Defect Modes in 3D Photonic Crystal for Microwave Applications

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3D photonic crystals with a diamond structure, which are composed of the SiO₂ coated TiO₂ ceramic particles dispersed in an epoxy lattice, were fabricated by stereolithography. The diamond structure showed a photonic band gap in the 14.0–17.0 GHz range along Τ–X ⟨100⟩ direction. Lattice defects named ‘air cavity’ were introduced into the diamond structure by removing a unit cell of diamond structure. Two types of air cavity, which were differed in the volume fraction, were also fabricated by stereolithography. The transmission of millimeter waves affected by multiple reflections at the air cavity was measured in the photonic band gap. When the volume fraction of the air cavity became larger, the resonant mode was shifted to the lower frequency range.

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1. Introduction

Three-dimensional photonic crystals have a periodic structure of dielectric medium, which forms the photonic band gap and reflects lights or electromagnetic waves with the wave length similar to the periodicity. When the periodicity corresponds to the wavelength of light, such crystals have potential in various applications including zero-threshold semiconductor lasers, light waveguides, and photonic integrated circuits. In the case of millimeter waves or microwaves, applications include various cavities, barriers and directional antennas. It is important, however, to develop the architecture of photonic crystals so that the design, construction and modification of the periodic structure matches each application.

However, it is necessary for real applications to develop the modification engineering of perfect photonic crystals such as introducing point, line and plane defects which can act as microcavities, wave guides, filters, respectively. These lattice defects can introduce resonant or localized modes in the band gap like impurity levels in semiconductors. The relation between the lattice defects and the defect modes in the diamond structure has not been analyzed yet.

In this study, the defects modes named “air cavity” were introduced into the diamond structure by using a CAD/CAM stereolithography system and characterized with respect to the resonant modes.

2. Experimental methods

The diamond structure was designed on a computer using a CAD program (Toyota Caelum Co. Ltd, Japan, thinkdesign ver. 5.0). Figure 1 shows a schematic illustration of the defect sample. The unit cell of the diamond structure is composed of dielectric rods of ϕ 4.33 × 6.50 mm in dimension. The unit cell dimension is 15 mm. The sample size of the diamond structure is 75 × 75 × 75 mm³, which is composed of 125 unit cells. The volume fraction of the dielectric lattice medium is 34%. The lattice defects were also modeled on a CAD program as shown in Fig. 1. The designed structure was converted into a rapid prototyping format (STL file), sliced into a set of thin sections, and transferred to a stereolithographic machine (D-MEC Co. Ltd, Japan, SCS-300P). This machine forms a three-dimensional object layer-by-layer by scanning a UV laser of 355 nm in wavelength over a liquid photopolymer epoxy resin. The thickness of each layer was 100 μm. The dimensional accuracy of the structure was within 0.15%. SiO₂ coated TiO₂ ceramic particles with a particle size of about 10 μm were dispersed into the epoxy resin in order to increase the dielectric constant of the lattice. The ceramic particles are composed of 48.8 wt.% of crystalline TiO₂ and 51.2 wt.% amorphous SiO₂. The amount of the ceramic powders contained in the epoxy resin is 10 vol.%. The dielectric constant of the bulk sample which contains the ceramic powder is measured to be 4 by using a dielectric probe kit (Agilent Technologies, Tokyo, Japan, HP–8570B).

The transmission amplitude of electromagnetic waves through the photonic crystal samples was measured in the frequency range of 3–20 GHz. The experimental setup is
shown in Fig. 2. A network analyzer (Agilent Technologies, Tokyo, Japan, HP8720D) is connected to two separate microwave horn antennas (Japan High frequency Co. Ltd., Kanagawa, Japan, WAN-101-20). These antennas act as a transmitter and a receiver of microwave. An electromagnetic wave with TE mode was transmitted from a transmitter antenna. The scale of the transmission is calibrated by the transmission through the air without sample. The interior of the measurement box and the sample side were covered with microwave absorbers to reduce background scattering of electromagnetic waves.

3. Results and discussion

Figure 3 shows photographs of a diamond structure sample (a) in which an air cavity is introduced at the center (b). The defect shape, size, position and number can be easily controlled by using CAD and stereolithography. The shape of the air cavity is a cubic form of $15 \times 15 \times 15$ mm$^3$ in size. Figure 4 shows the cross section of the fabricated lattice. TiO$_2$-based ceramic particles were dispersed uniformly in the lattice.

