Publication information

Title	Silicon microresonators for on-chip optical interconnects and optofluidics
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Source	2011 International Quantum Electronics Conference (IQEC) and Conference on Lasers and Electro-Optics (CLEO) Pacific Rim incorporating the Australasian Conference on Optics, Lasers and Spectroscopy and the Australian Conference on Optical Fibre Technology, Sydney, NSW, 2011, p. 168-169
Version	Pre-Published version
DOI	https://doi.org/10.1109/IQEC-CLEO.2011.6193611
Publisher	IEEE

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Silicon Microresonators for On-chip Optical Interconnects and Optofluidics

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Abstract: We will discuss the latest progress in our work on using microring and microdisk resonators on silicon chips for multi-channel on-chip optical interconnects, biosensing and optical manipulation of microparticles.

1. Introduction

Over the past decade, silicon optical microresonators that partially confine light by total internal reflection in a high-index-contrast micrometer-scale structure has been proposed and demonstrated as a versatile building block for a wide scope of technological applications including wavelength-division multiplexing telecommunications, on-chip optical interconnects and optofluidic biosensing. In this invited talk, we will review the latest progress in our work on using microring and microdisk resonators on silicon chips for multi-channel on-chip optical interconnects and optofluidics.

On the front of on-chip optical interconnects, we have been investigating silicon microresonator-based devices on silicon-on-insulator (SOI) substrates including electro-optical tunable delays [1], routers [2] and wavelength-selective photodetectors [3, 4]. On the front of optofluidics, we have been exploring silicon nitride (SiN) based cascaded-microdisk sensors [5] and microresonator add-drop devices for on-chip optical manipulation of microparticles [6, 7].

2. On-chip optical interconnects

Recently, we demonstrated electro-optical tunable time delay and advance using a silicon feedback-microring resonator that is laterally integrated with p-i-n diodes [1]. By controlling the feedback and round-trip phase shifts through the carrier-injection-based free-carrier dispersion effect, we obtained a large dynamic time tuning range (-88 ps to 110 ps) upon a dc bias voltage change in the range of few tens of millivolts at a given resonance wavelength. This is in sharp contrast to conventional microring resonator-based tunable devices which require resonance wavelength shifts. We also demonstrated tunable time delay and advance at various blueshifted resonance wavelengths within 0.76 nm wavelength range. Our on-going work focuses on measuring the tunable delayed / advanced waveform at a data rate of 10 Gb/s.

Optical routers are essential components for optical networks-on-chip. Previously, we proposed an $N \times N$ cascaded matrix switch design as an on-chip optical router [2]. Such design employs a single microring resonator-based switch laterally coupled to a waveguide crossing. We use carrier injection-type plasma dispersion effect to switch each microresonator. The waveguide crossing adopts a low-loss low-crosstalk multimode-interference design [8]. For proof-of-concept, we demonstrated a 2×2 matrix switch which comprised four microring switches. Our experiments revealed routing of four different wavelength channels at 5 Gbit/s data rate, with sub-ns switching speed upon a typical dc power consumption of few hundreds of μ W in a footprint of $\sim 100 \mu\text{m} \times 100 \mu\text{m}$. Our on-going work focuses on extending the router to a 3×3 matrix switch.

Photodetection in 1550 nm wavelengths using silicon microring and microdisk resonators have also been demonstrated recently by our group [3, 4]. Sub-bandgap photocurrent generation in silicon in the 1550 nm wavelength range can be realized by two mechanisms, namely nonlinear two-photon absorption (TPA) or linear surface-state absorption (SSA). The microresonator builds up the light intensity at the resonance wavelengths and thus enable wavelength selective enhancement in photocurrent. We studied the SSA- and TPA-generated photocurrent in p-i-n diode embedded silicon microring and microdisk resonators [3, 4]. We showed 20-fold cavity-enhanced SSA-generated photocurrent with 0.12 mA/W responsivity in a microring resonator with Q of 8000 [3]. We also showed up to three-orders-of-magnitude cavity-enhanced TPA-generated photocurrent in a multimode microdisk resonator with maximum Q of 10^5 [4]. The demonstrated cavity enhancement also

significantly improves the photovoltaic energy harvesting efficiency. Our current work focuses on the temporal responses of such sub-bandgap photodetection.

3. Optofluidics

Silicon microresonator-based optical sensors have been attracting significant attention due to key merits of high sensitivity to refractive index change ($\sim 10^{-4}$ – $\sim 10^{-5}$ RIU), compact size (tens of μm – $\sim 100\ \mu\text{m}$), and potential for large-scale-integration in optofluidics applications. Recently, our group proposed and demonstrated an alternative sensing principle using a coupled-microresonator optical waveguide (CROW) on a silicon nitride (SiN) substrate [5]. In principle, CROWs comprising identical microresonators exhibit periodic transmission bands due to the inter-cavity coupling induced mode splitting. Upon a minute change in effective refractive index that induces an inter-state transition at a fixed wavelength, the mode-field pattern varies significantly while the transmission bands only spectrally shifts within the bandwidth. For proof-of-principle demonstration, we recently reported a microdisk-based CROW sensor comprising 11 gaplessly coupled $40\mu\text{m}$ -diameter microdisks with input- and output-coupled waveguides [5]. Our preliminary measurement of the out-of-plane light scattering images within the CROW transmission band suggested a spectral sensitivity of $\sim 0.02\ \text{nm}$, which is limited by our laser wavelength tuning step. Further experiments with sensing fluids with different refractive indices are in progress.

In order to further expand the functionalities of optofluidic circuits, previously we proposed and demonstrated on-chip optical manipulation of microparticles using SiN microring [6] and microdisk resonators [7]. We realized a microparticle add-drop device by using a SiN microring resonator-based add-drop filter. Microparticles can be transported to the throughput-port, trapped in round-trips on the microring resonator and routed to the drop-port [6]. Our on-going work focuses on SiN microdisk resonator-based optical manipulation, which has recently revealed potentials of multiple whispering-gallery modes trapping with multiple trapping tracks within each mode [7]. We believe such on-chip optical manipulation techniques using silicon-based microresonators thus open doors to integrated optofluidic micro/nanoparticles circuits.

4. Acknowledgements

We acknowledge financial support from Research Grants Council of the Hong Kong Special Administrative Region, China (Project numbers 618707, 618308, 618010). We acknowledge the Nanoelectronics Fabrication Facility of HKUST for fabricating all the devices.

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