

Photonic bandgap properties of void-based body-centered-cubic photonic crystals in polymer

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Abstract: We report on the fabrication and characterization of void-based body-centered-cubic (bcc) photonic crystals in a solidified transparent polymer by the use of a femtosecond laser-driven microexplosion method. The change in the refractive index in the region surrounding the void dots that form the bcc structures is verified by presenting confocal microscope images, and the bandgap properties are characterized by using a Fourier transform infrared spectrometer. The effect of the angle of incidence on the photonic bandgaps is also studied. We observe multiple stop gaps with a suppression rate of the main gap of 47% for a bcc structure with a lattice constant of 2.77 μm , where the first and second stop gaps are located at 3.7 μm and 2.2 μm , respectively. We also present a theoretical approach to characterize the refractive index of the material for calculating the bandgap spectra, and confirm that the wavelengths of the observed bandgaps are in good correlation with the analytical predictions.

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1. Introduction

Photonic bandgap (PBG) materials are expected to revolutionize the fields of integrated optics and micro-photonics because they can control the behaviors of the light in such a way as semiconductors control the behaviors of the electrons [1,2]. Three-dimensional (3D) PBG structures with a complete bandgap in the transmission spectrum are a prerequisite for many useful applications such as thresholdless lasers and radiationless photonic crystal waveguides [3]. To achieve 3D complete PBG, high refractive index materials like silicon must be used. In fact, not all applications of photonic crystals suggested so far require the use of 3D complete PBGs. One of such examples is the familiar superprism effect in photonic crystals based on the specific dispersion properties enhanced at certain directions and wavelengths in comparison with a common optical prism that could be useful for governing light in on-chip all-optical photonic circuits [4,5]. In general, 3D periodic structures display more complicated bandgap properties than their two-dimensional (2D) counterparts and possess more flexibility in applications where the existence of partial stop gaps and a strong suppression rate of some wavelengths are important. Therefore, 3D photonic structures made of low refractive index materials such as polymers and glasses seem to be quite useful in photonic applications.

As has already been demonstrated, photonic crystals with air spheres in a dielectric material can possess larger bandgaps in comparison with photonic crystals created by a matrix of dielectric spheres in air [6]. Ultrafast laser-driven microexplosion method has been proved to be a promising way to fabricate such 3D void-based photonic crystals with flexible lattices [7-13]. By tightly focusing femtosecond laser light into a solid transparent material, microexplosion occurs at a focal point where the material is ejected from the center forming a void cavity surrounded by a region of the compressed material that processes a refractive index higher than that of the original material [14,15]. Using this method, we have successfully fabricated void-based photonic crystals with diamond and face-centered-cubic (fcc) lattices [7,8]. However, there is a discrepancy of the PBG position between the observed results and those predicted by the simple Bragg formula due to the refractive index change. Although the refractive index change has been considered for void-channel-based woodpile PBG structures [16], such a model is not applicable in the void-dot-based structures.

In this paper, we describe the impact of the refractive index change due to the microexplosion on PBGs of the body-centered-cubic (bcc) photonic structures and provide an accurate description of the PBG spectra using the block-iterative frequency-domain method [17]. The reason why we chose bcc structures is that bcc structure has a relative simple band structure and it is therefore easy to make a comparison between experiments and theory. In addition, bcc photonic structures with air spheres in a dielectric matrix have never been

demonstrated elsewhere so far. The fabrication process and bandgap properties are thus presented in the first part of this paper.

2. Materials and experimental setup

The material used in this work is a transparent photosensitive optical adhesive NOA 63 (Norland Product Inc., USA). The resin is shaped into a thin film with a thickness of approximately 100 μm with a standard cover slip on top of it and pre-cured by use of ultraviolet light. The experimental setup is similar to that described earlier [7]. A 740 nm femtosecond laser light beam with a pulse width of ~ 80 fs is generated by a Tsunami femtosecond oscillator (Spectra-Physics, USA). The laser light beam is then expanded by an inverse telescope system and tightly focused by a 1.4 numerical aperture, 60 $\times$ oil-immersion objective. A shutter is used to control the laser light power. The fabrication process can be *in situ* monitored by a CCD camera. The sample is affixed to a 3D piezoelectric scanning system (PI, Germany) that is controlled by a computer. By controlling the exposure time and power, we can control the size of the void dots [7] and therefore control the filling factor of the fabricated photonic structure. The bcc crystals are fabricated layer by layer with the deepest layer first. The start position of the deepest layer is calculated beforehand so that the top layer can be located at 5 μm below the top surface.

