Stereolithic Additive Manufacturing of Ceramic Components with Micropatterns for Electromagnetic Wave Control

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Stereolithic additive manufacturing was developed to create bulky ceramic components with functionally geometric structures. In this process, two-dimensional (2D) cross sectional patterns were created through photo-polymerization with an ultraviolet laser drawing on spread resin paste. Ceramic nanoparticles and three-dimensional (3D) composite models were sterically printed by layer lamination though chemical bonding. The created precursor was dewaxed and sintered in an air to yield full ceramic components. This review describes the computer aided design, manufacture, and evaluation of artificial dendrite structures called photonic crystals with spatially ordered micro cavities. A periodic arrangement in dielectric constants can exhibit forbidden regions called photonic band gaps in the transmission spectra through electromagnetic wave diffraction. The permitted modes of transmission peaks at theoretically calculated frequencies can be selected via the introduction of point, linear, and planar structural defects into the artificial crystals. Ceramic processing using stereolithic additive manufacturing with high accuracy on the micrometer scale will be presented in this paper.

Keywords: Additive Manufacturing, Stereolithography, Ceramic Particles, Resin Paste.

1. Introduction

Three-dimensional additive manufacturing using stereolithography and nanoparticle sintering techniques for creating microcomponents with geometrically designed patterns composed of functional ceramics are examined in this review. Nanometer-size ceramic particles with dielectric, biological, or electronic properties were dispersed in photosensitive liquid resins, and mixed slurries were solidified using laser scanning [1-3]. These composite precursors were dewaxed and carefully sintered, yielding micro-lattice structures. These components contained dendrite structures with periodic arrangements of micro-lattices, which could be used to effectively control and modulate electromagnetic wave propagation and the flow of liquid material. The technological details of the free forming ceramic and applications of the functional dendrite structures will be reviewed along with computer-aided design, manufacture, and evaluation of the photonic crystals with micro-dendritic patterns. These artificial crystals can modulate propagating electromagnetic wave at far infrared frequencies. The use of ceramic additive manufacturing for dielectric micro devices will be discussed.

2. Laser Scanning Stereolithography

Three-dimensional geometric patterns were modeled using computer-aided design software. These graphic models were automatically converted to a stereolithicographic format and sliced into a series of two-dimensional cross-sectional planes with uniform thickness of 50 μm. The numerical data were automatically transferred to the stereolithicographic equipment, and raster patterns for laser scanning were automatically created. Figure 1 shows a schematic illustration of the fabrication process. Photosensitive acrylic resin, which included a 40% volume fraction of ceramic particles with 200 nm diameter, was spread on a flat metal stage using a mechanical knife edge. The thickness was automatically maintained at 50 μm by varying the slicing pitch. A 355 nm ultraviolet laser was used to scan the ceramic slurry in order to create cross-sectional planes with 5 μm accuracy at the part edges. The 100 mW laser beam was focused to a spot size with 100 μm diameter. After forming a solid pattern, the elevator stage was moved downward by 50 μm (corresponding to the layer thickness), and the next cross-section was stacked. Three-dimensional structures were fabricated by stacking two-dimensional layers. Green bodies could be observed and their part accuracies could be measured using a digital optical microscope. The formed models were dewaxed at 600 °C for 2 h.

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at a heating rate of 1.0 °C/min in air, yielding completed ceramic components after sintering. The microstructures of the sintered components were examined using a scanning electron microscope (SEM). The relative densities of these ceramic components could be measured using the Archimedean method.

