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Multi-ceramic coupling diamond-structured photonic crystals based on rapid prototyping technology and its controllable microwave electromagnetic forbidden gap properties

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Abstract

The multi-ceramic coupling diamond-structured photonic crystals containing alumina and yttria simultaneously were successfully fabricated by rapid prototyping based on stereolithography and multi-step gel-casting process. The lattice constant of the photonic crystal structures was chosen as 7 mm and the measured forbidden gap range lies between 27.2 GHz and 34.9 GHz. The gradually varied solid loading in volume of Al_2O_3 powder and its controllable electromagnetic forbidden gap properties were investigated in such photonic crystals. It was found that, as the solid loading of Al_2O_3 powder increased, the electromagnetic forbidden gap width gradually increased and the center frequency shifted to a lower frequency when electromagnetic waves transmitted along the coupling direction of photonic crystals. When the solid loading reached 60 vol%, electromagnetic forbidden gap of the photonic crystals was observed from 27.2 GHz to 34 GHz, and the forbidden gap width was 6.8 GHz which was 126.4% of that of the yttria photonic crystal (the forbidden gap from 30.9 GHz to 35.9 GHz) and 115.3% of that of the alumina photonic crystal (60 vol%, the forbidden gap from 26.4 GHz to 32.3 GHz). These results indicate that a diamond-structured photonic crystal with multi-ceramic coupling could effectively expand the electromagnetic forbidden gap width and may be beneficial for applications of photonic crystals in device. Moreover, this work offers a rapid prototyping technology to three-dimensional photonic crystals with considerable flexibility of materials choice.

Keywords: A. Shaping; C. Electrical properties; Photonic crystals; Multi-ceramic coupling; Rapid prototyping.

1. Introduction

Diamond-structured photonic crystals (PCs) generate a complete bandgap to inhibit the propagation of electromagnetic waves in all directions [1,2]. The novel electromagnetic (EM) forbidden gap properties make PCs of great interest of scientists due to numerous potential applications [3–6]. Since the first diamond-structured PC was discovered, researchers have pursued the task of obtaining PCs possessing larger EM forbidden gaps and/or structures with large EM forbidden gaps that are easier to fabricate. Most of the research efforts on the diamond structure has focused on the structural parameters modifications and varying the dielectric constant in order to get the wider EM forbidden gap [7–10]. However, little work has been done on broadening the EM forbidden gap by gradient dielectric constant induced by multi-ceramic coupling (MCC) in a PC.

Various sophisticated techniques have been used for fabricating diamond-structured PCs [11–14]. But the techniques are complex, expensive and time consuming, and these are more suitable for operations at terahertz and optical wavelengths and less suitable for the MCC PCs at microwave frequencies. We proposed a rapid prototyping method based on stereolithography and multi-step gel-casting process [15–17] for the easy fabrication of the MCC PCs.

In the present work, diamond-structured PCs using separately yttria slurry and alumina slurries with different solid loading in volume were firstly fabricated and their EM forbidden gap

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properties were experimentally investigated. The lattice constant of the PCs was fixed at 7 mm. Experimental results were compared with the simulation results by Finite integration technique (FIT). Then the MCC PCs with the lattice constant of 7 mm containing alumina and yttria simultaneously were also fabricated. This method results in a gradient dielectric constant distribution. As a result, the structures would have a gradually varying EM forbidden gap when solid loading of alumina was varied and that of yttria kept constant. The MCC PC could serve as a new type of controllable PC based on varying of the solid loading of alumina. The variations of the EM forbidden gap profiles were investigated along the coupling direction of the PCs.

2. Experimental procedure

The fabrication method of the diamond-structured PCs was chosen as rapid prototyping based on stereolithography and gel-casting process in this research.

First, the PC models were designed based on the electromagnetic simulation results and fabricated using a stereolithography machine (Product SPS-450B, Hengtong Co. Ltd, Shaanxi, China). This stereolithography system used a laser beam spot of 100 μm in beam diameter with a scanning speed of 90 mm/s in operation and a single layer thickness of 100 μm. The accuracy of the part obtained was within 0.1%.

