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Direct characterization of focusing light by negative refraction in a photonic crystal flat lens

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Abstract: We report experimental measurements of the field distribution of the light spot focused by a two-dimensional photonic crystal flat lens at wavelengths 1.51-1.58 μm . The photonic crystal slab is fabricated on a silicon-on-insulator substrate by focused-ion-beam direct-milling. We demonstrate the light focusing by the photonic crystal slab through direct observation of the light spot entering into free space at the end facet of the slab lens. The beam profiles as the function of lateral position are measured and the minimal full-width-half-maximum of the beam 1.2 μm (0.77λ) is obtained.

Since Pendry proposed that a slab with negative index could act as a perfect lens [1], many experimental and theoretical works have been carried out to demonstrate the phenomenon of negative refraction. Shelby *et. al* first reported that a metamaterial structure composed by arrayed unit cells of copper stripes and split ring resonators has negative effective refraction index at microwave frequencies [2]. In the visible region, negative refraction was demonstrated in surface plasmon polariton waveguide [3], and recently in a three-dimensional fishnet metallic structure [4]. At infrared wavelength region, several studies have experimentally demonstrated negative refraction and even focusing effects by using dielectric photonic crystals (PhCs) [5,6], which is actually a type of diffraction phenomenon arising from the anomalous periodic structures [7,8]. The first experiment of the light focusing effect due to the negative refraction through a PhC slab was demonstrated in an

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InP-InGaAs-InP substrate [5], but the focusing beam width was not measured. In Ref. [9], focusing of light was directly observed in a two-dimension (2D) PhC slab lens at the optical far field region and the width of the focused beam was evaluated from the near-field images, but not the intensity profile directly at the exit of the PC. In [6], the field profile of the imaging by a silicon PhC slab was measured by arrayed wire waveguides, and the spot size was $1.7 \lambda_0$ for TM mode. Very recently, the light refocalization phenomenon was visualized by scanning near-field optical microscopy (SNOM) technique in the near field region [10].

In the present letter, we experimentally demonstrate the light focusing through a PhC slab. The PhC air holes are directly written on a silicon-on-insulator substrate by focused-ion-beam (FIB) milling near the sample cleaved facet. Therefore, the focused light by negative refraction in PhC slab can be directly observed and the intensity profile is measured as the function of the lateral position. The experimental data obtained show excellent agreement with the theoretical simulations. The minimum focused beam width is shown to be well below the wavelength.

The 2D PhC flat lens structure investigated here is similar to the one reported previously by Baba et al. [9]. The PhC has square-latticed air holes etched in the silicon-on-insulator substrate. In order for negative refraction to occur in near infrared region, the lattice constant is defined as $a = 500$ nm and the hole diameter is $d = 325$ nm. Fig 1 gives the equifrequency contours for the second TE mode (electric field perpendicular to the air holes) calculated by the plane wave expansion method, respectively. In PhC, the Poynting vector $\mathbf{S}$ is determined by the gradient of the frequency $\omega(k)$ with respect to k . Therefore $\mathbf{S}$ is always oriented perpendicular to the equifrequency contour in the direction along which ω is increasing. As shown in Fig 1, the equifrequency contours at the energy interval $a/\lambda=0.33\sim0.31$ (wavelength $1.5015\sim1.6181 \mu\text{m}$) is roughly circular along the Γ -M direction, so we can conclude that refraction at this wavelength range and with incidence along this particular direction is close to isotropic. Because of the negative gradient of the dispersion curve in the aforementioned frequency range, the Poynting vector $\mathbf{S}$ points toward the Γ point. This results in negative refraction of the beam [7].

Based on the above frequency-domain analysis, we then performed finite-difference time-domain

(FDTD) simulations of the device to verify whether the 2D PhC actually behaves as a lens to focus the light. Fig 2 (a) shows that the PhC slab focuses the light emitted by a ridge waveguide to a beam with a small width after the slab's end facet (air region) at wavelength 1550nm. The intensity distribution of the focused light beam is also shown as a function of lateral coordinate (x) in Fig 2 (b). The evaluated full-width-half-maximum (FWHM) of the beam is $1.57\mu\text{m}$ (1.0λ). For comparison, the light propagation in a silicon slab was also calculated as shown in Fig 2 (c), which shows that the light is spread into the air. The FWHM of slab light is $17\mu\text{m}$ (11λ), shown in Fig 2 (d).

There are two lithographic methods to define nanophotonic structures, namely deep UV lithography [11] and electron beam lithography [12]. After lithography, etching is usually conducted to achieve the final device. In contrast, FIB direct-writing technique is a single-step process with much flexibility. Especially, FIB is an ideal tool to make structures *in situ*, anywhere on a wafer [13]. Of course, there are drawbacks for FIB. Notably, for microfabrication of crystal silicon using FIB, the specimens inevitably suffering a certain amount of damages, such as ion implanting, material re-deposition, and sidewall amorphognosia, which are responsible for relatively high optical loss in the fabricated waveguide [14,15]. In order to minimize optical losses, a few fabrication strategies have been established such as high temperature annealing, use of a protective mask, gas-assisted etching and baking treatment in N_2 atmosphere [16, 17].

