Micrometer-scale all-optical wavelength converter on silicon

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We demonstrate a highly integrated micrometer-scale low-power wavelength converter based on the free-carrier dispersion effect in silicon. The conversion is achieved through all-optical modulation of a silicon ring resonator by use of modulated cw control light. The ring resonator has a radius of 5 μm and a Q of $\sim 10,000$. Both inverted and noninverted modulation are achieved at a bit rate of 0.9 Gbits/s with a control power of 4.5 mW. The scaling of the required control power for operation with respect to the characteristics of the ring resonator is established. © 2005 Optical Society of America

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Wavelength conversion is an important function for all-optical networks, allowing better utilization of the network resources under a dynamic traffic pattern.[1,2] All-optical converters based on optical fibers,[3] semiconductor optical amplifiers,[4,5] and GaAs microring resonators[6] have been investigated. Given both their size and the materials used, however, they are not suitable for low-cost, highly integrated applications. Recently, silicon-on-insulator (SOI) waveguides and devices, with their potential low cost and compatibility with silicon microelectronics, have been demonstrated as wavelength converters.[7] However, due to the weak optical nonlinearity of silicon, relatively large devices (length of the order of centimeters) and high pump powers (of the order of watts) were used.[7] Here we show a wavelength conversion operation using a highly integrated silicon ring resonator. Unlike the recently demonstrated all-optical switching using ultrashort pulses,[8] the high quality factor (Q) of the ring resonator used here permits all-optical modulation using a modulated cw control light with average power as low as 4.5 mW.

Figure 1 shows the schematic of the wavelength conversion experiment using the ring resonator. A coded pump light used as the control and a cw probe light used as the signal, tuned at two distinct resonances of the ring resonator, are coupled together and sent into the waveguide through a ring resonator. When the control light power is high (logic 1), free carriers are generated inside the ring resonator as a result of two-photon absorption (TPA).[9] The transmission of the signal changes because of the resonance shift. When the control light power is low (logic 0), the resonant wavelength and the transmission of the signal relax back due to the recombination of the free carriers. In this way, the information carried by the control light is transferred to the signal light.

The ring resonator used in this experiment has the same structure as that described in Ref. 8 and is fabricated on a SOI substrate using the process described in Ref. 10. Both the waveguide coupling to the ring and the one forming the ring have a width of 450 nm and a height of 250 nm. The radius of the ring is $R = 5\ \mu$m. Nanotapers are used at both ends of the waveguide to ensure low-loss coupling between the optical fiber and the waveguide.[10] The fiber-to-fiber insertion loss for the quasi-TE mode (electric field parallel to the substrate) is measured to be 10.4 dB. The transmission spectrum for the quasi-TE mode is shown in Fig. 2. From Fig. 2 one can see resonances at wavelengths $\lambda_1 = 1550.7$ nm and $\lambda_2 = 1568.7$ nm. The free spectral range (FSR) of this ring resonator is thus 18 nm, and the group index of the ring waveguide[11] is $n_g = 4.35$. The transmission of the waveguide drops by ≈ 16 dB at both resonances. The insets of Fig. 2 show enlargements of the spectra around both resonant wavelengths. The full width at half-maximal (FWHM) bandwidths of the resonances are $\Delta\lambda_1 = 0.14$ nm and $\Delta\lambda_2 = 0.16$ nm, corresponding to $Q_1 = 11,076$ and $Q_2 = 9804$, respectively. The weak split of the resonances, represented by the double-notch feature of the resonant spectrum, is caused by a weak reflection inside the ring resonator.[12,13] The photon lifetime of the ring resonator at λ_1 resonance can be obtained from Q as $\tau_{\text{cav1}} = Q\lambda/(2\pi c) = 9.1$ ps. This lifetime gives the fundamental limit to the modulation speed of the resonator. In practice, the modulation speed of the fabricated device is limited by the longer carrier lifetime.

In the experiment, both the control and the signal light are generated by a narrow-bandwidth cw tunable laser. The control light is modulated with non-return-to-zero PRBZ $2^7 - 1$ pseudorandom code at 0.9 Gbit/s. An erbium-doped fiber amplifier is used to compensate for the loss from the modulator. The waveform of the control light is shown in Fig. 3(a). Control wavelength λ_C is fixed at the shorter-wavelength edge of the λ_2 resonance. Signal wavelength λ_S is either on λ_1 resonance (λ_{S1}) for noninverted wavelength conversion or on the shorter-wavelength side of the λ_1 resonance (λ_{S2}) for inverted wavelength conversion, as illustrated in the insets of Fig. 2. The control and signal light are then coupled using a 90:10 fiber coupler and sent into the waveguide. The average optical power of the control light at the input of the waveguide is 4.5 mW. When the signal wavelength $\lambda_S = \lambda_{S1}$, the transmission of the signal light increases when the carriers are gener-

