Centimeter-Scale Super-Collimation in a Large-Area 2D Photonic Crystal

M. S. Dahlem, P. T. Rakich, S. N. Tandon, M. Ibanescu, M. Soljačić, G. S. Petrich, J. D. Joannopoulos, L. A. Kolodziejski and E. P. Ippen

Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, MA 02139, USA
mdahlem@mit.edu

Abstract: We studied super-collimation in a planar 2D photonic crystal at 1.5 μm wavelengths and observed an inherent robustness to short-scale disorder. A 2 μm-wide beam was propagated over more than 0.5 cm without diffraction.

OCIS codes: (120.1680) Collimation; (130.0130) Integrated optics; (200.4650) Optical interconnects; (250.5300) Photonic integrated circuits; (999.9999) Photonic crystals

1. Introduction

One of the interesting effects observed in photonic crystals (PhCs) is the propagation of optical beams without diffraction. Referred to as super-collimation (or self-collimation), this optical effect allows diffraction-free propagation of micron-sized beams over centimeter-scale distances. It is a natural result of the unique dispersive properties of PhCs. No nonlinearities or physical waveguides are required. Self-collimation was first observed by Kosaka et al. in a 3D PhC[1] and by Wu et al. in 2D triangular[2] and square[3] lattices, over relatively short distances (hundreds of microns). A natural metric for the scale of collimation experiments is the isotropic diffraction-length over which a Gaussian optical beam would normally spread by a factor of $2^{1/2}$ in an isotropic medium: $L_d = \pi.w^2 / \lambda_x$ where w is the Gaussian beam waist radius and $\lambda_x = 2\pi / k_x$ is the wavelength of the light in the direction of propagation. A figure of merit for super-collimation is the ratio of the observed length of collimated propagation to L_d . The utility of super-collimation is strongly linked to the distance over which it can be maintained, and the figure of merit is important since it dictates the maximum density and complexity of optical circuits based on super-collimation. Previous experimental studies showed figures of merit smaller than 6 [4]. In this paper we report observations of figures of merit of more than 400.

2. PhC Design

Super-collimation is studied over centimeter-length-scale distances in a large area 2D PhC with a square lattice of air holes in a thin silicon film – Fig. 1a. Our 2D PhC was fabricated in a silicon on insulator (SOI) wafer, using interferometric lithography and reactive ion etching[5], and was designed to operate in the 1500 nm wavelength range for TE radiation (electric field parallel to the 2D plane), in the lowest energy band (close to the edge of the bandgap). The lattice constant is a = 350 nm and the hole radius is $r = 0.3a$. The projected band structure of the PhC slab under study was computed with a 3D frequency-domain eigenmode solver, and around 1500 nm the computed surfaces showed remarkably little spatial dispersion in the transverse wavevector.

3. Experimental Results

We experimentally observed that the optimum wavelength for super-collimation was approximately 1500 nm, and we measured losses of (3.6 ± 0.5) dB/mm. A coarse contact-mode near field scanning optical microscopy (NSOM) technique[6] was used to obtain high resolution images of the beam profile at different positions along the PhC, showing that a 2 μm-wide beam was conserved over 0.3 cm of propagation – Fig. 1b. The beam profiles are fitted to Gaussian functions yielding full widths at half maximum (FWHMs) in intensity of 2.1, 2.1 and 2.3 (±0.2 μm), for positions (1)-(3), respectively. In addition, high-resolution confocal measurements confirmed super-collimation after 0.5 cm of propagation. The results of this experiment show figures of merit as high as 376, which correspond to super-collimation over more than 14,200 lattice constants. Additional studies of a 0.8 cm-long PhC device yielded measurements of beams with similar transverse profiles, and figures of merit closer to 600.

