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Smart Processing Development for New Joining and Materials†

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Abstract

A new concept of smart processing is proposed from JWRI. Based on this concept of joining and materials processing, a new research center named Smart Processing Research Center was established on April 1st, 2003. As an example of the smart processing development, the study on design and fabrication of 3D photonic crystals for application to new communication devices is introduced.

KEY WORDS: (smart processing) (photonic crystal), (stereolithography), (diamond structure)

1. Introduction

The word of "smart" is frequently used nowadays such as smart structures, smart materials, or smart solutions. The meaning of "smart" in these expressions seems to indicate an ability to respond to the environment and optimize the status and function of the material. A new concept of "smart processing" was proposed from our Institute last year. Based on this concept, a new research center named "Smart Processing Research Center" was established on April 1st, 2003 by reconstructing two attached centers in JWRI, "Research Center for Ultra High Energy Density Heat Source" and "Research Center for Materials Recycling and Integration".

The aim of this new center is to study the science and technology of smart processing which can deliver higher performances as well as damage and strain-free products, resulting in saving energy and resources, by fine and precise control of joining and manufacturing processes. We will contribute to establishing the next generation technology in manufacturing which can promote both industrial activities and environmental preservation by developing smart processing for products including nano- and micro-materials for which real production technology is not established yet.

The smart processing research center is composed of five research divisions: 1) Smart Beam Processing Research Division; where low temperature processes by finely controlled laser and particle beams are studied and developed. 2) Smart Coating Research Division; environment-friendly surface modifications by finely controlled plasma beam process are studied and developed. 3) 3D Nano and Micro Structure Control Research Division; 3D joining and integration technology for nano and micro structures and the remote fabrication system are studied and developed. 4) Nano Particles Bonding Research Division; synthesis of nano-sized composite particles and bonding are studied and developed. 5) Reliability Evaluation and Simulation Division; diagnosis and life time prediction for nano and micro structures and functions will be studied and developed.

As an example of the smart processing research, a topic on the development of 3D photonic crystals is introduced.

2. 3D Photonic Crystals for Application to New Communication Devices

A Photonic crystal is composed of a three dimensional periodic structure of dielectric lattices which can totally reflect electromagnetic waves with the wave length similar to the periodicity of the lattice [1,2]. The total reflection of electromagnetic waves is due to Bragg

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deflection and forms the photonic bandgap that is similar to the phenomenon of the electronic bandgap formation in semiconductors as shown in **Fig. 1.** When the periodicity of the photonic crystal is of nm order, the light can be totally reflected.

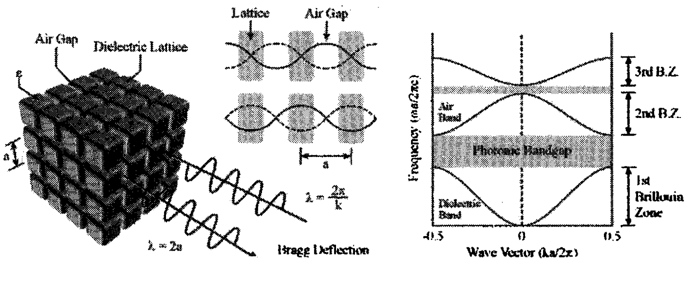

Fig.1. A schematic diagram on the principle of photonic crystal.

When the electromagnetic wave is in the range of light, various applications with zero-emission laser, light wave guide, photonic integrated circuit, polarization splitter, filter, prism, and others are expected. The research and developments on the photonic crystal for light are rapidly increasing in the world [3,4]. While, in the case of mm or microwaves, various cavities, barriers and directional antennae are applicable. We are investigating the fabrication of micrometer or mm order photonic crystals using stereolithography [5,6].

