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Photonic bandgap of gradient quasidiamond lattice photonic crystal

Xian-Zi Dong,[1,2] Qi Ya,[1,2] Xin-Zhi Sheng,[3] Zhi-Yuan Li,[4] Zhen-Sheng Zhao,[1] and Xuan-Ming Duan[1,a)]
[1]*Laboratory of Organic NanoPhotonics and Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, People's Republic of China*
[2]*Graduate School of Chinese Academy of Sciences, Beijing 100190, People's Republic of China*
[3]*Institute of Optical Information, School of Science, Beijing Jiaotong University, Beijing 100044, People's Republic of China*
[4]*Key Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China*

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A three-dimensional (3D) photonic crystal (PhC) structure consisting of gradient quasidiamond lattices was fabricated using multiphoton photopolymerization nanofabrication technique. The photonic bandgap (PBG) of this 3D PhC was experimentally confirmed by reflection and transmission measurements and simulated with finite-difference time domain calculations. The results indicate that a 3D PhC with gradient lattices could effectively expand the width of the PBG and may be beneficial for developing complete-bandgap PhCs with low refractive index materials for applications in polymer based optoelectronic devices and integrated systems. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2943278]

Photonic crystals (PhCs) are an interesting class of periodically structured materials, which exhibit unique properties for manipulating the propagation of light of a certain frequency.[1,2] The PhCs of various structures have been widely investigated through theoretical calculation and experimental evaluation. Among this variety of structures, PhCs with diamond lattice geometry are one of the most attractive class of structures, since they possesses a full photonic bandgap (PBG) even with low refractive index (n) materials, where differences in n can be as low as 2.0.[3,4] Intense effort has been focused on optimizing diamond like lattice structures.[5] The complexity of diamond lattice structures makes fabrication difficult. Typically, the fabrication of 3D PhCs of diamond lattice structure involves using dielectric spheres arranged by self-assembly.[6] However, it is impossible to make arbitrary changes in the structural parameters of such PhCs. Fortunately, multiphoton photopolymerization (MPP) nanofabrication techniques[7–10] have been developed into powerful tools for fabrication of three-dimensional (3D) microstructures of almost any complexity with nanometer scale resolution.[11–14] Various 3D microstructures including 3D PhCs[15,16] have been fabricated using MPP. In particular, PhCs with diamond lattice structures fabricated by MPP[17,18] have exhibited significant enhancement of the PBG compared to other structures.

Since the PBG of PhCs mainly depends on the periodicity in a given measurement direction, tunable PBGs are easily realized by fabricating PhCs with varying lattice parameters.[19] In addition, complex diamond structured PhCs[20] exhibit a widened PBG, which can be expected to obtain complete PBGs using low refractive index materials. Several groups have reported that PhCs with gradient lattice spacing exhibit bandgap broadening.[21–23] However, the relationship between the intrinsic structural parameters and the PBG of PhCs has not yet been investigated in detail. As an important step toward arbitrary PBG lattice designs for 3D PhCs, we herein report the fabrication and evaluation of a quasidiamond lattice 3D PhC with gradient lattice parameters.

Figure 1(a) illustrates a schematic of a regular diamond structure with a defined lattice constant, Λ,[17] which is composed of spheres and sticks. Here, the spheres represent atomic crystal elements, and the sticks connect these elements to a 3D diamond lattice. However, since the aspect ratio of voxels obtained with MPP nanofabrication is usually larger than 3,[24] when building this structure with MPP nanofabrication elliptic spheres and sticks would be achieved. Accordingly, the diamond structure schematic in Fig. 1(b) consists of elliptic spheres and sticks. For experimental realization of such quasidiamond lattice 3D PhC structures, we designed a quasidiamond lattice with elliptic spheres and sticks, as shown in Fig. 1(b). The parameters of this quasidiamond lattice can be tuned in various different directions

