Slow-light Si-wire Waveguide with Metamaterial

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Abstract: We propose a novel slow-light Si-wire waveguide using metamaterials, which can be easily integrated with other Si photonics devices, and the group index of more than 40 was obtained in both theoretical and experimental investigations.

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1. Introduction

Optical metamaterials offer new opportunities for innovation in the field of electromagnetic parameter design, such as the tuning of electric permittivity and magnetic permeability. This metamaterial paradigm facilitates further development of waveguide photonic devices with novel optical functionalities, such as the ultra-compact optical modulators [1], the CPA (coherent perfect absorber)-laser for lasing and anti-lasing [2], the unidirectional mode converters [3], the waveguide-integrated mode-selective nano-antennas [4].

One promising application of such metamaterials is the "slow-light" devices, which can decelerate the group velocity of the guided light waves. In this paper, we have investigated a slow-light silicon (Si)-wire waveguide with metamaterials, which is extremely simple and easier to integrate with other Si photonics devices rather than the conventional slow-light devices such as the electromagnetic induced transparency (EIT) devices [5] and the photonic-crystals (PhCs) [6]. The following sections first present numerical calculation based on the homogenization mode analysis [7] and then show experimental demonstration of slow-light effect in Si-wire waveguide with metamaterials.

2. Device structure and analysis results

Figure 1(a) shows the schematic image of our slow-light Si-wire waveguide with metamaterials, which consists of a SiO_2-embedded Si-wire waveguide with an array of nanoscale metal rings. The electrical field of the input TE-polarized optical wave is perpendicular to the gap direction of the metal rings, which leads to an *LC* resonance (i.e., the permeability changes) when the input frequency gets closer to the resonance frequency of the ring. Therefore, the group velocity of an optical pulse propagating through the waveguide can be significantly slowed down thanks to the huge dispersion of the permeability induced by the metamaterials.

Figure 1(d) shows calculated dispersion relations of the Si-wire waveguide with metamaterials, which was derived from the homogenization mode analysis [7] (dimensions used in this simulation are shown in Figs. 1(b) and 1(c)). Blue lines show the light lines of the SiO_2 cladding and the Si core, and red dots show the dispersion relations of the device. The slope of the dispersion curve drastically changes near the resonant frequency of the metal rings, leading that the group index of larger than 40 is expected to be obtained at optical communication frequencies.

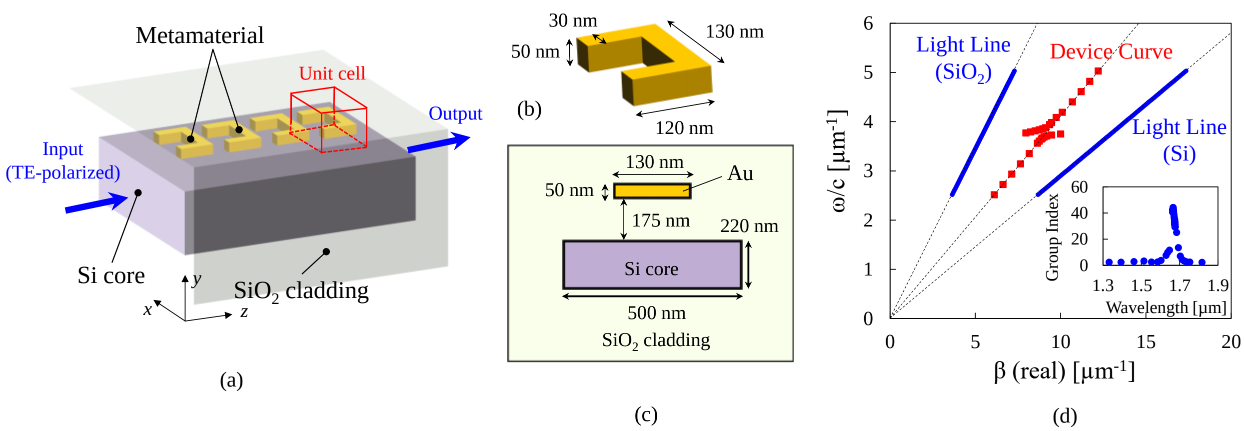

Fig. 1. (a) Schematic image of Si-wire waveguide with metamaterials. (b) Dimensions of individual metal ring. (c) Cross section of device. (d) Calculated dispersion relation of device derived by homogenization mode analysis (Inset is group index as a function of wavelength).