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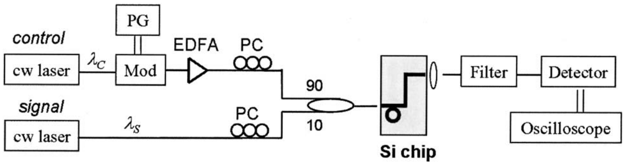

Fig. 1. Schematic of the experiment setup on wavelength conversion using a silicon ring resonator. PG, pattern generator; Mod, $LiNO_3$ electro-optical modulator; EDFA, erbium-doped fiber amplifier; PC, polarization controller.

ated and resonances are blueshifted, resulting in a noninverted modulation. The waveform of the signal output at this wavelength is shown in Fig. 3(b). When the signal wavelength $\lambda_S = \lambda_{S2}$, the transmission of the signal light decreases when resonances are blueshifted, resulting in an inverted modulation. The waveform of the signal output at this wavelength is shown in Fig. 3(c).

The small volume and high Q of the ring cavity are critical for the low control power operation. This can be shown by calculating the control power necessary for obtaining large modulations. Under critical coupling, the quality factor Q of the ring resonator is determined by the attenuation coefficient α of the ring waveguide as[11]

$$Q = \frac{\lambda_0}{\Delta\lambda} \approx \frac{\pi n_g}{\lambda_0}\frac{1}{\alpha}, \quad (1)$$

where λ_0 and $\Delta\lambda$ are the central wavelength and the 3 dB bandwidth of the resonance. When the ring resonator is on resonance, the optical intensity inside the ring is much higher than that in the input waveguide, with intensity enhancement factor $K = 1/(\alpha 2\pi R)$.[14]

When carriers are absent from the ring resonator, the wavelength of the control light is at the short-wavelength edge of resonance (see Fig. 2). When the control power is high, free carriers generated by TPA of the control light induce a decrease of the refractive index of silicon[15] and a blueshift of the resonant spectrum. This blueshift causes more control light to be coupled into the ring resonator and generates more carriers, which in turn causes more blueshift. This positive feedback process continues until the control wavelength is longer than the resonant wavelength. At this stable state, the change of the effective index n_{eff} of the ring because of the generated carriers is[16]

$$\Delta n_{\mathrm{eff}} = \Gamma n_f \Delta N = \Gamma n_f \frac{\beta I_{\mathrm{ring}}^2 \tau_c}{2h\nu} = \frac{\Gamma n_f \beta K^2 (2P_C)^2 \tau_c}{A^2 2h\nu_C}, \quad (2)$$

where $n_f \approx 1.35 \times 10^{-21}$ cm^3 (Refs. 15 and 17) is the ratio between the change of the refractive index of silicon and the electron–hole-pair density ΔN when $\Delta N \sim 10^{17}$ cm^{-3}, $\Gamma = 0.8$ is the mode confinement factor; $\beta = 0.8 \times 10^{-9}$ cm/W (Ref. 9) is the TPA coefficient, $\tau_c = 450$ ps (Ref. 8) is the carrier lifetime, $A = 1.1 \times 10^{-9}$ cm^2 is the cross-section area of the waveguide, $h\nu_C = 1.3 \times 10^{-19}$ J is the control photon energy, and P_C is the average input control power. To obtain large modulation, the blueshift of the resonance needs to be higher than $\Delta\lambda_1 = \lambda_1/Q_1$. Therefore, $\Delta n_{\mathrm{eff}}/n_{\mathrm{eff}} = \Delta\lambda_1/\lambda_1 \geq 1/Q_1$. This condition can be written as

$$P_C^2 \geq \frac{\pi^2 n_g^2 n_{\mathrm{eff}} h\nu_C V_{\mathrm{eff}}^2}{2\Gamma n_f \beta \lambda_2^2 Q_2^2 Q_1 \tau_c}, \quad (3)$$

where $V = A 2\pi R$ is the volume of the ring. With $n_{\mathrm{eff}} = 2.4$ for the fabricated device, we calculate that the required control power is ~ 5.8 mW. This switching power can be easily achieved with a modulated semiconductor cw laser. We can see from Eq. (3) that the switching power is proportional to $V_{\mathrm{eff}} Q^{-3/2} \tau_c^{-1}$. A small cavity volume and a high Q are therefore critical to reducing the switching power. The high index contrast of the SOI platform permits an ultrasmall waveguide cross section and a small bending radius (of the order of micrometers), both of which are critical to reducing the cavity volume and switching power.

