Visualizations of microwave emissions through pure copper photonic crystals†

TAKINAMI Yohei *and KIRIHARA Soshu **

KEY WORDS: (Visualization) (Microwave) (Photonic crystal) (Stereolithography) (Powder sintering process)

1. Introduction

Photonic crystals with periodic arrangements of metal or ceramic media exhibit forbidden bands in electromagnetic wave transmission spectra [1]. These artificial crystals have been developed to be applied to novel electromagnetic wave control devices such as band pass filters, telecommunication equipments, and waveguides [2]. In this investigation, pure copper photonic crystals were fabricated successfully in sub-millimeter to control microwaves by using stereolithography. The pure copper has thermal shock resistances and shows nearly perfect reflection properties. Moreover, the modified photonic crystals with compressed lattice spacing in specific direction were designed and fabricated. These compressed crystals can be expected to realize directional transmissions through anisotropic wave diffractions. To confirm directive emissions of microwave intensities, radiation patterns from a monopole antenna located inside the crystal were visualized by using finite difference time domain simulation.

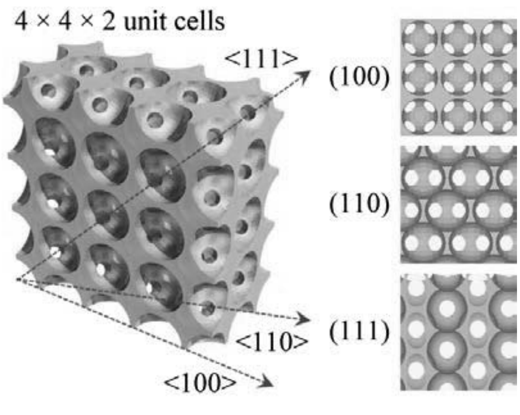

Fig. 1 Computer graphics of an inverse sphere structure with a body centered cubic arrangement.

2. Experimental Procedure

The photonic crystal structure was designed as an inverse type with the periodic arrangements of air spheres in a pure copper bulk by using a computer graphic application. **Figure 1** shows the designed models of the inverse photonic crystal. The air sphere diameters were optimized as 2.82 to 3.0 mm through the theoretical simulations and visualizations of the electromagnetic fields. The whole crystal was designed as 12 ×12×6 mm in edge lengths to include 4×4×2 numbers of the unit cells. Subsequently, the modified crystal structure with the compressed lattice spacing for the <100> direction at 70 % in size ratio was designed successfully. **Figure 2** shows a schematic illustration of the stereolithography system. In the fabrication process, photo sensitive resin paste including pure copper particles was spread on a substrate by a moving blade. An ultraviolet laser was scanned on the resin surface to create cross sectional patterns. Through the layer by layer process, solid composite objects were formed. Dense pure copper structures were obtained by successive dewaxing and sintering at 800 and 1080 °C in an argon atmosphere to prevent the metal phase oxidations. The microwave propagations through the fabricated photonic crystals were measured by a time domain spectroscopy system. Obtained results were compared with simulated ones. The microwave radiating patterns from the monopole antenna located inside the compressed crystal lattice were visualized to confirm the directive emission by using the finite element simulation.

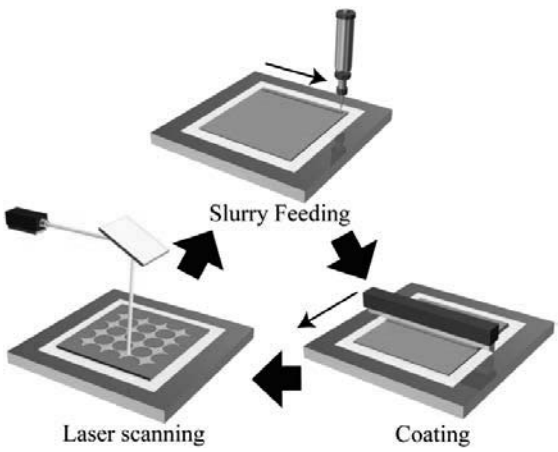

Fig. 2 A schematic illustration of stereolithography system of a computer aided design and manufacturing.

† Received on 30 September 2010
* Graduate school, Osaka University, Suita, Japan
** JWRI, Osaka University, Suita, Japan

Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

3. Results and Discussion

The crystal planes of the fabricated photonic crystal with the inverse body centered cubic arrangements are shown in **Fig. 3**. The hollow structures were precisely shaped without macro fractures or deformations. The smooth surfaces were obtained successfully through the layer by layer stacking of the thin cross sections in the micrometer order processing. Achieved spatial resolution was 1.0 % approximately. And, copper oxide peaks were not detected in an X-ray diffraction spectrum. In transmission spectra through the obtained metal photonic crystals, the common forbidden region especially called the perfect band gap was observed from 95 to 110 GHz in frequency range. The other opaque band was shown under 80 GHz meaning typical cut off effects through the metal hollows. In the simulated results, the perfect band gap was observed in the frequency range from 94 to 110 GHz nearly coinciding with the measured one. And, the measured microwave transmittances of the pass bands were lower than the simulated ones. The incident electromagnetic waves are considered to be scattered by the fabricated real surfaces of sintered pure copper. The copper inverse sphere structures were verified to forbid the propagations of microwave for all directions. **Figure 4** shows the visualization of the electric field distributions through the inverse photonic crystal for <100> direction. Bright areas mean the space with higher electronic intensity, while dark one indicates lower. At the frequency of the band gap region, propagating waves from left side were reflected perfectly. On the other hand, at the frequency of transmission region, the electric field intensities were concentrated into air spheres and the high transmittance properties were exhibited. These phenomena are considered to be caused through surface plasmon polariton effects. In the case of electromagnetic wave propagating into the metal structures, the surface plasmon polariton was excited on the metal surface with the periodic gaps. The high transmission properties are attributed to the resonant coupling of the free space electromagnetic waves vibrations with the occurred surface plasmon polariton [3]. **Figure 5** presents the radiation pattern from the monopole antenna inside the compressed photonic crystal at the frequency of 108 GHz. The forbidden bands for <100> and <010> crystal directions parallel and perpendicular to the lattice compression axis were exhibited in the frequency ranges of 112 to 130 and 104 to 118 GHz, respectively. In the selected frequency band from 105 to 110 GHz, the microwaves were permitted and prohibited wave propagations along the parallel or perpendicular routes for the compressed direction, respectively. The directional wave transmission and energy concentration for the limited angle area through the modified metal photonic crystal with the compressed lattice spacing were demonstrated clearly.

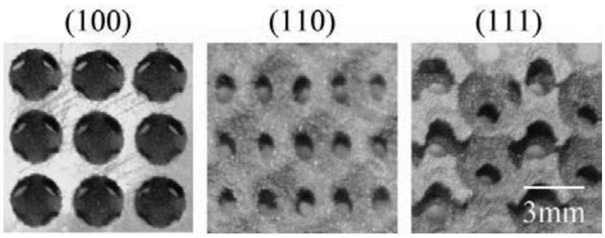

Fig. 3 Pure copper photonic crystals with the inverse body centered cubic structure fabricated by using the stereo-lithography and powder sintering processes.

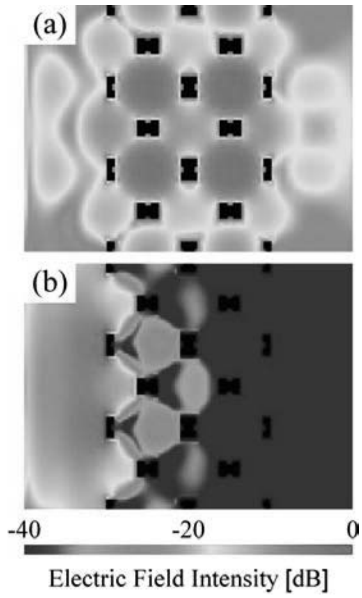

Fig. 4 Electric field distributions of (a) transmission and (b) band gap modes simulated by using a transmission line modeling method of a finite difference time domain.

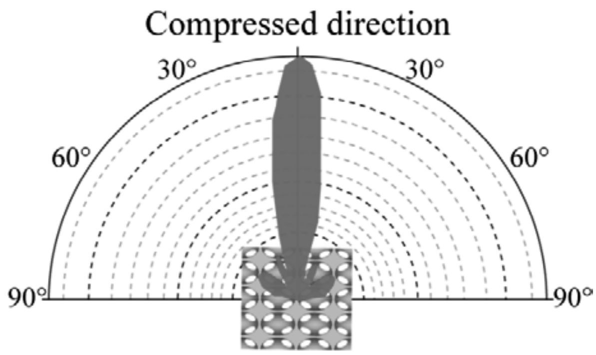

Fig. 5 A microwave radiation pattern from a monopole antenna embedded into the compressed crystal structure.

4. Conclusion

We succeeded in fabrications of pure copper photonic crystals with or without compressed lattice spacing by using stereolithography and a powder sintering process. Fine metal structures were precisely formed without delamination and fracture. The obtained photonic crystals showed perfect band gaps from 95 to 110 GHz in frequency. The modified crystal with compressed lattice spacing exhibited directional transmission properties at the frequency range from 105 to 110 GHz. Simulated and measured transmission properties of the microwave propagation through the copper crystals showed good agreements. The compressed metal crystals are considered to be capable of controlling the emission of high energy microwaves in the near future industrial fields.

Acknowledgments

This study was supported by Priority Assistance for the Formation of Worldwide Renowned Centers of Research - The Global COE Program (Project: Center of Excellence for Advanced Structural and Functional Materials Design) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References

[1] E. Yablonovitch: J. Opt. Soc. Am. B, 10, (1993), pp.283.
[2] M. Notomi, A. Shinya, S. Mitsugi, E. Kuramochi and H-Y. Ryu: Optics Express,12 , (2004), pp. 1551-1561
[3] F. Miyamaru and M Hangyo, appl. Phys., 84,(2004), pp. 2742,