3. Experimental results

Figure 1 shows schematically a unit cell of the bcc lattice. In the [100] direction of the lattice indicated in the figure, parallel planes of the lattice points are fabricated in the form of a square lattice. These are built up with a periodicity of two, offset by the distance $\sqrt{1/3}a$ in the x - and y -directions. Adjacent layers are separated by the distance $\sqrt{1/3}a$. Structures consisting of 28 layers of void dots with the top layer 5 μm below the surface have been fabricated by applying a power of 40 mW for an exposure time of 10 ms. The average diameter of the fabricated spherical void dots is approximately 1.5 μm . Due to a spherical aberration caused by a slight refractive index mismatch between the polymer ($n=1.56$) and the immersion oil ($n=1.52$) [18], the void dots are slightly smaller at a larger depth [8]. The light penetrates through the photonic crystals perpendicular to the polymer film in both the fabrication and the infrared transmission spectra measurement processes but with a significant restriction in the stop gaps.

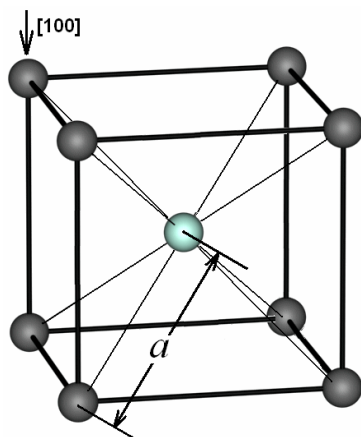


Fig. 1. Sketch of a 3D bcc structure with a lattice spacing parameter of a and the stacking direction [100] marked by an arrow.

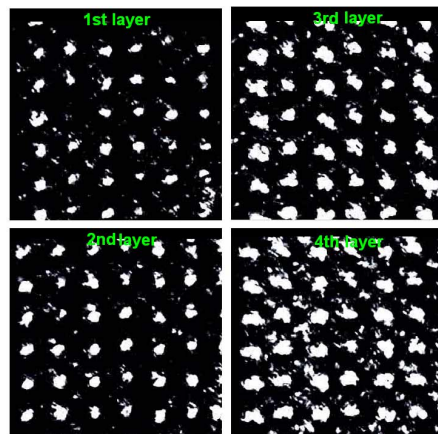


Fig. 2. Confocal reflection microscope images of the top four layers of a bcc structure stacked in the [100] direction with a lattice constant of 3.46 μm . A movie (1.62 MB) of the confocal reflection images of the top 6 layers.

The change in refractive index around the void dots has been examined using a reflection confocal microscope (Fluoview, Olympus, Japan). Figure 2 shows the images of the top four layers of void dots of a bcc structure with the lattice constant of $3.46\text{ }\mu\text{m}$ recorded by a confocal reflection microscope. The strong reflection signal from the dots indicates a high refractive index contrast between the fabricated and un-fabricated region, which verifies the generation of voids at the focal point [18]. In the visualization we see that each layer is composed of a square lattice as is to be expected for a bcc lattice. Comparing the images of the first and second layers, there is a $\sqrt{1/3}a$ shift in both the x - and y -directions. Because a bcc structure has a periodicity of two, the void dots pattern should repeat every second layer. Therefore, one can see that the pattern of the void dots in the first and third layers are the same, and for the same reason the second and fourth layers are the same. A movie that is linked to Fig. 2 shows a change of the confocal reflection signal as the focal point moves from the top layer to the 6th layer deep in the structure. It can be seen that the image quality degrades along the depth, which is caused by strong scattering of upper layers.

The PBGs of the fabricated structures of void dots are examined by measuring the transmission spectra with a Nicolet Nexus FTIR spectrometer [7]. The red curve in Fig. 3(a) shows the transmission spectrum of a 28-layer bcc structure stacked in the [100] direction with a lattice constant of $3.12\text{ }\mu\text{m}$. One can see that there is a wide trough from $2.8\text{ }\mu\text{m}$ to $4.5\text{ }\mu\text{m}$ with the maximum suppression rate of approximately 25%. To reduce the range of the incidence angle, an adjustable aperture has been attached to the FTIR objective, resulting in a hollow light cone with an adjustable outer angle of incidence and an inner angle of 10° . When reducing the aperture to achieve 17.3% of the total illumination (when without aperture) which corresponds to an outer angle of incidence of $\sim 19^\circ$, the trough in the transmission spectrum becomes narrower ($0.56\text{ }\mu\text{m}$ in a full width at half maximum, FWHM) and deeper (with a suppression rate of 39% at $4.1\text{ }\mu\text{m}$), as shown in the green curve in Fig. 3(a). Further reducing the aperture size to achieve 5% of the total illumination which corresponds to an outer incidence angle of $\sim 16^\circ$, the FWHM reduces to $0.45\text{ }\mu\text{m}$ and the suppression rate increases to 47% at $4.15\text{ }\mu\text{m}$. We also notice a small gap at $2.4\text{ }\mu\text{m}$ that corresponds to a higher-order gap. From the influence of the aperture size on the transmission spectra we see indications that the PBG properties are dependent on the photonic crystal directions.

