Electromagnetic wave control of ceramic/resin photonic crystals with diamond structure

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Abstract

Millimeter-order photonic crystals with the periodic arrangement of the dielectric constant were fabricated by infiltrating the mixed slurry of ceramics and polyester into the epoxy molds with an inverse form of a diamond structure. The epoxy molds are designed and processed by using a CAD/CAM process of stereolithography. The photonic crystals were prepared to have the diamond structure of the ceramic/polyester composite lattice, which is embedded in the epoxy matrix. The ceramic powders mixed with polyester are TiO\textsubscript{2}, SrTiO\textsubscript{3}, and BaTiO\textsubscript{3} with high dielectric constant. It is possible to control more freely and widely the dielectric constant of the photonic crystals by this method. These ceramic/resin photonic crystals formed the complete photonic band gaps in the microwave band of 7–11 GHz, which can totally reflect the electromagnetic wave for all crystal directions. Attenuation profiles of the transmission amplitude in the band gaps were controlled with the dielectric constant of the composite lattice. The obtained results fairly agreed with the theoretical simulation of the electromagnetic wave propagation through photonic crystals.

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1. Introduction

Photonic crystals composed of the dielectric materials with periodic arrangements can totally reflect electromagnetic wave whose wavelength is similar to the periodicity by three-dimensional wave diffraction and forms photonic band gap\cite{1-6}. The band gap is controlled by changing the dielectric constant and the volume fraction of the dielectric materials. Structural defects introduced into the photonic crystal forms the localized mode to permit the wave transmission in the photonic band gap\cite{7-9}.

We have successfully fabricated the millimeter order epoxy lattice dispersed with titania-based ceramic particles by using a stereolithography of rapid prototyping method\cite{10-12}. Three-dimensional diamond structure was processed exactly and the perfect photonic band gap formed in the microwave frequency range. The crystal structures with the graded lattice spacing for directional control of the electromagnetic wave emission were also fabricated\cite{13,14}.

Recently, the diamond photonic crystals consisting of the mixed media of BaTiO\textsubscript{3} particles with high dielectric constant and polyester resin were formed in an epoxy matrix. The BaTiO\textsubscript{3} dispersed polyester slurry was infiltrated into the epoxy mold with the inverse structure of the diamond which was fabricated by stereolithography. By controlling the BaTiO\textsubscript{3} content to increase the dielectric constant of the lattice, the wider photonic band gaps were formed in the range of 7–11 GHz.

In the present study, the TiO\textsubscript{2}, SrTiO\textsubscript{3} and BaTiO\textsubscript{3} particles dispersed polyester lattices with the diamond structure were formed in the epoxy matrix. The variations of the photonic band gap profiles were investigated by controlling the dielectric constant of the lattice. Comparing with the simulation of a plane wave expansion method, the engineered method of the photonic band gap control will be discussed based on the diffraction theory of the electromagnetic wave.
2. Relation of electromagnetic wave and photonic band gap

A unit cell of the photonic crystal drawn by a computer graphics is shown in Fig. 1. The dielectric rods are connected three-dimensionally forming the diamond structure. The lattice constant is indicated as \( a \). The dielectric constants and the volume fractions of the lattice and the matrix media are denoted as \( \varepsilon_a \) and \( \varepsilon_b \), \( v_a \) and \( v_b \), respectively.

The electromagnetic properties of the diamond photonic crystal can be simulated theoretically. The Maxwell’s Eqs. (1) and (2) were solved by means of the plane wave expansion method, where \( \omega \) and \( c \) denote frequency and light velocity, respectively [12].

\[
\nabla \times \left( \frac{1}{\varepsilon(r)} \nabla \times \right) \mathbf{H}_\omega(r) = \left( \frac{\omega}{c} \right)^2 \mathbf{H}_\omega(r) \tag{1}
\]

\[
\frac{1}{\varepsilon(r)} \nabla \times \nabla \times \mathbf{E}_\omega(r) = \left( \frac{\omega}{c} \right)^2 \mathbf{E}_\omega(r) \tag{2}
\]

Electric and magnetic field \( \mathbf{E}_\omega(r) \) and \( \mathbf{H}_\omega(r) \) were substituted by the following plane wave vibrations. The periodic arrangement of dielectric constant \( \varepsilon(r) \) was obtained automatically from CAD data, where \( \mathbf{G} \) and \( \mathbf{k} \) are reciprocal vector and wave vector, respectively.