Second, the gel containing ceramic slurry was prepared to cast into PCs molds. The casting alumina slurry was prepared firstly. In this process, premixed solution was prepared by dissolving organic monomer (CH_3CONH_2, AM) and cross-linking agent ($C_7H_{10}N_2O_2$, MBAM) in proper amount of deionized water. After adding sodium polyacrylate (25 percent of solid powder in mass) to the premixed solution, Al_2O_3 powder was dispersed into the premixed solution progressively. Alumina ceramic slurries with high solid loading (50 vol%, 55 vol%, 58 vol%, 60 vol% respectively) were prepared after ball milling for 3 h. After adding initiator (ammonium persulfate) and catalyst ($C_6H_{16}N_2$, TEMED) into the ceramic slurries, the ceramic slurries were stirred in the vacuum for 5 min to degas. The yttria ceramic slurry (40 vol %) was prepared in the same process, and then the alumina and the yttria ceramic slurry was smoothly poured into their molds. Meanwhile, the alumina slurries and the yttria slurry were also poured into the designed models of MCC PCs successively (Fig. 1 (a)). Then the ceramic slurries were in situ polymerized. The parts could be partially unmolded and then were dried in the freeze drying oven for 36 h under a vacuum degree of 3 Pa (Product DTY-1SL, Vacuum Freeze Dryer, Detianyou Technology co., Beijing, China). In the end, the samples were sintered at 1530 °C for 2 h. The resin prototypes were burned out and ceramic PCs of high quality were obtained. Fig. 1 (b) and Fig. 1 (c) shows the green and fabricated sample of multi-ceramic coupling PC, respectively.

The lattice constant a was 7 mm and the air sphere radius r was chosen to be $0.28a$ since the EM forbidden gap lies in the frequency region of 18–40 GHz according to the simulation results by FIT. The dimension of the diamond structure was 49 mm × 42 mm × 42 mm. The yttria PC and the alumina PCs (50 vol%, 55 vol%, 58 vol%, 60 vol% respectively) were fabricated. To investigate the EM forbidden gap properties of the MCC PCs, several coupling PCs with the solid loading of the alumina power of 50 vol%, 55 vol%, 60 vol% respectively and the same solid loading of the yttria power(40%) were also fabricated. The coupling direction of MCC PCs is along the Γ-X < 1 0 0 > direction.

Microfocus computed tomography (Micro-CT) (Y.cheetah, YXLON International GmbH, Hamburg, Germany) was used to evaluate structural array of alumina PC. The transmission properties of PCs were measured in the frequency of 18–40 GHz using a free space measurement system with a network analyzer (Agilent E8363B, Agilent Technologies Inc., Palo Alto, CA).

3. Results and discussion

Fig. 2 shows three-dimensional reconstruction images of the alumina PC (55 vol%) using Micro CT analyses. No deformation and crack were observed, and the dielectric unit cells had a good connection to build three-dimensional structure in Fig.2 (a). A periodic array structure can be clearly seen in Fig. 2 (b). The linear shrinkage ratio is approximately 7.5% in every axis. The volumetric shrinkage is about 20%.

Fig. 3 shows the transmittance of electromagnetic wave through the yttria PC and the alumina PCs. Solid lines show simulated band edges and solid squares show the measured band edges. The frequency area between higher and lower band edges shows the EM forbidden gap width. The EM forbidden gaps are taken at −10 dB. The measurement result demonstrates an electromagnetic gap between 30.9 GHz and 35.9 GHz of the yttria PC in Fig. 3 (a). Comparing the experimental result with the simulation result obtained by FIT, there is good agreement between the two. Fig. 3 (b) shows the EM forbidden gap variation of the alumina PCs against solid loading in volume with Al_2O_3 powder along the Γ-X < 1 0 0 > direction. In all cases, the structure parameters were kept unchanged and solid

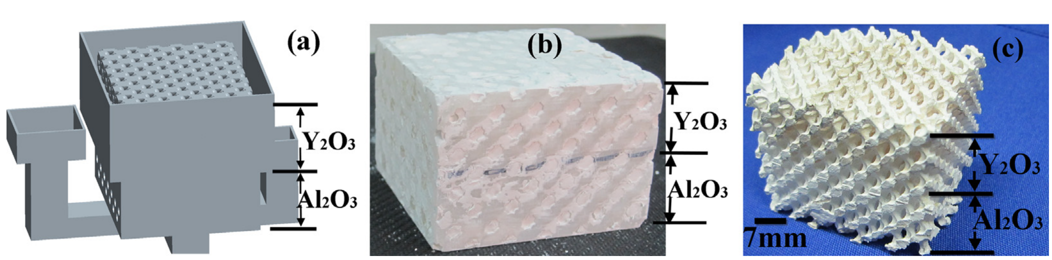

Fig. 1. The multi-ceramic coupling photonic crystal by rapid prototyping method. (a) the designed model, (b) the green sample and (c) the fabricated sample.