Abstract—We report an extremely compact (30 μm × 7 μm) silicon-based 2-D thermo-optically tunable photonic crystal (PhC) lens operated at around telecommunication wavelength (1.55 μm) with transverse-magnetic-like polarization light. A honeycomb lattice array of high index silicon rods with 340 nm in thickness, 234 nm in diameter, and 338 nm in lattice constant were embedded in 3-μm-thick low index silicon dioxide. A 150-nm-thick NiCr micro-heater was placed directly on top of the PhC structure to provide localized heating to the silicon rod array. The localized heating causes refractive index change in silicon due to thermo-optic effect which results in change of the focal length of the PhC lens. The device was characterized with a tunable laser light source in the wavelength range of 1500 ~ 1580 nm. Tuning of focal length in this device was experimentally demonstrated by applying different current through the heater. Such experimental results showed good agreement with the simulation results.

Index Terms—Lens, photonic crystal (PhC), silicon, thermo-optic, tunable.

I. INTRODUCTION

The photonic crystal (PhC) [1], [2] is an artificial structure in which the dielectric constant varies periodically. It has been extensively studied since it has great potential to be applied in the integrated optical circuit to control and manipulate the flow of lights for various wavelengths. Negative refraction which was first hypothesized by Veselago [3] in 1967 is one of the most fascinating features demonstrated by PhC. Pendry [4] theoretically proved the existence of negative refraction and applied it in a thin silver slab to make a lens. In 2001, Smith et al. [5] experimentally demonstrated the existence of negative refraction using unit cells of copper strips and split ring resonators. We reported first experimental observation of isotropic negative refraction in a silicon-based planar PhC structure at optical frequencies [6].

Numerous applications of negative refraction in PhC were demonstrated such as polarization-beam splitter [7], superlens [8], superlens [9], etc. Various kinds of PhC lenses were proposed. However, most of them are passive lenses which could not be tuned with external control signal. There have been several theoretical works reported on tunable PhC lenses such as the mechanically tunable PhC lens by Wu et al. [10] and the electrooptically tunable PhC lens by Ren et al. [11].

In this work, thermo-optic effect was utilized to realize a tunable 2-D silicon-based PhC lens. Silicon has a relatively high thermo-optic coefficient of 2.4 × 10⁻⁶ C⁻¹ at a temperature of around 440 °C [12], [13]. By utilizing refractive index change of silicon due to thermal heating, the photonic band structure could be modulated and the tunable focal length 2-D PhC lens could be realized.

II. DESIGN AND SIMULATION

To demonstrate thermo-optic tuning of the PhC device, the device was designed to integrate a PhC lens and a micro-heater in compact 3-D structure. In this work, a 2-D silicon-based PhC lens was designed in such a manner that a high index silicon rod array is embedded in low index silicon dioxide medium. A high electric resistivity nickel chromium (NiCr) alloy micro-heater was placed directly on top of the PhC structure. Current flowing through the NiCr heater generates heat which is conducted through the silicon dioxide layer and raises the temperature at the PhC lens as shown in Fig. 1.

In order to design a negative refraction-based PhC lens with a structure of spatial periodic distribution of high refractive index material (e.g., silicon rod) in low refractive index medium (e.g., silicon dioxide) which forms an inverted PhC structure, several different kinds of lattice structures were investigated using plane wave expansion method (PWEM). In inverted PhC design, most of the lattice structures (square, triangular) showed overlapping of negative refraction mode and positive refraction mode. However, a honeycomb lattice structure showed clear separation between the negative and positive refraction mode which prevents the multimode existence in operating wavelength. Refractive indices used for silicon and silicon dioxide in this work are 3.46 and 1.5, respectively, at room temperature. Due to thermo-optic effect, the refractive index of silicon is assumed to be 3.56 at 440 °C, while that of the silicon dioxide remains 1.5 due to a negligibly low thermo-optic coefficient of silicon dioxide (10⁻⁶ C⁻¹) [14]. Upon investigation of photonic band diagrams generated with different normalized radii...
Fig. 2. Equi-frequency contour of the inverted honeycomb lattice PhC showing negative refraction region in the second band.

![Equi-frequency contour of the inverted honeycomb lattice PhC showing negative refraction region in the second band.](image)

The fabricated tunable PhC lens was tested with a tunable laser light source with an operating wavelength in the range of 1500 ~ 1580 nm. The laser lights were coupled into the cleaved input waveguide edge and infrared camera images were taken.

In order to design a PhC lens which operates at a wavelength of around 1.5 \( \mu \)m, combining with equi-frequency contour as shown in Fig. 2, a normalized frequency \( (\sqrt{3}a/\lambda) \) of 0.39 was selected. As a result, the closest distance between neighboring silicon rods in honeycomb PhC and diameter of silicon rod were calculated to be 338 and 234 nm.

