Ultrafast all-optical modulation on a silicon chip

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We experimentally demonstrate ultrafast all-optical modulation using a micrometer-sized silicon photonic integrated device. The device transmission is strongly modulated by photoexcited carriers generated by low-energy pump pulses. A p-i-n junction is integrated on the structure to permit control of the generated carrier lifetimes. When the junction is reverse biased, carriers are extracted from the device in a time as short as 50 ps, permitting greater than 5 Gbit/s modulation of optical signals on a silicon chip. © 2005 Optical Society of America

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An integrated photonic device that uses one beam of light to control and redirect the flow of another beam of light is an important component of integrated optical communication systems.[1–3] Silicon is an ideal material platform for integrated photonics because of its maturity in the electronics industry, offering the possibility to combine both photonic and electronic devices all on one chip. Passive photonic structures that bend, split, couple, and filter light have been demonstrated in silicon,[4,5] but the flow of light in these devices is predetermined and cannot be readily modulated during operation. All-optical silicon modulators and switches based on photoexcited free-carrier concentrations have been demonstrated; however, these devices require the use of extremely high-powered control beams in large or nonplanar structures to achieve high modulation depths.[6–10] This is because silicon exhibits a weak change in its complex refractive index as a function of free-carrier concentration.[11,12]

High optical confinement in resonant structures can alleviate these limitations.[13] Using a micrometer-sized planar ring resonator device, we demonstrated in Refs. 14 and 15 that light from a probe beam can be strongly modulated using low-power pump pulses. We showed that the small refractive index change required for modulation of the devices' transmission can be induced through either linear or two-photon absorption, using a pump beam that is focused from the top or coupled through an adjacent waveguide, respectively.[14,15] In these experiments, however, the modulation time of the device was limited to 450 ps because this time is determined solely by fast recombination of the photoexcited free carriers on the unpassivated sidewalls of the structure.

Here we demonstrate all-optical modulation with picosecond modulation time by incorporating a p-i-n diode into the ring resonator device. The effective free-carrier lifetime of photoexcited carriers is greatly reduced using a reverse-biased p-i-n diode rib waveguide structure.[16,17] The applied voltage induces an electric field across the intrinsic region where the waveguide lies, permitting the extraction of the generated electron–hole pairs from the waveguide under reverse bias. A schematic drawing and the fabrication details of the p-i-n diode ring resonator device can be seen in Ref. 18.

A ring resonator coupled to a waveguide has an optical transmission that is highly sensitive to signal wavelength and is greatly reduced at wavelengths in which the circumference of the ring corresponds to an integer multiple of guided wavelengths. By tuning the refractive index of the ring waveguide, the resonant wavelengths of the device can be altered. Here we use 10 ps pump pulses with a wavelength of $\lambda_{\mathrm{pump}}=1528.6$ nm, close to one of the ring resonances, to inject free carriers through two-photon absorption inside the ring resonator,[7,15] thus inducing a change in the refractive index in the ring waveguide.[11] A continuous-wave probe beam with a wavelength close to another resonance will be strongly modulated by this induced refractive index change. Here the probe beam wavelength is set around a resonance at $\lambda_{\mathrm{probe}}=1559.0$ nm, corresponding to two free-spectral ranges (FSR=15.2 nm) away from the pump resonance. The transmission of the device is reduced by more than 13 dB at the probe resonance. The cavity quality factors for the pump and probe resonances are $Q_{\mathrm{pump}}\approx\lambda_{\mathrm{pump}}/\Delta\lambda_{\mathrm{FWHMpu}}=18{,}200$ and $Q_{\mathrm{probe}}\approx\lambda_{\mathrm{probe}}/\Delta\lambda_{\mathrm{FWHMpr}}=39{,}000$, where $\Delta\lambda_{\mathrm{FWHMpu}}=0.084$ nm and $\Delta\lambda_{\mathrm{FWHMpr}}=0.04$ nm are the full width at half-maximum bandwidths.

The theoretical modulation time of this device, if carrier effects are minimized, is dictated by the resonant cavity lifetimes as calculated to be $\tau_{\mathrm{pump}}=14.8$ ps and $\tau_{\mathrm{probe}}=32.3$ ps.[14,15] In this work the carrier effects are greatly reduced by extracting the photoexcited carriers using a reverse-biased diode. To measure the extraction time of the photoexcited carriers the probe signal wavelength ($\lambda_{\mathrm{probe}}=1558.973$) and pump energy coupled to the chip (8 pJ) are set so that the probe wavelength is tuned to the linear spectral region of the probe resonance. This is done to ensure that the probe transmission time response is governed by the carrier dynamics. Here we use the experimental setup described in Ref. 15. Figure 1 shows the measured extraction time as a function of reverse-bias voltage with error bars derived from the uncertainty due to photodetector response time and cavity lifetime. The inset of Fig. 1 shows the probe signal for a reverse bias voltage of 4 V. As can be seen from the figure, the probe signal initially decreases after the pump pulse is applied. The time it takes for this transition to occur is determined by the resonant

