Optical Signal Processing in SOI Waveguide Devices

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Abstract

We experimentally demonstrate optical signal processing in silicon ring resonators, including slow-light delay of digital and microwave photonic signals, dense wavelength conversions/multicasting, optical up-convertion, format conversions, temporal differentiation, and bio-sensing.

Introduction

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

In this paper, we firstly study the system performances of an on-chip slow-light device based on the silicon micro-ring resonator for different digital modulation formats [1], including return-to-zero (RZ), carrier-suppressed return-to-zero (CSRZ), return-to-zero duobinary (RZ-DB), and return-to-zero alternate-mark-inversion (RZ-AMI). On-chip optical delay line is attractive due to its potential applications in future optical interconnections and packet-switching systems for data buffering and synchronization. Furthermore, we demonstrate that the device can be used to delay microwave photonic signals [2]. Conventionally, a practical implementation of arrays with thousands of elements is limited by the size and complexity of the phase-shifting elements. However, the use of miniaturized and integrated devices to perform this function is of much interest due to the advantages of low cost, compact size and on-chip integration.

We also demonstrate dense wavelength conversion [3] based on free-carrier dispersion effect induced by non-linear absorption in a silicon micro-ring resonator. 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 modes. 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. We demonstrate high-speed wavelength conversion using the split modes at 1-Gb/s rate. In addition, we demonstrate wavelength multicasting in this mode-split microring resonator. Wavelength multicasting is a process where a single data packet is converted into packets at multiple wavelengths. Previous multicasting approaches mainly used discrete devices such as semiconductor optical amplifier (SOA) and highly nonlinear fiber. Simultaneous wavelength conversion to multiple channels in the silicon photonic devices has not been demonstrated. In our experiment, a 1.25-Gb/s non-return-to-zero (NRZ) data carried by a pump signal is simultaneously converted to two probes located at the two resonance splits spaced by ~0.32 nm.

The optical up-conversion of baseband data to microwave photonic signal is a key technique in radio over fiber systems. Previous schemes are not suitable for low-cost and highly integrated applications due to the limitations of the size and the materials used. We present and experimentally demonstrate a novel micrometer-scale optical up-converter in RoF systems utilizing the free-carrier dispersion effect in a resonance-split silicon microring resonator [4]. In the experiment, a pump light is modulated by a baseband data, while an optical carrier suppressed signal is obtained in a probe path. By using free-carrier dispersion effect in a resonance-split microring resonator, the information carried by the pump light is transferred to the probe signal, thus obtaining an up-converted optical signal.

We also propose and experimentally demonstrate format conversion from NRZ to frequency shift keying (FSK) based on the free carrier dispersion effect induced selective filtering by using the mode-split ring resonator,. The split mode can provide large and variable frequency deviation for the FSK signal. FSK format has received considerable attention in passive optical network (PON) applications which are an attractive solution to provide broadband access. In this paper, 1-Gb/s NRZ signal is successfully converted to FSK format with a frequency deviation of 40 GHz. We also perform 10-Gb/s format conversion from NRZ to AMI signal [5] 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.

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We show that the microring resonator can be employed in analog applications. Optical temporal differentiator, which takes the time derivative of the complex optical field, would be useful in analog-digital conversion, pulse shaping, and optical processing of microwave signals. Several methods have been proposed based on long-period and phase-shifted fiber gratings, transversal filter structure, and Mach-Zehnder interferometer. However, most of these optical differentiators are discrete devices and exhibit a size of ~1 mm or larger. To the best of our knowledge, no experimental demonstration has been performed with ultra-compact, integrated, optical differentiator on chip. Here, we demonstrate an optical temporal differentiator based on a silicon microring resonator operating near the critical coupling region [6]. This differentiator can process signals with data rates up to 10G. The performance of the device is tested using signals with typical shapes such as square, Gaussian, and sinusoidal pulses.

Commercialized micro-arrays bio-sensors usually require labeled molecules detection. However, the labeling step complicates the sample preparation and detection process, as the labels can alter the molecules' binding properties and therefore decrease the reliability. Label-free biosensors using direct detection methods attempt to overcome the stability and reliability problems of biosensors as seen in the labeled molecules issues, such as by using SOI ring resonators. However, for SOI micro-rings, it is still a challenge in practice to achieve deep notches in the transmission spectra for the single-waveguide- single-ring structure. In addition, the sensing area is also limited by the small cross-section of the single-mode ring/waveguide. In this paper we propose and desmonstrate a two-concentric ring structure to effectively improve the notch depth and increase the sensing area at the same time [7].

Conclusions

We report various all-optical signal processing functions using silicon microring resonators with a 450×250-nm cross section. These demonstrations include slow-light delay of phase-modulated digital data and microwave photonic signals, wavelength conversion/multicasting, optical up-conversion, format conversions, optical differentiation, and bio-sensing. This work was supported by the NSFC (60777040), Shanghai Rising Star Program Phase II (07QH14008), Swedish Foundation for Strategic Research (SSF), and the Swedish Research Council (VR).

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