In the above analysis, the power of the signal light is assumed to be negligible. In the experiment, the signal power is $\approx 10\%$ of the peak power of the control

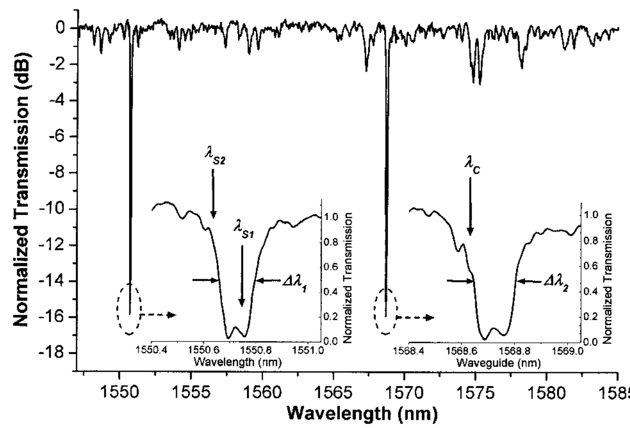

Fig. 2. Transmission spectra of the ring resonator on a dB scale. The insets are the spectra on a linear scale at each resonance. The control and signal wavelengths are marked in the insets.

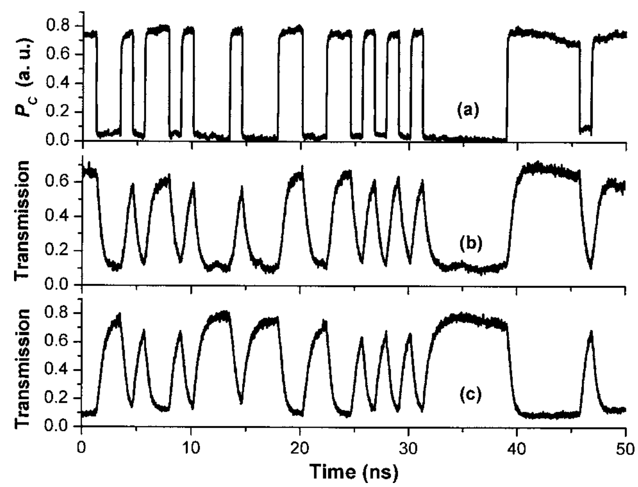

Fig. 3. (a) Input waveform of the control light. (b) Output waveform of the signal light at the wavelength of λ_{s1}, showing noninverted wavelength conversion. (c) Output waveform of the signal light at the wavelength of λ_{S2}, showing inverted wavelength conversion.

light. We expect some contribution due to the TPA of one control photon and one signal photon when both the control and the signal light couple into the ring resonator simultaneously. This effect causes an ~10% reduction of the required switching power for the inverted modulation case.

The maximum bit rate of the wavelength converter is limited by the carrier lifetime to 0.9 Gbit/s. The carrier lifetime can be greatly reduced by ion implantation or by actively extracting the carriers by using a reverse-biased p-i-n junction,[18,19] which will reduce the pattern dependent effect in the modulation and increase the bit rate. With the latter approach, carrier lifetimes of ~30 ps (Ref. 19) have been shown, permitting ~10 Gbit/s wavelength conversion. Note that the small cross section of the waveguide is necessary for achieving such a low lifetime.[18,20] As we can see from Eq. (3), the switching power increases when the carrier lifetime is reduced. For the fabricated device, if the carrier lifetime is reduced to ~30 ps for 10 Gbit/s operations, the switching power is calculated to be ~23 mW. The switching power can be reduced by increasing the Q of the ring resonator cavity and (or) reducing the cavity volume. Ring resonators with Q of ~40,000 have been demonstrated,[19] which corresponds to a photon lifetime of ~33 ps. Such a Q would reduce the switching power to ~3 mW. Note that further increasing the cavity Q would limit the modulation speed because of the long photon lifetime. The performance of the device is also affected by the thermal effect with temperature change caused by the control light. The thermal effect can be reduced by, for example, using the strain in silicon.[21] On the other hand, the extra absorption in the ring caused by the free carriers does not affect the performance of the device significantly. For the noninverted modulation, the signal light is out of resonance when the carriers are generated and therefore the transmission is not affected; for the inverted modulation, low transmission is needed for the signal light when the carriers are generated, and therefore absorption due to the free carriers may improve performance.

In conclusion, we have shown wavelength conversion at 0.9 Gbit/s using a SOI ring resonator with an average control power of 4.5 mW. The high-confinement nature of a ring resonator based on a SOI strip waveguide is essential to achieve high-speed and low-power operation.

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