All-optical compact silicon comb switch

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Abstract: We demonstrate a 1x2 all-optical comb switch using a 200 μm diameter silicon ring resonator with a switching time of less than 1 ns. The switch overcomes the small bandwidth of the traditional ring resonator, and works for wavelength division multiplexing applications. The device has a footprint of ~0.04 mm^2 and enables switching of a large number (~40) of wavelength channels spaced by ~0.85 nm.

OCIS codes: (130.3120) Integrated optical devices; (230.2090) Electro-optical devices; (230.5750) Resonators

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Recent breakthroughs in the field of silicon photonics include low-loss and compact silicon-on-insulator (SOI) passive waveguide devices [1-2], high speed silicon modulators [3-7], Ge on SOI detectors [8], silicon Raman lasers [9, 10], silicon broadband amplifiers based on four-wave mixing [11], and hybrid III-V silicon lasers [12]. These devices have provided the possibility to construct CMOS compatible optical interconnection systems with low power consumption, high bandwidth and low latencies [13-15]. A critical device for the implementation of such systems, that remains to be demonstrated, is a broadband and compact silicon switch operating in the nanosecond regime [16].

Fast modulation and switching in silicon has been achieved using the plasma dispersion effect [4-7, 17], where the index of refraction of silicon is changed by generating free carriers. However, the demonstration of low powered and compact active silicon devices has remained a challenge due to the small index change that can be attained by this carrier dispersion effect. We have recently demonstrated the use of highly confined resonant structures for overcoming this limitation by confining both optical field and electrical carriers in a small region [18]. Using 10 μm diameter ring resonators, we have demonstrated 12.5 Gbps electro-optical modulators [6]. However in such high quality factor devices, the optical bandwidth is sacrificed, and therefore these devices are not suitable for Wavelength Division Multiplexing (WDM) and other broadband signal applications. Although cascaded ring resonators can be used for multiple-wavelength operation, the resonance of each resonator is difficult to control due to fabrication and temperature variations [19]. Therefore, an efficient and compact silicon switch suitable for WDM is needed at present.

In this paper, we propose and demonstrate a technique of comb switching by using a single ring resonator for WDM applications. The ring resonator has a relatively small free spectral range (FSR) corresponding approximately to the wavelength spacing used in dense WDM (0.8 nm), and can simultaneously switch on and off a large number of wavelength channels. Therefore, the advantage of the high quality factor is maintained while allowing the traditional small bandwidth limitation to be overcome. The demonstrated switch has a switching time of less than 1 ns and a footprint of only 200 μm x 200 μm.

We fabricated a 250 nm thick silicon-on-insulator ring resonator with a 200 μm diameter and a 450 nm width using electron beam lithography and plasma reactive ion etching. Subsequent deposition of oxide serves as the top cladding. The ring is coupled to two straight waveguides with the same cross section, one acting as an input port and through port, and the other acting as a drop port, as shown in Fig. 1. The gaps between the waveguides and the ring’s outer edges have a distance 400 nm and 430 nm for the through port and drop port, respectively. The gap difference is set to satisfy the critical coupling condition, which requires that the coupling to the ring from the input waveguide is equal to the sum of waveguide loss per round in the ring and the coupling to the drop waveguide from the ring

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[20]. Off resonance, the input light is directly transmitted to the through port. At resonance, i.e. when the circumference of the ring corresponds to an integer multiple of guided wavelengths, the input light will be coupled into the ring and collected by the drop waveguide. The resonant wavelengths of the ring resonator can be changed by altering the index of refraction, resulting in light switching between the drop port and the through port. Note that all of the resonance wavelengths are shifted simultaneously, enabling the switching of multiple wavelengths simultaneously using a single ring resonator.

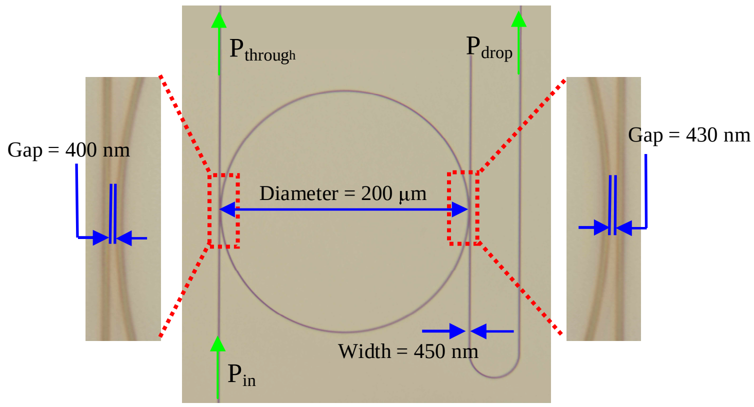

Fig. 1, Top-view microscopic picture of the fabricated device.

