Fabrication of Photonic Crystal Structures by Laser Lithography

Vygantas Mizeikis, Kock Khuen Seet, Saulius Juodkazis, Hiroaki Misawa

Abstract:

Using femtosecond laser lithography technique, we have fabricated 3D PhC structures having woodpile and spiral architectures in photoresists, and investigated their photonic properties. The fabricated structures exhibit good structural quality, evidenced by long-range periodicity and absence of deformations, and photonic stop-gaps at near-infrared and infrared wavelengths, evidenced by spectral bands of high reflectivity. These structures can be used as templates for further enhancement by infiltration of metals or high refractive index materials, such as Si.

Keywords: *photonic crystals, laser lithography.*

1. Introduction

Photonic crystals (PhC) are periodically structured dielectric/metallic materials, which offer possibilities to control propagation, absorption and spontaneous emission of optical radiation *via* photonic band gap (PBG) effect [1], [2]. Since PBG occurs at wavelengths close to the PhC lattice period [3], periodic structuring of materials with high resolution is required in order to fabricate functional PhC structures. This is a challenging task, especially in the case of three-dimensional (3D) PhC structures with PBG at optical (visible to infrared) wavelengths. Laser lithography technique is natively suited for 3D fabrication, and therefore is attractive as a tool for fabrication of 3D PhC structures [4]. It is based on drawing in photosensitive media (such as photoresists) by translating focal spot of a tightly-focused laser beam, and blends achievements of microscopy, non-linear optics, and photochemistry [4]. Here we demonstrate fabrication by this technique, called direct laser writing (DLW), of PhC structures having complex 3D woodpile and spiral architectures in photoresists, and describe their structural and photonic properties.

2. Fabrication technique and samples

Fabrication by DLW technique involves translation of laser beam focal spot along a pre-defined path, such that linear photomodified regions in 3D space are drawn [x]. The samples were films of SU-8 (NANO™, Microchem) [5] formulation 50, spin-coated to a 50 mm thickness on glass substrates. SU-8 is an epoxy-based negative ultra-thick photoresist which is widely used for the single-photon lithography of high aspect ratio micro-mechanical devices. Single-photon absorption in SU-8 is negligible at wavelengths longer than 400 nm [6]. As irradiation source, Hurricane X (Spectra Physics) Ti:Sapphire laser system with a pulse length Δt_{pulse}=130 fs, a central