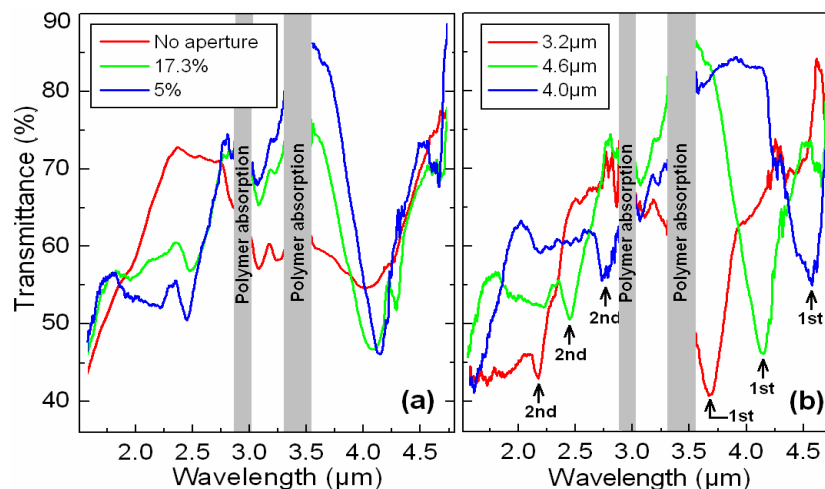


Fig. 3. (a) A variation of the transmission spectra of a bcc structure with a lattice constant of $3.12\text{ }\mu\text{m}$ stacked in the [100] direction when different apertures are used. (b) Transmission spectra of bcc structures stacked in the [100] direction with lattice constants of $2.77\text{ }\mu\text{m}$, $3.12\text{ }\mu\text{m}$, and $3.46\text{ }\mu\text{m}$. The first and second gaps are marked.

To confirm that the PBG wavelength should be in proportion to the lattice constant, we fabricate several bcc structures stacked in the [100] direction with different lattice constants. Figure 3(b) shows the transmission spectra of a 28-layer bcc structures stacked in the [100] direction with lattice constants of 2.77 μm , 3.12 μm and 3.46 μm , respectively. All of the observed gaps shift to longer wavelengths as the lattice constant increases as would be expected when analyzing and observing a PBG effect. For the structure with a lattice constant of 2.77 μm , the central wavelength of the observed second gap can be down to 2.2 μm . When we reduce the lattice constant further a high-order stop gap at 1.5 μm can be observed.

4. Theory and discussions

We use the block-iterative frequency-domain method [17] to solve the Maxwell equations for the 3D bcc structure. It is known that such bcc lattices should exhibit bandgaps in the [100] direction. When the refractive index of the polymer $n = 1.56$ is used to calculate the bandgap spectra, the theoretical results do not match well with the experimental data, as shown in Fig. 4(a). A clear difference is that the theoretical results do not show the presence of the second-order bandgap observed in experiments and shown in Fig. 3(b). To remove this inconsistency, below we suggest the idea of a “bruising” effect caused by the increase in the density of the polymer surrounding the microexplosion after the laser fabrication process.