We measured the quasi-TM transmission spectrum of this device using a tunable continuous wave laser operating at the telecommunication wavelengths. The power from the laser is fixed at 0 dBm. In order to increase the coupling efficiency between the optical fiber and the waveguides, we used nanotaper structures at both the input and output ends of the waveguides [21]. Fig. 2(a) shows the measured output power versus wavelength. The FSR of this ring resonator is approximately 0.85 nm. The quality factor Q in the spectral range from 1533 nm to 1566 nm is approximately 19000, allowing for a possible data rate through the device as high as ~ 10 Gbps [22-23]. From the spectra in Fig. 2(a), we extract the absolute maxima and minima of transmission for both ports in Fig. 2(b), from which the optical parameters that characterize the performance of the 1x2 switch can be obtained. These parameters include extinction ratio, insertion loss, and crosstalk. We show these optical parameters as a function of resonance wavelength in Fig. 2(c). The extinction ratio of the through port is defined as the power ratio between switch-on (off resonance) and switch-off (at resonance) power at this port. In the same way, the extinction ratio of the drop port is defined as the power ratio between on-resonance and off-resonance power at the drop port. We find from Fig. 2(c), that the extinction ratio for both ports exceeds 15 dB for the spectral range between 1532 nm and 1565 nm. From Fig. 2(c), the maximal extinction ratio at the through port occurs at about 1555 nm, which indicates that the critical coupling condition is reached at this wavelength. The extinction ratio of the drop port, however is not optimized at this wavelength. The spectral dependence of the ring device limits the number of wavelength channels in WDM applications. Using MMI as in/out couplers, rather than directional couplers in the present ring, one can obtain resonators with a wavelength independent Q and extinction ratio [24].

The insertion loss of this ring device is determined by the power loss in the ring while the input light is circulating in it, which can be measured by the power difference between the on-resonance power at the drop port and the off-resonance power at the through port (which corresponds to approximately the input power). It is seen that the insertion loss of the ring is less than 3 dB over the entire spectral range from 1532 nm to 1565 nm. The crosstalk between the through port and drop port is larger than 15 dB as evident from Fig. 2(c). If an extinction ratio and crosstalk of 15 dB are considered as operating requirement for a comb switch, then

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from Fig. 2(c), 40 channels are available and the overall optical bandwidth of the device is 33 nm. From the spectra in Fig. 2(a), it is seen that the total insertion loss from the laser to the detector is ~10 dB, which includes the propagation losses and the coupling loss in and out of the waveguides.

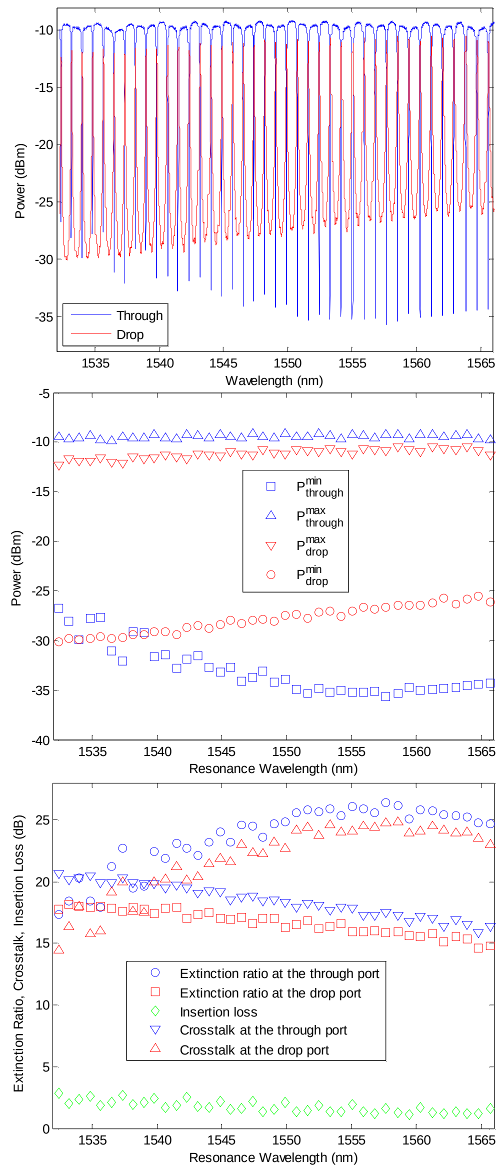

Fig. 2. (a). Transmission spectra of the ring resonator. Blue line: transmission spectrum of the through port. Red line: transmission spectrum of the drop port. (b) The minimal and the maximal output power at the through port (blue) and drop port (red) versus resonance wavelength, extracted from the spectra in (a). (c) Extinction ratio, insertion loss and crosstalk versus resonance wavelength.