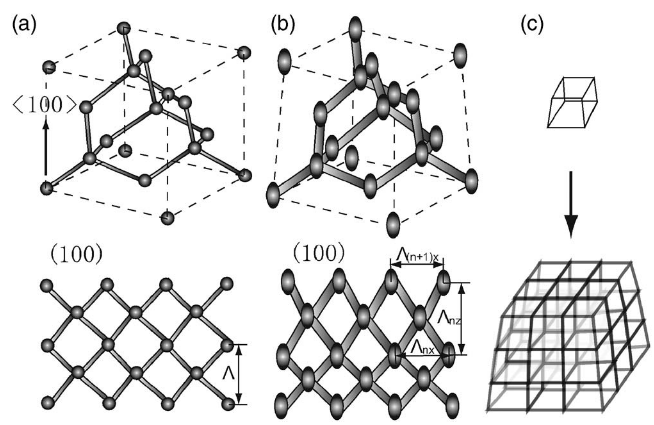

FIG. 1. (a) Unit cell of a regular diamond lattice using a spheres and sticks model (above) and its (100) plane (below). (b) Unit cell of a quasidiamond lattice composed of elliptic spheres and sticks (above) and its (100) plane (below). (c) Schematic illustration of a gradient quasidiamond lattice 3D PhC.

a)FAX: +86-10-8254-3597. Electronic mail: xmduan@mail.ipc.ac.cn.

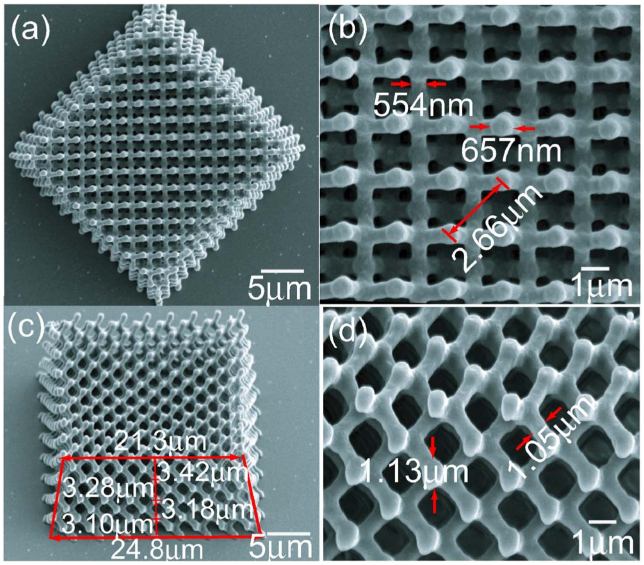

FIG. 2. (Color online) Scanning electron microscope (SEM) images of the gradient quasidiamond lattice 3D PhC fabricated by MPP. (a) Top view of the 3D PhC. (b) Magnified image of the top layer. (c) Side view (45° angle) of the 3D PhC. (d) Locally magnified image of (c).

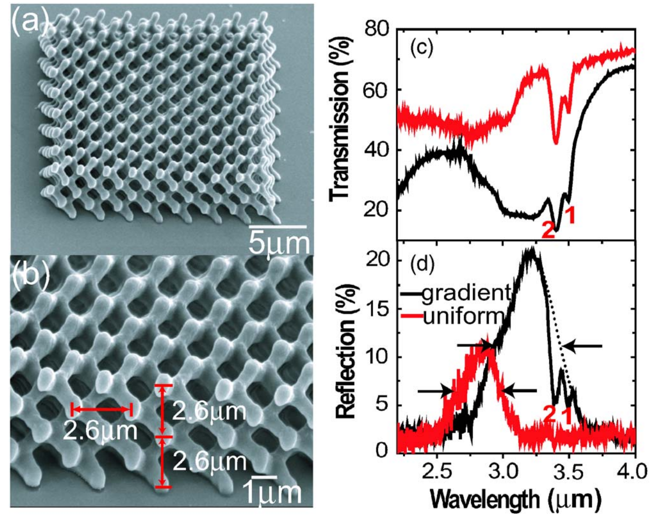

FIG. 3. (Color online) (a) Side view (45° angle) of a SEM image of the uniform diamond lattice 3D PhC. (b) Locally magnified image of (a). Experimental transmission (c) and reflection (d) spectra of the uniform and the gradient quasidiamond lattice 3D PhC measured at ⟨100⟩ direction. The peaks marked with numbers 1 and 2 indicate the absorption of SCR500.

