All-optical switching on a silicon chip

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We present an experimental demonstration of fast all-optical switching on a silicon photonic integrated device by employing a strong light-confinement structure to enhance sensitivity to small changes in the refractive index. By use of a control light pulse with energy as low as 40 pJ, the optical transmission of the structure is modulated by more than 97% with a time response of 450 ps. © 2004 Optical Society of America

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Photonic integrated circuits that bend, split, couple, and filter light have recently been demonstrated in silicon.[1] However, these structures are usually passive, which means that their optical properties are predetermined by the structure design and thus cannot be modified once fabricated. All-optical switches and modulators have been demonstrated by employing III–V compound materials based on photoexcited free-carrier concentrations resulting from one- or two-photon absorption.[2–4] In silicon, all-optical switching has been demonstrated only by use of extremely high powers[5–11] in large or nonplanar structures in which the modulated light propagates out of plane. Such high powers, large dimensions, and nonplanar structure geometries are inappropriate for effective on-chip integration. The difficulty in modulating light with silicon structures arises from the weak dependence of silicon's refractive index and absorption coefficient on the free-carrier concentration.[12,13] As an example, for a 300-μm-long, 1.55-μm Mach–Zehnder modulator based on rib waveguides with a mode-field diameter of approximately 5 μm, a minimum optical pump-pulse energy of 2 mJ is needed to modify the refractive index by $\Delta n = -10^{-3}$ to achieve 100% modulation.[14] The absorption due to free carriers under such high powers is also small (16 dB/cm for a 450-nm-wide and 250-nm-high rectangular cross-sectional waveguide), which requires a straight waveguide as long as 600 μm to achieve a modulation depth of 90%.[7,15]

We recently proposed the use of high optical confinement in resonant structures for efficient light modulation to overcome the aforementioned limitations of silicon photonic structures[16]; our results indicate that a refractive-index change as small as 10^{-3} can induce a large modulation depth of 80% in a compact 20-μm-long structure. Using these theoretical predictions, here we present experimental results on an all-optical gate based on a silicon micrometer-size planar ring resonator that operates with low pump-pulse energies.

A ring resonator coupled to a single waveguide presents optical transmission that is highly sensitive to the signal wavelength and is greatly reduced at wavelengths in which the ring circumference corresponds to an integer number of guided wavelengths. Figure 1 shows a silicon-on-insulator ring resonator with a 5-μm radius, patterned by electron-beam lithography and subsequently etched by plasma reactive-ion etching[17]; both the waveguide and the ring resonator are channel waveguides with 450-nm-wide by 250-nm-high rectangular cross sections. Figure 2(a) shows the quasi-TM transmitted spectral response of the structure in Fig. 1. The quasi-TM mode is characterized by the magnetic field oriented predominantly along the plane of the chip. On resonance the transmission drops by more than 10 dB with respect to that off resonance. The losses at off-resonance wavelengths are 3.5 dB, which include the fiber-to-waveguide coupling losses and the propagation losses in the 7-mm-long waveguide. The cavity quality factor is $Q \cong \lambda_0/\Delta\lambda_{\mathrm{FWHM}} = 2290$, where $\lambda_0 = 1555.5$ nm is the resonance wavelength and $\Delta\lambda_{\mathrm{FWHM}} = 0.68$ nm is the resonance FWHM. This quality factor corresponds to a cavity photon lifetime of ${\lambda_0}^2/(2\pi c \Delta\lambda_{\mathrm{FWHM}}) =$ 1.8 ps,[18] where c is the speed of light in vacuum. Therefore, despite the resonant nature of the structure, the temporal response of this ultrasmall optical gate can theoretically be as short as a few picoseconds.

Tuning the effective index of the ring waveguide modifies the resonance wavelength, which induces a strong modulation of the transmitted signal. Here we use femtosecond pump pulses centered at a wavelength of $\lambda_{\mathrm{pump}} = 400$ nm to inject free carriers into the ring resonator and thereby tune its effective refractive index. At this wavelength the strong linear absorption

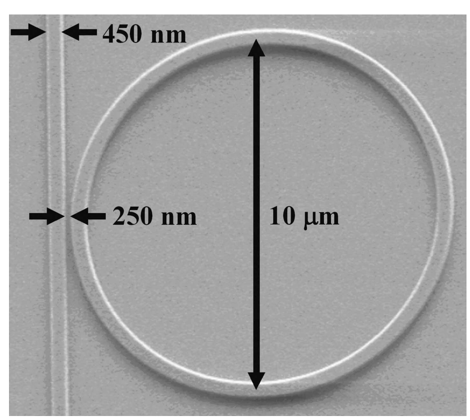

Fig. 1. Scanning electron micrograph showing the top view of a 5-μm-radius ring resonator coupled to a waveguide.