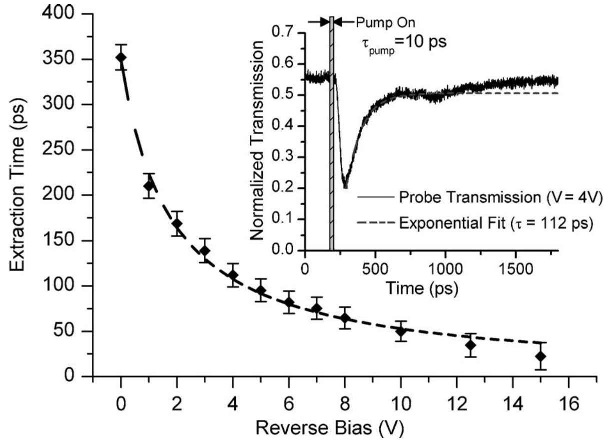

Fig. 1. Carrier extraction time as a function of reverse-bias voltage. The inset shows the temporal probe signal for reverse bias $V=4$ V and the exponential fit used to obtain the extraction time ($1/e$ point).

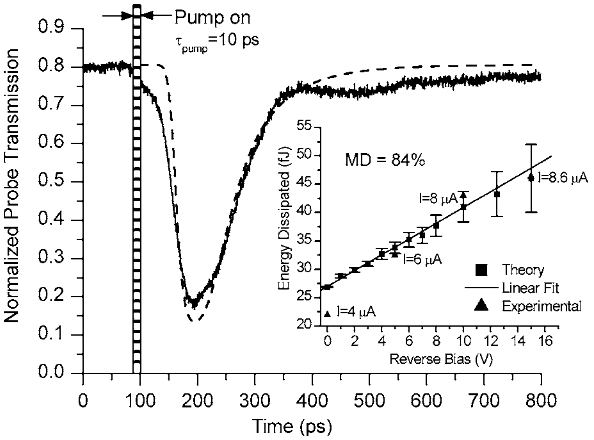

Fig. 2. Experimental (solid curve) and theoretical (dashed curve) temporal response of the probe signal with reverse bias $V=10$ V. The inset shows the energy dissipated for different biases for a MD of 84%.

cavity lifetime, τ_{probe}, which dictates how quickly the optical field in the resonator is built up. The initial decrease is then followed by an exponential increase, corresponding to the extraction time of the photoexcited carriers as determined by fitting a simple exponential decay to this part of the probe signal temporal response (shown as a dashed curve over the temporal signal). After the exponential increase, the probe signal does not return to its initial state but instead slowly increases as a fraction of the carriers generated in the ring are not extracted by the diode because it encompasses only two-thirds of the ring. The dynamics of any carriers in the remaining third is determined solely by slow recombination mechanisms and is thus equivalent to an open-circuit recombination time of 1.19 ns. If the diode were to encompass the entire ring then the carrier dynamics would be determined solely by the reverse-biased diode carrier extraction time.

Figure 2 shows the time dependence of the probe signal transmission as obtained with a probe wavelength set to $\lambda_{\mathrm{probe}}=1558.95$ nm, a pump pulse energy coupled to the chip of 19 pJ, and a reverse-bias voltage set to 10 V (extraction time 50 ps). The amount of modulation, defined by $\mathrm{MD}=(I_{\max}-I_{\min})/I_{\max}$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum transmitted probe powers, is measured to be $\mathrm{MD}_{\mathrm{probe}}=79.5\%$. This modulation depth (MD) is limited by the photodetector response time, so the actual amount of modulation is estimated to be 84%. The time it takes for the probe signal to be restored to its maximum value from the minimum of its transmission is measured to be $\tau=122$ ps. This time is longer than the extraction time (50 ps) because the time response of the device is determined by the convolution of the free-carrier dynamics (an exponential decay of 50 ps) and the nonlinear modulated spectrum (a Lorentzian), at this pump energy and probe wavelength. Another contributing factor is the third of the ring waveguide where the carriers cannot be extracted. This region has a stronger contribution here because of the larger pump energy used to achieve a high modulation depth. In turn, the slowly recombining carriers act to slow the return of the probe transmission to its maximum value.