3. Photonic Crystal

Periodically arranged dielectric structures are called photonic crystals [4-7]. They have photonic band gaps in which no electromagnetic wave can propagate. Localized modes appear in the band gap if the local periodicity is changed by introducing a defect [8-11]. This localization function of electromagnetic waves can be applied to various devices, including resonators, waveguides, and antennas. Three-dimensional photonic crystals with diamond structure are regarded as ideal photonic crystal, as they can prohibit propagation of electromagnetic waves in any direction in the band gap [12,13]. However, they are difficult to fabricate due to their complex structure. In our previous investigations, we succeeded in fabricating micrometer-scale diamond structures using a stereolithographic method based on computer-aided design and manufacturing (CAD/CAM) [14-19]. A photosensitive resin slurry with nanometer-sized ceramics was solidified continuously through laser beam scanning, which allowed accurate fabrication of dielectric lattice structures. We found that this resulted in the formation of a complete photonic band gap in the terahertz frequency range. We subsequently investigated how using the CAD/CAM process could be modified to the diamond lattice structure, thuds controlling terahertz wave propagation [20-24]. In the future, terahertz electromagnetic waves with micrometer-scale wavelengths may be applied to various types of novel sensors that can detect gun powder, drugs, bacteria in foods, microscopic cracks in electric devices, cancer cells in human skin, and other physical, chemical, and biological events [25-30]. In this paper, we will introduce a novel stereolithography was used to fabricate micro-diamond photonic crystals using the ceramic slurry with nanoparticles. In addition, resonance and localization of a terahertz waves in various structural defects will be examined based on results from electromagnetic simulations.

4. Band Gap Formation

Photonic crystals composed of dielectric lattices form band gaps for electromagnetic waves. These artificial crystals can totally reflect light with wavelength comparable to the lattice spacing by Bragg deflection, as shown in Fig. 2. Two different standing waves oscillating in air and in the 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, namely, introducing defects or varying the lattice spacing, can be used to control the propagation of light. The theoretical band diagram of the photonic crystal is drawn based on results from electromagnetic simulations.

5. Applications of Photonic Crystals

Figure 3 shows the expected use of photonic crystals for controlling electromagnetic waves in various wavelength ranges [32]. Nanometer-scale air guides formed in a photonic crystal will be used as a lightwave circuit in a perfectly reflective structure. When a light emitting diode is placed in an air cavity within a photonic crystal, efficient laser emission can be enhanced due to coherent localization function of electromagnetic waves can be applied in a terahertz crystal, efficient laser emission can be enhanced due to coherent resonance in the microcavity. Correspondingly, millimeter-scale periodic structures can effectively control microwaves. Directional antennas and filters composed of photonic crystals can be used in millimeter wavelength radar devices for intelligent traffic systems (ITS) and wireless communication. Photonic crystals can provide perfect reflection of millimeter waves and will be useful as barriers to prevent wave interference. Terahertz waves with micrometer wavelengths are expected to be applied as various types of sensors for detecting bacteria in foods, microscopic cracks in electronic devices and cancer cells in human skin. Micrometer-scale photonic crystals can be used in terahertz wave cavities, filters, and antennas.

6. Geometry of Artificial Crystals

Typical photonic crystal structures are shown in Fig. 4. A woodpile structure (a) with a simple stacked rod structure can exhibit a...
perfect photonic band gap. Photonic crystals composed of GaAs or InP were fabricated using semiconductor processing techniques [33]. A lightwave circuit (b) in the periodic structure of arranged AlGaAs pins was processed using electron beam lithography and etching techniques [34]. A layered structure (c) composed of Si and SiO₂, which have different dielectric constants, polarizes light and exhibits the superprism effect [35]. These layers were stacked via self-organized growth with alternating sputtering and etching. An inverse opal structure (d) is composed of air spheres with FCC crystal structure in a TiO₂, Si, Ge, or CdS matrix [36]. Initially, polystyrene spheres can be arranged through self-organization in colloidal solutions. Then, a slurry of the dielectric media was allowed to infiltrate the periodic structure, followed by sintering. The optical fiber (e) with photonic crystal structure can guide light efficiently along the central core [37]. Silica fibers and glass capillaries were bundled by wire drawing at high temperature. Diamond-type photonic crystals (f) composed of TiO₂, SiO₂, or Al₂O₃ can be fabricated using stereolithography and successive sintering. The wider perfect band gap corresponds to microwave and terahertz wave frequencies.

