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Diamond electromagnetic band gap structure based on $Bi(Nb_{0.992}V_{0.008})O_4$ ceramic

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Abstract Three-dimensional (3D) diamond structure electromagnetic band gap (EBG) structures containing high-K $Bi(Nb_{0.992}V_{0.008})O_4$ (BVN) ceramic, fabricated by rapid-prototyping (RP) and gel casting methods, were investigated. The simulations based on finite element method (FEM) were employed to model the band structures. High-K $Bi(Nb_{0.992}V_{0.008})O_4$ ceramic was made into gel to cast into the diamond structure molds fabricated by rapid-prototyping method. Then the green bodies were sintered at 900 °C to obtain well densified EBG samples. The transmission characteristics of the EBG structures were measured by transmission/reflection (T/R) methods using a vector network analyzer. Wide complete band gap was observed in the transmission characteristics from 10.08 to 12.59 GHz and it agreed well with the simulation results, which was from 10 to 12.19 GHz.

1 Introduction

In recent years, a lot of work has been carried out on artificial electromagnetic materials such as photonic crystals [1], electromagnetic band gap (EBG) structures [2, 3] etc., which are broadly classified as metamaterials. The EBGs, which are arranged periodically with dielectric materials, can be considered as a kind of photonic crystals working at microwave range. If an EBG structure prohibits the propagation of electromagnetic waves traveling in any direction, it is considered to have a complete band gap. An EBG structure can generate a complete band gap only when it satisfies the following conditions: (1) a high permittivity contrast between the constituent dielectrics of the structure [4]; (2) nearly spherical in shape of the first Brillouin zone in reciprocal space [5]. Hence, only a three-dimensional (3D) EBG structure can generate a complete band gap. Various 3D EBG structures such as Yablonivite [6], woodpile [7–9], opal [10], and diamond structures [11] have been fabricated and experimentally investigated. Among all these EBGs, the diamond structure is considered as an ideal candidate that can generate a complete band gap.

In this work, a new route to fabricate diamond 3D EBG of ceramics using rapid-prototyping (RP) method together with gel casting and sintering techniques was proposed. Considering $Bi(Nb_{0.992}V_{0.008})O_4$ (BVN) ceramic's good microwave dielectric properties and its application in antennas substrate [12, 13], it was chosen as the high-K part of the EBGs. The simulations, the fabrication method as well as the sintering process, and the band gap formation of the diamond structure EBG of BVN were reported and investigated.

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2 Experimental

The proposed procedure for the fabrication of 3D EBG is shown in Fig. 1. First, the CAD models of the EBGs with inverse diamond structure expanding from the unit cell were generated by Ansoft HFSS. The Wigner–Seitz unit cell and the irreducible Brillouin zone of the diamond

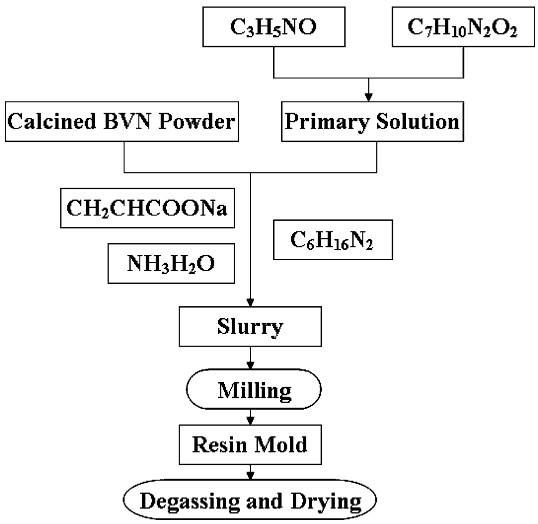


Fig. 1 Flowchart of the fabrication process

structure are shown in Fig. 2. The CAD models of boxes to accommodate the EBGs inside with the size rightly matching the EBGs were also made by Ansoft HFSS. The EBG and the box molds were then fabricated by RP machine according to the designed CAD models.