\[
\mathbf{H}_{k,n}(r) = \sum_{\mathbf{G}} \mathbf{H}_{k,n}(\mathbf{G}) e^{i(\mathbf{k}+\mathbf{G}) \cdot r} \tag{3}
\]

\[
\mathbf{E}_{k,n}(r) = \sum_{\mathbf{G}} \mathbf{E}_{k,n}(\mathbf{G}) e^{i(\mathbf{k}+\mathbf{G}) \cdot r} \tag{4}
\]

\[
\frac{1}{\varepsilon(r)} = \sum_{\mathbf{G}} \frac{1}{\varepsilon(\mathbf{G})} e^{i\mathbf{G} \cdot r} \tag{5}
\]

An electromagnetic band diagram of the diamond structure was drawn theoretically as shown in Fig. 2. The dielectric constants ratio and volume fraction of the matrix and lattice, \( \varepsilon_a \) : \( \varepsilon_b \) and \( v_a \) : \( v_b \) are 1:7 and 2:1, respectively. The band gap is opened for all crystal directions.

Fig. 3 shows a schematic illustration to explain the band gap formation. At the boundary between the first and second Brillouin zones, the standing waves A and B are formed. The electromagnetic energy of the wave A and B are relatively concentrated at the lattice and the matrix media, respectively. The wave vector \( \mathbf{k} \) in the photonic crystal is expressed as \( \mathbf{k} = p/a = p/\lambda_c \) where \( \lambda_c \) is the wavelength. The standing wave frequencies of \( f_a \) and \( f_b \) correspond to the higher and lower bands.

3. Experimental procedure

Three different types of the crystal mold corresponding to the transmission directions of microwave along \( <110> \), \( <100> \), and \( <111> \) were designed by using a CAD software (Toyota Keram Ltd, Think Design Ver.8.0) as shown in Fig. 4. Each unit mold was \( 15 \times 32 \times d \) mm\(^3\) in dimension, where \( d \) denotes one lattice spacing along these directions. Diameter and length of the air lattice were 4.3 and 6.5 mm, respectively. The lattice constant of the unit cell was 15 mm. The volume fraction of the air lattice was 33%. An electronic file of the model structure was converted into a rapid prototyping format (STL file) and sliced into a set of thin sections. Then, the processing data were
transferred to a stereolithography machine (D-MEC Ltd, Japan, SCS-300P).

In the stereolithography process, the liquid resin of the photosensitive epoxy was used to form the solid crystal molds. An UV laser of 355 nm in wavelength was scanned on the liquid surface with a speed of 90 mm/s according to a computer operation. A two-dimensional layer was formed through the polymerization by laser scanning, eventually building up a three-dimensional structure through the layer-by-layer stacking process. The laser beam was focused to a spot of 100 μm in diameter with 100 mW in power. Thickness of each layer was 100 μm, and a part accuracy of the laser scanning is 0.1%.

TiO₂, SrTiO₃ and BaTiO₃ ceramic powders with an average particle size of 2 μm were mixed into a polyester resin with 10, 20 and 30% in volume, respectively. After the polymerizing agent was added to the ceramic slurry, it was infiltrated into the epoxy crystal mold under a vacuum. The polyester resin was polymerized at the room temperature in 24 h. The bulk samples of the polyester resin including the same ceramic particles with the same contents as the lattice were fabricated in order to observe the microstructure and measure the density by using SEM and a pichnometer, respectively.

Fig. 3. Schematic illustration of the band gap formation in a photonic crystal with diamond structure.

Fig. 4. Three-dimensional models of epoxy molds having the air hole network with diamond structure in the bulk component.

Fig. 5. The polyester lattice with the diamond structure containing TiO₂ particles of 30 vol% in the epoxy matrix.
Attenuations of the microwave transmission through photonic crystals were measured by using a metal cavity and a network analyzer (Agilent Tech. Inc., HP-8720D). The crystal samples with four unit cells along $\Gamma$-$X$, $\Gamma$-$100$, $\Gamma$-$K$, $\Gamma$-$110$, and $\Gamma$-$L$, $\Gamma$-$111$ directions were joined and inserted to the metallic cavity. The dielectric constants and dielectric loss of the ceramic dispersed polyester lattice and the epoxy medium were measured using their bulk samples by using a dielectric probe kit (Agilent Tech. Inc., HP-8570B).