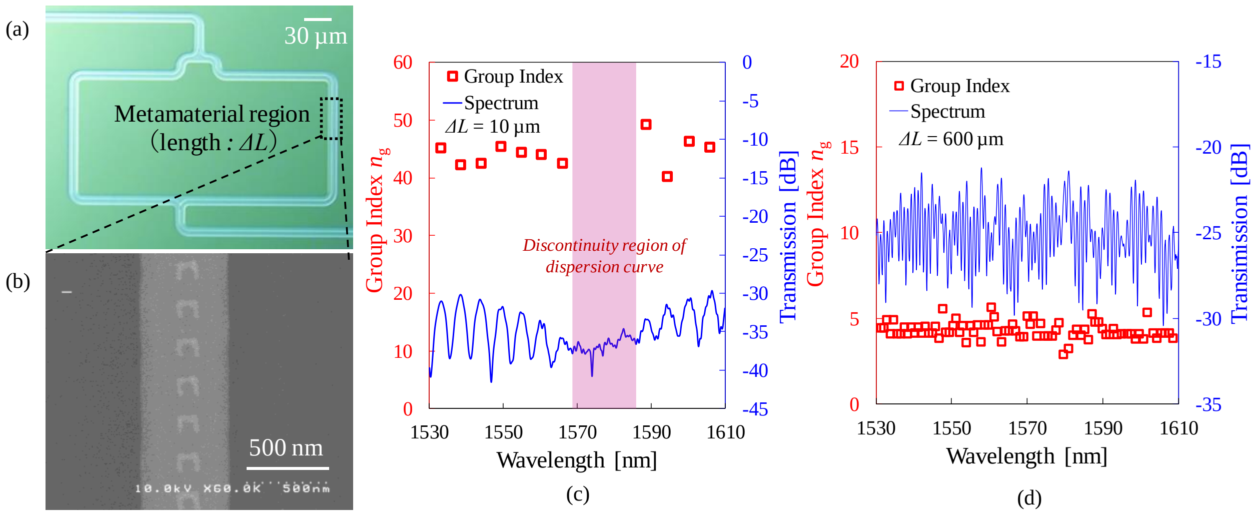

Fig. 2. (a) Optical microscope image and (b) SEM image of the fabricated device. (c) TE-mode transmission spectra and derived group index of Si MZI with metamaterials. (d) TE-mode transmission spectra and derived group index of Si MZI without metamaterials.

3. Fabrication process and measurement results

Silicon photonic waveguides with metamaterials were fabricated from a commercial Si-on-insulator wafer with a 220-nm thick Si layer on a 1.5-µm-thick oxide buffer layer. First, the waveguide pattern was written on a resist through electron-beam lithography (EBL) and then transferred to the Si core by an inductively coupled plasma etching process, followed by a 175-nm-thick SiO_2 deposition on the top Si layer. After that, the metamaterials were formed using the EBL and lift-off process. Finally, the waveguide was buried under a 1-µm-thick SiO_2 cover layer by plasma enhanced chemical vapor deposition. Dimensions of the device are set to be the same as those of simulation one (see Figs. 1(b) and 1(c)).

In order to evaluate the group index n_g, we prepared devices with the shape of the Mach-Zehnder interferometer (MZI). The formula $n_g = (\lambda_{min} \cdot \lambda_{max}) / (2 \cdot \Delta L \cdot \Delta\lambda)$ allows us to determine the wavelength dependence of the group index from the interference fringes [8] (λ_{min} and λ_{max} are the spectral positions of minima and maxima, ΔL is the length difference of the MZI arms and $\Delta\lambda$ is the spectral distance between adjacent minima and maxima, respectively). Figure 2(a) shows the optical microscope image of a fabricated device. The two arms of the MZI have a path length difference of ΔL, where metamaterials are placed on the Si core (see SEM image of Fig. 2(b)).

Figures 2 (c) and 2(d) show the TE-mode transmission spectra of the MZI with and w/o metamaterials, respectively, measured with an ASE light source from 1530 to 1610 nm (the group indices derived from the measured transmission spectra are also plotted). These results indicate that the group index of the Si-wire waveguide with metamaterials is increased to more than 40 (10 times larger than that of the normal Si-wire waveguide w/o metamaterials ($n_g \sim 4.3$)). In addition, the clear interference fringes were not observed near the wavelength of 1575 nm, which reflects the discontinuity point of the dispersion curve of the device (see Fig. 1(d)).

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