Nanophotonic Devices for Three-Dimensional Control of Optical Beams

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Abstract: Spatially-variant photonic crystals (SVPCs) are new nanophotonic devices that control the propagation of optical beams in three dimensions. This work reports the fabrication and characterization of the first SVPC that operate at 1550 nm.

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1. Introduction

Controlling and directing the propagation of optical beams in three dimensions (3D) remains a challenging but essential requirement for future innovations in photonics, imaging, and sensing. Several approaches for 3D beam control have been advanced, each with its own advantages and disadvantages, including those based on integrated micro-optical systems [1], plasmonics [2], meta-materials [3], and functionally graded photonic crystals [4].

Spatially-variant photonic crystals (SVPCs) are new devices that offer a means for engineering multiple optical functions into a single, low-foot-print structure [5,6]. Foremost among these functions is the ability to bend and steer beams through 3D turns with a bend radius of $R < 10\lambda_0$, where λ_0 is the vacuum wavelength of the optical beam. SVPCs are diffraction-based devices that control the flow of optical power through the self-collimation effect. The unit-cell of a photonic crystal can be engineered to have strong spatial dispersion that forces power to flow along preferred directions in the lattice [5]. The periodic lattice can then be spatially varied in a manner that preserves the self-collimation effect and yet forces light to propagate along a defined path.

This work demonstrates that SVPCs can be designed and then fabricated in photopolymers using 3D multiphoton lithography (MPL). Optical characterization of SVPCs at $\lambda_0 = 1550$ nm shows that the devices can bend beams through tight turns as small as $R = 7\lambda_0$ while preserving the spatial profile of the beam.

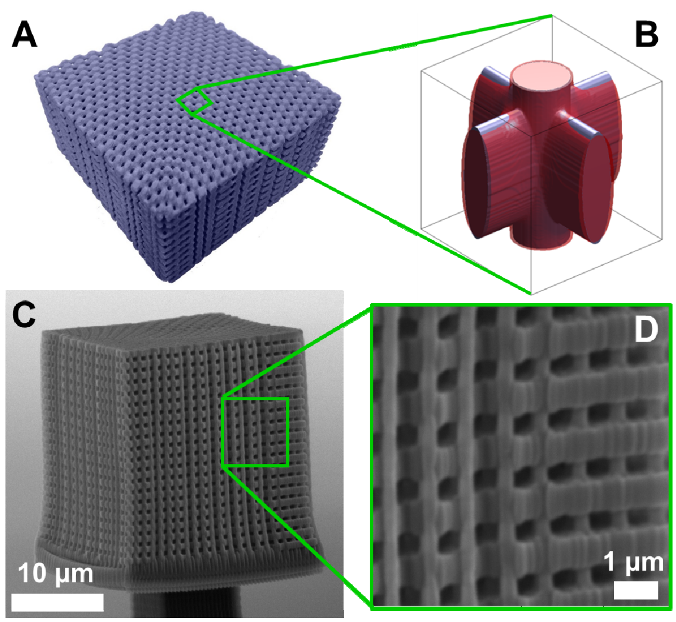

Fig. 1. A) Design of an SVPC that steers an optical beam through a tight turn having radius $R < 10\lambda_0$ and B) the crossed-rod unit cell upon which the SVPC is based. C) Wide-view and D) close-up SEM images showing an example of an SVPC fabricated by 3D multiphoton lithography in the photopolymer IP-Dip. This structure has a volumetric fill-factor of 55%.

2. Experimental

The SVPCs reported here (Fig. 1) were designed using a computational method described elsewhere [5,7] and were engineered so they could be fabricated in a low-refractive-index photopolymer (n = 1.51 at λ_0 = 800 nm). The devices are derived from a cubic lattice based on a crossed-rod unit cell (Fig. 1B) that is strongly self-collimating at λ_0 = 1550 nm. The orientation and shape of the unit cells are spatially varied throughout the lattice so that an optical beam incident at the input face is directed through a sharp 90º turn to the output face. The SVPCs were fabricated onto glass substrates by 3D multiphoton lithography (MPL) in the cross-linkable acrylate IP-Dip (Nanoscribe) using the tightly focused output of a Ti:sapphire laser (Coherent Mira, λ_0 = 800 nm, 76 MHz repetition rate, 120 fs pulse duration). MPL has been described previously [8], and the specifics of our implementation are reported elsewhere [9]. The average laser power measured at the sample was P_{avg} = 1 mW to 3 mW, and the focal spot was scanned within the material at 50 μm s^{-1}. The volumetric fill-factor of the SVPCs could be adjusted by varying P_{avg} and by writing multiple partially overlapping lines to control the shape and volume of the rods comprising the lattice. After laser patterning, residual photopolymer was removed by rinsing in propylene glycol methyl ether acetate, leaving the SVPC standing freely on the substrate. The SVPCs were optically characterized (Fig. 2) by introducing light at λ_0 = 1550 nm onto the entrance face through a "source" optical fiber and then scanning fibers at the other faces to collect light exiting the device and for quantifying throughput, losses, beam-bending efficiency, and other optical properties.