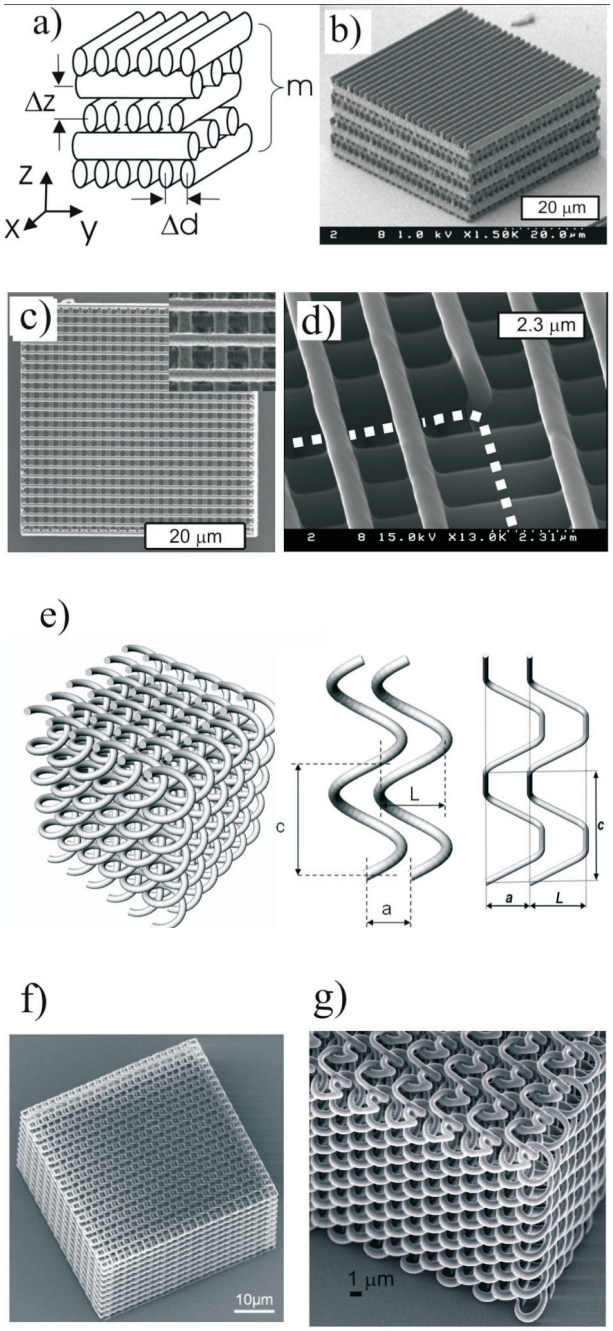

Fig. 1. (a) Structural parameters of a woodpile Dd-distance between the rods, Dz-distance between the layers, m - number of layers, (b, c)~SEM images of woodpile structure recorded in SU-8 by DLW, (d) demonstration of linear defect with 90° bend, (e) spiral structure and its main parameters: L- length of the spiral arms, c-lattice period in the z-axis direction, a-period 2D square lattice in the x-y plane, (f, g) SEM images of quare and circular spiral structures.

wavelength λ_{pulse}=800 nm, and a repetition rate of 1 KHz was used. Therefore, two-photon absorption is responsible for the photomodification involving photo-acid generation and polymer cross-linking which renders SU-8 stable against subsequent chemical development. The fabrication was performed in Olympus IX71 microscope with oil-immersion objective lens having numerical aperture NA=1.4. 3D drawing was accomplished by translating the sample using a piezoelectric transducer-controlled translation stage along 3D trajectory defined with a few nanometers accuracy using personal computer. More details on the fabrication can be found in the literature [7,8]. The samples were inspected using a scanning electron microscope (SEM), JSM-6700FT (Jeol). Their optical reflection at infrared wavelengths was measured using Fourier-Transform Infra Red (FT-IR) spectrometer (Valor III, Jasco) with a microscope attachment (Micro 20, Jasco) equipped with a 16×, NA=0.5 objective lens.

3. Results and discussion

Woodpile architecture [9] and definition of its parameters are shown in Fig. 1(a). Woodpiles can be formed by stacking layers of uniformly spaced dielectric rods along the z-axis direction. Fig. 1(b, c) shows SEM images of the woodpile sample recorded in SU-8 at a pulse energy of 0.55 nJ and a focal spot scanning step of 80 nm. The sample is a perfect parallelepiped with dimensions of (48×48×21) μm, the individual SU-8 rods have smooth surfaces and elliptical cross-sections with diameters of 0.5 mm in the *x-y* plane and 1.3 mm along the *z*-axis. Their elongation in the focusing direction by a factor of about ~2.6 is due to the ellipsoidal shape of the focal region.

Fig. 1(d) demonstrates woodpile structure with waveguide type defects formed by missing halves of two rods in the two neighboring top layers. Though refractive index of SU-8 is too low to achieve real waveguiding, this example illustrates that defects with required geometry can be easily created by simply shutting off the laser beam for appropriate time intervals during the recording.

Spiral architecture [10], illustrated schematically in Fig. 1(e) consists of spirals that have square or circular shapes with parameters defined Fig. 1(e). Extended spiral structures are generated by centering the spirals on the nodes of a two-dimensional square lattice with period *a*. The structures are diamond-like, and yield spectrally wide PBGs [10]. Using DLW, these, and even more complex structures consisting of intertwined/circular and phase-shifted spirals can be obtained. Fig. 2(f) shows SEM image of a sample with size of (48×4×830) μm, and parameters *a*=1.8 μm, *L*=2.7 μm, and *c*=3.04 μm, fabricated with pulse energy *I*=0.6 nJ using the 100 NA=1.35 objective lens. Figure 1(g) shows a circular spiral structure with parameters *a*= 1.8 μm, L=2.7 μm, c=3.6 μm. Notice the 180° phase shift between the adjacent spirals, which would be impossible to achieve by any other known fabrication technique.

