.196. Simulation results show that six beams of THz waves can be modulated simultaneously with high performance. This modulator's extinction ratio is as large as 34.25 dB, its insertion loss is as low as 0.147 dB, and its modulation rate is 2.35 GHz.

Keywords : Multi-wavelength, Photonic crystal, THz wave, Triple lattice, Modulator

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I. INTRODUCTION

Nowadays the demand for broadband data communication is growing rapidly, owing to the information explosion. Optical communications systems have been researched for a long time, and the study of THz communications systems has become an inevitable trend. The THz modulator is one of the key devices in a THz communications system. Recently, there has been growing interest in studying THz wave modulators, especially multi wavelength THz modulators [1-3]. Currently dual-wavelength and four-wavelength THz modulators based on a compound-lattice photonic crystal (PC) have been proposed [4, 5]. A novel type of six-wavelength THz modulator based on a triple-lattice photonic crystal is proposed in this paper.

As is well known, various methods may be used to realize THz wave modulation [6, 7]. The PC material plays an important role in a THz modulator because of its excellent characteristics and production technology [8, 9]. A PC has the characteristics of a photonic band gap (PBG) and photon localization [10, 11]. A high-efficiency, controllable multi wavelength photonic crystal modulator can be fabricated by using a PC with defects. Using the disappearing-defect-mode

theory, we have designed a six-wavelength THz modulator that has the advantages of high extinction ratio and low insertion loss.

II. MODULATION MECHANISM

Defect-mode disappearance is based on the photon-localization characteristic of a PC. This characteristic of a PC is due to the combination of both point and line defects. Line defects are introduced as waveguides to transmit THz wave with frequencies located in the PBG, while point defects are used as resonant cavities, in which only THz frequencies in accord with the resonant frequency (or defect-mode frequency) can be selected. Figure 1 is a schematic diagram of the modulation based on defect-mode disappearance. When the point defects are filled with a tunable material and the pump light is applied to the point defects, the refractive index of the material will change and the defect modes of the point defects will disappear. Therefore, the input THz wave cannot resonate in the cavity and the modulator is in the "off" state, as shown in Fig. 1(a). However, if there is no pump light, the THz wave will resonate in the cavity and the modulator

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FIG. 1. Schematic diagram of modulation based on defect-mode disappearance: (a) “off” state, (b) “on” state.

is in the “on” state, as shown in Fig. 1(b) [12, 13].

III. STRUCTURAL DESIGN AND PERFORMANCE ANALYSIS

3.1. Structural Design

A triple-triangular-lattice PC is composed of three triangular-lattice photonic crystals, including circular, square, and triangular dielectric cylinders. Figure 2 shows the lattice structure of the PC. Its structural parameters are: lattice constant $a = 92 \mu\text{m}$, radius of circular dielectric cylinders $r = 13.9393 \mu\text{m}$, width of square dielectric cylinders $w = 25.0909 \mu\text{m}$, rotation angle of square dielectric cylinders $\theta = 45^\circ$, base length of triangular dielectric cylinders $w' = 41.8181 \mu\text{m}$, and height of triangular dielectric cylinders $h = 30.6666 \mu\text{m}$. The material of the dielectric cylinders is silicon (Si) with refractive index $n_1 = 3.418$ in the THz region. The substrate material is air with refractive index $n_2 = 1$.

The band structure of this triple-triangular-lattice PC for TE waves, as calculated by the plane-wave method (PWM), is shown in Fig. 3.

The shaded part in Fig. 3 is the PBG. The normalized frequency a/λ of the PBG is 0.326–0.522, corresponding to wavelengths of 176.24–282.2 μm . The width of the PBG

FIG. 2. The structure of the triple-triangular-lattice PC: (a) three-dimensional, (b) two-dimensional.

FIG. 3. The PBG diagram of the triple-triangular-lattice structure.

is 0.196, which is much wider than that of a compound-lattice structure [4, 5].

To achieve multi wavelength modulation, two point defects and two line defects are introduced into the photonic crystal at the same time, as shown in Fig. 4. The point defects and line defects are directly coupled.

FIG. 4. The structural model of the multi wavelength photonic-crystal modulator for the THz range: (a) three-dimensional view, (b) two-dimensional view.

The tunable material used in the point defects is gallium arsenide (GaAs), for which the THz refractive index in the photo-excited condition is complex and defined as $N = n - in'$, where n and n' are the real and the imaginary parts of the refractive index respectively. The complex refractive index N depends on the wavelength and intensity of the external excitation light wave (pump light) [14]. According to the modulation mechanism mentioned above, when the pump (wavelength 810 nm) intensity is $0.4 \mu\text{J}/\text{cm}^2$, n' of GaAs changes and the defect modes of the point defects disappear. Thus the input THz wave cannot resonate in the cavity and the modulator is in the “off” state. However, if the pump light is absent, the THz wave will resonate in the cavity and the modulator is in the “on” state.