A series of 2-D finite-difference time-domain (FDTD) simulations using commercially available software EMPLab (EM Photonics) were carried out. Fig. 3(a)–(c) shows 2-D FDTD simulation results of the designed PhC lens at 25 °C, 235 °C, and 440 °C, respectively. The light source with a wavelength of 1.5-\( \mu \)m transverse-magnetic (TM) polarization was placed at (a) 25 °C, (b) 235 °C, and (c) 440 °C away from the PhC at 30 °C, 235 °C, and 440 °C, respectively.

ANSYS simulation was carried out to evaluate the effectiveness of localized heating in the designed PhC tunable lens. Due to high electric resistivity, NiCr was selected as the micro-heater material. A test strip of 150-nm-thick NiCr was fabricated and its electric resistivity was measured to be \( 1 \times 10^{-5} \) \( \Omega \)m. The NiCr micro-heater was designed to be 12 \( \mu \)m wide, 70 \( \mu \)m long, and 0.15 \( \mu \)m thick and situated directly on top of the PhC lens with a 1-\( \mu \)m silicon dioxide insulation layer. Fig. 4 shows a 2-D lateral temperature distribution profile at the Si–SiO\(_2\) PhC lens which shows a uniform temperature of 380 °C throughout the PhC lens when 7.5 V is applied.

III. FABRICATION

Silicon-on-insulator (SOI) wafer with the top silicon thickness of 340 nm and 2-\( \mu \)m buried silicon dioxide was used as substrate. Photoresist S1813 (Shipley Co., Marlborough, MA) was patterned using conventional optical lithography to create 100-nm-thick Cr layer by a lift-off process. Poly(methyl methacrylate) (PMMA) was spin-coated and a honeycomb PhC structure was patterned by electron beam lithography. Cr was evaporated and lifted off to transfer the PMMA pattern to Cr. Cr structure defined by optical lithography and electron beam lithography was used as a silicon etch mask and the silicon layer was dry etched by CF\(_4\)-O\(_2\) (91.25%:8.75%) plasma. Then, the Cr etch mask was removed and 1-\( \mu \)m-thick silicon dioxide was deposited on top of the whole device area by plasma-enhanced chemical vapor deposition (PECVD) to prevent direct electrical contact of the PhC lens and the micro-heater. The NiCr micro-heater (0.15 \( \mu \)m thick) and gold electric pads (0.2 \( \mu \)m thick) were deposited on top of PhC lens by photolithography and a lift-off process.

Fig. 5(a) shows an optical photomicrograph of the top view of the fabricated tunable PhC lens. It should be noted that the micro-heater comprehensively covers the entire area of the PhC lens to realize uniform localized heating. Fig. 5(b) shows a scanning electron micrograph (SEM) image of the top view of the fabricated honeycomb lattice PhC Si rods.

IV. CHARACTERIZATION

The fabricated tunable PhC lens was tested with a tunable laser light source with an operating wavelength in the range of 1500 ~ 1580 nm. The laser lights were coupled into the cleaved input waveguide edge and infrared camera images were taken.
from the top of the device. Constant current in the range from 0 to 25 mA was applied using a dc probe which were directly applied to the Au pads. Fig. 6(a)–(d) shows infrared camera images taken at a wavelength of 1520 nm with different applied powers of 0, 37.6 mW (10 mA), 146 mW (20 mA), and 187.5 mW (25 mA). The temperatures at the edges of the silicon deflection block.

In order to characterize the focal length tuning effect, a light intensity profile at the edge of the silicon deflection block was extracted from a series of infrared camera images taken by the infrared CCD camera using a specifically programmed Matlab code (Fig. 7).

Fig. 8 shows experimentally measured light spot sizes (a full-width at half-maximum method) as a function of various applied currents. It could be observed that as the applied current increases, lateral size of the peak light spot at the deflection block decreases as expected.

Fig. 8 shows experimentally measured light spot sizes (a full-width at half-maximum method) as a function of various applied currents. This indicates focal point moves away from the PhC lens as applied power increases as expected by the 2-D FDTD simulation results.

V. CONCLUSION

A 2-D silicon-based extremely compact thermo-optically tunable PhC lens operated at around 1.5-μm TM-like polarized light was designed, fabricated, and characterized. It was found that thermo-optic tuning in silicon is an effective method to realize a compact tunable lens. This extremely compact tunable lens has a great potential to be integrated with other components to demonstrate broad applications of nanoscale optical imaging. In order to avoid light confinement issues in the rod-based PhC, a PhC made of air holes in silicon may be considered.

REFERENCES