Terahertz wave behaviours in ceramic and metal structures fabricated by spatial joining of micro-stereolithography

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Abstract. We have newly developed micro-stereolithography system to realize freeform fabrication of micrometer order 3D metal structures. In this process, the photo-sensitive resin paste mixed with nanometer sized ceramic and metal particles was spread on a glass substrate with 10 µm in layer thickness by using a mechanical knife edge, and two-dimensional images of UV ray were exposed using DMD (Digital Micro-mirror Device) with 2 µm in part accuracy. Through the layer by layer stacking process, micrometer order three-dimensional objects were formed. Dense metal structures could be obtained by dewaxing and successive sintering of the formed objects. In our recent investigation, micro photonic crystals with lattice structures of alumina or pure copper were fabricated in order to control electromagnetic wave propagation in a terahertz (THz) frequency range. The micro photonic crystals with a diamond structure perfectly reflected the THz wave by Bragg diffraction

1. Introduction
We have newly developed micro-stereolithography system to realize spatial joining of micrometer order ceramic or metal structures with three-dimensional distributions of dielectric or conductive materials. The final goal of our investigation is to control electromagnetic waves in a terahertz frequency range with micrometer wavelength effectively. In near future, the terahertz wave will be expected to apply to various types of novel sensors which can detect gun powders, drugs, bacteria in foods, micro cracks in electric devices, cancer cells in human skin and other physical, chemical and living events. To control terahertz waves effectively, micrometer sized electromagnetic devices composed of dielectric ceramics applying for cavities, filters and antennas will be necessary [1,2].

Photonic crystals composed of dielectric lattices form band gaps for electromagnetic waves [3-6]. These artificial crystals can totally reflect light or electromagnetic wave at wavelengths comparable to the lattice spacings by Bragg deflection. The two different standing waves vibrating in the air and dielectric matrix form higher and lower frequency bands in the first and second Brillouin zones, respectively. The band gap width can be controlled by varying the structure, filling ratio, and dielectric constant of the lattice. Structural modifications by introducing defects can control the transmission of electromagnetic wave as well [7-9]. The introduced structural defects in the periodic arrangement can localize the electromagnetic wave energy and form the transmission mode in the band gap frequency range according to the size and dielectric constant of a defect region. The photonic crystal with a diamond structure can form the perfect band gap which opens for all crystal directions [10,11].

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have fabricated the millimeter sized dielectric photonic crystal with a diamond structure to control the microwave by using a structural joining method of stereolithography [12,13]. In our recent study, micrometer sized alumina and pure copper lattices with a diamond structure were fabricated by using a newly developed micro-stereolithography system [14]. These photonic crystals showed the perfect band gap, which prohibited the terahertz wave propagation in all directions. Recently, we successfully fabricated a twinned diamond structure with a plane defect between mirror symmetric lattice patterns. A localized mode to transmit terahertz wave selectively was formed in the photonic band gap. In this study, transmission spectra of terahertz wave through alumina and pure copper diamond structures were measured. The selective transmission mode in the band gaps were observed for the twinned diamond structure and discussed in relation to the terahertz wave localization at the plane defect.

![Figure 1. A schematic illustration of micro-stereolithography.](image)

