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Polarization conversion by a three-dimensional photonic crystal mirror with a diamond structure

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Abstract

We report experimental and numerical studies of a polarization conversion by a three-dimensional photonic crystal. The (0 0 1) surface of a photonic crystal with a diamond structure has been shown to act as a mirror-type polarization convertor under normal incidence. When the direction of the incident wave polarization is along [0 1 0], the direction of the reflected wave polarization is converted to [1 0 0]. This has been found to be due to approximately a half-wave phase shift between the eigenpolarizations of [1 1 0] and [1 $\bar{1}$ 0] upon reflection. This result has been discussed in relation with a polarization-dependent Goos–Haenchen effect.

Keywords: Photonic crystal; Three-dimensional photonic crystal; Polarization conversion; Goos–Haenchen effect; FDTD calculations

1. Introduction

When a light beam is subjected to total internal reflection at a dielectric–air interface, the beam suffers a lateral shift, which is known as the Goos–Haenchen (GH) effect [1]. This takes place also for external total reflection upon a photonic crystal with a photonic band-gap (PBG) [2]. The GH effect can be physically interpreted as follows. Upon total reflection, evanescent waves are generated in the photonic crystal in the vicinity of the interface. Then, it can be assumed that the reflection plane is effectively shifted from the actual interface toward the inside of the photonic crystal, resulting in a lateral beam shift. Recently, the GH effect in photonic crystals has attracted much attention [3–7]. Felbacq and Smaali [3] have discussed the influence of the GH effect on the direction of waves in propagating modes. Large negative GH shifts have been shown to occur in photonic crystals with a negative refractive index by He et al. [4]. Enhancements of GH effect for one-dimensional photonic crystals containing a defect layer have been discussed by Wang and Zhu [5], and by Hou et al. [6]. Garcia-Pomar et al. [7] have analyzed a GH effect in self-waveguiding photonic crystals.

In this paper, we demonstrate that the (0 0 1) surface of a three-dimensional photonic crystal with a diamond structure acts as a mirror-type polarization convertor under normal incidence. We show that the polarization conversion originates in a polarization-dependent positional shift of the effective reflection plane. Therefore, this phenomenon is closely related with a polarization-dependent GH effect, although no lateral beam shift is relevant because of normal incidence.

2. Methods

The photonic crystal structure that we studied consists of dielectric rods connecting the tetrahedral

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bonds in the crystalline diamond structure [8,9]. This structure is known to be best three-dimensional (3D) photonic band-gap (PBG) structure; it exhibits the largest PBG among all the 3D photonic crystals studied thus far [10,11]. This structure was fabricated in a microwave regime, which is shown in Fig. 1, according to the method described in a previous paper [9]. The refractive index n and the extinction coefficient κ of the rods were approximately 3.0 and 0.03, respectively for 30-GHz microwaves (λ = 10 mm in air). κ is so small that we can neglect absorption of microwaves. The volume fraction of the rod in the constructed structure is 22% and the rest is air. Then, the volume-weighted average $\bar{n}$ of refractive index is approximately 1.4. Each rod is $d \approx 3$ mm in length and $r \approx 0.78$ mm ($0.26d$) in radius. The size of the fabricated structure is approximately $x \times y \times z = 70\ \text{mm} \times 70\ \text{mm} \times 35\ \text{mm}$ ($23.3 \times 23.3 \times 11.7d^3$), where the crystalline axes of [1 0 0], [0 1 0] and [0 0 1] are along x, y and z directions, respectively, as shown in Fig. 1.

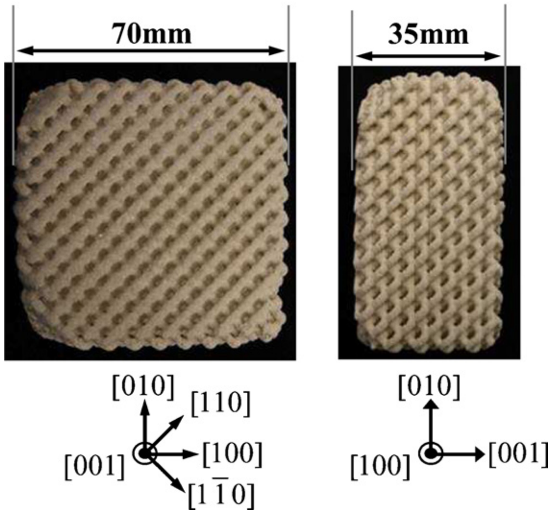

Fig. 1. Fabricated photonic crystal with a diamond structure.

Microwave reflection and transmission measurements were done by a free-space method using a vector network analyzer (HP Model 8722D, Agilent Technologies) in the frequency range 20–30 GHz. For reflection measurements, we cannot realize completely the normal incidence-reflection condition in our experimental setting; the directions of incidence and reflection were deviated from the normal axis by about 20° toward $\pm x$ direction. Linearly polarized microwaves were incident on the (0 0 1) surface, where the polarization direction was along the [0 1 0] axis. The intensity of the transmitted microwaves of parallel-polarized component and those of the reflected microwaves of parallel- and cross-polarized components were measured.

The reflection and transmission spectra were simulated by finite difference time domain (FDTD) calculations in the configuration shown in Fig. 2(a). The size of the rectangular parallelepiped cell was $x \times y \times z = a \times a \times 5a$ (a: the lattice constant of the photonic crystal; $a = 4d/\sqrt{3} \approx 6.9$ mm). The crystalline axes of [1 0 0], [0 1 0] and [0 0 1] are along x, y and z directions, respectively. The periodic boundary (P.B.) condition was applied in the x and y directions, and at

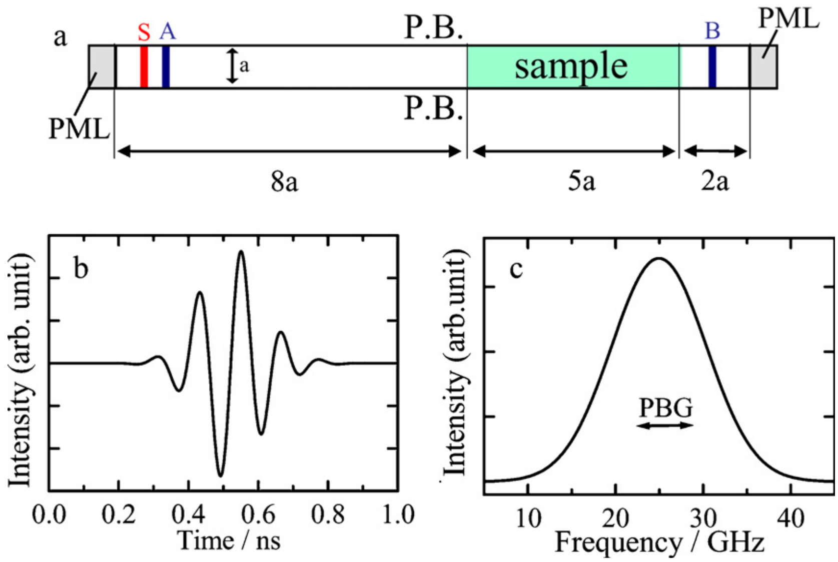

Fig. 2. Configuration for FDTD calculations of reflection and transmission spectra (a), and time-domain (b) and frequency-domain (c) spectra of the Gaussian pulse of the incident waves. The frequency range of the photonic band gap (PBG) deduced by a plane-wave expansion method is indicated in (c).