Visualizations of terahertz frequency amplifications in water cells introduced into alumina diamond photonic crystals†

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KEY WORDS: (Photonic crystal) (Terahertz waves) (Micro stereolithography) (Transmission line modeling) (Localized mode)

1. Introduction

Photonic crystals with periodic variations in dielectric constants can exhibit forbidden band in transmission spectra of electromagnetic waves to realize total reflections through Bragg diffraction [1]. Diamond lattice structures with three-dimensional periodicities can prohibit the wave propagations for all directions in the perfect band gaps. By introducing artificial defects of air cavities into the periodic arrangement, the waves corresponding to the defect sizes can be localized and amplified in the photonic crystals [2]. Our investigation groups have fabricated successfully the ceramic photonic crystal with diamond structures composed of fine ceramic lattices to controlled terahertz waves by using micrometer order stereolithography. In the near future industries, the terahertz waves can be expected to be applied to various types of novel sensors for detecting harmful substances in human bloods, early stage cancer cells in human skins and micro bacteria in vegetables [3]. In this study, we designed and fabricated terahertz wave micro resonators composed of aqueous cavities introduced the diamond photonic crystals to amplify the sensing signals in the liquid region. Their wave properties were measured by spectroscopy and compared with theoretical visualizations of electromagnetic fields.

2. Calculations

Figure 1(a), (b) and (c) show schematic illustrations of a unit cell of the diamond photonic crystal, components of the resonance structures, and the cross sectional image of the terahertz wave resonator, respectively. The micro glass cells including pure water were sandwiched as a plane defect between two alumina photonic crystals with the diamond lattice. In order to operate this resonator under the low loss conditions within the terahertz region, geometric parameters of the models were calculated and optimized by using a transmission line modeling simulator (Flomerics, Micro-Stripes) of a finite difference time domain method. In the unit cell of the artificial crystals, the lattice constant and the aspect ratio of the dielectric lattice were optimized as 375 μm and 1.5 to create the wider band gap in the terahertz frequencies. The localized frequency is tunable by adjusting the defect thickness of the resonator. In this investigation, the plane defect was designed as a water cell of 470 μm in thickness composed of two quartz plates of 160 μm and an aqueous cavity of 150 μm. The resonance qualities can be enhanced by increasing the number of diamond structural units in the resonator. However, the transmission level of the localized mode peak becomes lower through the perfect confinement of the electromagnetic wave energy into the defect domain. The diamond lattices composed of two units in the period number were optimized in order to detect the sharp localization peak in the transmission spectrum.

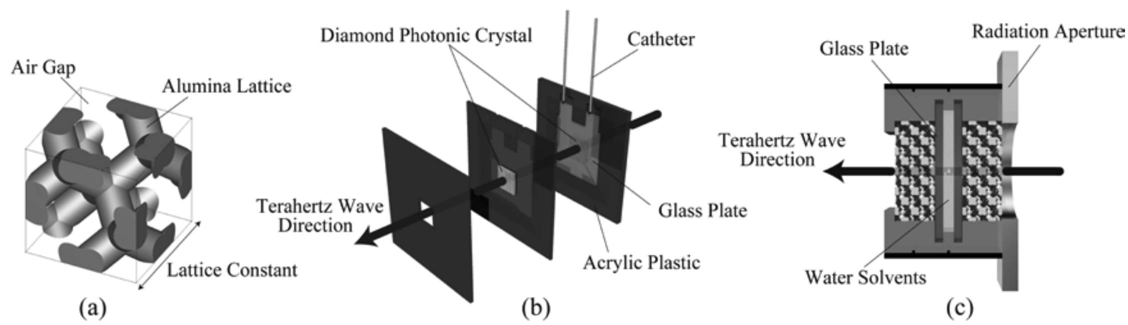

Fig. 1 Schematic illustrations of a unit cell of diamond structure (a), components of resonance cells (b), and a terahertz wave resonator (c). The resonator is composed of two diamond photonic crystals to localize the terahertz waves in an aqueous phase.

† Received on 30 September 2010
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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

3. Experimental Procedure

The diamond lattices were designed exactly by using a graphic application (Toyota Caelum, Think-Design). Whole size of the crystal component was 5×5×1 mm consisting of 10×10×2 unit cells. After slicing operation, these data were transferred into a micro stereolithographic equipment (D-MEC, SI-C 1000) as schematic illustrated in **Fig. 2**. Photo sensitive acrylic resin including alumina particles of 170 nm in average diameter at 40 percent in volume contents were supplied on a glass substrate with 15 μm in layer thickness by using a mechanical knife edge. And, two dimensional images of a visible ray were exposed through a digital micro mirror device with 2 μm in part accuracy. Through the layer by layer stacking under the computer control, the acrylic resin component with the alumina particles dispersion was obtained. The composite precursor was dewaxed at 600 °C for 2 hs and sintered at 1500 °C for 2 hs in air atmosphere. Subsequently, in order to create a plane defect between two diamond structures, a micro glass cell was also fabricated by the micro stereolithography. The quartz plates of 160 μm in thickness were inserted into the photosensitive acrylic resins during the stacking and exposing. Finally, the micro cell was put between the diamond photonic crystals, and the terahertz wave resonator was integrated successfully by using acrylic resin flames. These flames were glued together by using the photo sensitive resin and the light exposure solidification. Water solutions were infused through catheters connected on the top side of the micro resonance cell. The transmission properties of terahertz waves were analyzed by using the time domain spectroscopy (Advanced Infrared Spectroscopy, J-spec 2001 spc/ou). The intensity profiles of electric field in the resonator were simulated and visualized at the localized frequency by using the transmission line modeling method.