2. Experimental Procedure

The three-dimensional diamond structures were designed by using a 3D-CAD program (Toyota Caelum Co. Ltd., thinkdesign ver. 7.0). In the photonic crystal with diamond structure, the lattice constant was 1 mm. The whole structure was 6×6×2 mm³ in size, consisting of 6×6×2 unit cells. The aspect ratio of the metal lattices was designed to be 1.5. The CAD data was converted into a STL file of a rapid prototyping format. After the slicing process of 3D model into a series of two-dimensional cross-sectional data into thin sections, this data was transferred to micro-stereolithographic equipment (D-MEC Co. Ltd., Japan, SI-C10008). In our system, photo sensitive acrylic resins dispersed with alumina or pure copper particles of 170nm or 5 µm in diameter at 40 or 54 vol. %, respectively, were fed over substrates from dispenser nozzles. The highly viscous resin paste was fed with controlled air pressure. It was spread uniformly by moving a knife edge. The thickness of each layer was controlled to 10 µm. A two-dimensional pattern was formed by illuminating visible laser of 405 nm in wavelength on the resin surface. The high resolution has been achieved by using a Digital Micromirror Device (DMD) and an objective lens. Figure 1 shows a schematic of the micro-stereolithographic system. The DMD is an optical element assembled by mirrors of 14 µm in edge length. The tilting of each tiny mirror can be controlled according to the two-dimensional cross sectional data by a computer. The three-dimensional structures were built by stacking these patterns layer by layer. In order to avoid deformation and cracking during dewaxing, careful investigation for the dewaxing process was required. The precursors with diamond structures were heated at various temperatures from 100°C to 600°C while the heating rate was 1.0 °C/min. The dewaxing process was observed in respect to the weight and color changes. The alumina or pure copper particles could be sintered at 1500
Figure 2. A dielectric photonic crystal composed of micro alumina lattices with diamond structure fabricated by using stereolithography.

Figure 3. A transmission spectrum of terahertz wave for Γ-X <100> direction in the alumina photonic crystal with the diamond structure.

Figure 4. A twinned diamond photonic crystal with a plane defect between mirror symmetric alumina lattices parallel to (100) layers.

Figure 5. A localized mode of a transmission peak in a photonic band gap formed through the twinned diamond structure of the alumina lattice.
or 1000°C, respectively. The heating rate was 8.0°C/min. The density of the sintered sample was measured by the Archimedes method. The microstructures were observed by optical microscope and scanning electron microscopy (SEM). The transmittance and the phase shift of incident terahertz waves were measured by using terahertz time-domain spectroscopy (Advanced Infrared Spectroscopy Co. Ltd., Japan, J-Spec2001 spc/ou). Measured terahertz properties were compared with simulation by using a Transmission Line Modeling (TLM) simulation program (Flomerics: Micro-Stripes Ver. 7.0).

3. Results and Discussion

Three-dimensional lattice structures composed of the alumina dispersed acrylic resin were processed exactly by using micro-stereolithography. The spatial resolution was approximately 0.5 %. Figure 2 shows a (100) plane of the sintered diamond structure composed of the micrometer order alumina lattice. The deformation and cracking were not observed. The linear shrinkage on the horizontal axis was 23.8 % and that on the vertical axis was 24.6 %. The relative density reached 97.5 %. Dense alumina microstructure was formed, and the average grain size was approximately 2 µm. The measured dielectric constant of the lattice was about 10. The terahertz wave attenuation of the transmission amplitude through the alumina diamond structure for \( \Gamma -X <100> \) crystal direction is shown in figure 3. The forbidden gap is formed at the frequency range of from 0.37 to 0.52 THz. The dotted lines show the higher and lower band gap edges calculated by using the TLM method of a finite element method. The similar transmission spectra for \( \Gamma -K <110> \) and \( \Gamma -L <111> \) directions were obtained. These measured results of the photonic band gap frequencies were verified to have good agreements with the simulated ones within a tolerance of 5 %. A common band gap was observed in every direction at the frequency range form 0.40 to 0.47 THz, where the electromagnetic wave cannot transmit through the crystal and is totally reflected in all directions. This common band was included in the calculated perfect photonic band gap by using a plane wave expansion (PWE) method. In this theoretical calculation, the plane wave propagations were simulated for all directions in the periodic arrangements of the dielectric materials by solving Maxwell’s equations. And the photonic band distributions were drawn along the symmetry lines in the Brillouin zone. Figure 4 shows the twinned diamond structure composed of the mirror symmetric alumina lattices. The plane defect forms parallel to the (100) crystal layer. The transmission spectrum for the \( \Gamma -X <100> \) crystal direction of the twinned diamond structure is shown in figure 5. The localized mode forms in the photonic band gap. At the peak frequency, the incident terahertz wave localized in the plane defect, and the amplified wave propagated to the opposite side. The three-dimensional photonic band gap structure to form the localized mode can be applied to the terahertz wave filters.