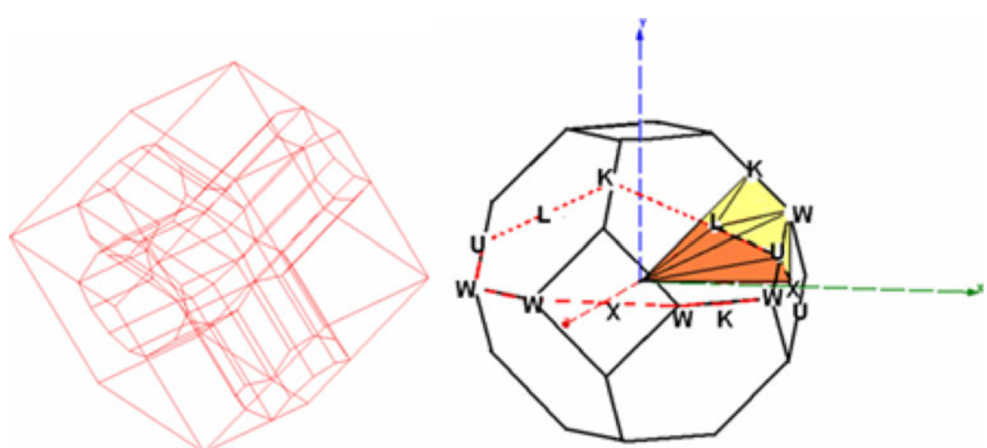
The liquid resin of a photosensitive epoxy was used to fabricate the inverse diamond structure molds and boxes by a RP machine (Hengtong, SPS450B, Xi'an, China). A laser beam was scanned across the surface of the epoxy resin based on the CAD data. The epoxy was solidified layer by layer through photopolymerization with single layer as thin as 100 μm, eventually forming a 3D structure. The diameter of the laser spot is 100 μm and the scanning speed is 90 mm/s. The dimensional accuracy of the structure was within 0.1%.

High-K dielectric ceramic BVN powders were prepared via traditional solid state reaction method as described in our previous work [12]. The gel-casting method was employed in this work to enhance the strength of the green body and decrease the defect in the EBG structures. The primary solution which is composed by C_3H_5NO and $C_7H_{10}N_2O_2$ mixed well with water was prepared and the weight percentage of the organic compound is 20 wt%. The BVN powder was added into the primary solution and the dispersant $CH_2CHCOONa$ was gradually added in. The weight percentage of the BVN ceramic powder is 75 wt%. A little $NH_3 \cdot H_2O$ was dropped into the slurry to adjust the pH value to 9–10. The slurry was milled for 3 h after the activator $C_6H_{12}N_6$ was added. Then the evocator $(NH_4)_2S_2O_8$ was added into the slurry. The gel was prepared well by now. The viscosity of the slurry was measured using a viscosimeter (Brookfield, LVDV-C, MA, USA). The viscosity of the slurry in this work was 600 cP. After the diamond structure molds and the boxes were fabricated, the gel slurry was cast into the box to about a half volume. Then putting the EBG molds into the boxes and pressing the systems slightly, the slurry gradually permeated into the interstices of the diamond structure molds. The samples were kept still for 2 h and then evacuated under −0.09 MPa to degas. The samples were dried in air at room temperature for 24 h.

Removing the crust boxes, the EBG green bodies were obtained, which were composed of epoxy resin inverse diamond lattice and the diamond lattice high-K BVN ceramic part. The thermal decomposition of the epoxy resin was analyzed by a thermoanalyzer system (TA, TQ600, New Castle, USA) at a heating rate of 10 °C/min. The temperature was slowly increased to 450 °C and kept for 4 h to burn off the epoxy molds, leaving behind a ceramic lattice with diamond structure. The samples were sintered at 900 °C for 2 and 3 h at last, respectively.

The EBG samples were measured by transmission/reflection (T/R) methods with a network analyzer (HP 8720ES, Hewlett-Packard, Santa Rosa, CA). In the T/R method, the sample under test is inserted into a segment of transmission line, and the permittivity and permeability of the sample are derived from the scattering equations. T/R

Fig. 2 The Wigner–Seitz unit cell and the irreducible Brillouin zone of the diamond structure lattice



methods were used in this work to obtain the transmission parameters S_{21} of the EBG samples in order to study its propagation properties.

3 Results and discussions

Figure 3 shows the photographs of two BVN EBGs samples sintered at 900 °C for 2 h (Fig. 3a) and 3 h (Fig. 3b), respectively. It is clear that the designed diamond structure was maintained well after sintering. The density of the lattice rod is 5.7 g/cm^3 when sintered at 900 °C for 2 h and 6.5 g/cm^3 for 3 h. Dense sintering is important to obtain solid EBGs. It is obvious that the sample sintered for 3 h is much denser than the one sintered for 2 h. The surface of the sample sintered for 3 h is much smoother than the one sintered for 2 h. This result indicates that, the sintering time influences the EBG samples and the longer sintering time can result in good EBG structures. Inevitably, the sintering process will cause the shrinkage of the EBG structures. The average shrinkages of the EBG samples sintered at 900 °C for 2 and 3 h are about 12 and 15%, respectively.

The inset of Fig. 3 shows the SEM photos of the ceramic samples sintered for 2 h (the inset of Fig. 3a) and 3 h (the inset of Fig. 3b) respectively. The images reveal the influence of the sintering time on the ceramic microstructures. For ceramic sample sintered for 2 h, homogeneous dense microstructure can be observed and the grain size lies between 1.5–3 μm. When sintering time increased to 3 h, dense microstructure can also be obtained. However, many grains grew bigger and grain size reached about 7 μm. This indicates a start of secondary growth of grain. From our previous study [14], the sintering time has only weak influence on the microwave permittivity and a little influence on the microwave dielectric loss after ceramic sample was sintered dense. The sample sintered for 3 h with higher density was measured by transmission/reflection (T/R) methods.