The electromagnetic band diagram was calculated along the symmetry lines in the Brillouin zone by means of the plane waves propagation method. The plane waves of 127 in number were propagated for the diamond structure.

4. Results and discussion

The three-dimensional polyester lattice of a diamond structure including TiO$_2$, SrTiO$_3$, and BaTiO$_3$ particles were formed in the epoxy matrix. Fig. 5 shows the (110), (100) and (111) crystal planes composed of the 30 vol%-TiO$_2$ dispersed polyester lattice. The composite lattice contained no air bubbles.

SEM images of the ceramic particles dispersed polyester lattices are shown in Fig. 6. The TiO$_2$, SrTiO$_3$, and BaTiO$_3$ particles are dispersed uniformly without coagulation. The dimples observed at surface of the polyester matrix are the traces of particles exfoliation.

Fig. 6. SEM images of TiO$_2$, SrTiO$_3$, and BaTiO$_3$ particles dispersed in the polyester lattice.

Fig. 8. Microwave attenuations of TiO$_2$, SrTiO$_3$, and BaTiO$_3$ dispersed polyester lattice with the diamond structure for $\Gamma$-$X$, $\Gamma$-$100$ direction.

Fig. 7. Dielectric constant and dielectric loss of the polyester lattice containing TiO$_2$, SrTiO$_3$, and BaTiO$_3$ particles with different contents.

$\Gamma$-$K$, $\Gamma$-$110$, and $\Gamma$-$L$, $\Gamma$-$111$ directions were joined and inserted to the metallic cavity. The dielectric constants and dielectric loss of the ceramic dispersed polyester lattice and the epoxy medium were measured using their bulk samples by using a dielectric probe kit (Agilent Tech. Inc., HP-8570B).
The dielectric constant and dielectric loss of the polyester lattice are plotted as a function of the ceramic composition are shown in Fig. 7. These values show the linear relationships between them within 30 vol% of the ceramics. The BaTiO3/polyester system has the highest dielectric constant and dielectric loss.

The microwave attenuations of transmission amplitude though the photonic crystal samples for $\Gamma$-X < 100 > direction are shown in Fig. 8. The contents of TiO2, SrTiO3 and BaTiO3 particles are 30 vol%. The photonic band gap is formed in wide frequency ranges. The maximum attenuations are about 25 dB. The attenuation of transmission amplitude through bulk samples of the TiO2, SrTiO3 and BaTiO3 dispersed polyester were about 0 dB. The lattice structures of the higher dielectric constant exhibit the wider photonic bandgap.

The calculated band diagrams is shown in Fig. 9. The content of TiO2, SrTiO3 and BaTiO3 in the polyester lattice is 30 vol%. Open circles denote the measured bandgap edges for $\Gamma$-X < 100 >, $\Gamma$-K < 110 > and $\Gamma$-L < 111 > directions. The measured bandgaps agreed with the calculated ones. The perfect band gaps are exhibited in all samples.

The variation of the measured band gap frequency is plotted as the function of dielectric constant of the lattice in Fig. 10. Open marks and dotted lines denote the measured band edges and the calculated ones, respectively. The lattices with the higher dielectric constant exhibit the wider photonic band gaps. The measured frequencies of the lower band edges diverge from the calculated ones with increasing dielectric constant of the lattice. The band gap edges correspond to the standing wave frequencies formed in the crystal structure as shown in Fig. 3. The band gap width increases with the energy contrast of the standing waves depending on the dielectric constant ratio between the lattice and matrix. The lattice with the higher dielectric loss absorbs the standing wave energy to decrease the band gap width.

5. Conclusions

Photonic crystals with diamond structure were fabricated by infiltrating the mixed slurry of the ceramic particles of TiO2, SrTiO3 and BaTiO3 and the polyester resin into a epoxy mold formed by stereolithography. The ceramic particles were dispersed from 10 to 30 vol% in order to control the dielectric constant and dielectric loss of...
the lattice. The photonic crystal samples showed wide
perfect band gaps in the frequency range of 7–11 GHz. The
wide bandgap was formed by increasing the dielectric
constant of the lattice. The measured band gaps showed
fairly good agreement with the calculated ones by plane
wave propagation method. The lower bandgap frequencies
were influenced by the dielectric loss of the lattice.

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