Ultrafast and bias-free all-optical wavelength conversion using III-V-on-silicon technology

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Using a 7.5 μm diameter disk fabricated with III-V-on-silicon fabrication technology, we demonstrate bias-free all-optical wavelength conversion for non-return-to-zero on–off keyed pseudorandom bit sequence (PRBS) data at the speed of 10 Gbits/s with an extinction ratio of more than 12 dB. The working principle of such a wavelength converter is based on free-carrier-induced refractive index modulation in a pump–probe configuration. We believe it to be the first bias-free on-chip demonstration of all-optical wavelength conversion using PRBS data. All-optical gating measurements in the pump–probe configuration with the same device have revealed that it is possible to achieve wavelength conversion beyond 20 Gbits/s.

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In the past decade, there has been an increased focus on the use of the mature complementary metal-oxide semiconductor (CMOS)-compatible silicon-on-insulator (SOI) fabrication technology for realizing different photonic components and devices. Until now, only a few researchers have reported on the use of III-V/SOI fabrication technology for realizing photonic switching devices required for ultrafast information processing. The rationale to use hybrid III-V/SOI technology lies in the fact that, at present, the III-V/SOI technology has been used to realize the most advanced devices and the most advanced photonic integrated circuits (PICs) [1]. It is the most promising technology for fully functional optical chips, which necessarily need to include active devices such as flip-flops and shift registers. Such kinds of active devices need microlasers and their derivatives with a satisfactory level of performance. Optoelectronic devices in silicon, such as lasers, have not shown an acceptable level of performance for on-chip communication so far. Pure silicon-based all-optical switching is energy inefficient and challenging owing to the slow dynamics of two-photon generated free carriers [2]. Hybrid (III-V/SOI) all-optical switching devices are promising due to the smaller recovery time (~tens of picoseconds) of photogenerated carriers in III-V material [3] while still taking advantage of mature CMOS technology for SOI waveguide circuits.

Owing to their smaller achievable size and enhanced nonlinearity originating from the resonant behavior along with high optical confinement, microdisks/rings are considered to be promising building blocks for high-density PICs. So far, ultrafast (of the order of 10 Gbits/s) all-optical switching, modulation, and wavelength conversion in microrings/disks on the SOI platform have been demonstrated using reverse bias [2], ion implantation [4], and forward bias [5]. Realization of bias-free on-chip all-optical functions results in easy packaging of the chips due to the reduced number of pins required.

In our previous work [6], we demonstrated a 10 GHz all-optical gating in a 10 μm diameter III-V/SOI disk, but the use of reverse bias was necessary to achieve this speed, and the extinction ratio was only 4.5 dB. Using the same concept as in [6], here we report on all-optical wavelength conversion of a non-return-to-zero (NRZ) on–off-keyed (OOK) pseudorandom bit sequence (PRBS) data signal at the speed of 10 Gbits/s in a 7.5 μm diameter III-V(InGaAsP-InP)/SOI microdisk. The microdisks are fully fabricated in a CMOS pilot line. The III-V stack is molecularly bonded on top of the SOI waveguide circuit, and the microdisks are defined by deep ultraviolet lithography. A full description on the fabrication will be reported elsewhere [7].

Before proceeding to dynamic all-optical wavelength conversion experiments, all-optical gating measurements were performed to estimate the achievable speed and corresponding power consumption. First, the microdisk resonator is characterized statically to locate the transmission resonances. The wavelength of a cw beam from a tuneable laser is scanned and is coupled to the SOI waveguide, lying beneath the microdisk. In- and outcoupling to/from the SOI waveguide happens through grating couplers at each end of the waveguide. Light couples between the microdisk resonator and the SOI waveguide via evanescent coupling. Two resonances corresponding to two azimuthal modes separated by an FSR of 30.8 nm, one around 1550.1 and another around 1580.9 nm, are located. A higher extinction ratio is seen at the longer wavelength resonance, because it lies closer to the bandgap of the active material of the microdisk and hence has less absorption compared to that of the shorter wavelength resonance. Measurements of the influence of the power on the extinction ratio are carried out to identify the critical coupling around 1580.9 nm. Near-critical coupling in cw is obtained for −4.25 dBm coupled optical power with an extinction ratio of ~25 dB. By fitting the resonator transmission spectrum, the power coupling coefficient from the SOI waveguide to the disk is found to be ~6%. Taking the resonance position of this mode for −13 dBm of power in the SOI waveguide as a reference, the relative change in the resonance position as

