Resonance- and coupling-tunable silicon ring resonator based on low-voltage MEMS with large FSR

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***Abstract*—Reconfigurable silicon ring resonators are critical components in integrated photonics and have significant applications in various fields, including optical switching and microwave processing. In this study, we propose a novel design of resonance and linewidth tunable all-pass ring filters, which exhibit a free spectral range (FSR) of 6 nm, a loaded quality factor (Q) of 5116, a bias voltage lower than 12V, and a resonance tuning range of 1.2 nm. The proposed device operates based on micro-electro-mechanical systems (MEMS) technology and is implemented using silicon photonics.**

Keywords—ring resonator, MEMS, silicon photonics

I. Introduction

Silicon photonics has emerged as a powerful platform with applications ranging from optical communication to optical computation. Micro-ring resonators (MRRs) have the potential to enable wavelength division multiplexing (WDM) systems for on-chip spectrometry, optical communication, and advanced optical computation. For various WDM systems, different combinations of 3 dB resonance bandwidth, free spectral range (FSR), extinction ratio (ER), and resonance tuning range are required. Reconfigurable MRRs can serve as wavelength-selective switches [1], infinite impulse response (IIR) filters [2], and matrix-vector multipliers [3].

A reconfigurable silicon micro-ring resonator can be implemented by thermo-optic phase shifter with mW-level power consummation. Recently, phase shifter and tunable coupler based on MEMS electrostatic actuators has been introduced into silicon photonics to achieve low-power consumption. MEMS micro-ring resonators with different combinations of quality factors (Q), FSR, resonance tunability and coupling tunability have been developed. However, previous implementations have limitations in terms of their performance parameters. MRRs proposed by Ming C. Wu et al. [4,5] demonstrated linewidth-tunable add-drop filters without resonance tunability, while Hane et al. [6-8] proposed MRRs with a large FSR and resonance tuning range but a low Q value of only 1600. Young J. Park et al. [9] and Pierre Edinger et al. [10] reported their own micro-ring add-drop filter with continuous tunable resonance and coupling, respectively, but with limited resonance tuning range less than 0.5 nm. Here we demonstrated an all-pass ring resonator with 1.2-nm-wide continuous tunable resonance and tunable coupling with 6 nm FSR, 5166 loaded Q and actuator voltage <12 V.

II. Design and Simulation

The tunable MEMS ring resonator is a sophisticated structure composed of a suspended strip waveguide, which is supported by a shallow-etched rib waveguide converter, and two MEMS comb actuators. These comb actuators are responsible for phase shifting and coupling coefficient tuning, and are driven by the attractive Coulomb force between their teeth. As shown in Fig. 1, when a voltage is applied to the device, the MEMS comb is pushed towards the ring resonator. The relationship between the voltage *V*, the Coulomb force *F*, the displacement *x*, the spring constants *k*, and the comb capacitance *C* is governed by:

$$F_x = \frac{1}{2}\frac{\partial C}{\partial x}V^2 = -k_x x \tag{1}$$

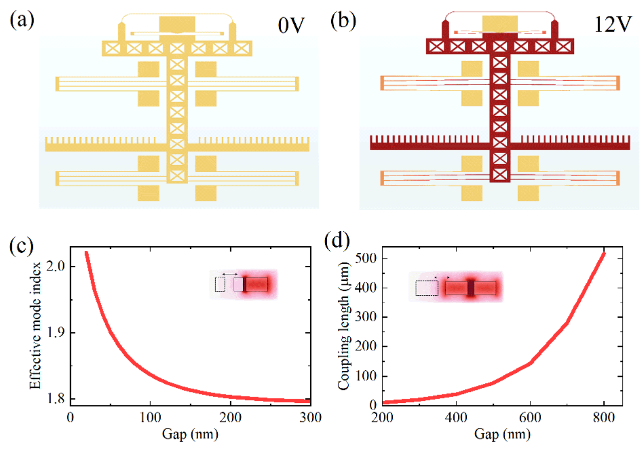

Fig. 1. (a) The phase shifter at passive state; (b) The phase shifter at active state; (c) Phase shifter tune the effective index of the ring waveguide; (d) Directional coupler tune the coupling.

