Focusing of light by negative refraction in photonic crystal slab superlens on SOI substrate

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Abstract

We experimentally observed the focusing of light by the negative refraction in a photonic crystal slab superlens at near infrared wavelengths λ of 1.26 – 1.42 μm . The photonic crystal with optimized interfaces low reflection and diffraction losses was formed in silicon-on-insulator. The near field pattern of the focusing was observed using intentional out-of-plane radiation or scattering of guided light in the slab. The minimum focused spot affected by the aberration was 1.8 μm (1.4λ) in width. The focusing characteristics were in good agreement with theoretical ones obtained from photonic band and finite-difference time-domain analyses.

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Photonic crystals (PCs) allow the negative refraction of light, which is actually a sort of diffraction caused by the anomalous dispersion characteristics in multi-dimensional periodic structures [1, 2]. The PC superlens [3, 4] focuses diverging incident light beam by the negative refraction of a wide range of angular components. Due to the focusing mechanism completely different from that of conventional index lenses with curved surfaces, the superlens can form real images of objects with a large numerical aperture (NA) [4] and achieve the subwavelength resolution under optimum condition by the flat surface [5]. In addition, a negative refractive index, which obeys the Snell's law, can be defined when equi-frequency contours of the dispersion characteristics (dispersion surface) are rotationally symmetric near the Γ point [4]. The negative refraction and the focusing have been mainly demonstrated in experiments using dielectric-rod-type and airhole-type two-dimensional (2D) PCs at millimeter-waves [6-8] and in finite-difference time-domain (FDTD) simulation [9-11]. An experiment was also done at lightwaves using the airhole-type 2D PC with a low index contrast slab structure [12]. However, the focusing of light was not still clear, because the optical confinement was weak in the low index contrast slab, and the unwanted reflection and diffraction at input and output (I/O) ends of the PC disordered the light propagation. A high index contrast PC slab based on, e.g., silicon-on-insulator (SOI) substrate might be expected to improve the optical confinement. However, the perfect optical confinement rather disturbs the observation of the focusing. In addition, the high index contrast makes the reflection and diffraction more serious. Recently, we found an optimum interface in the FDTD simulation, which suppresses the reflection and diffraction losses to 0.56 dB [11]. In this paper, we describe the fabrication of this structure in the SOI slab and demonstrate the clear focusing of light through the intentional out-of-plane radiation or scattering. We also discuss the correspondence of the results to theoretical ones.

In the experiment, we prepared an SOI substrate whose Si layer was 0.26 μm thickness and SiO_2 layer was 1 μm thickness. We formed the PC pattern by e -beam lithography and SF_6 inductively coupled plasma etching, and the air-bridge structure by HF wet etching. Figure 1(a) and (b) show top views of the fabricated device.

Let us first explain the design of the PC of airholes in a square lattice rotated by 45° . Figure 1(b) also shows the second dispersion surface calculated for the in-plane polarization (TE polarization) by the plane wave expansion method, where the airhole diameter normalized by the lattice constant $2r/a$ is 0.689 and the effective index of the slab is 2.963. In the PC, Poynting vectors S are determined by the gradient of an equi-frequency contour. As indicated by arrows for a normalized frequency a/λ of 0.31, as an example, the negative refraction occurs for a wide range of angular components. These arrows satisfy the propagation condition with no out-of-plane radiation, because the contour of this a/λ lies outside of the air light line shown by the thick solid line. At a/λ inside the light line, the light is radiated to the air, and so the light propagation is observed from the top within the capability of the used optical setup. The thick dashed line in Fig. 1(b) shows the observable condition of radiated light when the NA of objective lens used for observation is 0.5. On this condition, the negative refraction is also expected, as indicated by arrows at $a/\lambda = 0.37$, as an example. Figure 1(c) shows the ray tracing performed for the arrows at $a/\lambda = 0.31$, when the full divergence angle 2θ of incident light arriving from the point source of 50λ distance is assumed to be 12° . Here, the light is focused, and the focused spot affected by the aberration particularly for larger incident angles is 1.4λ in width. As mentioned above, we found that the reflection and diffraction at I/O ends is suppressed by an optimum interface, i.e., deformed airholes just at the boundary, each of which has a front shape of the fourth order function of $2.8r$ height and a triangular back shape of $0.4r$ height, as shown in Fig. 1(b). Figure 1(d) shows the light propagation calculated by the FDTD method, where the same model as for Fig. 1(c) with the deformed airholes and Gaussian beam input are assumed. The focusing of light corresponding to the ray tracing is confirmed and the full width at half maximum (FWHM) of the focused spot $2w$ is 1.3λ .