3. Experimental

Stereolithography is a kind of rapid prototyping which can form three dimensional structures of polymer resin. When an ultra violet laser beam irradiates the surface of the photosensitive liquid resin, the irradiated part is polymerized and solidified. The laser beam is scanned following the structure design of a CAD program. When one layer is formed, the platform goes down one step of about 100 μm and the second layer is formed eventually constructing a 3D object by the layer by layer stacking process as schematically illustrated in **Fig. 2.**

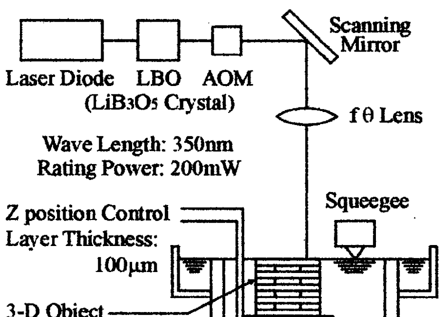

Fig.2. A schematic illustration of stereolithographic machine.

We mixed fine titania-based ceramic particles having high dielectric constant with the liquid epoxy resin in order to increase the dielectric constant of the lattice. The diamond structure is designed by using CAD which is an ideal structure of photonic crystals because it can form a perfect bandgap and therefore reflect electromagnetic waves for all directions. Transmission amplitudes of microwaves through photonic crystal samples were measured using the microwave cavity and network analyzer.

4. Results and Discussion

Figure 3 shows lattice planes of the fabricated diamond structure on (100), (110), and (111) and the attenuations of microwaves to each plane. In the epoxy lattice, 10 vol% of titania based ceramic particles of about 10 μm in size are dispersed. The dielectric constant of the ceramic/epoxy composite is 4 which is two times higher than that of the epoxy. All attenuations are very sharp and can be used for filters, but frequency levels are different from 7.7 to 18.6 GHz depending on the periodic distance of each direction, and no perfect common bandgap is formed in this photonic crystal probably due to the low filling factor of the dielectric lattice in the space.

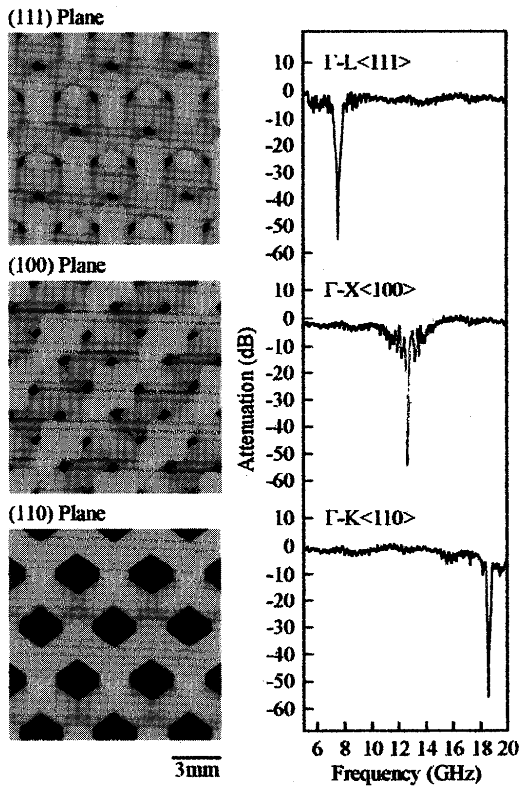

Fig.3. Diamond lattice and attenuation of microwaves.

In order to increase the filling factor of the dielectric lattice, the inverse diamond structure was formed which consists of the diamond lattice of air holes in the dielectric media. Such modification of the lattice is very easily accomplished by using CAD. **Figure 4** shows each plane of the inverse diamond fabricated and the attenuation curves. The broad and common bandgap is formed.