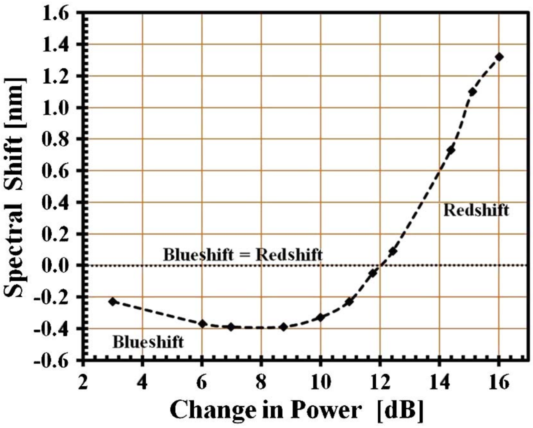

Fig. 1. (Color online) Spectral shift as a function of power change in the SOI waveguide.

a function of relative change in the power is plotted in Fig. 1, which shows the spectral shift due to the generation of free carriers and heat generated in the device (thermo-optic effect).

It is clear from Fig. 1 that initially there is a blueshift due to the generation of free carriers, and as the power increases, the carrier heating effect starts to take over. With the 12 dB change in power, the blueshift is completely canceled by the redshift and the redshift dominates for further power increase. Next, dynamic measurements were performed for all-optical gating in a pump–probe [6] configuration, keeping the probe wavelength around the longer wavelength resonance and nearly critically coupled. The reason to choose the higher wavelength resonance as a probe is that it has a higher static extinction ratio as compared to that of the shorter resonance wavelength and will give higher extinction ratio in the output. A pump with 1.5 mW average power in the SOI waveguide is tuned around the shorter wavelength resonance and is essentially a pulse train of 10 GHz repetition rate. Every pulse is Gaussian in shape and has a duration and the extinction ratio of 8 ps (FWHM) and 22 dB, respectively. The pump occupies 1 nm spectral width (FWHM). The gating output is shown in Fig. 2(a), while Figs. 2(b) and 2(c) detail the transient responses. It can be seen that the extinction ratio is more than 12 dB and the rise and fall time are 18.6 and 26.4 ps, respectively, implying an achievable gating and all-optical wavelength conversion speed beyond 20 Gbits/s. The fast switch-off time is due to the fast recombination of free carriers owing to the high surface-to-volume ratio and rough side walls of the microdisk. Use of a smaller diameter (7.5 μm) microdisk here as compared to that in our previous work (10 μm) [6] has contribution to a faster switch-off time, but at the same time we believe that the probe beam also acts as a seeding beam and contributes to the faster response. It is observed that the extinction ratio increases with increasing pump power, but the switch-off time also becomes larger. The switching energy (which is 150 fJ in the SOI waveguide) can still be optimized further by properly choosing a pump source that matches the resonance width of the microdisk pump resonance (which is ~0.52 nm wide at FWHM). The reduction in the extinction ratio in the dynamic case (more than 12 dB for the dynamic case while its ~25 dB in static measurements) is due to the partial shift of the resonance and the change in absorption in the presence of the pump pulses. The thermo-optic effect is not visible in these measurements, as it appears on a microsecond time scale.

