Optical Signal Processing in Silicon Nano-waveguides

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Abstract – All-optical tunable delay, dense wavelength conversion, and non return-to-zero (NRZ) to alternate-mark-inversion (AMI) format conversion are experimentally demonstrated using silicon microrings with a 450 x 250 nm cross-section size.

Introduction

The recently developed silicon-on-insulator (SOI) structure has proved to be an excellent platform for monolithic integration of photonic devices due to its high index contrast between the silicon core and the silica substrate, which allows strong confinement of light and enables ultra-compact devices. Silicon ring resonators with high Q-values can be explored for all-optical signal processing applications to achieve compact device size, high date rate, and low power consumption.

In this paper, we experimentally demonstrate optically tunable delay line in a silicon microring resonator with a 20-μm radius. The tuning mechanism is based on the thermal nonlinear effect that red-shifts the resonance. We investigate the delay performance of three modulation formats: non-return-to-zero (NRZ), return-to-zero (RZ) and differential phase shift keying (DPSK) signals at different data rates. We achieve tunable delay by controlling the power of a continuous wave (CW) pump with very low tuning threshold. This delay unit can be used in microring-resonator based slow-light structures.

We then demonstrate wavelength conversion based on free-carrier dispersion effect induced by non-linear absorption in a silicon micro-ring resonator. The pump and signal wavelengths are set by the 0.4-nm-spaced split resonances. The resonance splitting is introduced by nanometre-scale periodic sidewall roughness, which works as gratings. In the previous reports, the control (pump) and signal resonances are separated by at least one free spectrum range (FSR). For small-radius ring resonators in SOI, large FSRs usually limit the choices of wavelengths that can be converted. Mutual mode coupling due to sidewall gratings generates both propagating and counter-propagating. The grating and in turn the split-resonance separation can be tuned by varying the E-beam lithography scan size and exposure dose. The split modes enable more channels for conversions, thus increasing the system capacity. In this paper, we demonstrate high-speed wavelength conversion using the split modes at 1-Gb/s rate.

We also perform 10-Gb/s format conversion from NRZ to alternate-mark-inversion (AMI) signal using the linear filtering effect, which is the highest rate in silicon microring resonator, to the best of our knowledge. AMI is a RZ-like format with phase inversions that improve the signal tolerance to nonlinear propagation effects. It can also be explored for clock recovery at the receiver.

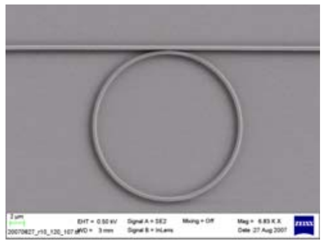


Fig. 1. SEM photo of a 10-μm silicon microring.

Silicon microrings

The silicon microrings in our experiments are fabricated on SOI wafer with a 250-nm-thick silicon slab on top of a 3-μm silica buffer layer [1]. The cross section of the silicon waveguides is 450×250 nm with a mode area of about 0.1μm^2 for transverse-electric (TE) optical mode in such a high-index-contrast structure. The microrings are side coupled to the straight waveguides with an air gap of 120 nm. The radii of the rings range from 10 μm to 40 μm. The devices are fabricated by E-beam lithography followed by reactive ion etching. The surface roughness is reduced by oxidizing 20Å of silicon surfaces using wet chemistry. A scanning electron microscope (SEM) photo of a 10-μm radius silicon microring resonator is shown in Fig. 1. At each end of the straight silicon waveguide, gold grating is added to couple light near-vertically with the single mode fiber (SMF) [2]. There is an adiabatic taper between the grating coupler and a 150-μm-long access straight waveguide. This vertical coupling method has advantages in terms of easy alignment and simple fabrication of the mode converter compared to other coupling methods. The measured fiber-to-fiber coupling loss is ~20 dB.

All-optical tunable delay

The experiment setup is depicted in Fig. 2. The pump and the probe signal sit at two adjacent resonances in the vicinity of 1550 nm. A Mach-Zehnder modulator (MZM) is driven by an electrical pseudo random bit sequence (PRBS) signal of 2^7-1 pattern length. We used the 2^7-1 PRBS to facilitate the measurements of the delay, and the experimental result shows that there is little difference if a longer pattern length is used. The RZ signal is obtained by cascading a pulse carver through driving a second MZM using a sinusoidal signal with a same frequency as the data rate, hence the duty cycle of the RZ signal is 50%. When the probe signal is DPSK format, we use a Mach-Zehnder delay interferometer (MZDI) to demodulate the DPSK signal. The measured results for the NRZ, RZ and DPSK formats are provided in Fig. 3.

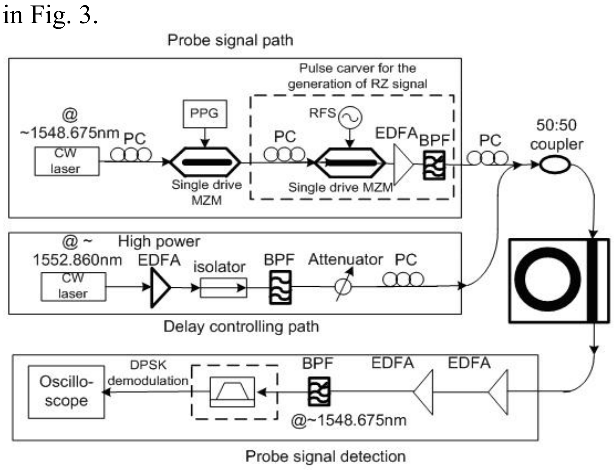


Fig. 2. All-optical tunable delay using a silicon microring.