Indeed, it is clear that the material located in the void region before the fabrication is not removed from the sample, but is ejected into the nearby area forming a high-density compressed region. The increase of the density should result in an increase of the effective refractive index, n_{eff} . The average refractive index n_{avg} of the whole structure is proposed to be a constant of 1.56 because the total mass and volume don't change before and after the fabrication process. A simple approximation to calculate n_{avg} is the summation of the refractive index of each component multiplied by its volume ratio. Each Weigner-Seitz cell consists of one void dot. Therefore, the ratio of the void dot can be written as

$$R_{\text{void}} = \frac{V_{\text{void}}}{V_{\text{WS}}} = \frac{(4/3)\pi(r/a)^3}{4/(3\sqrt{3})} = \sqrt{3}\pi\left(\frac{r}{a}\right)^3 \quad (1)$$

As such, the effective refractive index n_{eff} of the fabricated structure can be written as

$$n_{\text{eff}} = (n_{\text{avg}} - R_{\text{void}})/(1 - R_{\text{void}}) \quad (2)$$

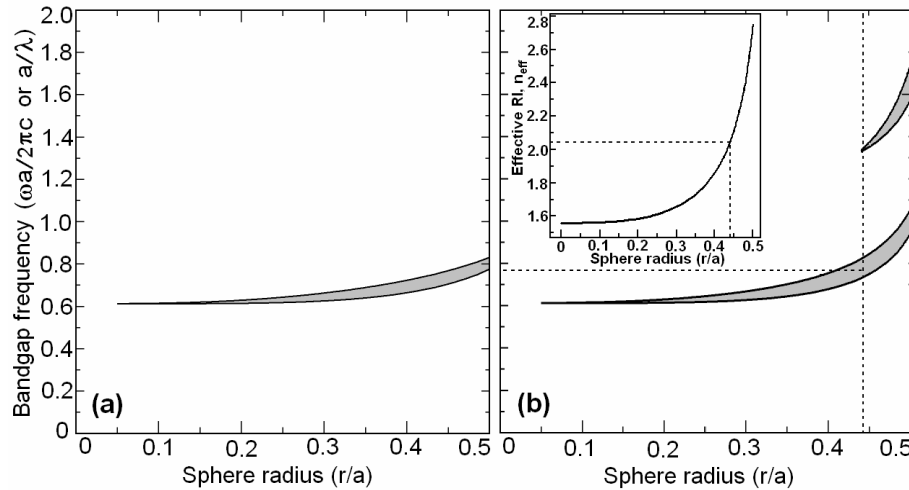


Fig. 4. Calculated photonic bandgap in the [100] direction for various sphere radius based on (a) the refractive index of the polymer before fabrication ($n=1.56$) and (b) the effective refractive index. Inset shows the effective refractive indices as a function as the sphere radius.

Based on Eq. (2), the effective refractive index can be calculated as a function of the relative void radius (r/a), as shown in the inset of Fig. 4(b), and it increases dramatically when the radius of the void increases. For example, if the radius is $0.44a$, the effective refractive index increases to 2.05. Further increasing the radius becomes difficult experimentally because a higher laser power will damage the polymer and also the voids will joint together.

When this approximation is included into the numerical calculation of the bandgap spectra, we obtain significantly improved results, as shown in Fig. 4(b). When the void radius is equal to $0.44a$, the second-order bandgap appears as observed in experiment. In the meantime, the central position of the first bandgap is located at $4.5\ \mu\text{m}$, which is very close to the experimental result $4.6\ \mu\text{m}$. These results match very well the experimental data and they provide a confirmation to the approximation of the effective refractive index suggested above. A slight difference between the theory and experiment may come from a number of aspects. First, a spatial distribution of the polymer density outside the voids is not taken into account. Second, although a small aperture was added to reduce the angle of incidence in the FTIR measurement, the measured results are still an average over a small angle range. Finally, due to a slightly refractive index mismatch between the refractive index of the polymer ($n = 1.56$) and the immersion oil ($n = 1.52$), the size of the void dots is slightly smaller in larger depth.

4. Conclusions

We have fabricated 3D bcc photonic crystals in a pre-cure transparent NOA 63 resin by using the femtosecond laser-driven microexplosion method. Reflection confocal microscope images show that the void dots are stacked into well-correlated bcc lattice structures. The suppression rate of the observed first gap can be 47% for the structures stacked in the $[100]$ direction by adding a small aperture before the FTIR objective. We have analyzed the transmission spectra of the fabricated photonic crystals with various lattice constants and have observed that the wavelengths of the first and second stop gaps are proportional to the lattice constant. We have suggested an analytical approach to take into account a change in the material refractive index caused by microexplosion due to the “bruising” effect, and we have demonstrated that the theoretical results are in good agreement with the experimental data. While our analytical approximation does not take into account the distribution of the polymer density outside the voids, it seems to be accurate enough for a design of microexplosion photonic crystals. We believe that photonic crystals with partial bandgaps such as the bcc structures reported here may find their applications in many interesting physical problems such as the self-collimation or superprism effects based on the specific properties of wave dispersion and diffraction.

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