EXPERIMENTAL DEMONSTRATION OF BROADBAND SELF-COLLIMATION EFFECT IN 3D HEXAGONAL LATTICE FABRICATED USING A LOW-REFRACTIVE-INDEX POLYMER

Chun Xia[a], Stephen M. Kuebler[a,b*], Noel P. Martinez[c], Manuel Martinez[c], Raymond C. Rumpf[c,d], Jimmy Touma[e]

[a]*CREOL, The College of Optics and Photonics, University of Central Florida,*
Orlando, FL 32816, USA
[b]*Chemistry Department, University of Central Florida,*
Orlando, FL 32816, USA
[c]*EM lab, Department of Electrical and Computer Engineering, University of Texas at El Paso,*
El Paso, TX 79968, USA
[d]*Computational Science Program, University of Texas at El Paso,*
El Paso, TX 79968, USA
[e]*Integrated Sensing and Processing Branch, AFRL/Munitions Directorate*
Eglin AFB, FL 32542, USA

*kuebler@ucf.edu

***Abstract* — Wide-angle self-collimation from the E- to L-band is experimentally demonstrated in a hexagonal lattice of air-holes fabricated in a low-refractive-index medium by multiphoton lithography.**

Keywords — Photonic crystal, self-collimation, multiphoton lithography, nanophotonics.

I. INTRODUCTION

Photonic crystals (PhCs) are periodic dielectric materials first introduced by John and Yablonovitch in 1987 [1, 2]. PhCs have been a focus of intense research for their potential applications in optical integration due to their rich dispersive nature. There are several ways to introduce dispersion in a PhC, including material dispersion and structural dispersion. These forms of dispersion enable complex functionalities, such as anomalous dispersion, zero group velocity dispersion (GVD), and wave guiding. Material dispersion is a property that can be modified with nonlinear effects when high optical power is used. PhCs offer abundant opportunities for controlling dispersion through multiple combinations of materials, lattice symmetries, and geometry of the repeated unit cell. For a given PhC, the observed dispersion comes from the shape of the photonic bands. Strategies employing PhCs can be divided into applications using band-gap or not. For applications with band-gap, significant research has been dedicated to increasing the width of the bandgap and using it to make functional devices such as photonic crystal fibers [3]. For applications without band-gap, the dispersion properties of PhCs can be understood by studying equifrequency contours (EFCs) in the bands. Given that optical power flows normal to the EFCs, the shape of the EFCS gives rise to many novel effects including negative refraction [4], slow-light [5], the superprism effect [6], and self-collimation (SC) [7].

As light diffracts and tends to spread naturally, controlling optical power flow is a fundamental need for photonic devices and interconnects. In PhCs that exhibit SC, light is forced to propagate along certain directions where the EFCs are flat. Many 2D and 3D functional devices such as waveguides [8] and beam splitters [9] have been fabricated in silica that are based on SC. Different geometries and lattices were designed and analyzed to improve the bandwidth and collimation angle inside of high refractive index material ($n > 3$). However, investigations of devices using low refractive-index materials, which are inherently easy to fabricate, are still lacking.

Kosaka and Wu reported PhCs whose optical properties exhibited either SC or the superprism effect, depending upon the wavelength or angle at which light was coupled into the device [7, 10]. Rakich reported an experimental demonstration of SC in a centimeter-scale two-dimensional PhC slab formed by a square lattice of air holes in a 205-nm-thick silicon film for TE mode radiation [11]. Li and co-workers simulated a slanted beam incident on a PhC and observed SC and a shift in the beam center as it propagated within the lattice [12]. Experimental demonstration of SC at microwave frequencies was achieved by scanning a monopole within a 3D PhC to observe the evolution of the beam-width inside the PhC. Hsieh observed the near-field distribution using near-field scanning optical microscopy with scattered light inside of the PhC [13]. To the best of the authors' knowledge, investigations of SC have not included PhCs created with low-index materials, probe beams incident at angles greater than 10°, and light propagating along out-of-plane directions.