Next, let us explain the pattern layout of the fabricated device, as shown in Fig. 1(a). The Si wire waveguide of $0.5\ \mu\text{m}$ width was used as a source of the Gaussian beam. For the simultaneous formation of the air-bridge wire waveguide and the air-bridge PC, the waveguide was supported by crossbeams of $20\ \mu\text{m}$ interval. An elliptical mode expander [13] of $1.52\ \mu\text{m}$ width and $7.2\ \mu\text{m}$ length was inserted at each crossbeam to suppress the crosstalk and light scattering. In addition, a 90° bend was inserted to the waveguide to eliminate the on-axis noise. The waveguide was connected to the Si slab of $77\ \mu\text{m}$ length through a parabolic taper of $2.3\ \mu\text{m}$ width so that the same Gaussian beam as for Fig. 1(d) was excited. The FWHM of the beam width was typically $13\ \mu\text{m}$ at the input end of the PC at wavelengths used in this experiment. In some device samples, a groove of $20\ \mu\text{m}$ width was placed at the output end of the PC. For these samples, the beam width can be measured from the near field pattern (NFP) of scattered light at the groove. By connecting these NFPs for various PC lengths L , the light propagation inside the PC can be indirectly evaluated. In this study, we prepared samples with different L ranging from $1 - 11\ \mu\text{m}$. For other samples without groove, on the other hand, the scattered light cannot be observed, and so the NFP of light propagation can be directly observed only on the observable condition, as discussed above.

In the measurement, TE-polarized light from tunable laser was coupled to the wire waveguide and incident to the PC through the slab waveguide. Direct NFPs of radiated light and connected NFPs of scattering light were taken from the top using an objective lens of $\text{NA} = 0.5$, as shown in Fig. 2, where $a = 0.45\ \mu\text{m}$, and $2r = 0.28$ and $0.31\ \mu\text{m}$ for the former and the latter, respectively. Direct NFPs at $\lambda = 1.26 - 1.31\ \mu\text{m}$ clearly show that the light is focused in the PC and intensified at the focal point. The light beam after passing the focal point rapidly decays due to

the out-of-plane radiation. The optical path of smaller angular components incident almost normal to the PC disappears on the longer wavelength side. It is understood from Fig. 1(b); the smaller angular components are the first to escape from the observable condition, as the frequency becomes lower. At $\lambda > 1.32 \mu\text{m}$, all angular components are outside of the observable condition, and so the focusing characteristics are only observed in the connected NFPs. Due to the resonance inside the groove, each NFP exhibits a nonuniform standing-wave profile in the lateral direction. The intensity variation in the propagation direction is difficult to evaluate, because the connected NFPs were not precisely evaluated on the same condition. However, rapid decay along the propagation direction, like those at $\lambda = 1.26 - 1.31 \mu\text{m}$, is not observed. The FWHM of the focused spot $2w$, focal length f , and NA evaluated from the NFPs are shown in Fig. 3, where solid lines are obtained from the ray tracing for $2\theta = 12^\circ$. Experimental plots almost agree with theoretical lines, and the minimum $2w$ was $1.8 \mu\text{m}$ (1.4λ). Although the ray tracing suggests a smaller $2w$ of $\sim 1 \mu\text{m}$ at $\lambda = 1.28 - 1.30 \mu\text{m}$ and the resolution of the used optical setup was less than $1 \mu\text{m}$, the experimental $2w$ was no smaller than $1.8 \mu\text{m}$. It can be explained by the diffraction limit of the focusing, depending on all angular components of the incident light. The resolution of the plots for f and NA was not sufficient at $\lambda > 1.3 \mu\text{m}$, since the connected NFPs were taken for every $2 \mu\text{m}$ of L . Still, they roughly behave like the theoretical curve. The maximum NA estimated from f and the beam width at the input end was as large as 0.96 due to the very short f .

In conclusion, we fabricated the PC superlens in the SOI substrate with optimized I/O interfaces for low reflection and diffraction losses, and observed the focusing characteristics due to the negative refraction in a wide wavelength range of $1.26 - 1.42 \mu\text{m}$. We also confirmed their good agreement with theoretical characteristics obtained from the dispersion surface and the FDTD simulation. The minimum focused spot width was $1.8 \mu\text{m}$ (1.4λ). The reduction in aberration and loss for larger incident angles will reduce the spot width. This unique lens is expected to provide novel design principles in optical coupling devices and imaging systems.

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Fig. 1 Device structure and theoretical characteristics. (a) Total view of fabricated device. (b) Magnified view of PC with deformed airholes as the optimum interface, and dispersion surface of designed PC. Thin lines are equi-frequency contours. Solid and dashed thick lines are the light line and observable condition of radiated light by objective lens with NA = 0.5, respectively. Arrows show Poynting vectors $\mathbf{S}$ inside the PC. (c) Ray tracing at $a/\lambda = 0.31$. (d) FDTD simulation of light propagation (square of the magnetic field component in the vertical direction) at $a/\lambda = 0.31$.

Fig. 2 NFPs showing the focusing of light. They were directly observed using out-of-plane radiation at $\lambda = 1.26 - 1.32 \mu\text{m}$, while indirectly evaluated from the scattered light at the groove at $\lambda = 1.33 - 1.39 \mu\text{m}$.

Fig. 3 Experimental plots and theoretical curves of focusing characteristics. (a) FWHM of focused spot $2w$. (b) Focal length f . (c) NA.