Supercollimation in Photonic Crystals Composed of Nano-scale Silicon Rods

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Abstract: Supercollimation is the diffraction-less propagation of light using the dispersion properties of specially-designed photonic crystals. We have measured supercollimation in photonic crystals composed of nano-scale rods over distances of up to one thousand lattice periods.

OCIS codes: (230.5298) Photonic crystals; (130.5296) Photonic crystal waveguides

Introduction

Appropriate design of a photonic crystal (PhC) gives rise to dispersion properties that enable supercollimation, the propagation of a light beam without diffraction within a perfectly periodic (defect-less) PhC. Supercollimation has been demonstrated theoretically and experimentally in two-dimensional (2D) PhCs composed of air-holes within a dielectric slab [1-3]. We present, to our best knowledge, the first experimental demonstration of supercollimation in 2D PhCs composed of silicon rods in air at a wavelength of λ=1530nm [4].

Theoretical Modeling and Simulations

The PhC was designed to exhibit supercollimation at λ = 1550nm. Band-structure simulations were performed using the freely-available MIT Photonic Bands software [5]. The PhC was engineered to have a square lattice of silicon rods (n_{Si} = 3.52) with a lattice constant of a = 437.5nm, a rod radius of r = 125nm, and a rod height of h = 700nm.

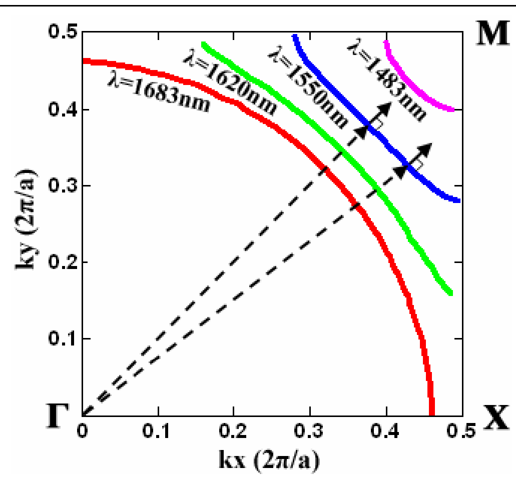

Figure 1. Equifrequency contours of the first band for the PhC composed of a square lattice of Si rods.

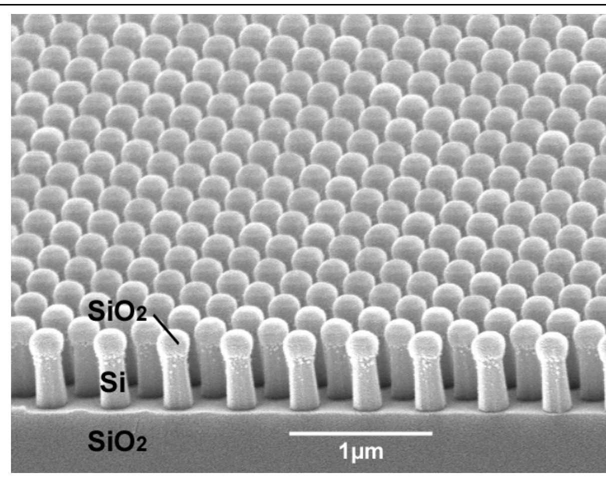

Figure 2. Scanning electron micrograph of a supercollimating photonic crystal composed of nano-scale Si rods, residing on SiO_2.

In a 2D PhC supercollimator, light is guided in the plane via supercollimation, but is confined in the vertical direction through slab index waveguiding. To confine the mode within the silicon slab, a 3µm-thick low-index layer of SiO_2 (n_{Ox} = 1.53) was used to separate the layer of silicon rods from the underlying silicon substrate. The equifrequency contours of the first band are shown in Figure 1. The dashed arrows indicate the in-plane wave vectors while the solid arrows indicate the group velocities of the plane waves inside the PhC. The equifrequency contour for λ = 1550nm is flat in the ΓM direction, which prevents the divergent propagation of electromagnetic energy, allowing for supercollimation. In the simulations, the refractive indices were assumed to be constant across the range of relevant frequencies.