and positions. Modifying the parameters between the lower layers (Λ_{nX}) and the top layers ($\Lambda_{(n+1)X}$) of the lattice along the x direction on the (100) plane [Fig. 1(b)] allows us to design a gradient quasidiamond lattice 3D PhC, as depicted in Fig. 1(c). In particular, the lattice parameters in the z direction, Λ_{nZ}, can easily be modified by changing the distance between each layer. Consequently, a gradient quasidiamond lattice 3D PhC was easily designed, as shown in Fig. 1(c).

We performed MPP fabrication using a mode-locked Ti:sapphire laser system (Tsunami, Spectra-Physics) with a center wavelength of 780 nm, a pulse width of 80 fs, and a repetition rate of 80 MHz to fabricate quasidiamond 3D PhCs with gradient lattices. A commercially available photocurable resin (SCR500, JSR), consisting of urethane acrylate oligomers and benzoyl cyclohexanol benzyl as a photoinitiator and morpholinophenyl amino ketones as a photosensitizer was used in the MPP microfabrication experiments. The beam was tightly focused with an oil-immersion objective lens ($\times 100, \mathrm{NA}=1.4$) into the liquid photoresist and scanned in the horizontal directions by a pair of galvano mirrors (SCANLAB, HurrySCAN 14). A piezostage (PI, P-622.ZCL) was used to move the laser focus spots in the axial direction.

Figure 2(a) shows a scanning electronic microscope image of the resulting gradient quasidiamond lattice 3D PhC, which consists of four periods in the ⟨100⟩ direction and eight periods in the other two directions. The periodicity of a single lattice in the top layer [Λ_{5X}, (100) plane] is 2.66 μm as shown in Fig. 2(b), leading to a total width of 21.3 μm for the PhC. The periodicity (Λ_{1X}) in the lowest layer was expanded to 3.1 μm, corresponding to a base width of the PhC of 24.8 μm, as shown in Fig. 2(c). The distances (Λ_{nZ}) between layers in the ⟨100⟩ direction were changed from 3.10 μm (Λ_{1Z}) to 3.18 μm (Λ_{2Z}), 3.28 μm (Λ_{3Z}), and 3.42 μm (Λ_{4Z}), as shown in Fig. 2(c). Typical diameters of the elliptical spheres and sticks are 657 and 554 nm along the short axis and 1.13 and 1.05 μm along the long axis [Figs. 2(b) and 2(d)], which leads to aspect ratios for the elliptic spheres and sticks of 1.73 and 1.87, respectively. In this gradient quasidiamond lattice PhC, the filling ratio was 30.84%. We also fabricated a uniform diamond PhC, shown in Fig. 3(a) to compare the PBG to the gradient quasidiamond lattice 3D PhC. The uniform PhC was composed of two periods in the ⟨100⟩ direction and eight periods in the other two directions. Here, the lateral constant Λ_X as well as the distance between layers in the ⟨100⟩ direction Λ_Z is 2.6 μm as shown in Fig. 3(b), whereby the filling ratio is 35.2%.

The bandgap effect of the PhCs was examined using a Fourier-transform infrared spectrometer (Continuum Spectra Tech) coupled with an infrared microscope (Thermo Nicolet, NEXUS 670, ×32 microscope objective, NA of 0.65, liquid-N_2-cooled InSb detector). Figures 3(c) and 3(d) show transmission and reflection spectra in the ⟨100⟩ direction of both the uniform, and the gradient quasidiamond 3D PhC structures. Transmission minima were observed at 3.0 μm with a transmittance of 42% for the uniform PhC and at 3.19 μm with a transmittance of 17.6% for the gradient quasidiamond lattice PhC, respectively [Fig. 3(c)]. Reflection maxima appeared at 2.83 μm with a reflectance of 12.5% for the uniform diamond PhC and at 3.23 μm with a reflectance of 20.9% for the gradient quasidiamond lattice PhC [Fig. 3(d)]. To evaluate the width of the PBG we measured gap-to-midgap wavelength ratios ($\Delta\lambda/\lambda_G$), where $\Delta\lambda$ is the width at half reflectance and λ_G represents the maximum wavelength of reflection. From the reflection spectra shown in Fig. 3(d), $\Delta\lambda$ was obtained as 0.32 μm for the uniform PhC and 0.5 μm for the gradient structure. Consequently $\Delta\lambda/\lambda_G$ was obtained as 11.3% for the uniform diamond structure and 15.6% for the gradient quasidiamond lattice PhC. Although the filling ratio of the gradient PhC was decreased, the $\Delta\lambda/\lambda_G$ of the gradient PhC was increased by a factor of 1.38 compared to the uniform structure. This result clearly indicates that a gradient lattice is effective for widening the PBG of 3D diamond lattice PhCs.