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To demonstrate the concept of comb switching, we input two continuous wave tunable lasers at two separate resonance wavelengths as probe signals into the ring device. We use a femtosecond pulse laser centered at a wavelength 415 nm to generate free carriers into the ring resonator through absorption by focusing the pump pulses on the top surface of the ring [3]. At this wavelength the laser is strongly absorbed by the silicon layer and free electron and hole pairs are generated in a time scale of less than 1 ps. We measured the transmitted power as a function of time when both probes are turned on, and when only one of the probes is turned on. We compare transmission response of each of probes to the one obtained by subtracting the power when only one of the probes is on from the total transmitted power and could not detect any effect on the transmission due to the crosstalk between the two probes. Fig. 3 shows the time dependence of the two probe signal transmissions. The power of the drop port is normalized to its maximal value and that of the through port is normalized to the off-resonance power. The light from both lasers is initially transmitted through the drop port (note that a small percentage of the input light at 1542.30 nm is directed to the through port initially due to the fact we could not accurately tune the input wavelength at the resonance). We see that after the pump is turned on, both input signals are redirected to the through port. Due to the recombination of free carriers, the resonance of the ring returns to its original value and therefore the input signals are transmitted back to the drop port after approximately 1 ns. The modulation depth is more than 90% for both the through and drop ports. The actual modulation depth is expected to be the same as the extinction ratio as shown in Fig. 2(c), however in reality it is limited by the slow rise time (~100 ps) of our detector. The switch-off time is determined by the free carrier lifetime of the photon-excited carriers and is measured to be ~450 ps [3]. Note that this time is much longer than the photon lifetime of the resonator and consequently determines the maximum switching time of our device. Theoretically, the switch-on time depends on the photon lifetime, which is about 15 ps. Here we measure a switch-on time of ~100 ps limited again by the rise time of our detector. The measured 20 to 80 % transmission switch-off time is 0.93 ns, which verifies that the switching speed of this device can be nanosecond. The rings' resonant wavelengths are shifted by $\Delta\lambda$ = -0.2 nm, which corresponds to an effective index change of -0.52×10^{-3}. This refractive index change is caused by a maximum carrier concentration of $\Delta N=\Delta P=0.88\times10^{17}cm^{-3}$ [4]. From the generated carrier concentration, we estimate that the energy per pulse absorbed by the ring resonator is only 3.2 pJ [25].

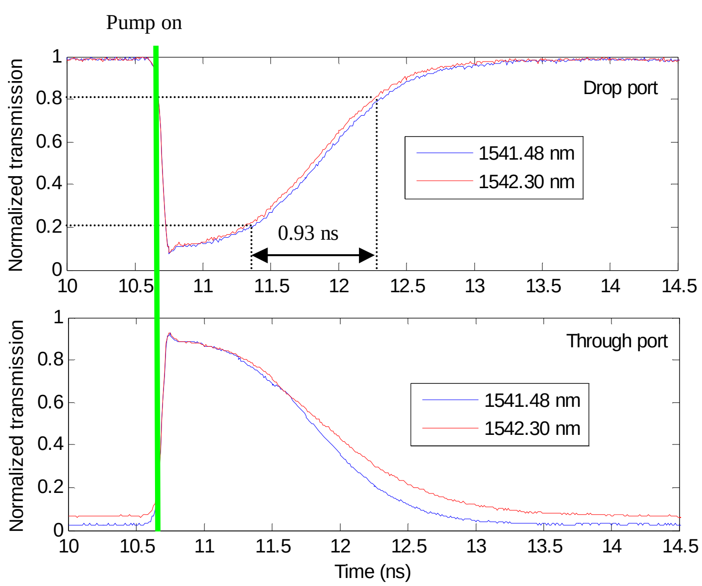

Fig. 3. Experimental temporal response of the probe signal for wavelength 1541.48 nm (blue curves) and 1542.30 nm (red curves). The green bar indicates when the pump pulse is on.

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The switching operation of the device relies on the plasma dispersion effect in silicon, opening the door for electro-optical switches using either a forward p-i-n structure [5] or a reverse pn structure [26] embedded in the structure. Similar structures have already been demonstrated in silicon ring resonators with 12.5 Gbps performance [6]. This demonstrates that the switching time can be in the nanosecond regime, which is well above the requirements of all optical networks on chip [16]. For on-chip all-optical interconnects applications, the size of the switches is required to be small due to area budgets of chips. The proposed switch has a footprint of ~0.04 mm^2, suitable for on chip optical interconnects. The performance of our device can be improved by reducing the ring loss. Assuming the silicon waveguide loss is ~1 dB/cm and the bending loss for a 100 μm radius is negligible [2], one can expect that the insertion loss of our device to be less than 0.5 dB, and the crosstalk and extinction ratio to be larger than 20 dB.

The silicon ring switch may suffer from the dispersion of silicon waveguides which affect the FSR of the ring resonator. However, it has been shown that the dispersion of silicon waveguides can be tuned from anomalous to normal by designing the cross sectional dimensions [27, 28]. Note also non-linear phenomena (including Raman, Kerr nonlinearity and two photon absorption) in silicon become significant at power levels of MW/cm^2 and above [9, 11, 29]. Therefore care needs to be taken to ensure that such power levels are not reached in order so that the performance of the switch is not affected.

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