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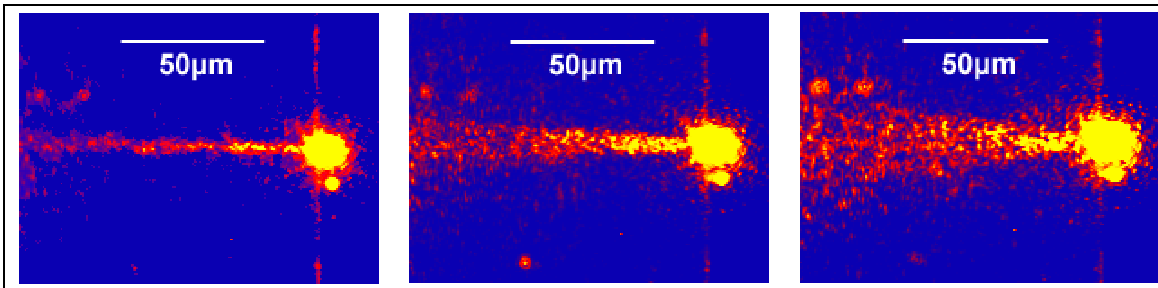
Nanofabrication

The PhCs were fabricated using a silicon-on-insulator (SOI) wafer. First, a SiO_2 etch-mask deposited by plasma-enhanced chemical vapor deposition and a tri-layer resist stack were applied. Pattern definition was performed with a Lloyd's Mirror interference lithography system, and pattern transfer, from the photoresist through the intermediary layers to the silicon, was achieved with reactive ion etching (RIE). The pattern was transferred through the tri-layer resist stack with a sequence of RIE steps using CF_4 and He/O_2, and then transferred to the SiO_2 etch-mask by RIE using CF_4. RIE with Cl_2 was used to pattern the nano-scale rods in the Si device layer. For a more symmetric device, the remaining SiO_2 etch-mask was not removed after the Cl_2 etch. A completed device is shown in Figure 2. The size of the supercollimating PhC samples varied from 2mm to 7mm on a side.

Experimental Results

To demonstrate supercollimation, TM-polarized light from a tunable laser source was coupled into the PhC sample through a single-mode lensed fiber with a spot size of 1.5μm (full-width at half-maximum). An infrared camera positioned above the sample captured the light that was scattered out of the plane, producing the images shown in Figure 3. The experimentally-observed wavelength for supercollimation was λ=1530nm (approximately 1% away from the 1550nm target), and the beam exhibited typical diffraction-like propagation at other wavelengths. The bright out-of-plane scattering is an indication of loss, which is estimated to be close to 20dB/mm in these samples, largely due to short-scale disorder, such as fabrication roughness introduced during RIE. Further refinement of the processing should yield lower-loss devices. Supercollimation is shown in Figure 3 over more than 200 lattice periods, or about 8 isotropic diffraction-lengths (Λ). Further studies resulted in observations of supercollimation over distances closer to 0.5mm (>1000 lattice periods), or 40Λ.



λ = 1530nm λ = 1570nm λ =1610nm

Figure 3. Infrared images showing the wavelength dependence of a beam propagating from right to left inside a rod-based supercollimating PhC. Supercollimation is observed at λ = 1530nm; the beam diverges as λ is increased or decreased (not shown here). The intense bright spot is scattering at the PhC-air interface, as the laser beam is coupled into the structure.

Conclusions and Applications

We have demonstrated supercollimation at λ = 1530nm over distances of hundreds of microns in a PhC composed of silicon rods. Such structures can be utilized for integrated optical routing without the need for predefined aligned waveguides. Moreover, in contrast to most hole-based supercollimators, which guide TE-polarized light, rod-based supercollimators guide TM-polarized light. Rod-based PhCs may also find use in the field of optofluidics, where the nano-scale rods may allow for better fluid penetration. In the realm of sensing, our calculations suggest that dielectric rods in air are about six times more sensitive to ambient index changes than air-holes in a dielectric slab. Furthermore, the silicon material system is well-suited for the integration of these advanced photonic devices.

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