The transmission curve exhibits an obvious band gap property with a frequency range from 10.08 to 12.59 GHz for the EBG structure is shown in Fig. 4. The simulation results based on FEM (Ansoft HFSS 11.0 version) is shown in the inset of Fig. 4. The edges of the underside and upside of the band gap all increase slightly compared with the simulation results. The underside edge of the band gap shifts from the simulation result 10 to 10.08 GHz in the measurement and the upside shifts from the simulation result 12.19 GHz to the measured result 12.59 GHz. Accordingly, the center frequency of the band gap increases and width of the band gap also increases 0.32 GHz in comparison with the simulation results, which are probably caused by the shrinkage during the sintering process. The average shrinkage of the EBG sample sintered at 900 °C is 15% and this shrinkage leads to the decrease of the lattice constant. Because of the decrease of the dimension of the EBG structure, the frequency range of the band gap shifts to the higher frequency range. The transmission scattering parameter S_{21} drops more than −40 dB within the band-gap, which indicates that over 99% electromagnetic wave will be reflected in the band gap frequency range. At frequencies below and above the

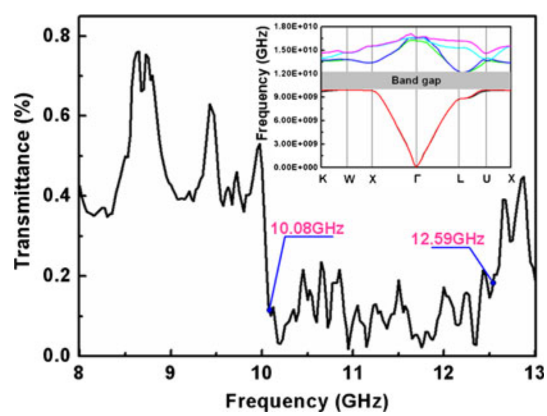


Fig. 4 The band structure simulation results of the EBG and the measured transmission spectrum of the electromagnetic wave

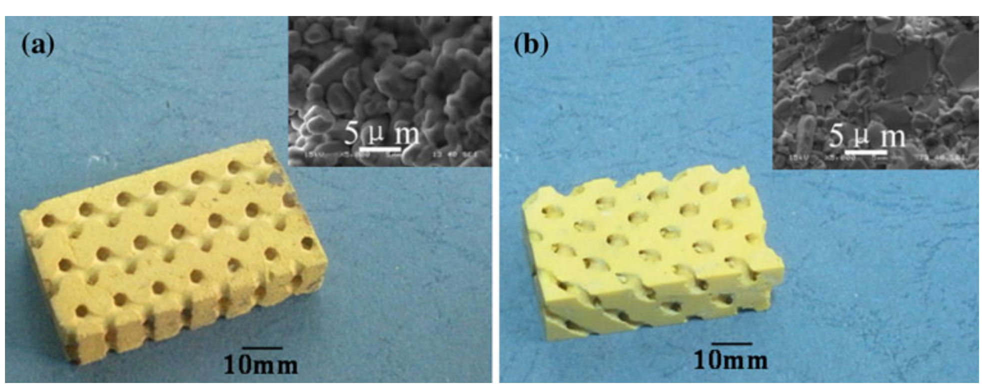


Fig. 3 The final diamond structure BVN EBG samples and SEM photos of the $Bi(Nb_{0.992}V_{0.008})O_4$ EBG structures sintered at 900 °C for 2 h (**a**) and 3 h (**b**)

stop band, the transmission exhibits ripple structures, with an average value around −12 dB, which means the electromagnetic waves can propagate freely. It is also noteworthy that the band gap edge is clear and sharp. Although along the direction of the electromagnetic wave propagation the EBG structure has only five unit cells, it can be found that the microwave is effectively reflected by the EBG structure. Below the band gap frequency range and in the band gap there are several resonant peaks, and this is probably caused by the intrinsic defects produced during the sintering process. However, these defects do not give too many effects on the propagation of the electromagnetic wave in the EBG structures. The band gap property is still very good.

4 Conclusions

In summary, a method using $Bi(Nb_{0.992}V_{0.008})O_4$ ceramic to fabricate 3D diamond structure EBG structures was proposed. Rapid-prototyping technique was used to fabricate the accurate EBGs and the flexible adjusting of the constituent materials. The gel casting method was employed to increase the strength of the green body. The green body was sintered at 900 °C to obtain the strong ceramic EBG. The band gap property of the EBG structure was experimentally confirmed by T/R method measurements. Complete band gap has been observed from 10.08 to 12.59 GHz for the EBG structure. The results agreed well with the theoretical simulations by FEM calculations. The RP method in making EBGs flexibly shows an effective way for EBGs manufacturing in perspective applications and high-K microwave dielectric ceramics can play an important role in the EBGs application.

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