In the present work, we explored the SC effect in a PhC consisting of a hexagonal arrangement of air-holes. The PhC was fabricated by multi-photon lithography in the commercially available, low-refractive index photopolymer IP-Dip (NanoScribe). The EFCs of the PhC were calculated using a frequency-domain eigenmode solver [14]. The refractive indices used for the simulations were $n_{\text{IP-Dip}} = 1.525$ and $n_{\text{air}} = 1$. The SC bandwidth was calculated using the criterion that the maximum deviation angle should not exceed 5° for the first seven bands. The simulations showed that when the ratio between the radius of the air-holes r and the lattice spacing a varied from $r/a = 0.35$ to 0.43, all-angle SC should be observable across a wide range of normalized frequency, $\omega_n = 2.6$ to 4.0. It is worth noting that although the refractive index of polymerized IP-Dip varies slightly with multi-photon exposure [15], no significant changes were calculated for the bandwidth of SC when the refractive index was reduced to 1.515.

The hexagonal PhC shown in Fig. 1 was fabricated using a home-built multi-photon lithography system that has been described elsewhere [16]. The lattice consists of a 7 × 7 array of air-holes (even-numbered layers have only six air-holes). Individual overlapping lines that define the interior volume of the structure were fabricated by scanning the sample relative to the laser beam at 50 μm/s. A 3 μm wide frame was fabricated around the PhC to provide additional structural support. The whole structure was fabricated at an expanded scale of 7% to pre-compensate for linear shrinkage. After photo-exposure, the unexposed photopolymer was removed by developing the sample for 30 min. in three separate portions of propylene glycol methyl ether acetate (PGMEA, Sigma-Aldrich), rinsing with isopropyl alcohol (Sigma-Aldrich), then rinsing with deionized water. Scanning electron microscopy (SEM) was used to structurally characterize the lattice and confirm that developing was complete.

Light having a vacuum wavelength of $\lambda_0 = 1550$ nm was coupled into the device and observed as it exited using scanned single-mode fibers (Thorlabs 1550 BHP). To prevent fibers from dragging on the substrate during scanning, the cladding was etched to a diameter of 30 μm using buffered-oxide etch (BOE, J.T. Baker 1178-03). Probe light was derived from an amplified femtosecond laser ($\Delta\lambda_{1550} \sim 40$ nm, $\Delta\tau_{\text{pulse}} \sim 120$ fs, Coherent Legend) pumping two optical parametric generators. The PhC was positioned atop a rotational stage so that the entry angle of the source light could be adjusted, and the detection fiber was mounted on a rotational stage and a computer-controlled 3D linear stage so that the intensity of light exiting the device could be mapped. Beam-width information was extracted from the intensity field distribution.

Optical measurements showed that the beam coupled into the lattice had a spot-size of 9 μm ± 1 μm immediately after exiting the fiber and that it diverged to 15 µm ± 1 µm after propagation in air for 150 µm. In contrast, light coupled into a PhC having a length of 150 µm emerged with a spot-size of 9 µm ± 1 µm, indicating that SC within the lattice prevented divergence of the beam. Similar experiments conducted at 1350 nm also revealed that divergence was suppressed. These results indicate that a hexagonal lattice fabricated from a low-index photopolymer can exhibit strong SC.

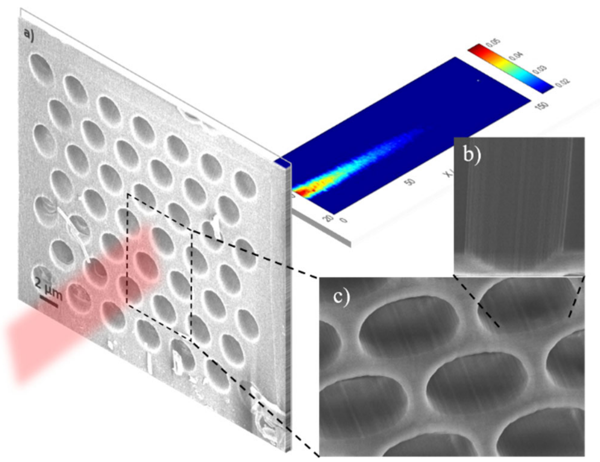

Fig. 1. a) Scanning electron microscopy (SEM) images of the front surface of a hexagonal air-hole PhC having $r/a = 0.35$. b) Zoomed-in view of the interior of an air-hole visible at the top of a partly fabricated PhC. b) Zoomed-in view of interior of the PhC at its entrance face. The colored inset shows optical characterization of a beam exiting after traversing through the PhC.