To analyze the widening of the PBG in the gradient quasidiamond lattice, we simulated the transmission spectra of such a gradient quasidiamond lattice PhC by performing a

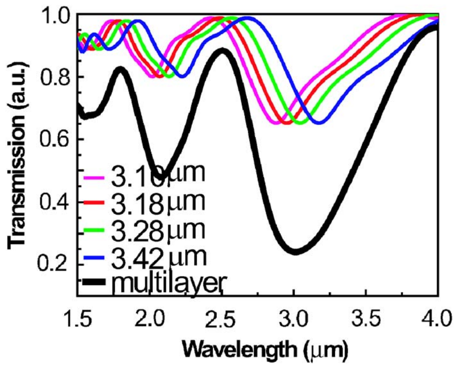

FIG. 4. (Color online) Calculated transmission spectra of the diamond lattice 3D PhCs where corresponding lattice constants were obtained from the structure shown in Fig. 2, and that of a superposed "gradient" quasidiamond lattice 3D PhC.

finite-difference time domain (FDTD) calculation using a commercially available software (FULLWAVE, RSoft), for comparison to our experimental measurements. Here we used a diamond lattice which consisted of elliptic sticks and spheres without the distortion of lattice as a basis model in our simulation of the PBG effect, in order to simplify the model building and improve the calculation performance. We first calculated transmission spectra of four lattices where the lattice constants are similar to those obtained from experimental measurements in the ⟨100⟩ direction, as the distances in this direction directly affect the PBG of each lattice. The refractive index of the material used in the simulation was 1.53, similar to the actual value of photocured SCR500 resin. Figure 4 shows the simulated transmission spectra of the four lattices. The bandgap wavelengths of the transmission spectra λ_G were obtained as 2.87, 2.96, 3.05, and 3.17 μm, where the corresponding distances in the ⟨100⟩ direction of these lattices Λ_{nZ} are 3.10, 3.18, 3.28, and 3.42 μm. The widths at half of transmission peak ($\Delta\lambda$) were found to span 0.47, 0.48, 0.50, and 0.51 μm for the corresponding lattices mentioned above. Accordingly, the $\Delta\lambda/\lambda_G$ of all of these lattices was estimated at about 16%. Superposing these lattices similar to the experimental condition creates a larger bandgap at λ_G=3.0 μm with a transmission width of 21%, showing a 5% width expansion and implying that the width of the PBG may be expanded by gradient lattices employing varying lattice constants. Additionally, since in all of these cases the PBG occurs at the normalized frequency of 0.93 as defined by λ_G/Λ_z, the bandgap wavelength can be easily tuned by changing the structural parameters of the lattice.

In summary, a PBG in a gradient quasidiamond lattice 3D PhC structure was demonstrated by experimental measurements and FDTD simulation. Using a MPP nanofabrication technique, we fabricated 3D PhCs with uniform and gradient lattices based on a quasidiamond lattice structure. The significant PBG widening of the gradient quasidiamond PhC was experimentally confirmed by reflection and transmission measurements as well as by theoretical simulation using FDTD calculations. This work represents an important step toward developing complete-bandgap PhCs in low refractive index materials, and for applying PhCs in polymer based optoelectronic devices and integrated systems.

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