1-55752-813-6/06/$25.00 ©2006 IEEE

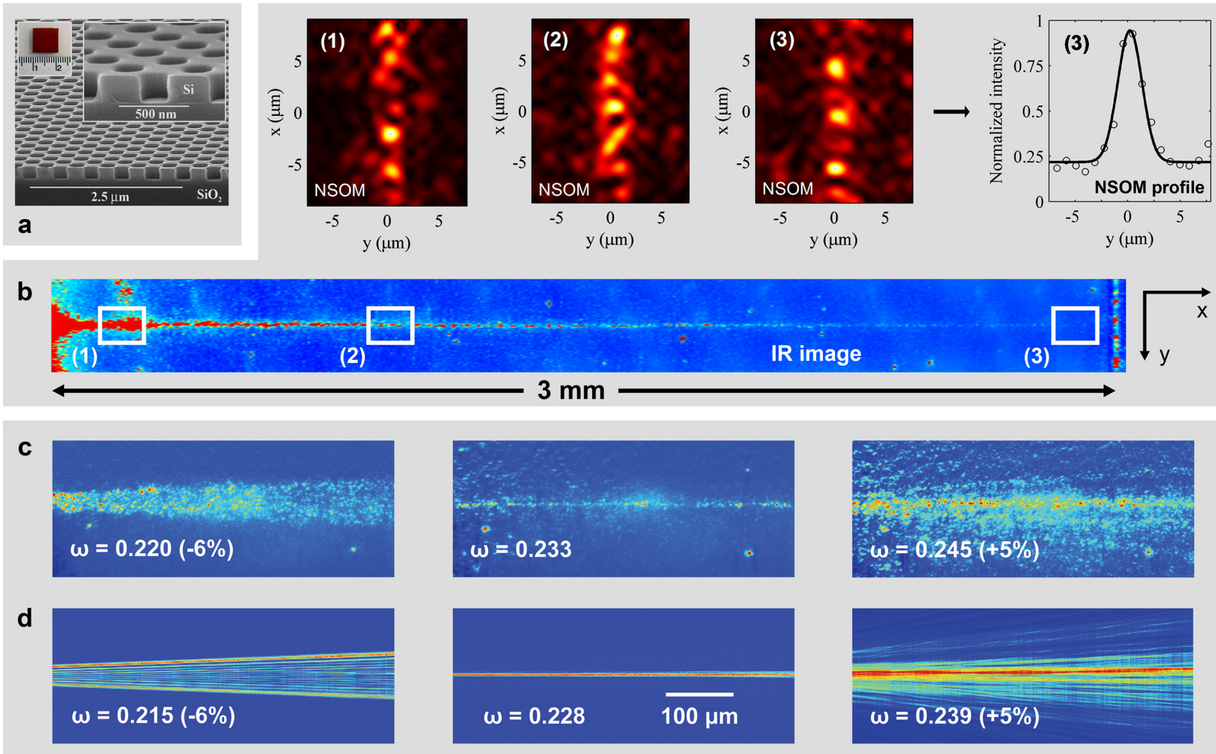

Fig. 1 – PhC design and experimental results: **a** SEM image of the fabricated large-area PhC, **b** IR image and NSOM measurements showing super-collimation over 0.3 cm, and **c-d** experimental and simulated frequency dependence and disorder effects on super-collimation.

Both frequency dependence and effects of disorder were observed experimentally – Fig. 1c – and studied through the beam propagation method (BPM), based on the computed dispersion surfaces – Fig. 1d. For the normalized frequency $\omega = a/\lambda = 0.233$ the beam divergence is negligible. The discrepancy between measurements and simulations is 2%, and the beam break-up is due to short-scale disorder, such as fabrication roughness (RMS fluctuation in the hole-radius of 0.6 nm).

4. Summary

We have studied super-collimation in a planar 2D photonic crystal at wavelengths around 1500 nm. IR imaging, NSOM and confocal measurements showed that a 2 µm-wide beam (FWHM) was maintained over 0.5 cm of propagation (~400 isotropic diffraction lengths), corresponding to propagation over more than 14,200 lattice constants. In addition, we have demonstrated that super-collimation possesses inherent robustness with respect to short-scale disorder.

5. References

[1] H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, “Self-collimating phenomena in photonic crystals,” Appl. Phys. Lett. **74**, 1212-1214 (1999).

[2] L. J. Wu, M. Mazilu, and T. F. Krauss, “Beam steering in planar-photonic crystals: From superprism to supercollimator,” J. Lightwave Technol. **21**, 561-566 (2003).

[3] L. Wu, M. Mazilu, J.-F. Gallet, and T. F. Krauss, “Square lattice photonic-crystal collimator,” Photonics and Nanostructures - Fundamentals and Applications **1**, 31-36 (2003).

[4] H. Kosaka, T. Kawashima, A. Tomita, T. Sato, and S. Kawakami, “Photonic-crystal spot-size converter,” Appl. Phys. Lett. **76**, 268-270 (2000).

[5] S. N. Tandon, M. Soljacic, G. S. Petrich, J. D. Joannopoulos, and L. A. Kolodziejski, “The superprism effect using large area 2D-periodic photonic crystal slabs,” Photon. and Nanostruct. **3**, 10-18 (2005).

[6] S. Bourzeix et al., “Near-field optical imaging of light propagation in semiconductor waveguide structures,” Appl. Phys. Lett. **73**, 1035-1037 (1998).