In Fig. 4 the width of the upper square point defect is $w_1 = 2.49 w$ and the rotation angle of the upper point defect is 15° , while the width of the lower square point defect is $w_1 = 2.49 w$ and its rotation angle is 35° . The upper and lower line defects used to transmit the beams of the THz wave correspond to the upper and lower point defects respectively. The larger red, circular dielectric cylinder

FIG. 5. The transmission spectrum of the photonic-crystal modulator.

in Fig. 4 is the result of fine tuning used to increase the transmittance of the defect modes of the square point defects.

Figure 5 displays the simulation results for the transmission spectrum. Six beams of the THz wave propagate through the modulator when the modulator is in “on” state, as shown. Each square point defect can modulate three beams of the THz wave. The wavelengths of the three defect modes produced by the upper square point (blue line) are $197.86 \mu\text{m}$, $205.64 \mu\text{m}$, $222.91 \mu\text{m}$ respectively. The wavelengths of the three defect modes produced by the lower square point (green line) are $191.67 \mu\text{m}$, $200.92 \mu\text{m}$, $216.82 \mu\text{m}$ respectively. The sum of the numbers of defect modes produced by upper and lower square points is six.

3.2. Performance Analysis

For the case of the six beams of the THz wave being incident simultaneously, the extinction ratio and insertion loss of the modulator are analyzed in detail below. From Fig. 5, the six incident wavelengths are set as $191.67 \mu\text{m}$, $197.86 \mu\text{m}$, $200.92 \mu\text{m}$, $205.64 \mu\text{m}$, $216.82 \mu\text{m}$, and $222.91 \mu\text{m}$ respectively. All of the incident THz waves are Gaussian and continuous.

The extinction ratio is an important index to evaluate the capacity of modulation. The time-domain steady-state response is shown in Fig. 6. As registered by the upper detector in Fig. 4, Figs. 6(a) and 6(b) show the “on” and “off” states of the modulator respectively. As registered by the lower detector in Fig. 4, Figs. 6(c) and 6(d) show the “on” and “off” states of the modulator respectively.

The definition of extinction ratio is

$$\eta = 10 \log (I_{\max} / I_{\min}) \quad (1)$$

where $I_{\max}$ is the maximum transmission intensity of the

FIG. 6. Time-domain steady-state response of (a) “on” state and (b) “off” state as registered by the upper detector, and of (c) “on” state and (d) “off” state as registered by the lower detector.

THz wave after modulation, I_{min} is the minimum transmission intensity of the THz wave after modulation, and η is the extinction ratio of the modulator. The value of I_{max} is the sum of the values in Figs. 6(a) and 6(c), while the value of I_{min} is the sum of the values in Figs. 6(b) and 6(d) respectively. From Fig. 6 we can obtain the value of I_{max} as 5.8 and the value of I_{min} as 2.179×10^{-3} . From Eq (1), we obtain an extinction ratio of 34.25 dB.

The definition of insertion loss is

$$\gamma = 10 \log (I_{in}/I_{max}) \quad (2)$$

where I_{in} is the intensity of the incident THz wave and I_{max} is the maximum transmission intensity of the THz wave after modulation. The value of I_{in} is 6, and from Eq (2) we obtain an insertion loss of 0.147 dB.

The definition of the modulation rate is

$$\nu = 1/T \quad (3)$$

$$T = T_1 + T_2 \quad (4)$$

where T is the response time of the system and ν is the modulation rate. T is determined by the sum of the response time of $GaAs$ material's change in refractive index (T_1) and the stability time of the “on” or “off” state of the modulator (T_2). Here T_1 is 100 ps [15] and T_2 3.2499×10^{-10} s from Fig. 6. The modulation rate is 2.35 GHz, as obtained from Eqs. (3) and (4).

The steady-state THz wave field intensity distributions of in “on” ($n'=0$) and “off” states ($n'=2.55$) are shown in Figs. 7(a) and 7(b) respectively.

Figure 7 shows that the six beams of the THz wave

FIG. 7. Steady-state THz wave field intensity distribution of E_y : (a) in the “on” state ($n'=0$), (b) in the “off” state ($n'=2.55$).

were modulated effectively by the multi-wavelength photonic-crystal THz modulator with a large extinction ratio.

The simulation results show that this novel multi wavelength photonic-crystal THz modulator can effectively modulate a THz wave, with large extinction ratio and low insertion loss.

IV. CONCLUSION

A novel multi wavelength THz modulator based on a triple-triangle-lattice-structure photonic crystal is proposed. By changing the GaAs refractive index, the modulation of six wavelengths ($191.67\ \mu\text{m}$, $197.86\ \mu\text{m}$, $200.92\ \mu\text{m}$, $205.64\ \mu\text{m}$, $216.82\ \mu\text{m}$, and $222.91\ \mu\text{m}$) can be realized. The extinction ratio is as large as $34.25\ \text{dB}$, the insertion loss as low as $0.147\ \text{dB}$, and the modulation rate $2.35\ \text{GHz}$. This modulator presents a theoretical foundation for research in communications devices for the THz range, and can also meet the requirements of future THz wave communications systems better.

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