Figure 6 shows a precursor of the metal photonic crystal consisting of copper particles dispersed resin fabricated by micro-stereolithography. The spatial resolution was approximately 0.5 %. By the dewaxing and sintering process, full-metal diamond structures were successfully obtained. Figure 7 shows the sintered samples. The deformation and cracking were not observed. The lattice constant of the diamond structure is 900 µm. The linear shrinkage was 10%. It is possible to obtain the uniform shrinkage by designing an appropriate elongated structure in the vertical direction for compensation to the gravity effect. The relative density reached 89.7 %. Figure 8 shows the transmittance intensity and the phase shift spectra along \( \Gamma -X <100> \) directions. Opaque regions were formed and phase shifts became discontinuous, indicating the formation of photonic band gaps, at the frequency range from 0.39 to 0.48 THz. The band gap frequency was compared with calculations by using the TLM method as shown in figure 9. The measured opaque region corresponded to the calculation. In the photonic band gap, the incident wave are diffracted by multiple reflections in the periodic structure composed of the three dimensional pure copper lattices. As shown in figure 8 and figure 3, the transmission spectra obtained through the pure copper metal structures and the alumina ceramic ones exhibit different profiles. The electromagnetic wave can transmit with resonances and absorptions into the alumina ceramic lattices. However, the pure copper metal lattices reflect the wave on the surface without transmission. These different behaviours of the electromagnetic wave diffractions in the periodic lattices cause the variations of band gap profiles in the transmission spectra.
Figure 6. The diamond photonic crystal of acryl lattices with the pure copper dispersion formed by using micro stereolithography.

Figure 7. The pure copper photonic crystal with the diamond lattice structure composed of the micrometer order conductive metal rods.

Figure 8. The terahertz wave transmittance and phase shift spectrum for the Γ-X <100> direction through the pure copper photonic crystal with the diamond lattice structure.

Figure 9. The simulated transmission spectrum in the terahertz wave frequency for the photonic crystal composed of the pure copper diamond lattices by using TLM method.
4. Conclusion

We have fabricated three-dimensional micro photonic crystals with a diamond structure composed of alumina or pure copper dispersed acrylic resin by using micro-stereolithography. By the careful optimization of process parameters regarding dewaxing and sintering, we have succeeded in fabricating dense alumina or pure copper micro diamond structures. The sintered photonic crystals formed complete photonic band gaps at the terahertz region. A twinned diamond photonic crystal composed of alumina lattices with a plane defect between mirror symmetric lattice structures was also fabricated. A localized mode of transmission peak was observed in the forbidden bands. In electromagnetic wave simulations, the localized mode with multiple reflections was formed in the plane defect between the twinned lattice patterns. These micro components of ceramic and metal photonic crystals have potentials to be used as cavities, filters and antennas in a THz range.

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6. References

[1] Woodward M R, Wallacel P V, Arnonel D D and Linfield H E 2003 J. Biological Phys. 29 257
[2] Exter V M, Fattinger C and Grischkowsky D 1989 Optics Lett. 14 1128
[3] Yablonovitch E 1987 Phys. Rev. Lett. 58 2059
[4] Ohtaka K 1979 Phys. Rev. B 19 5057-5067.
[5] John S and Wang J 1990 Phys. Rev. Lett. 64 2418
[6] Soukoulis C M 1996 Photonic Band Gap Materials (Netherlands: Kluwer Academic Publisher)
[7] Brown R E, Parker D C, Yablonovich E 1993 J. Optical Society of America B, 10 404
[8] Noda S, Yamamoto N, Kobayashi H, Okano M and Tomoda K 1999 Appl. Phys. Lett. 75 905
[9] Kawakami S 2002 Photonic Crystals (Tokyo: CMC)
[10] Ho H K, Chan T C and Soukoulis M C 1990 Phys. Rev. Lett. 65 3152
[11] Haus W J 1994 J. Modern Optics 41 195
[12] Kirihara S, Takeda W M, Sakoda K, Miyamoto Y 2002 Solid State Communications 124 135
[13] Miyamoto Y, Kirihara S and Takeda W M 2006 Chem. Lett. 35 342
[14] Kirihara S, Miyamoto Y 2008 Ceram. Interconnect and Ceram. Microsystems Technol. 5 254