The fabrication of the 2D PC slab lens was carried out in a FEI Quanta 3D FEG dual-beam system. The structure is directly drilled on a SOI wafer which has a 250 nm silicon top layer and $3\mu\text{m}$ Buried Oxide (BOX) layer, where an additional 250 nm thick silica layer acting as an etching mask. After that, rapid thermal annealing (RTA) is performed to remove the implanting gallium ions and to recrystallize the amorphous layer. RTA is conducted at 1000 degree for 30 s in N_2 atmosphere. Finally, the silica layers beneath and above of the PhC are selectively etched away in hydrofluoric (HF) acid to form an air-bridge structure. Fig 3 (a) shows the SEM image of the devices consisting of a PhC structure made of eleven-row of air holes in a square lattice. A silicon-wire waveguide of $0.5\mu\text{m}$ width is used as a source, whose end is at a distance of $d=22.8\mu\text{m}$ from the PhC structure. The

distance between the front boundary of the PhC and its cleaved end facet is $L=1.5\text{ }\mu\text{m}$. For comparison, a silicon slab structure without air holes was also fabricated, as shown in Fig 3 (b).

An end-fire coupling system is used to observe the light scattering on the end of the cleaved facet, and therefore to measure the beam profile of the focused light. A tunable continuous-wave laser provides the light source, which is coupled into the silicon waveguide by a conical lens. The transmitted light is collimated by a micro-objective (60/0.6), diverged into two parts by a splitter. One beam perpendicular to the objective normal direction is captured by a CCD camera. The other beam discriminated by a TE polarizer is focused into a single mode fiber. The micro-objective and the fiber are mounted by a piezo-electric controlling stage for the measurement of the light intensity profile as a function of the lateral distance x from the cleaved facet. Fig 4 (a) shows an image of TE light ($\lambda=1550\text{ nm}$), which is focused by a 2D PhC slab. The mode is bright and well defined, and its intensity profile is Gaussian-like (Fig 4 (c)). In contrast, no well defined bright spot can be observed for the TM polarization. The same measurement is repeated on the silicon slab sample without the PhC structure (Fig 4 (b)). The output light is significantly broadened in shape. Fig 4 (d) shows the intensity profile of the slab light and derived FWHM is $13\mu\text{m}$. The observed spot light and the Gaussian like profile suggest that we have successfully realized light focusing by negative refraction using a 2D PhC flat lens.

Fig 5 shows the lateral intensity distribution of the focused light beam at different wavelengths. For each wavelength, the focused light beam is Gaussian-like. Negative refraction occurs for a broad range of wavelengths from 1510 to 1580 nm, which is in good agreement with the equifrequency contours shown in Fig 1. The results also agree with our FDTD predictions. The FWHM of the focused spot W is evaluated from the intensity profile. The minimum W is found to be $1.2\mu\text{m}$ (0.77λ) at 1560 nm. From Fig. 4 and Fig. 5, the focusing effect of the 2D PhC due to negative refraction is thus clearly demonstrated.

In summary, we have fabricated a 2D PhC slab lens on a SOI substrate by using the FIB direct-milling method. Our experimental measurement shows clearly focusing characteristics arising from negative refraction phenomenon of the PC structure. A bright and well defined spot light at the

end facet of the PC slab was captured by a CCD camera. The lateral intensity profiles of the focused light beam were measured. It is evident that the negative refraction effect occurs in a large wavelength range from 1.51-1.58 μm . The minimum focused beam width is 1.2 μm (0.77λ), well below the wavelength.

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Figure Caption

Fig 1. Equipfrequency contours of the second TE band for a 2D PhC with air holes in SOI substrate.

Fig 2. Device structures and FDTD simulation results. (a) The electric field intensity distribution in the x-y plane. (b) The lateral intensity distribution of the focused light beam. (c) The electric field intensity distribution in the x-y plane, the absence of the PC structure. (d) The lateral intensity distribution of the light beam derived from (c).

Fig 2.

Fig 3. SEM images of the fabricated devices. (a) The device consisting of the silicon slab and the 2D PhC. (b) A silicon slab without PhC structure.

Fig 3.

Fig 4. (a) Near-field image of the light beam at the focus point by a 2D PhC slab. (b) Near-field image of the spread beam directly from the slab, i.e without a PhC structure. (c) The lateral intensity profile of the focused light beam. (d) The lateral intensity profile of the spread light beam. The blue lines are the experiment data, and the green lines are the fitting curves.

Fig 5. (a)-(g): Measured lateral intensity distributions of the focused light beam at different wavelengths. The blue lines are the experiment data, and the green lines are the fitting curves.

Fig 5.

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