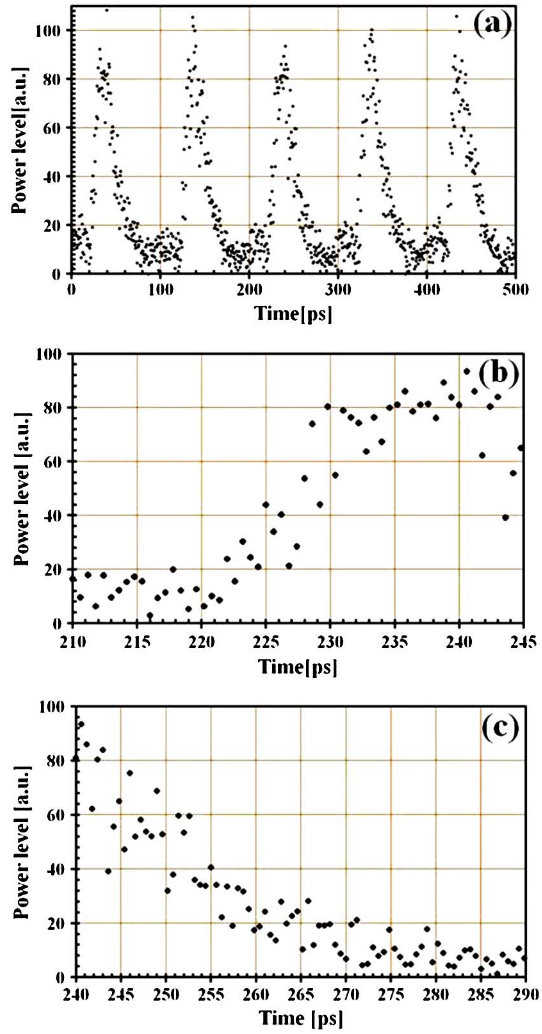

Fig. 2. (Color online) (a) Gating output waveform, (b) rising, and (c) falling transient details.

All-optical wavelength conversion was done for 10 Gbits/s PRBS data having a pattern length of $2^7 - 1$ as the control (pump) signal. The sketch of the experimental setup used for these measurements is shown in Fig. 3. TL1 is used as a probe signal and it has the same specifications as described in the previous section. Electrical PRBS data at the speed of 10 Gbits/s generated from the pulse pattern generator driven by a RF source at 10 GHz are converted into optical PRBS data using an electro-optic LiNbO3 Mach–Zehnder modulator and a cw optical signal from TL2 tuned at the shorter wavelength resonance. In this way, the generated optical PRBS control signal has an extinction ratio of 14 dB and pulse duration of 85 ps (FWHM) for a logic 1 level. A circulator is used to collect the probe signal. The backreflected control signal is suppressed by a wideband bandpass optical filter tuned to pass the probe signal. Afterward, the probe signal is amplified and ASE is removed with a sharp filter before being detected by the photodiode connected to a scope. A variable optical attenuator is used to control the

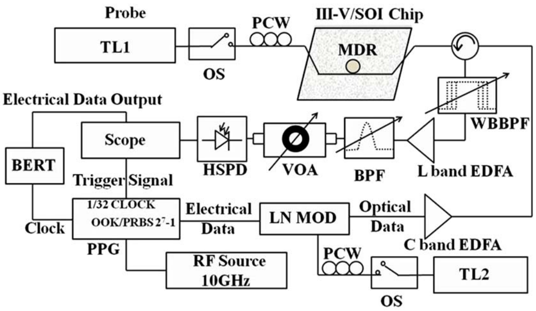

Fig. 3. (Color online) Schematic of the experimental setup used for all-optical wavelength conversion, TL1 and TL2, tunable lasers; OS, optical switch; PCW, polarization controlling wheels; MDR, microdisk resonator; WBBPF, wideband bandpass filter—it has a passband of 10–15 nm and is used to suppress the backreflection of the original control signal from the fiber facets and grating couplers making sure that only the probe signal is seen on the scope; BPF, bandpass filter—it has a bandwidth of 1.2 nm (FWHM) and is used to suppress the amplified spontaneous emission noise from the EDFA; HSPD, high-speed photodiode (30 GHz); LN MOD, lithium niobate Mach–Zehnder modulator; PPG, pulse pattern generator; VOA, variable optical attenuator.

received optical power into the high speed photodiode. The electrical output of scope is connected to a bit error rate tester for carrying out the bit error rate (BER) measurements.