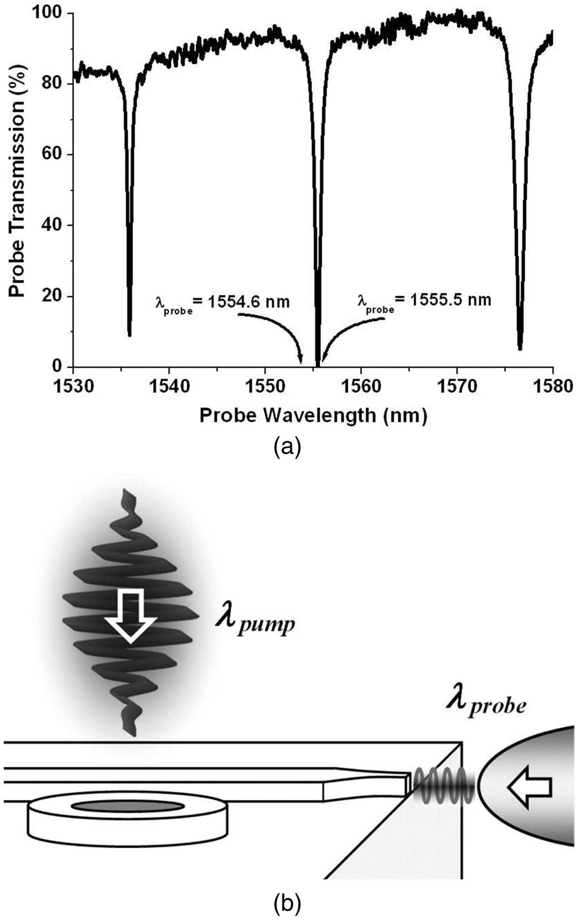

Fig. 2. Device characterization. (a) Quasi-TM spectral response of a singly coupled ring resonator with no optical pump incident on the sample. Both probe wavelengths used in this work for characterizing the dynamic response of the switch are indicated. (b) Schematic of the pump-and-probe setup, showing an in-plane cw optical probe (λ_{probe}) coupled from a tapered-lens fiber into a nanotaper and an out-of-plane femtosecond optical pump (λ_{pump}).

in silicon causes 90% of the photons transmitted into the top silicon layer to be absorbed within a thickness of only 250 nm. After the pulse is absorbed, photoexcited free-carrier electron–hole pairs are generated inside the ring resonators and subjected to recombination dynamics dictated by the free-carrier lifetime.

Figure 2(b) shows the schematic of the pump-and-probe setup used for characterizing the device in which the pump laser beam incident on the ring from free space is focused by a lens onto a spot diameter of 14 μm centered on the ring resonator. The laser source for the pump is a mode-locked Ti:sapphire laser that generates 100-fs pulses at 800 nm with 5 nJ of energy at an 80-MHz repetition rate. A β-barium borate crystal is used to generate second-harmonic femtosecond pulses centered at $\lambda_{\mathrm{pump}} = 400$ nm. The energy of the pulse incident on the ring resonator plane is less than 40 pJ. A tunable continuous-wave laser provides the probe signal, which is coupled into the silicon waveguide by an external tapered-lens fiber and an on-chip fiber-to-waveguide nanotaper coupler.[17] The quasi-TM transmitted light is collimated by a lens (0.55 N.A.), discriminated by a polarizer, and focused into a multimode fiber through a collimator. The probe signal is detected by a high-speed dc 5-GHz photodetector with a nominal fall–rise time of 70 ps. A 20-GHz digital sampling oscilloscope is used to record the probe signal. The temporal response of the transmitted probe signals is shown in Fig. 3 for two distinct probe wavelengths: $\lambda_{\mathrm{probe}} = 1554.6$ nm (below resonance) and $\lambda_{\mathrm{probe}} = 1555.5$ nm (on resonance). These probe wavelengths were tuned relative to the ring resonance to maximize the modulation depth when the transmission without the pump was high and low. The modulation depth is defined as $\mathrm{MD} = (I_{\max} - I_{\min})/I_{\max}$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum transmitted probe optical power, respectively. We measure MD = 75% for $\lambda_{\mathrm{probe}} = 1554.6$ nm and MD = 97% for $\lambda_{\mathrm{probe}} = 1555.5$ nm. The measured modulation depth is limited by only the photodetector response time. For a photodetector with a response time of less than 20 ps we expect to measure modulation depths of nearly 100% at both probe wavelengths.

