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Fabrication of a Three-dimensional Terahertz Photonic Crystal Using Monosized Spherical Particles

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Abstract

Three-dimensional artificial crystals with periodicity corresponding to terahertz wave lengths were fabricated by self-assembling monosized metal spherical particles. The metal crystals were weakly sintered to utilize them as templates. The metal templates were inverted to air spheres crystal embedded in dielectric resin though infiltration and etching. The resulting resin inverted crystals clearly presented the photonic stop gaps within terahertz wave region and the frequencies of the gaps were confirmed to agree well with calculation by plane wave expansion method.

Keywords : self-assembly, monosized particles, 3D inverted crystal, terahertz, photonic band gap

1. Introduction

Terahertz (THz) waves having wavelengths between the microwave and infrared had been an underexploited part of electromagnetic waves so far. Recent advances in THz wave generators and detectors have yielded fascinating applications[1]: THz-imaging of biological tissues, detections of explosive, high-speed communications and so on. On the other hand, realization of practical devices utilizing THz wave requires a wide variety of components such as sharp-bend waveguides, small-sized lasers and modulators.

Photonic crystals (PhCs), in which dielectric materials are periodically arrayed, have been successful in controlling and confining millimeter and visible light waves. Although some researchers have paid attention to THz wave PhCs, there are a few reports on three-dimensional (3D) PhCs, otherwise others concern for a two-dimensional one. This is because of no suitable fabrication process for 3D PhCs in sub-millimeter order, whereas mechanical processes and semiconductor technologies have promoted the development of 3D PhCs for millimeter waves, infrared and visible lights.

In this report, a 3D array with a periodic structure in hundreds micrometer order was fabricated through a means of assembling monosized particles[4] and its feasibility for a THz wave PhC has been demonstrated.

2. Experimental and Results

The fabrication process of inverse crystals includes four steps: preparing monosized metal particles, arraying the particles for a template, impregnating dielectric filler into the template and removing the template. (see the reference 4 for detail)

Pure copper was chosen as material of monosized particles, because it can be easily etched away by conventional chemical method. The copper monosized particles were prepared by a pulsated orifice ejection method (POEM)[2,3], which have an average diameter of 267 μm and narrow size distribution with a standard size deviation of 6.67% and the obtained particles present high sphericity without distortion due to grain boundary and void. It is well known that monosized spheres confined in a pyramidal space are naturally close-packed into f.c.c structure by gravity and vibration. The particles were filled into a dimple of equilateral quadrangular pyramid and adequately vibrated. The array with the graphite dimple was weakly sintered at 1323 K for 30 min in hydrogen atmosphere to make sure the neck formation and channels for liquid etchant. After the template was prepared, its interstitial space was filled with dielectric medium for fabrication of the inverse crystal. After curing the resin, the internal copper template was completely etched away by iron chloride solution.

Scanning electron microscopy (SEM) image of the resulting array indicates that the single crystal f.c.c. was formed without defect (Fig.1(a)). The four tilted-faces and bottom face are {111} planes and (110) plane, respectively. Fig.1(b) shows that the sintering process formed a typical neck of approximately 30 μm in diameter at contact points between the adjacent particles. However, no sintering shrinkage was found from the SEM observation for the {111} planes in shown Fig.1(a), so that the lattice constant of the sintered f.c.c. crystal could be determined to be $\sqrt{2} \times 267 \approx 378\,\mu$m.

Fig.2(a) shows the inverse artificial crystal consisting of epoxy resin after removal of the template. The configuration of embedded air spheres was well copied from the template. The cross sectional image perpendicular to (111) plane of the sample is depicted in Fig.2 (b).

A terahertz wave time domain spectroscopy was used to study the presence of a photonic stop gap in the fabricated inverse crystals. Two kinds of pyramidal inverse crystal were cut into plates with thickness of 2mm perpendicular to [111] direction. The transmittance spectrums examined in vacuum of 10^{-2} Pa by incident normal to the [111] plane were shown in Fig.3. It is found that the transmittance gradually decreases as frequency increases and finally closes to zero at approximately $30cm^{-1}$ because of absorption of epoxy resin. However, the epoxy inverted crystal clearly represents the dip of transmittance in the range from 16 to $21cm^{-1}$ (0.48- 0.64 THz), as seen in Fig.3(a). This frequency range agrees well with the band gap predicted, so that the dip was proven to be the photonic band gap. With the increase of dielectric constant of the inverse lattice, the photonic band gap shifted toward lower frequency in (Fig.3(b)). Thus, it is confirmed that the crystals derived from the monosized particles is applicable for THz wave photonic crystals.

3. Summary

The three-dimensional artificial crystals with sub-millimeter periodicity were fabricated by assembling the monosized spherical metal particles that were prepared by the pulsated orifice ejection method. The dielectric resin inverted crystal was fabricated using the above crystal as a template and presented photonic band gap in the terahertz wave region. The result demonstrated the possibility of this method using the monosized particles for fabrication process of terahertz wave photonic crystal.

4. References

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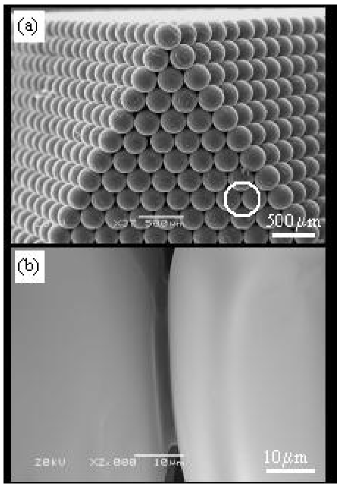

Fig. 1. SEM images of (a) three-dimensional template composed of monosized spherical copper particles and (b) showing a neck observed at the circle in (a).

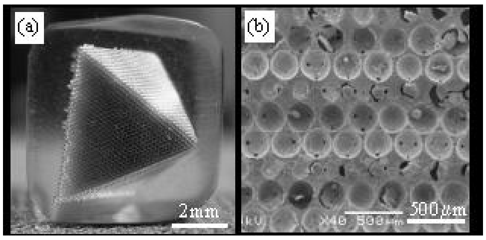

Fig 2. Micrographs of the epoxy inverted photonic crystal. (a) Optical image of overview. The air spheres array with pyramidal shape is embedded in the transparent epoxy resin. (b) SEM cross-sectional image normal to (111) plane.

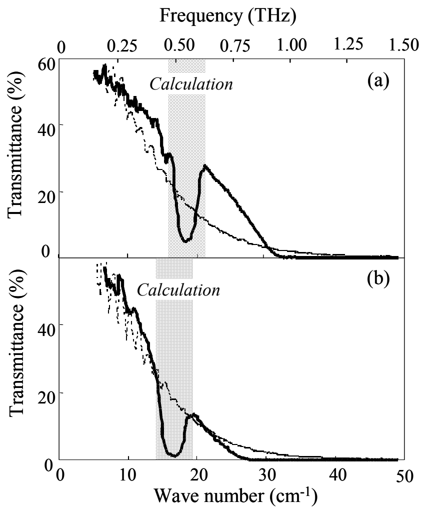

Fig. 3. Measured transmittance in the [111] direction of the resin-inverted crystals. The inverse crystals are composed of (a) epoxy with dielectric constant of 2.72 and (b) 10vol% titania-epoxy with dielectrical constant of 3.70. Solid lines represent crystals and dotted lines dense plates without crystal.