Optimization of Photonic Crystal Interfaces for High Efficiency Coupling of Terahertz Waves

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***Abstract*—We present an efficient method to couple terahertz waves from a dielectric medium into a two-dimensional photonic crystal. The design parameters of the photonic crystal interface to minimize reflection can be optimized using the conventional antireflection coating theory and the finite-difference time-domain simulations. We investigate the transmission spectra of a terahertz photonic crystal with and without the optimization of the crystal interface. It is shown that the transmission of the specific terahertz wave of interest can be significantly improved through the optimization of the photonic crystal interface.**

I. Introduction

SINCE the discovery of the interesting anomalous light propagation in photonic crystals (PCs), a number of efforts have been devoted to realize the dispersion based optical devices such as non-channel waveguides , beam splitters , super lenses, demultiplexers, and so on. As these PC devices utilize the lights which are allowed to propagate inside PCs, the minimization of the unwanted reflection at the interface between a two-dimensional (2D) PC and an outside dielectric has been considered an important issue and still remained as a crucial problem to be solved for practical applications [1, 2].

Terahertz (THz) technology now has been a very attractive research field due to its wide potential applications such as security screening, medical image, high-speed communication and biological sensing [3-5]. Recently, it has been shown that the unique dispersive properties of PCs can be used to manipulate the propagation of the THz waves [6].

In this paper, we propose an efficient method to minimize the unwanted reflection at the 2D PC interfaces. As a part of efforts to realize the dispersion based THz PC devices, we apply the PC interface optimization to the THz PC, and show that the transmission of the specific THz wave of interest can be remarkably improved through the finite-difference time-domain (FDTD) simulations and the THz time domain spectroscopy.

II. Model and Method

When a light beam is normally incident from region 1 onto region 2which is placed between two semi-infinite homogenous media (region 1 and 3) as shown in Fig. 1, the reflectance of the incident light becomes zero when the following two conditions are satisfied simultaneously:

$$\left|r_{12}\right| = \left|r_{23}\right| \ , \tag{1}$$

and

$$e^{i(2\beta+\delta_{23}-\delta_{12})} = -1 \, , \tag{2}$$

where $\left|r_{ij}\right|$ and δ_{ij} correspond to the amplitude and the phase factor of the reflection coefficient of light propagating from region i to j, respectively. In this simple case, the optimal antireflection parameters, the refractive index $n_2 = \sqrt{n_1 n_3}$ and the optical thickness $h = \lambda / 4$, are easily obtained from Eqs. (1) and (2) by using the reflection coefficients given by the Fresnel equations. In our previous study, it was theoretically shown that reflection at the interfaces between a 2D PC and a homogeneous background material can be effectively eliminated by optimizing the parameters such as the radius R_{arc} of the hole and distance d_{arc} between the antireflection structure and PC truncation (see Fig. 1(b)) [2]. In this work, we introduce new antireflection parameters, H1 and H2 of Fig. 1(c), to minimize the reflection at the interfaces between a 2D hole-type PC and a outside dielectric. These design parameters can be optimized by the FDTD simulations as described in Ref. [2], provided that r_{ij} are properly modified. In this analysis, r_{23} is the reflection coefficient of the semi-infinite PC when the light is incident upon it from silicon, and r_{12} is that of the interface between silicon and air when the light propagates from air to the silicon, as shown in Fig. 1 (d). Note that, the reflection coefficient r_{12} is a function of the design parameter H1.

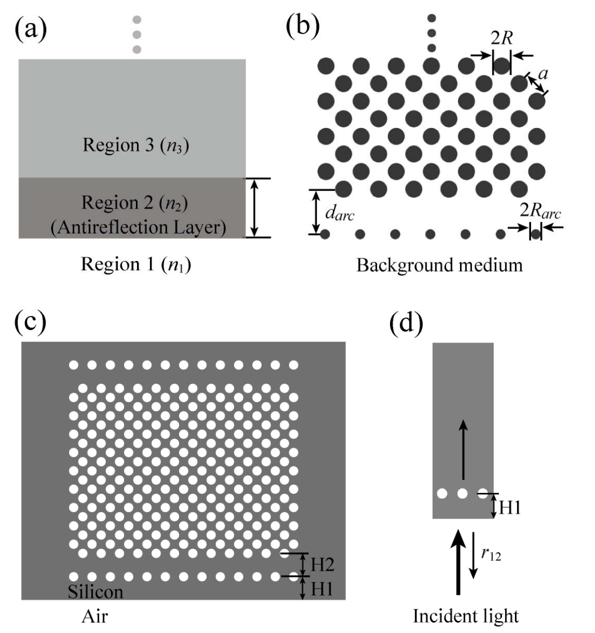

Fig. 1. (a) In the conventional 1D case, the antireflection parameters are the refractive index n_2 and the thickness h of an antireflection layer. (b) In Ref. [2], the antireflection parameters are the radius of rods or holes R_{arc} and the distance d_{arc} between the antireflection structure and the crystal truncation. (c) In this study, antireflection parameters are distance H1 and H2. (d) The reflection coefficient r_{12} is a function of H1.