7. Design of Diamond Structure

Electromagnetic band diagrams of diamond structures were used to determine their geometric parameters using the PWE method. The dielectric constant of the alumina lattice was set to 10 in the calculation. Figures 5 (a), (b), and (c) show a unit cell of the diamond structure, the definition of the aspect ratio, and the calculated complete band gap width as a function of the aspect ratio, respectively. According to Fig. 4 (c), the band gap is widest when the aspect ratio is 2.0. A wider band gap leads to easier localization of electromagnetic waves in the presence of a defect. When the aspect ratio is 1.5, the lattice rods become thick and the band gap width is approximately 84% of that when the aspect ratio is 2.0. Thus, the aspect ratio of the diamond structure was designed to be 1.5. The lattice constant was 500 μm. The entire structure was 4×4×2 mm³ and was composed of 8×8×4 unit cells.

8. Measurement of Electromagnetic Wave

In recent years, terahertz waves have received attention as they have many interesting features that make them applicable in various fields, including materials, communication, medicine, and biology. It is possible to detect gun powder, and ceramic blades hidden in bags, clothes, and envelopes using terahertz waves since they can penetrate plastic, paper, and clothes without causing radiation damage to living bodies. It is also possible to identify toxic drugs from their spectral fingerprint or absorption spectra. Moreover, they can be used to distinguish cancerous cells from healthy cells due to the different absorption rates [38-39]. Terahertz wave attenuation of transmission amplitudes through diamond photonic crystals was measured using a terahertz time domain spectrometer (TDS) apparatus (Advanced Infrared Spectroscopy Co. Ltd., Japan, Pulse-IRS 1000). Figure 6 shows a schematic illustration of the measurement system. Femtosecond laser beams were used to irradiate a microscale emission antenna formed on a semiconductor substrate to generate terahertz wave pulses. The terahertz waves were transmitted perpendicularly through the micropatterned samples. The dielectric constants of the bulk samples were measured through phase shift counting. Diffraction and resonance in the dielectric pattern were theoretically calculated using a transmission line modeling (TLM) simulator (Flomerics, UK, Microstripes Ver. 7.5) and a finite difference time domain (FDTD) method [41].
with dimensions on the order of hundreds of micrometers. The lattice constant and linear shrinkage were measured with the DOM; the lattice constant was 375 μm, linear shrinkage on the horizontal axis was 23.8%, and that on the vertical axis was 24.6%. It was possible to obtain uniform shrinkage by designing a structure appropriately elongated along the vertical direction to compensate for gravity. Deformation and cracking were not observed. The relative density of the alumina microstructure was 99%. SEM images of the structure are shown in Fig. 9 (b). A dense alumina microstructure was formed, and the average grain size was approximately 2 μm. The measured dielectric constant of the lattice was about 9. The forbidden band along the <111>, <100>, and <110> crystal directions in the transmission spectra was analyzed, and the dielectric constant of the alumina lattice (9.8) was measured using terahertz time-domain spectroscopy (THz-TDS). The higher and lower edges of the gap regions were plotted in the calculated PWE band diagram. The measured results agree well with the calculated results, and a perfect photonic band gap was found to range from 0.4 to 0.47 THz. The dense alumina lattices had a coordination number of four. We verified that light propagation was isotropic in these structures. These results show that the lattice structures shrunk equally in all crystal directions without any dimensional deviations during dewaxing and sintering.

10. Point Defect Introduction

A diamond structure containing a cubic air defect with the same dimensions as the unit cell is shown in Fig. 10, and the resulting transmission spectrum along the Γ-X <100> direction is shown in Fig. 11. Two peaks were observed in the band gap at 0.42 and 0.46 THz. The measured peak frequencies agree well with the...
TLM simulation results shown in Fig. 12. The first and second peaks in Fig. 11 are labeled mode A and mode B, respectively. The electric field distribution for each modes was simulated using TLM. Figures 13 (a) and (b) show cross sectional images of these distributions. The red area in the images indicates high electric field intensity, whereas the blue and green area indicates low electric field intensity. Thus, one can see that mode A concentrated the field (half wavelength) with an antinode in the cube, whereas mode B concentrated the field on the sides of the cube with a node in the cube. Therefore, it was confirmed that introducing a defect into the structure localized the terahertz waves.

