Thermo-optically tunable silicon photonic crystal light modulator

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We designed, fabricated, and characterized a thermo-optically tunable compact (10 μm × 10 μm) silicon photonic crystal (PhC) light modulator that operates at around 1.55 μm for TE polarization. The operational principle of the device is the modulation of the cutoff frequency in a silicon-based line defect PhC. The cutoff frequency is shifted because of the thermo-optic tuning of the silicon refractive index, which is realized by localized heating on the PhC. The modulator is formed by a triangular lattice array of cylindrical air holes on a silicon-on-insulator wafer. Optical characterization was carried out, and the result clearly showed thermo-optic tuning of the cutoff frequency around 1.55 μm.

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Optical modulators play a key role in many photonic integrated circuits by providing the transduction of information onto an optical carrier. However, owing to their large sizes (a few hundred micrometers to a few millimeters), conventional silicon-based light modulators [1,2] can hardly be directly integrated in integrated optical circuits. Photonic crystals (PhCs) [3] have provided various solutions to make the light modulators small, fast, and efficient.

Line defect PhC waveguides (LDPCWGs) [4] have attracted considerable attention, because they guide the light at an ultracompact scale with a reasonably low loss of energy and effective confinement of the light in the vertical direction. The LDPCWG is usually applied in the two arms of the Mach–Zehnder interferometer (MZI). By actively controlling the group velocity (electro-optic and thermo-optic) in one arm, a relative phase shift can be induced between the two arms, and upon recombining the signals in the two arms, this leads to a modulation of the light intensity. Camargo et al. [5] demonstrated a compact (15 μm × 22 μm) thermo-optic PhC light switch by using MZI with a switching power of 42 mW. They also demonstrated asymmetric PhC MZI [6] with a switching power of 28 mW. Vlasov et al. [7] combined slow light and MZI, effectively reducing the size (250 μm long), the operating power (2 mW), and the switching time (∼100 ns) of the modulator. Beggs et al. [8] also introduced slow light in a silicon PhC-based optical switch to further reduce the device size. The switching energy is estimated to be 200 pJ. The device was designed to be a directional coupler that has two supermodes. Because of the slow-light mode, the switching length of the directional coupler could be as short as 5.2 μm. Wang et al. [9] also proposed a slow-light MZI with compact size (∼42.6 μm), low driver voltage (1.25 V), and a high-modulation bandwidth (100 GHz).

Other than MZI, the cutoff effect can also be used to directly realize the light modulator. In a properly designed LDPCWG, there is an abrupt drop of the light transmittance at a certain frequency known as cutoff [10,11]. Based on LDPCWG, Tinker and Lee [11,12] proposed a theoretical model of a thermo-optically tunable PhC light modulator utilizing this cutoff effect. By locally increasing the temperature of the LDPCWG, the cutoff frequency can be modulated. These modulators could be realized in a few micrometers with extinction ratios up to 50 dB [11].

In the present work, we report the design, fabrication, and characterization of an ultracompact (10 μm × 10 μm) tunable PhC light modulator based upon LDPCWG. The modulator functions in the telecommunication C band, around the wavelength of 1.55 μm. At these wavelengths, the device operates for TE polarization. The modulator is capable of completely cutoff light transmission at less than four periods of its lattice (1.7 μm, switching length) at the cutoff region. The extinction ratio approaches 30 dB, and the insertion loss is 4.2 dB.

Figure 1 shows a schematic diagram of the device, which consists of the PhC light modulator in the middle and the nickel chromium (NiCr) alloy microheaters placed symmetrically on both sides of the PhC structures to provide localized heating to the PhC light modulator. The PhC light modulator is fabricated on a 220-nm-thick silicon slab with 2-μm-thick buried oxide. Light is guided into and out of the modulator through the input and output silicon waveguides. Once the NiCr heaters are turned on, the temperature at the PhC light modulator is locally raised, and this causes a change in the refractive index of the silicon. This refractive index change in turn causes a change in the photonic band structure and consequently shifts the cutoff frequency of the modulator.

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To demonstrate the thermo-optically tunable PhC light modulator, the design has been divided into two parts: (1) the design of a LDPCWG with an abrupt drop in its transmission spectrum and (2) the design of an efficient microheater to provide sufficient heat to the PhC light modulator to realize thermo-optic tuning.

To obtain the cutoff feature in the spectrum of the LDPCWG at room temperature, a plane-wave expansion method (PWEM) analysis was carried out to find out the intrinsic features in various PhC structures. The design considered the substrate of a silicon-on-insulator (SOI) wafer with a top silicon thickness of 220 nm and 2-μm-thick buried oxide. After an evaluation of various lattice structures, the triangular lattice PhC structure, which has periodic air holes formed in the silicon slab, was selected. Figure 2 shows the two-dimensional (2D) photonic band diagram of a triangular lattice LDPCWG along the Γ–K direction (light propagation direction) with a normalized radius \( r/a \) of 0.33765.

In the band diagram, the waveguide mode and the cutoff region were adjacent to each other, causing an abrupt drop of the light transmittance in the Γ–K direction. The cutoff frequency, which lies at the interface of the waveguide mode and the cutoff region, is modulated through the predictable thermo-optic change of the silicon refractive index. Because of the relatively high thermo-optic coefficient of the silicon \((2.4 \times 10^{-4} \, ^\circ C^{-1})\) [11], the refractive index of silicon could be increased by 0.02 with a temperature change of approximately 83 °C. The PWEM analysis shows that the cutoff frequency shifts to a larger wavelength as the temperature increases. Based on the band diagram, the light modulator is designed to have the lattice constant of 425 nm and an air hole diameter of 287 nm. The shift of the cutoff frequency is verified by 2D finite-difference time-domain (FDTD) simulations, as shown in Fig. 3.

Figure 3(a) shows the cutoff of the light at the wavelength of 1540 nm (TE) at room temperature by the PhC light modulator, while Fig. 3(b) shows transmission of the same wavelength light at the elevated temperature of 110 °C. The transmittance spectra in Fig. 4, based upon a series of 2D FDTD simulations, shows the cutoff wavelength modulation more clearly. As the temperature increases from room temperature to 110 °C, the transmission spectrum shifts 5 nm toward the larger wavelength.

Finite element modeling using COMSOL was carried out to design the heaters, which provide the needed heat via the microheater.
After removing the aluminum, the measured spectra without current and the spectrum has 70 dB. However, the overall insertion loss was thus estimated to be 12.8 dB. The discrepancy of the insertion loss was due to the light coupling and outcoupling losses at the edges of the input and output waveguides, which were accounted for in the experimentally estimated insertion loss.

In summary, a thermo-optically tunable PhC light modulator was designed, fabricated, and characterized. The device is extremely compact in size and is applicable to a variety of optical integrated circuits to function as a light modulator in the wavelength range of 1500–1580 nm for TE polarized light.

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