Novel Resonance-based Silicon Nanophotonic Structures

Mohammad Soltani, Amir H. Atabaki, Qing Li, Ali A. Eftekhar, Siva Yegnanarayanan, and Ali Adibi,
Member, IEEE

***Abstract*—The development of ultra-compact integrated nanophotonic structures for communications, sensing, and signal processing has been of great interest lately. In this review paper, we first present the requirements for practical realization of integrated nanophotonic chips and then explain how these requirements are met by using low-loss waveguides and high quality resonators with careful engineering of the coupling between them. We will show that the ultimate realization of high Q microresonators can enable a wide range of applications including very compact on-chip spectrometers, tunable filters, and sensing modules.**

I. INTRODUCTION

THe development of ultra-compact integrated nanophotonic structures for communications, sensing, and signal processing has been of great interest lately [1]. The use of compact microresonators (e.g., microrings, racetracks, and microdisks) with high quality factors has resulted in order of magnitude reduction in the size of functional integrated photonic structures that used to be formed using waveguides [2]. Such resonators can be effectively tuned using free carrier injection and/or using the thermo-optic effect. This feature can be used to form reconfigurable photonic structures. Among existing substrates, silicon (Si) is the most promising one for infrared wavelengths due to the existence of excellent CMOS-based fabrication facilities. With recent advances in the design and fabrication tools for photonic nanostructures, Si-based integrated photonic platforms are a strong candidate for the realization of ultra-compact functional photonic microchips for a wide range of applications including signal processing, communications, and sensing.

II. HIGH-Q PHOTONIC RESONATORS

A high-Q resonator is a building block component for any large-scale integrated photonics system. The two key attributed are the strongly enhanced light-matter interaction at the resonance and their realization as a compact device which enables their dense on-chip integration [3]. In integrated optical sensing applications, optical resonators with enhanced light-matter interaction have been identified as critical for enhanced sensitivity of the sensor and also for reducing the sensor area. Figure 1 shows the spectrum of the microdisk resonator. As can be seen from Fig. 1(a), several different resonant modes with Q's ranging from $1.5\text{x}10^5$ up to $2.0\text{x}10^6$ were observed, corresponding to different radial mode orders. Figure 1(b) shows a ultimate miniaturized Si microdisk resonator with R=1.53μm exhibiting a high-Q (> 10^5) and a large FSR over 60nm with a single-mode operation.

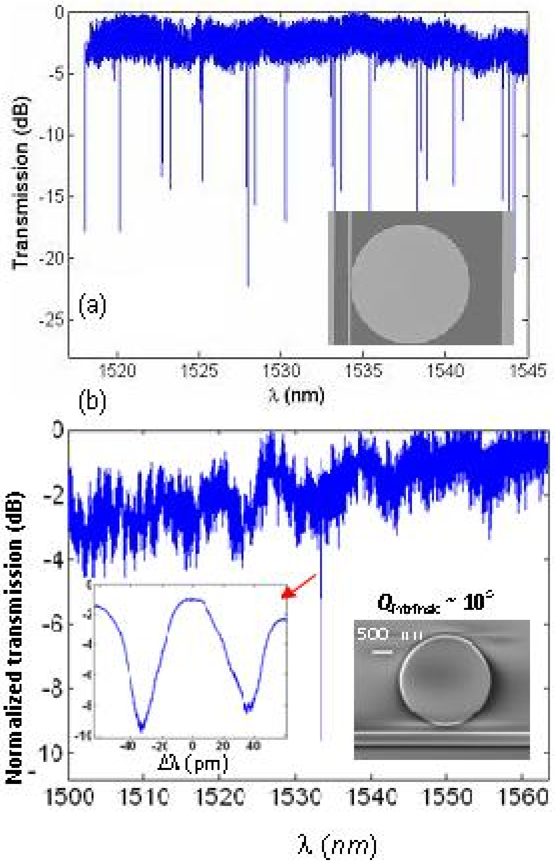

Fig. 1. (a) Spectrum of the R=20μm microdisk resonator shown in inset. An ultra-high $Q=2\text{x}10^6$ was observed at λ=1520.188 nm with an FSR of 5.1 nm (b) Spectrum of the R=1.53 μm microdisk resonator shown in inset. A $Q=10^5$ was observed at λ=1535 nm with an FSR larger than 60 nm.

Manuscript received May 13, 2010. This work was supported by the Air Force Office of Scientific Research (G. Pomrenke) and the Air Force Presidential Early Career Award for Scientists and Engineers (PECASE).

M. Soltani was with the School of Electrical and Computer Engineering Engineering, Georgia Institute of Technology. He is now with the Department of Physics, Cornell University, Ithaca, NY, 14853 (e-mail: ms2295@cornell.edu).

A. Atabaki, Q. Li, A.A. Eftekhar, S. Yegnanarayanan, and A. Adibi are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Dr., Atlanta, GA, 30332-0250 (e-mail: adibi@ece.gatech.edu).

978-1-4244-7017-4/10/$26.00 ©2010 IEEE

III. EFFICIENT COUPLING TO PHOTONIC RESONATORS

For high-*Q* resonators, efficient coupling of the light into the resonator is an important task in realizing a functional system. Depending on the application, undercoupled, overcoupled, or critically coupled resonators are needed. We have developed extensive coupling optimization strategies for these requirements. Figure 1 shows normal coupling, where phase matching was used to achieve a critical coupling to a high-Q microdisk mode. Figure 2 shows two different coupling conditions, namely strong over-coupling and interferometric coupling. For strong over-coupling we have developed a novel pulley-coupling architecture where the waveguide is wrapped around the resonator. The long interaction length enables enabling strong over-coupling while the high sensitivity to phase-mismatch strongly suppresses coupling to undesired modes of the microdisk resonator, enabling single-mode operation. We have also developed interferometric coupling architectures that enable highly controllable and reconfigurable coupling to desired modes of the photonic resonator.