Figure 5(a) shows attenuations of transmission amplitude with TE mode through a cavity-free diamond structure along $\Gamma$-$X$ $\langle 100 \rangle$ direction as a function of frequency. The transmission amplitude is decreased between 14.0 GHz and 17.0 GHz frequency range, which implies the existence of photonic band gap. An oscillation curve at 10.0–14.0 GHz and 14.0–14.6 GHz frequency range is due to multiple reflections between the incident and exit surfaces of the sample of microwaves and background scattering of electromagnetic waves. Figure 5(b) shows plotted measured upper and lower band edges of the photonic band gap at $\Gamma$-$L$ $\langle 111 \rangle$, $\Gamma$-$X$ $\langle 100 \rangle$, and $\Gamma$-$K$ $\langle 110 \rangle$ directions. The complete photonic band gap, in which no electromagnetic wave can exist against all directions, is formed in the frequency range between 14.3 GHz and 15.8 GHz.

Figure 6 shows the transmission properties of propagation through the air cavity along the $\Gamma$-$K$ $\langle 110 \rangle$ direction. The resonant modes are observed at 15.2 and 16.2 GHz. The peak at 14.8 GHz is attributed to the background scattering of microwaves rather than the defect modes, since such a peak disappears when the attenuation curve of the diamond structure with an air cavity in Fig. 6 is normalized by the curve of the diamond structure as shown in the inset. When the transmitted direction through the air cavity was changed to $\Gamma$-$X$ $\langle 100 \rangle$, no resonant mode was observed. The cross section of the air cavity for $\langle 100 \rangle$ direction [$15 \times 15$ mm$^2$] is smaller than that for $\langle 110 \rangle$ [$15 \times 21.2$ mm$^2$]. The resonant modes at the frequency of 15.2 GHz and 16.2 GHz have the wavelengths of 19.7 mm, and 18.5 mm, respectively. Each wavelength is longer than the side lengths of the cavity against $\langle 100 \rangle$ direction. Therefore, the electromagnetic wave propagating along $\Gamma$-$X$ $\langle 100 \rangle$ direction cannot resonate inside the air cavity.

We tried to modify the volume of the air cavity in the diamond structure. Figure 7 shows a CAD image of the diamond sample contained larger air cavity defect. The air cavity was designed by extracting three unit cells aligned with a
Fig. 5. (a) Attenuation of transmission amplitude with TE mode through the photonic crystal with a photonic band gap along the \(\Gamma\)-X \(\langle100\rangle\) direction as a function of frequency. (b) Upper and lower band edges of the photonic band gap along \(\Gamma\)-L \(\langle111\rangle\), \(\Gamma\)-X \(\langle100\rangle\), and \(\Gamma\)-K \(\langle110\rangle\) directions.

Fig. 6. Attenuation of the transmission amplitude through the photonic crystal with a diamond structure, including an air cavity at the center along the \(\Gamma\)-K \(\langle110\rangle\) direction as a function of frequency. A spectrum of the localized modes after normalizing with the spectrum of the cavity-free diamond structure is shown in the inset.

Fig. 7. CAD images of the diamond structure containing an air cavity defect along the Y direction. The microwave was transmitted along the Z direction.

Fig. 8. Frequency dependence of the transmission amplitude through the diamond structure with an air cavity positioned along the Y direction. Spectra of the resonant mode after normalizing with that of the cavity-free diamond structure is shown in the inset.

We have fabricated photonic crystals with a diamond structure by stereolithography, which are composed of TiO2-based ceramic particles dispersed in an epoxy lattice. The diamond structure showed the complete photonic band gap at the 14.3–15.8 GHz frequency region. The cube defect of an air cavity was introduced inside the diamond structure. Insertion of the cube defect produced two resonant modes at 15.2 and 16.2 GHz. A larger air cavity, which has a rectangular shape, was also inserted into the diamond structure. The resonant mode was observed at 15.8 GHz. The resonant mode was shifted to the lower frequency range by increasing the air cavity size.

4. Conclusions

rectangular shape of \(15 \times 45 \times 15 \text{ mm}^3\) in size at the center of the crystal sample. The direction of the air cavity is set to Y direction. The microwave was transmitted along Z direction.

**Figure 8** shows the frequency dependence of the transmission amplitude through the diamond structure samples in which the rectangular air cavity is formed as a defect. A resonant mode was observed at 15.8 GHz with a peak transmission amplitude of 27%. In comparison with the resonant mode (16.2 GHz) in Fig. 6, the frequency was shifted to the lower frequency range from 16.2 GHz to 15.8 GHz. An electromagnetic wave which has longer wavelength needs a larger air cavity to resonate inside the air cavity. The size of the air cavity in Fig. 8 is three times larger than that of Fig. 6, and electromagnetic wave with a longer wavelength can resonate inside the air cavity. Therefore, the resonant mode was shifted to the lower frequency range.

References

1) Joannopoulos, J. D., Meade, R. D. and Winn, J. N., *Photic