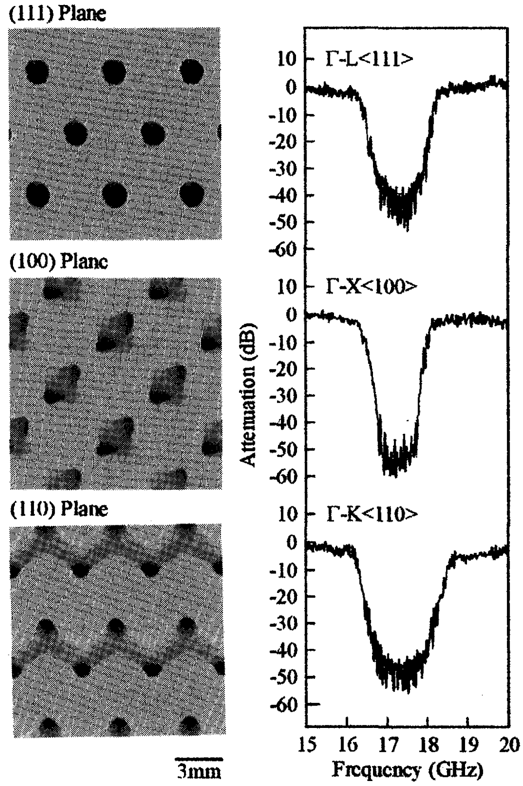

Fig.4. Inverse diamond lattice and attenuation of microwaves.

Figure 5 shows the band diagram calculated for the inverse diamond structure. We can use the position data in a CAD model for the structure factor in band calculation. The common bandgap is opened for all directions. The open circles are the experimental data which are well agreed to the calculated bandgap.

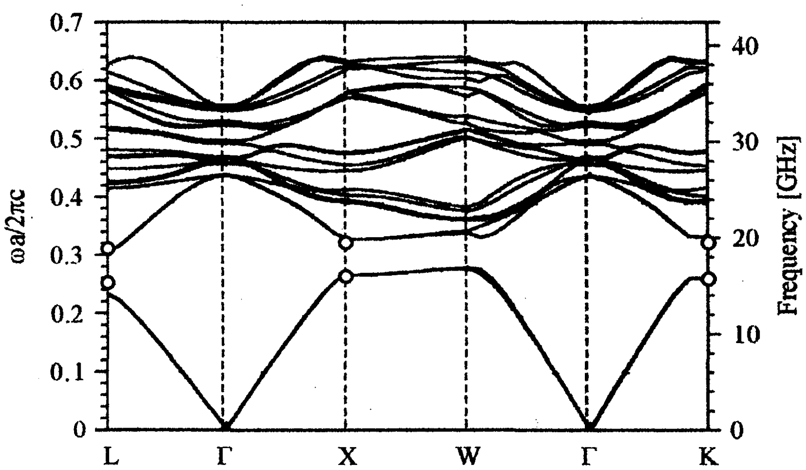

Fig.5. Calculated band diagram and measured bandgaps for the inverse diamond lattice.

It is very easy to tailor the graded lattice structure by using CAD and stereolithography. **Figure 6** is the graded lattice formed by stretching the lattice with every 10% and the attenuation curve for <100> direction. The bandgap is broadened due to the gradual change of the periodicity. The graded lattice has a large potential in the development of the photonic crystal devices.

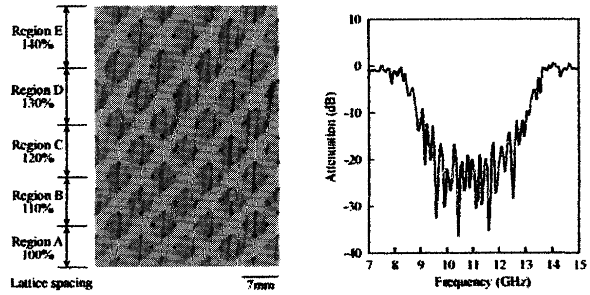

Fig.6. Graded lattice and attenucation of microwave.

Crystal defects can be easily introduced in the photonic crystal by CAD and stereolithography so that it is very important to control the electromagnetic waves in the photonic crystal. In **Fig. 7**, one layer is missing in the graded lattice so that the lattice change is 20 % between the region B and D. The defect level appeared in the midpoint of the bandgap which can allow the low transmission of the microwave near 10.5 GHz.