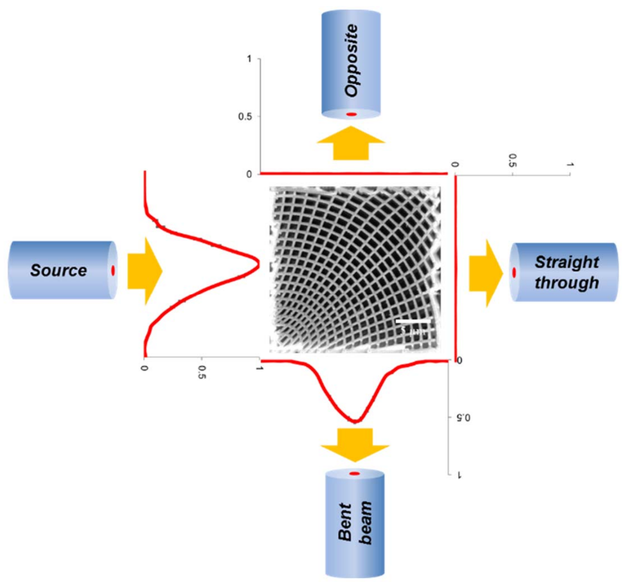

Fig. 2. Horizontal line-scans (*red traces*) showing the relative intensity of light at λ_0 = 1550 nm at the input and output faces of an SVPC (*center*), as imaged from above by SEM (5 μm scale bar). This SVPC has a fill-factor of 47% and bends vertically polarized light out of the straight-through path to the "bent-beam" face with a total-power efficiency of 52.5%. The peak-to-peak contrast ratio of light exiting at the bent-beam face versus the straight-through face is 79.

3. Results and Discussion

Scanning electron microscopy (SEM) was used to evaluate the SVPCs after fabrication and to compare their structural form to the targeted design. Structures having a fill-factor below 35% did not have sufficient mechanical integrity to survive the post-exposure developing process and either collapsed or were severely deformed. Structures having fill-factors between 35% and 70% could be readily fabricated. The example shown in Figs. 1C, 1D has a fill factor of 55% and an average lattice spacing of ~1 μm, as needed for operation at 1550 nm.

Figure 2 shows an example of the intensity line-scans that were used to optically characterize the SVPCs. SVPCs with a fill-factor near 45% direct vertically-polarized light through the turn toward the "bent-beam" face. Previous studies of SVPCs fabricated for operation at λ_0 = 2.94 μm show that the anisotropy of the unit cell causes these device to exhibit high polarization selectivity, so horizontally polarized light passes through the structure without bending through the turn [10]. The device shown in Fig. 2 has a fill-factor of 47%. It steered light through the turn with an efficiency of [100% × (*total-power-in*/*total-power-out*)] = 52.2%. The intensity-contrast of light exiting at the bent-beam face versus the straight-through face was 79:1. The peak of the line-scans show that the effective turn-radius of the SVPCs is 7λ_0.

Two-dimensional (2D) line-scans were used to map the intensity distribution of light incident on the SVPC and the resulting spatial profile of light exiting at the bent-beam face. When a single-mode fiber was used as the source, 2D line scans confirmed that light entering the SVPC had the expected Gaussian spatial profile of the lowest-order mode. Under these conditions, 2D line-scans at the bent-beam face showed that the light exiting the device also had a Gaussian profile. These observations indicate that the self-collimating action of the SVPC preserves the spatial profile of an incident beam as it is steered through the turn.

4. Conclusion

The work reported here confirms that SVPCs can be designed and fabricated to obtain devices that can be used to control light at $\lambda_0 = 1550$ nm. Beam-bending SVPCs can steer light through tight turns with radius as small as $R = 7\lambda_0$. This turn radius is far smaller than what is possible using conventional waveguides of similar refractive index and it is smaller than what can be practically achieved with other dielectric devices [11]. Although tighter turns are possible using plasmonic structures, SVPCs can be entirely dielectric and therefore exhibit much lower loss. The maximum beam-bending efficiency reported here does not represent a fundamental upper limit and it can be increased by incorporating index-matching structures that improve input- and output coupling, and also by improving the fabrication and post-exposure developing to minimize irregularities in the structure that increase scattering losses. Significantly, the SVPCs can be designed to direct the flow of light parallel to the substrate, perpendicular to the substrate, or along a more complex path. This opens a route to a wide range of nanophotonic devices that could be used for off-chip and on-chip optical coupling, wave guide jumpers, mismatch-tolerant couplers, and more. Future work will focus on investigating the fundamental performance limits of SVPCs and demonstrating a wider range of SVPC-based devices.

5. Acknowledgements

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6. References

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