By assuming an instantaneous spectral shift of the spectrum shown in Fig. 2(a), followed by a simple exponential decay representing the free-carrier lifetime, we obtain from the experimental data a wavelength peak shift of $\Delta\lambda = -1.1$ nm and a relaxation time of $\tau_{\mathrm{fc}} = 450$ ps. The measured free-carrier lifetime, much shorter than that in bulk silicon, is not a fundamental limit on the speed; it is primarily due to fast recombination mechanisms on the unpassivated sidewalls of the structures. Manipulating the degree of surface passivation or using ion implantation[19] could further reduce the free-carrier lifetime. The wavelength peak shift of the ring resonator corresponds to an effective-index change of $\Delta n_{\mathrm{eff}} = -1.45 \times 10^{-3}$ or equivalently to a refractive-index change in the silicon core of $\Delta n_{\mathrm{Si}} = -1.6 \times 10^{-3}$. This refractive-index change is caused by a free-carrier concentration of $\Delta N = \Delta P = 4.8 \times 10^{17}$ cm^{-3}. Considering the physical dimensions of the ring resonator, we estimate that the optical pulse energy that needs to be absorbed by the ring resonator to excite such a free-carrier

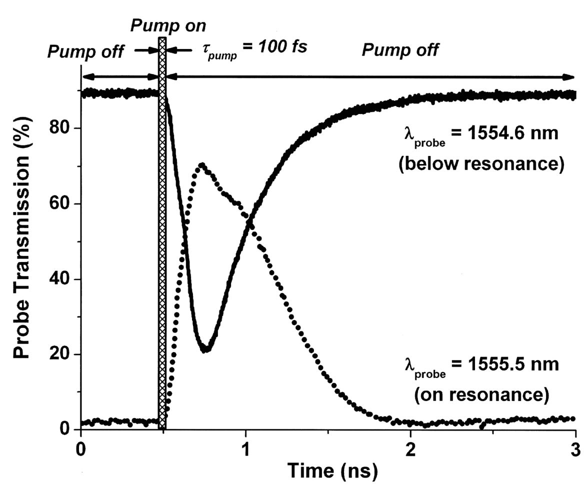

Fig. 3. Temporal response of the probe signal to the pump excitation, showing transmission for probe wavelengths below resonance (solid curve) and on resonance (dotted curve).

concentration is only 0.9 pJ. The losses due to the probe absorption,[2] estimated from the free-carrier concentration are $\Delta\alpha = 6.9\ \mathrm{cm}^{-1}$, significantly lower than the estimated scattering losses in the ring resonator of $\alpha_{\mathrm{ring}} = 33.6\ \mathrm{cm}^{-1}$. The low absorption losses are of foremost importance for the application of the proposed device as an all-optical gate, allowing nearly 100% transmission of the data signal when the gate is open. The relatively low absorption losses indicate that the observed modulation is due only to a refractive-index change and that thermal effects can be neglected. Our calculations predict that a temperature increase of only 2 K is expected for a 2-GHz modulation rate; this has a negligible effect on the all-optical switch performance because the typical time scale of the thermo-optic effect, of the order of a few microseconds,[8] is much longer than that of the device, of the order of 450 ps.

The device described here is achieved by use of the concept of strong light confinement and is approximately 7 orders of magnitude faster than available silicon optical switches.[20] We expect that a variety of existing fabrication methods may be used to further improve the speed of the proposed device. The present device could function as an all-optical switch, modulator, or router in applications relevant to optical interconnects. It could form the basis for new interconnect architectures including cabinet-to-cabinet, board-to-board, chip-to-chip, and on-chip architectures, with lower power, less skew, and less jitter relative to the wiring approach of the electrical interconnects.[21,22] In addition, the device shown here could form the basis for an ultrahigh interconnection bandwidth by employing architectures based on wavelength division multiplexing.[22] For logic applications a scheme of optical pumping using the same wavelength as the propagating signal is necessary; this would require the demonstration of efficient two-photon optical mechanisms in silicon.[6]

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