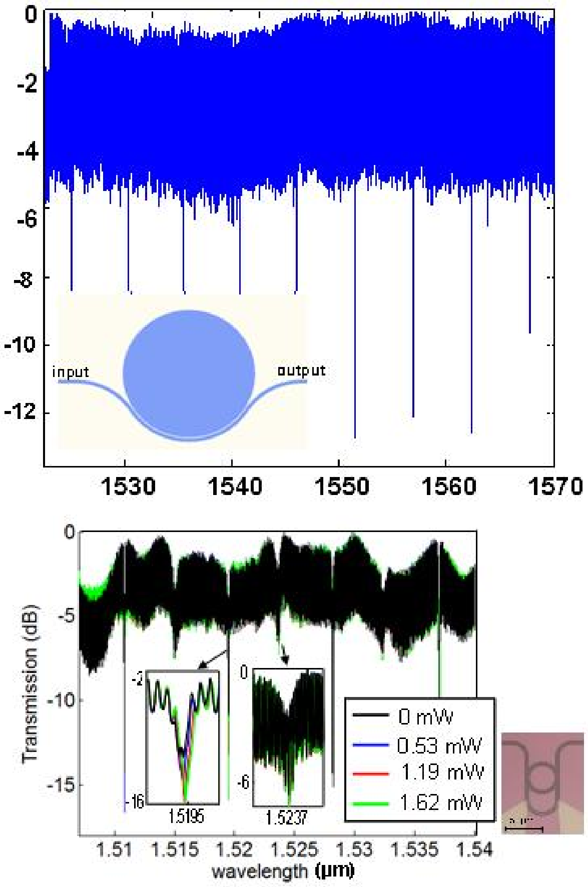

Fig. 2. (a) Pulley coupling resonance spectrum of the R=20µm microdisk resonator. Single radial-mode (3rd order) coupling is observed without excitation of other radial modes (b) Transmission spectrum of the interferometric coupling structure shown in inset consisting of a microring with R=20µm inserted inside an interferometer whose length exactly matches the microring resonator circumference. This results in a sinusoidal variation of coupling with wavelength and every alternate FSR exhibits weak coupling and strong coupling as seen in the experiment results. Thermal tuning in the interferometer can then be used to fine tune the coupling as shown in the curves at different applied power levels to the heater.

IV. THERMAL RECONFIGURATION

The luxury of reconfigurability in Si photonics not only relaxes the tolerance to fabrication errors but also opens the door to a plethora of applications such as adaptive filtering, reconfigurable add-drop multiplexing (ROADM) and dispersion compensation. Strong thermo-optic effect in Si enables efficient reconfiguration. We have performed extensive numerical modeling and optimization of geometry of the thin-film heaters to achieve higher heat transfer and speed. Figure 3 shows a 34.7 GHz resonance frequency shift in a 20µm diameter microring is achieved per milli-watt dissipated power by using 0.5µm wide heaters which is the highest value reported [4].

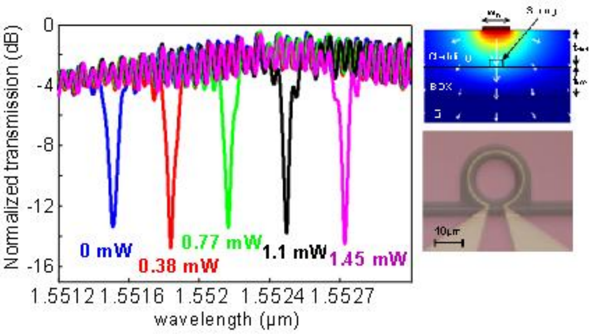

Fig. 3. Highly-efficient thermo-optic reconfiguration of a microring resonator with efficiency of 34GHz/mW is achieved. Inset shows simulated temperature distribution at the cross-section of a SOI waveguide as heat is generated in the metallic micro-heater. Inset shows optical micrograph of a 20µm diameter micro-ring with 1µm wide micro-heater on top.

In conclusion, recent advances in the fabrication of efficient nanophotonic devices and the implementation of novel highly-efficient thermo-optic tuning have led to the emerging field of reconfigurable Si nanophotonics. The available expertise in the fabrication of these devices in current silicon foundries and the possibility of realizing hybrid systems with electronic components on the same chip provides low-cost manufacturing opportunities of chip-scale systems with a multitude of functionalities for optical sensing and signal processing applications.

REFERENCES

[1] B. Momeni, S. Yegnanarayanan, M. Soltani, Ali A. Eftekhar, Ehsan Shah Hosseini, and A. Adibi, “Silicon nanophotonic devices for integrated sensing,” J. Nanophoton. **3**, 031001 (2009).

[2] M. Soltani, S. Yegnanarayanan, and A. Adibi, “Ultra-high *Q* planar silicon microdisk resonators for chip-scale silicon photonics,” Opt. Express **15**, 4694-4704 (2007).

[3] M. Soltani, Q. Li, S. Yegnanarayanan, and A. Adibi, “Ultimate Miniaturization of Single and Coupled Resonator Filters in Silicon Photonics,” *Conference on Lasers and Electro-Optics/International Quantum Electronics Conference*, OSA Technical Digest (2009).

[4] A.H. Atabaki, A.A. Eftekhar, S. Yegnanarayanan, and A. Adibi, “Sub-microsecond thermal reconfiguration of silicon photonic devices,” *LEOS Annual Meeting Conference Proceedings, 2009. LEOS '09. IEEE*, 495-496, (2009)