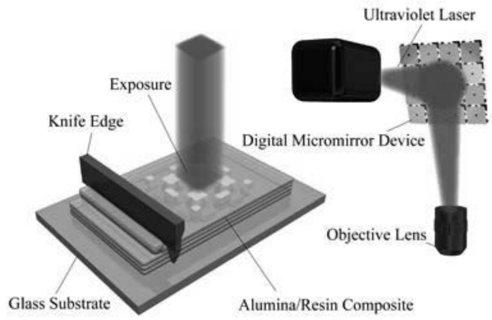

Fig. 2 A schematically illustrated micro stereolithography system of a computer aided manufacturing.

4. Results and Discussion

The photonic crystals composed of the acrylic lattices with the alumina particles dispersion were formed by the micro stereolithography. The spatial resolution was approximately 0.5 %. **Figure 3**(a) shows the alumina ceramic lattice with the diamond structure formed through the powder sintering. Cracks or deformations were not observed in the obtained components. Average linear shrinkage was 25 %. The lattice constant of the sintered diamond structure was 375 μm. Relative density of the ceramic sample reached 97.5 %. The integrated terahertz wave resonator is shown in Fig. 3-(b). Two diamond lattice components were attached on the quartz glasses, and these plates were arranged with 150 μm in parallel interval. Tolerance for the transmission direction of the electromagnetic wave converged within 5 μm. In the transmission spectrum through the resonator including distilled water, the localized mode of transmission peak was observed at 0.410 THz in the band gap. The measured peak frequency has good agreement with the simulated result by the transmission line modeling. The cross sectional profiles of the electric field intensity corresponding to the localized modes were simulated and visualized theoretically as shown in **Fig. 4**. Bright and dark areas indicate the high and low intensities of the electric field, respectively. The incident terahertz waves were resonated and concentrated strongly through the multiple reflections in the liquid cell between two diffraction lattices with the diamond structures. By replacing the water with ethanol, the localized frequency was shifted from 0.410 to 0.430 THz in frequencies due to the change of dielectric properties in the liquid area. From these results, the fabricated resonator is considered to be a promising candidate as the novel device to determine the dissolved components in the aqueous solution.

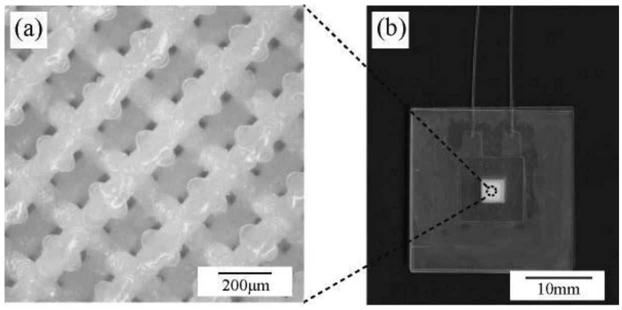

Fig. 3 The sintered alumina photonic crystal (a), and the fabricated terahertz wave resonator (b).

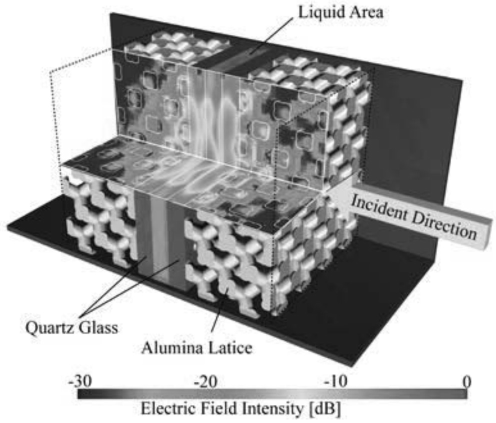

Fig. 4 A cross sectional distribution profile in electric field intensities inside of an photonic crystal resonator.

5. Conclusions

A terahertz wave resonator of ceramic photonic crystals with diamond structure was fabricated successfully by using micro stereolithography system. Transmission spectra were measured through the resonator including pure water or ethanol. Localized modes of sharp transmission peaks were observed in photonic band gaps. In a distribution profile of electric field intensity simulated by using a transmission line modeling, the localized modes were formed by the multiple reflections in the liquid cells between the diffraction lattices. Moreover, the localized mode peak was shifted clearly from higher to lower frequencies through replacing the pure water with the ethanol. The fabricated resonator is considered to be a promising candidate for novel devices to detect the compositional variations in aqueous phase environments.

Acknowledgements

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.

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