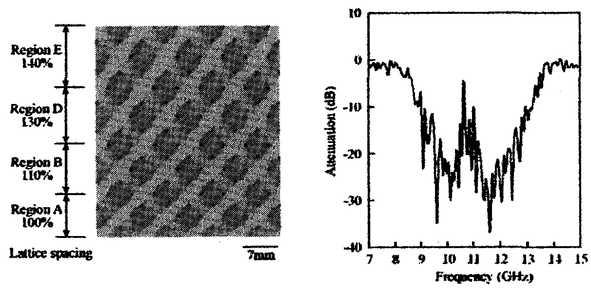

Fig.7. Defect graded lattice and attenuation of microwave.

Figure 8 is a joined photonic crystal with normal and graded lattice structures. When a microwave with a similar wave length to the normal lattice period is emitted at the central interface between the normal and stretched structure, such a wave is reflected by the normal structure and directed toward one direction. The microwave emitted is collected toward this direction and amplified to 100 times against the all directions emission.

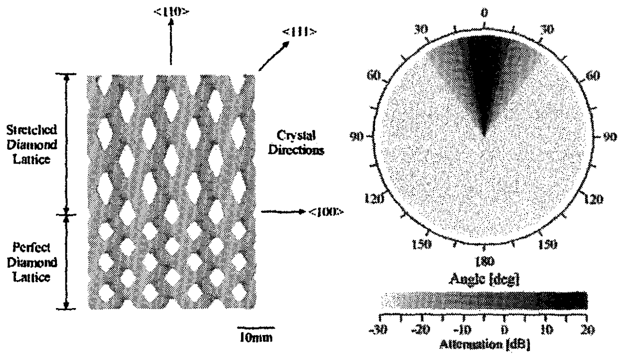

Fig.8. A graded photonic crystal device with a normal and a streched lattice.

If we can form a smaller photonic lattice with a periodicity of several ten to hundreds μm, such a beam device emitting THz wave with several tens to hundreds μm wave length can be used as a micro radar sensor system which is expected to detect surface cracks or defects of materials, bacterium in foods, cancer in living bodies having similar size of wave length. When the lattice rods become thin in micro or nanometer size, nanometer sized ceramic particles must be dispersed into the epoxy lattice. **Figure 9** shows nano-sized TiO_2-SiO_2 particles dispersed photonic crystal.

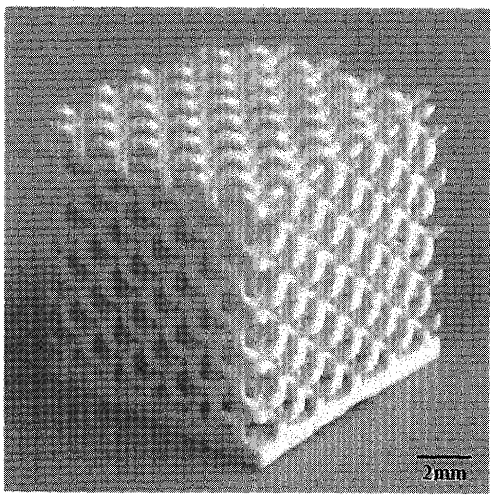

Fig.9. Nano-sized TiO_2-SiO_2 particles dispersed photonic crystal with diamond structure.

The control of various defects and lattice modifications such as the graded lattice can lead to the formation of the module of the electromagnetic circuit in which wave guide for selected waves and antenna, filters barriers are integrated. Three dimensional wave circuits can be produced by integrating various photonic crystal parts by stereolithography. It is possible to construct a remote fabrication system by linking smart processing with the internet as well.

5. Summary

The new concept of smart processing on joining and materials was proposed and the establishment of the smart processing research center in our joining and welding research institute, Osaka University was introduced. As a smart processing development, research on the design and fabrication of photonic crystals having a diamond structure of titania-based ceramic particles dispersed in epoxy lattices with mm order periodicity by a 3D freeforming process of stereolithograpy was demonstrated. Such photonic crystals can be applied to various communication devices in a wide high frequency range from GHz to THz.

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