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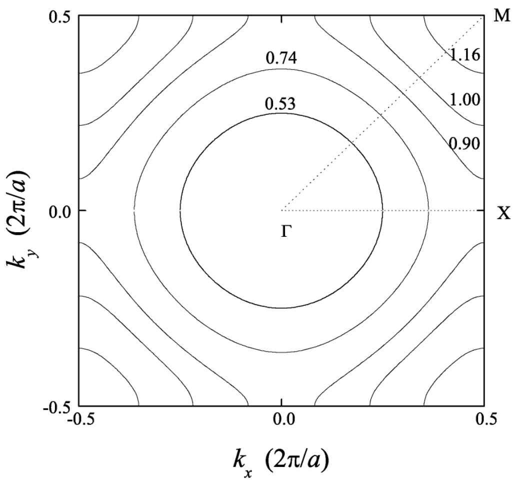

Fig. 2. Several EFCs of the first band of a THz PC. Frequencies are represented in unit of THz.

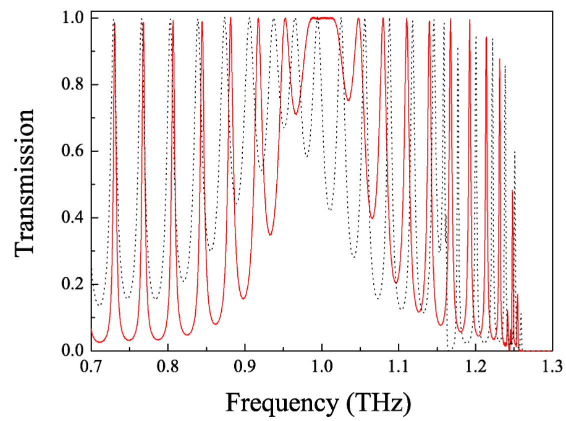

Fig. 2. Transmission spectra of the PC sample. Red solid and black dotted lines represent the transmission through the PC with and without the interface optimization, respectively.

III. RESULTS

To see the effects of the interface optimization on the reflection of light beam, we consider a 2D square lattice PC which consists of air holes with the lattice constant a = 57 ㎛ and hole radius r = 0.35a in silicon. In recent years, the self-collimated light propagation in 2D PCs have inspired great interests due to its potential applications in implementing on-chip photonic integrated circuits. However, to our knowledge, there has been no study on the self-collimated propagation of the THz wave. Hence, we will mainly focus our attention on the reflection minimization of self-collimated beams at the 2D THz PC interfaces.

To find the frequency range in which the self-collimation phenomenon occurs, we calculated the equifrequency contours (EFCs) by employing the plane wave expansion method and found that the self-collimation phenomenon occurs when H-polarized lights, which have the magnetic field parallel to the hole axis, of frequencies around f = 1 THz propagate along the (11) direction of square lattice (ΓM direction). Fig. 2 shows the several EFCs of the first band. In the calculation, we used the refractive index of silicon n = 3.418 [7].

We first calculated $|r_{23}|$, and then $|r_{12}|$ as a function of H1 for the light of frequency f = 1 THz by using the FDTD simulations. It is found that $|r_{12}|$ = $|r_{23}|$ = 2.844 at H1 = 57.74 ㎛. In order to find the optimal value of H2, the total reflectance is calculated as a function of H2 when H1 = 57.74 ㎛ and found that the reflectance becomes zero when H2 = 70.11 ㎛. Next, the transmission spectra of the finite size THz PC are calculated with and without the optimization of the interface and the results are shown in Fig. 2. The FDTD simulations are performed for the PC sample of size $17\sqrt{2}$ in the ΓM direction, the propagation direction of the incident THz waves, and both the input and output interfaces are optimized. The calculated transmission spectra of the THz PC clearly demonstrate that the optimization of the PC interface effectively remove the unwanted interface reflection for the THz waves of frequency around f = 1THz.

We also applied the interface optimization to the propagation of the THz wave of frequency f = 1.16 THz and found that most of the incident power is transmitted through the PC sample for the lights of frequencies around f = 1.16 THz.

IV. CONCLUSION

In conclusion, we introduce new antireflection parameters to minimize the reflection at the interfaces between a 2D hole-type PC and air. It is theoretically shown that the transmission of the specific THz wave of interest can be significantly improved through the optimization of the photonic crystal interface. Experimental results obtained from the THz time domain spectroscopy will be also presented.

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