11. Twinned Lattice Arrangement

Alumina photonic crystals with twinned diamond lattices can be formed successfully through micro-stereolithography and powder sintering. As shown in Figs. 14 (a) and (b), the defect interfaces of the (100) and (111) planes are sandwiched between mirror-symmetric domains with four and three periods, respectively. These periods can be optimized with TLM, yielding clear localized modes with sharp transmission peaks in the band gaps. The transmission spectra through the twinned crystals can be analyzed using THz-TDS. As shown in Figs. 15 (a) and (b), localized mode peaks with transmission intensities of 22% and 38% exist at 0.414 and 0.409 THz through the (100) and (111) defect interfaces, respectively. These localized modes are included in the perfect photonic band gap. Figure 16 shows the cross-sectional images of the electric field intensity at the localized frequencies simulated by TLM. The incident electromagnetic waves should resonate and be strongly localized due to the multiple reflections in the twinned defect interfaces between the mirror-symmetric diffraction lattices. The amplified electromagnetic waves can propagate to the opposite side, and transmission peaks should form in the band gaps. An electromagnetic wave can strongly concentrate in the vicinity of defect interfaces in the (111) plane compared with the (100) plane. These simulated results agree with the disparity in the measured peak intensities of the localized modes, as shown in Fig. 16.
12. Terahertz Wave Resonator

In order to obtain a plane defect between two diamond structures, a microsized glass cell was fabricated using micro-stereolithography. Figure 17 (a) schematically illustrates the components of the resonant cell. Quartz plates with 160 μm thickness were inserted into the photosensitive acrylic resins during stacking and exposing. Finally, the resonant micro-cell was placed between the diamond-structured photonic crystals, and the terahertz wave resonator was integrated using acrylic resin frames, as shown in Figure 17 (b). These frames were glued together with photosensitive liquid resin and solidified by exposure to ultraviolet light. Water solutions were injected through catheters connected on the top side of the resonance cell. The integrated terahertz wave resonator is shown in Fig. 18. The two diamond lattice components were attached on the quartz plates. The two plates were subsequently arranged parallel with 150 μm spacing; the cell capacity was 0.02 mL. The tolerance for the transmission direction of electromagnetic waves was within 5 μm. Figure 19 (a) shows the measured transmission spectra for the resonators after injection of distilled water or ethanol. In the case of distilled water, two localized modes were observed with transmission peaks in the photonic band gap at 0.410 and 0.491 THz. In the case of ethanol, an amplification peak was observed at 0.430 THz. The measured band gap ranges and the experimental localized mode frequencies agree well with the simulated transmission line modeling results shown in Fig. 19 (b). In the transmission spectrum through the water-filled photonic crystal resonator, localized modes corresponding to the higher and lower peak frequencies are defined as mode A and mode B, respectively; the localized mode peak in the transmission spectrum through the ethanol is defined as mode C.

13. Conclusion

Three-dimensional photonic crystals with a micrometer-scale diamond-type structure were constructed from acrylic resin loaded with alumina nanoparticles using stereolithographic additive manufacturing. The dewaxing and sintering process parameters were carefully optimized, yielding dense alumina micro-lattice structures. The sintered photonic crystal of alumina formed a complete band gap in the terahertz region. Localized modes were obtained by introducing a point defect in the form of a cubic air cavity, and a plane defect between twinned diamond structures. These results agree well with the simulation results. To create terahertz wave resonators, a microsized glass cell was placed between two photonic crystals composed of alumina lattices with diamond structure. Transmission spectra were measured through the photonic crystal resonators filled with pure water or ethanol, and sharp transmission peaks corresponding to localized modes were observed in the photonic band gaps. This photonic crystal resonator is promising for use in novel devices for detecting variations in natural aqueous environments.

References
