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A terahertz isolator based on a silicon heterojunction photonic crystal

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ABSTRACT

A terahertz isolator based on a heterojunction silicon photonic crystal is analyzed numerically by the three dimensional finite difference time domain method (3D-FDTD), which can be operated at room temperature and without external magnetic field. Simulation results show that the maximum isolation is related to the hole radii of two photonic crystals. A maximum isolation of 25 dB can be obtained when the hole radius ratio is optimum ($R1/R2 = 0.49$ at 0.52 THz).

1. Introduction

Isolator is fundamental in the THz signal processing, which provides critical functionalities such as isolation and circulation in the THz system. Because the nonreciprocal materials responding at THz frequencies are very rare, the nonreciprocal THz transmission mechanism is still unclear. Until recently, some preliminary works have been reported. In 2001, Fei Fan et al. proposed a magnetically tunable terahertz isolator based on structured semiconductor magneto plasmonics [1], which has a bandwidth of 80 GHz with the maximum isolation of higher than 90 dB and a low insertion loss of 5% and its central operating frequency can be broadly tuned from 0.9 to 1.4 THz. But this isolator is not practical because of it needs an external magnetic field of about 1 Tesla and a very low temperature of 195 K. In 2012, B. Hu et al. proposed a broadly tunable terahertz isolator based on nonreciprocal surface magneto plasmons [2], which its central operating frequency can be broadly tuned from 0.36 to 1.5 THz. But this isolator needs an external magnetic field of about 0.5–5 Tesla and its power tolerance is very low. In 2013, Mostafa Shalaby et al. proposed a broadband magnetic isolator extending over a frequency decade by using $SrFe_{12}O_{19}$ material [3]. But this isolator needs an external magnetic field of about 0.54 Tesla.

A linear, time-independent and passive THz isolator based on a silicon heterojunction photonic crystal (PC) is proposed as shown in Fig. 1, which can be operated at room temperature and without external magnetic field. It consists of two photonic crystals with same lattice constants $\boldsymbol{a}$ and different hole radii ($R1$ and $R2$) on an intrinsic silicon chip. The field intensity distribution diagram of a doubled-isolator is shown in Fig. 2, which THz wave forward transmits in the front isolator and backward transmits in the latter isolator. THz wave is normally refracted in the forward transmission and negatively refracted in the backward transmission on the interface of two photonic crystals. That is, the input in-plane THz wave from port A would propagate and one from port B would be isolated. In this paper, the forward/backward transmissivity and isolation changes induced by the geometrical parameters are studied by using 3D-FDTD.

2. Theoretical analysis

The negative refraction of backward transmission is induced by the special dispersion of photonic crystals, which the effective refractive index is more than zero and it is called right-hand negative refraction [4]. This kind of negative refraction is very sensitive to such as interface and direction of crystal lattice and it needs coupled Bloch modes of the incident wave/PC and two PCs [5,6].

In the backward transmission case, the wave vector ratio of two PCs satisfies $\sqrt{3}/2 < \left|k_A/k_B\right| < 1$ if the interface angle of two PCs is optimum, in which the suffix $\boldsymbol{A}$ corresponds to PC1 with small holes and suffix $\boldsymbol{B}$ corresponds to PC2 with large holes. It meets Bloch mode coupled conditions, so the incident THz wave is negatively refracted. But in the forward transmission case, the wave vector ratio of two PCs $\left|k_B/k_A\right| > 1$, so it doesn't meet Bloch mode coupled conditions and the incident THz wave is normally refracted.

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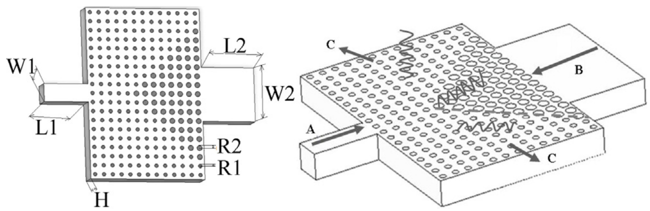

Fig. 1. Notation used for describing on-chip silicon heterojunction structure.

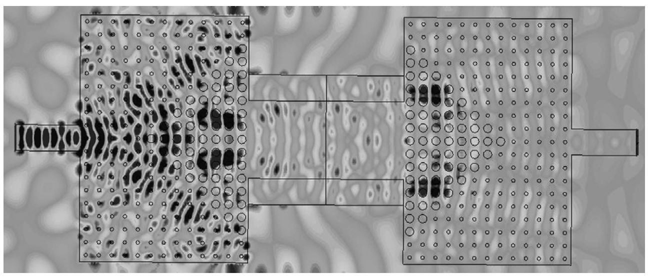

Fig. 2. Field intensity distribution diagram of a doubled-isolator structure.

3. Numerical simulation and analysis

In order to understand changes of isolation characteristics induced by the geometrical parameters, the THz wave propagation through a terahertz isolator with different hole diameters is studied numerically by 3D-FDTD, which the crystal lattice period $\boldsymbol{a} = 150\,\mu$m, input port length L1 = 750 μm (5$\boldsymbol{a}$) and width W1 = 300 μm (2$\boldsymbol{a}$), output port length L1 = 750 μm (5$\boldsymbol{a}$) and width W1 = 900 μm (6$\boldsymbol{a}$), thickness H = 75 μm (0.5$\boldsymbol{a}$).