The information contained in the control signal at the lower resonance wavelength is transferred to the higher resonance wavelength (cw probe beam) and is plotted in Fig. 4. The eye diagram corresponding to the wavelength-converted signal is shown in the same figure (below) and has an ER of 11.7 dB. Bit error rate measurements have shown that error free wavelength conversion at

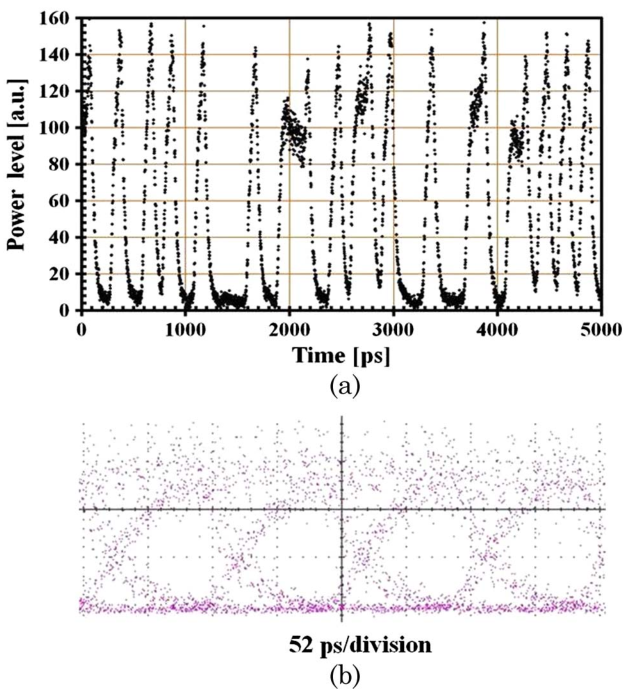

Fig. 4. (Color online) All-optical modulation response of the microdisk resonator for NRZ-PRBS control data: (a) time trace and (b) eye diagram.

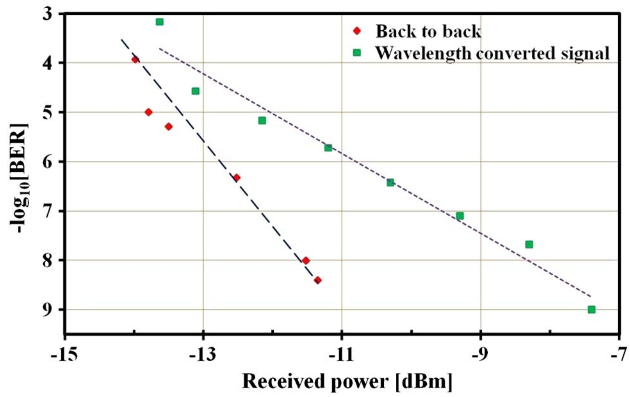

Fig. 5. (Color online) BER curves corresponding to the wavelength-converted signal and back-to-back measurements taken after the C band EDFA. The dashed lines are the linear fits to their respective data points.

10 Gbits/s is possible with a power penalty of ~3.5 dB. BER curves are shown in Fig. 5.

In conclusion, we have demonstrated high-extinction-ratio and bias-free all-optical wavelength conversion at a speed of 10 Gbits/s with a NRZ-OOK PRBS control data signal in a small-size microdisk resonator fabricated in a CMOS pilot line. Because the device is based on a resonator, it only works for the specific wavelengths corresponding to the cavity resonances. Wideband wavelength conversion can be done by using an array of devices with varying probe resonance wavelengths. Applications of such microdisks can be extended to all-optical (de)multiplexing, logic gates, data flip-flops, and even more complex functions such as shift registers, leading to the realization of high-speed and high-density PICs.

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