The theoretical time dependence of the probe signal transmission shown in Fig. 2 (dashed curve) is calculated using an analytical model for the ring resonator transmission[19] and a model of the carrier dynamics governed by the following rate equations:

$$\frac{\mathrm{d}\Delta N}{\mathrm{d}t}=-\frac{2}{3}\frac{\Delta N}{\tau_{\mathrm{extract}}}-\frac{1}{3}\frac{\Delta N}{\tau_{\mathrm{open}}}+\frac{n}{\tau_{\mathrm{probe}}},$$

$$\frac{\mathrm{d}n}{\mathrm{d}t}=-\frac{n}{\tau_{\mathrm{probe}}}+\frac{N_{\mathrm{ph}}}{2(\tau_{\mathrm{pump}}/2)\sqrt{\pi}V_{\mathrm{ring}}}\exp\left[-\frac{t^2}{(\tau_{\mathrm{pump}}/2)^2}\right], \tag{1}$$

where ΔN is the change in free-carrier concentration, $\tau_{\mathrm{extract}}=50$ ps is the extraction time with a reverse bias of 10 V, $\tau_{\mathrm{open}}=1190$ ps is the open-circuit extraction time, n is the number of photoexcited carriers per unit volume, $\tau_{\mathrm{probe}}=32.3$ ps is the resonant cavity lifetime, N_{ph} is the total number of absorbed photons, V_{ring} is the volume of the ring resonator, and $\tau_{\mathrm{pump}}=10$ ps is the pump pulse duration. From Eq. (1), the change in the refractive index and the optical absorption of the silicon ring waveguide is obtained.[11] These changes are applied to an analytical model of the ring resonator transmission response to obtain the theoretical temporal response of the probe signal.[19] From this model we determine that the probe resonance is shifted by $\Delta\lambda=-0.044$ nm, which corresponds to an effective index change of $\Delta n_{\mathrm{eff}}=-1.12\times10^{-4}$, or equivalently to a refractive index change in the silicon waveguide of $\Delta n_{\mathrm{Si}}=-1.08\times10^{-4}$. This refractive index change is caused by a maximum carrier concentration of $\Delta N=\Delta P=1.93\times10^{16}\ \mathrm{cm}^{-3}$.[11] We estimate that the amount of pump pulse energy absorbed inside the ring to excite such a carrier concentration is only 41 fJ. Thus, only a small part of the pump power is actually absorbed. The remaining pump power, which is necessary for the two-photon absorption effect,[15,20] is scattered off the ring in this device. By adding another adjacent waveguide to the ring this scattered pump power could be recycled for use with other modulators on the same chip.[21] The amount of probe absorption induced by the excited free-carrier concentration is estimated to be only $\Delta\alpha = 0.3\ \mathrm{cm}^{-1}$,[11] which has the effect of reducing the achievable modulation depth by only 3.4%.

For a given modulation depth the required pump energy increases as a function of the applied reverse bias. This is because the faster the carriers are extracted the smaller the maximum carrier concentration is (and, in turn, the refractive index change). Thus, more pump energy is needed to achieve the same modulation depth. By use of the carrier extraction times shown in Fig. 1 and the theoretical model described above, the absorbed pulse energies required to maintain the same amount of modulation depth ($\mathrm{MD} = 84\%$) are obtained for different applied voltages. Note that here we consider only the energy absorbed by the pump pulse, not that scattered off the ring, since the latter could be recycled in an add–drop configuration. In the inset of Fig. 2 we show the pump energy dissipated as a function of the applied voltage. Error bars are derived from uncertainty in the extraction times in Fig. 1. The required pump energy increases linearly with voltage; a modulator operating under a 15 V reverse-bias voltage dissipates almost twice the amount of energy as a modulator under 0 V bias. Also shown are the experimentally derived absorbed pulse energies for four different reverse-bias voltages (triangles), as obtained from the measured diode currents.

The device that we have demonstrated can be used as a modulator in all-optical networks. The modulation bit rate of the device is determined by the carrier extraction time. Using a micrometer-sized ring resonator, under a reverse-biased voltage of 10 V, a bit rate of 5 Gbits/s is possible.[22] Such a rate would be realizable if the diode were to encompass the entire ring. We estimated that the pump energy needed to be coupled into the ring resonator at this bit rate is as low as 2.2 pJ.[19,20] This estimated energy is lower than that used in this work (19 pJ) because the pump pulse used here has a bandwidth of 0.37 nm,[15] which is approximately 4.4 times wider than the device's pump resonance. Thus, less than a quarter of the pump energy was actually coupled to the ring. A pump beam with a sufficiently narrow bandwidth, operating at a 5 Gbit/s bit rate, would require an average power of only 11 mW, which is easily achievable using fiber-based amplifiers.

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