Both woodpile and spiral samples have exhibited only minor structural imperfections, such as non-parallelism of the samples' vertical edge directions (about 0.5°), hence they are nearly deformation and shrinkage-free. The structures retain their initial shapes even after being dislodged from the substrates.

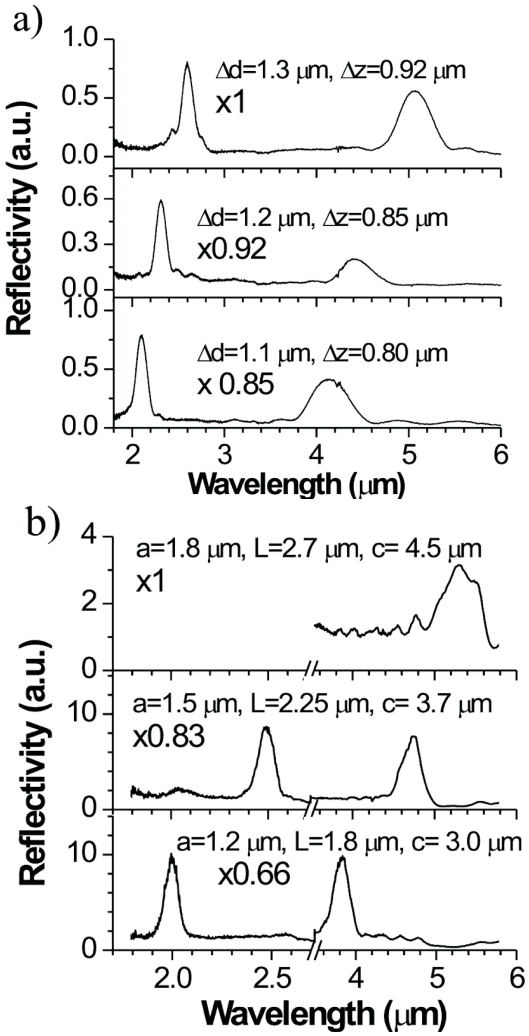

Fig. 2. Maxwell's scaling in the measured infrared reflectivity spectra of woodpile (a) and square spiral (b) samples with lattice parameters proportionally scaled down (the lattice parameters and scaling factors are indicated in the plots.

Figure 2(a) shows reflection spectra of three samples measured along the *z*-axis. The measurement direction coincided with *z*-axis. The structures have lattice parameters proportionally scaled down compared to the first sample (the topmost spectrum) as indicated in the plots. In all spectra two major high reflectance regions can be seen centered at shorter (near 2.0 μm) and longer (near 4.0 μm) wavelengths. Shapes and relative amplitudes of the reflectivity peaks are well reproduced by transfer-matrix calculations for model structures with appropriately chosen parameters .

Figure 2(b) presents reflection spectra of three spiral samples in the same manner as in Fig. 2(a). Just as for the woodpile samples, pairs of reflectivity peaks are seen in the spectra, and their central wavelengths scale together with the lattice parameters (given in the plots). These peaks are spectrally matched by the dips in the transmission spectra (not shown). The wavelength interval 2.7-3.6 μm is omitted in Fig. 3(b) because it contains some bands of intrinsic SU-8 absorption, which suppress PBGs. The suppression is evident in the topmost spectrum where the short-wavelength peak apparently falls within the absorption band, and therefore is suppressed.

Multiple reflectivity peaks in the fabricated samples signify multiple photonic stop-gaps, or forbidden spectral ranges existing along certain directions only. Comparison with photonic band structure calculations indicates that the long-wavelength peaks correspond to the fundamental stop-gaps of these structures, while the short-wavelength peaks represent the second-order stop-gap. Second- and higher-order stop gaps are an evidence of good structural quality achieved, because higher photonic bands are more susceptible to disorder. In addition, they can be exploited for achieving photonic band gap effects in structures with larger structural parameters. Spectral positions of the major reflectivity peaks in these samples depend on the lattice scaling factor in qualitative agreement with Maxwell's scaling, which constitutes clear evidence of their photonic band nature.

4. Conclusions

The fabricated SU-8 photonic crystal structures have low deformations, sufficient mechanical and chemical robustness, and exhibit substantial signatures of photonic band dispersion. Hence, these structures can be used as templates for the infiltration by other materials with higher refractive index.

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