Acknowledgment

This work was partly supported by National Science Foundation grant no. 1711356 and Air Force Research Lab contract no. FA8651-19-1-0003. Distribution A Approved for Public Release, Distribution Unlimited (96TW-2020-0093).

References

[1] S. John, "Strong Localization of Photons in Certain Disordered Dielectric Superlattices," Physical Review Letters, vol. 58, no. 23, p. 2486, 1987.

[2] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," Physical Review Letters, vol. 58, no. 20, p. 2059, 1987.

[3] T. A. Birks, J. C. Knight, and P. S. J. Russell, "Endlessly Single-Mode Photonic Crystal Fiber," Optics Letters, vol. 22, no. 13, pp. 961-963, 1997.

[4] E. Cubukcu, K. Aydin, E. Ozbay, S. Foteinopoulou, and C. M. Soukoulis, "Negative Refraction by Photonic Crystals," Nature, vol. 423, no. 6940, pp. 604-605, 2003.

[5] T. Baba, "Slow Light in Photonic Crystals," Nature Photonics, vol. 2, no. 8, p. 465, 2008.

[6] H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, "Superprism Phenomena in Photonic Crystals," Physical Review B, vol. 58, no. 16, p. R10096, 1998.

[7] H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, "Self-Collimating Phenomena in Photonic Crystals," Applied Physics Letters, vol. 74, no. 9, pp. 1212-1214, 1999.

[8] C. Chen, A. Sharkawy, D. M. Pustai, S. Shi, and D. W. Prather, "Optimizing Bending Efficiency of Self-Collimated Beams in Non-Channel Planar Photonic Crystal Waveguides," Optics Express, vol. 11, no. 23, pp. 3153-3159, 2003.

[9] D. M. Pustai, S. Shi, C. Chen, A. Sharkawy, and D. W. Prather, "Analysis of Splitters for Self-Collimated Beams in Planar Photonic Crystals," Optics Express, vol. 12, no. 9, pp. 1823-1831, 2004.

[10] L. Wu, M. Mazilu, and T. F. Krauss, "Beam Steering in Planar-Photonic Crystals: From Superprism to Supercollimator," Journal of Lightwave Technology, vol. 21, no. 2, p. 561, 2003.

[11] P. T. Rakich, M. S. Dahlem, S. Tandon, M. Ibanescu, M. Soljačić, G. S. Petrich, J. D. Joannopoulos, L. A. Kolodziejski, and E. P. Ippen, "Achieving Centimetre-Scale Supercollimation in a Large-Area Two-Dimensional Photonic Crystal," Nature Materials, vol. 5, no. 2, p. 93, 2006.

[12] M. Li et al., "All-Angle Quasi-Self-Collimation Effect in a Rod-Type Silicon Photonic Crystal," IEEE Photonics Journal, vol. 7, no. 1, pp. 1-8, 2015.

[13] P. Hsieh, C. Chung, S. Kocaman, C. Biris, M. Lu, N. Panoiu, and C. Wong, "Near-Field Observations of Self-Collimation in Photonic Crystal Superlattices," in Quantum Electronics and Laser Science Conference, 2012: Optical Society of America, p. QF2H. 2.

[14] S. G. Johnson and J. D. Joannopoulos, "Block-Iterative Frequency-Domain Methods for Maxwell's Equations in a Planewave Basis," Optics Express, vol. 8, no. 3, pp. 173-190, 2001.

[15] S. Dottermusch, D. Busko, M. Langenhorst, U. W. Paetzold, and B. S. Richards, "Exposure-Dependent Refractive Index of Nanoscribe Ip-Dip Photoresist Layers," Optics Letters, vol. 44, no. 1, pp. 29-32, 2019.

[16] H. E. Williams, Z. Luo, and S. M. Kuebler, "Effect of Refractive Index Mismatch on Multi-Photon Direct Laser Writing," Optics Express, vol. 20, no. 22, pp. 25030-25040, 2012.