Forward/backward transmissivity and isolation curves of isolator are shown in Fig. 3, where $R1 = 25$ um, $R2 = 51$ um. A double-peak structure of forward transmissivity is induced by the overlap of pass bands of two photonic crystals. The backward THz wave is scattered by the special structure of isolator and the backward transmissivity is very low. So a maximum isolation of 25 dB can be obtained in 0.52 THz.

Transmission spectrum and maximum forward transmissivity as a function of $R1$ are shown in Fig. 4, where $R2 = 51\,\mu$m. The two peaks of forward transmissivity are closed when the difference of hole radii ($R2$–$R1$) decreases. And the maximum forward transmission decrease little first and then increases near linearly with the increase of $R1$.

Backward transmission spectrum and minimum backward transmissivity as a function of $R1$ are shown in Fig. 5, where $R2 = 51$ um. The backward transmissivity is evidently lower than the forward transmissivity because of the scattering effect induced by the negative refraction. And the minimum backward transmission fluctuates at low level first and then increases fast (when $(R1/a) > 0.2$) with the increase of $R1$.

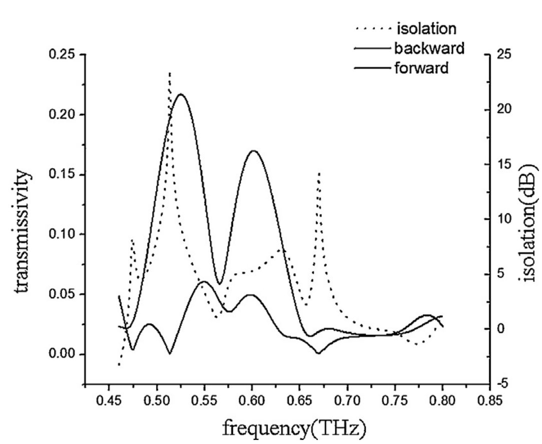

Fig. 3. Forward/backward transmissivity and isolation curves of isolator.

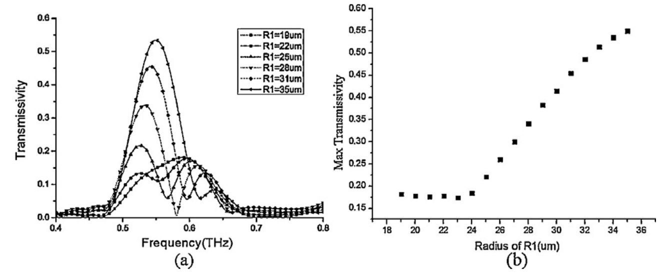

Fig. 4. (a) Transmission spectrum and (b) maximum forward transmissivity as a function of R1.

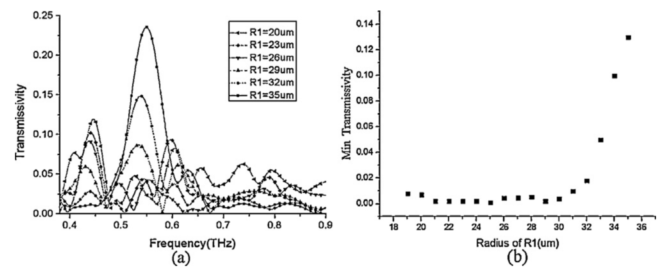

Fig. 5. (a) Backward transmission spectrum and (b) minimum backward transmissivity as a function of R1.

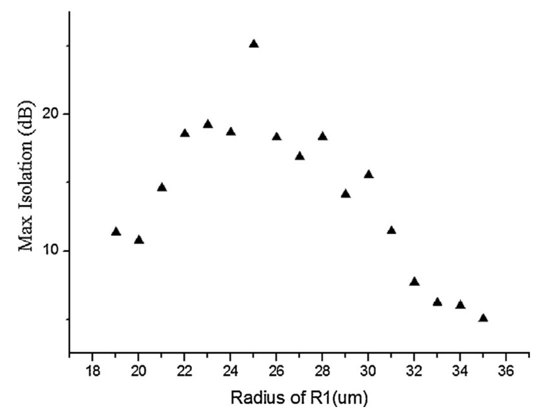

Fig. 6. Maximum isolation as a function of R1.

Maximum isolation as a function of $R1$ is shown in Fig. 6, where $R2 = 51$ um. The maximum isolation increases firstly and then decreases with the increase of $R1$, where a maximum isolation of 25 dB can be obtained in 0.52 THz.

4. Conclusion

A THz isolator based on a heterojunction silicon photonic crystal is analyzed and optimized by 3D-FDTD, which can be operated at room temperature and without external magnetic field. Simulation results show that the maximum isolation is related to the hole radii of two photonic crystals. A maximum isolation of 25 dB can be obtained when the hole radius ratio is optimum ($R1/R2 = 0.49$ at 0.52 THz).

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