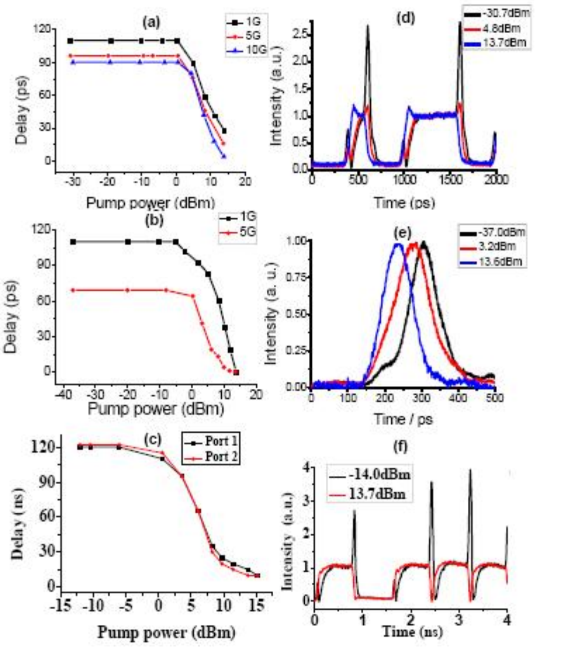
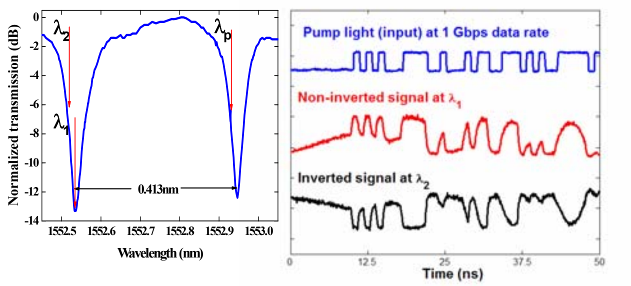


Fig. 3 Delay values vs. pump power for the a) NRZ, b) RZ, c) demodulated DPSK signals, d)-f) are the corresponding waveforms at 5-Gb/s rate.

By comparing the experimental results of the three modulation formats, we find that: 1) the maximum group delays are nearly the same (~ 120 ps) when the data rate is low; 2) the needed pump power to detune the signal from on-resonance to about half of the maximum group delay is ~ 6 dBm and the required pump power to shift the probe signal from on-resonance to off-resonance is ~15 dBm at the input fiber.

Dense wavelength conversion

The sidewall gratings along the 10-µm-radius ring give rise to the mode splitting effect as shown in Fig. 4a. The left resonance at 1552.534 nm has a full-width half-maximum bandwidth ($\Delta\lambda_{FWHM}$) of 0.092 nm and the notch depth is 13.2 dB, while the right resonance is at 1552.947 nm with $\Delta\lambda_{FWHM}$ = 0.071 nm and a notch depth of 12.4 dB. The signal wavelength λ_1 is close to the left resonance for the non-inverted case and λ_2 around the left resonance for the inverted case. The pump power is 14.3 dBm and the signal power is 6 dBm at the input of the fiber. Both non-inverted and inverted waveforms at 1 Gb/s are provided in Fig. 4b [3].



a) b)

Fig. 4. a) resonance spectrum, b) converted signal waveforms.

Format conversion

We use a high-Q ring resonator with a radius of 40 µm as a narrow band filter to perform NRZ to AMI conversion if the central component of the input NRZ signal can be well suppressed. Figs. 5a and 5b depict the waveforms of the input NRZ data and the converted AMI data, respectively. Sharp pulses of AMI data appear at both the rising and falling edges in "1" bits of NRZ data due to the effective suppression of the optical carrier and thus enhancement of the optical clock component in the notch filter transmission. The AMI data has a pulse width of ~32 ps and provides well-defined 10-GHz clock information.

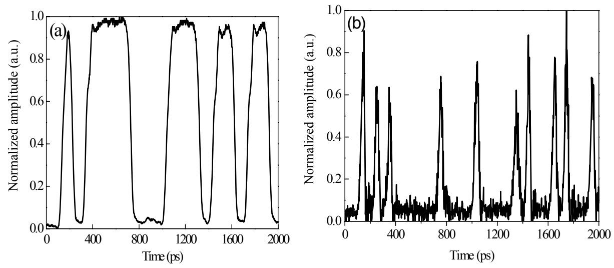


Fig. 5 a) and b) are waveforms of the input NRZ signal and the converted AMI signal, respectively.

Conclusions

We have demonstrated optical tunable delay, dense wavelength conversion, and format conversion using SOI ring resonators. This work was supported by the NSFC (60777040), Shanghai Rising Star Program Phase II (07QH14008), the Swedish Foundation for Strategic Research (SSF) through the future research leader program, and the Swedish Research Council (VR).

References

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