Simulated by COMSOL MEMS Module, the MEMS comb used for the phase shifter has a spring constant of 0.227 N/m and tunable coupler has a spring constant of 0.67 N/m. Softer springs allow for larger displacements with smaller voltages. $\partial C/\partial x$ of a pair of comb teeth is about 2.392×10^{-11} F/m, which is constant at small displacement.

To achieve a larger FSR, the ring waveguide width is 350 nm so that the interaction lengths both of phase shifter and direction coupler are reduced. And its bending radius is as small as 3µm. Due to the strong confinement provided by fully suspend waveguide, the compact geometry does not introduce significant loss. The ring is designed as triangular shape as a trade-off between interaction length and total length. The designed total length is 73 µm and FSR is about 6 nm at 1550 nm.

The MEMS phase shifter changes the effective mode index by moving another 150 nm wide freestanding silicon strip toward the ring waveguide. The width cannot support any mode at 1500 nm to avoid losses. By changing the gap between the narrow silicon strip and ring waveguide, the effective mode index (n_{eff}) can vary from 1.79 to 2.02 at 1550 nm, corresponding to the maximum displacement allowed by the mechanical stoppers. The simulated change in the n_{eff} with respect to the horizontal coupling gap is plotted in Fig. 1(c) (Lumerical MODE).

To realize the tunable coupler, the 5 µm long movable bus waveguide is connected to the mechanical shuttle beam using MMI crossings and is anchored to the silicon edge of the MEMS undercut cavity using rib-strip waveguide converter as illustrated in Fig. 2(a). The simulated change in the coupling length with respect to the horizontal coupling gap is plotted in Fig. 1(d) (Lumerical 3D FDTD). In its passive state, the coupling gap is 500 nm, resulting in a power coupling coefficient of 0.024 at 1550 nm. As the coupling gap is decreased, the coupled power increases up to the simulated value of 0.76 for the gap of 200 nm.

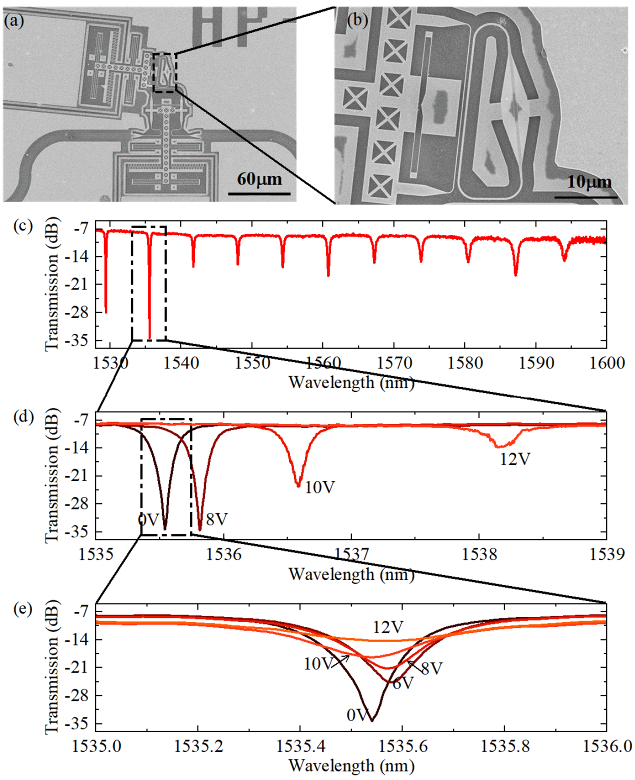

Fig. 2. (a)-(b) SEM top-view of our device; (c) Passive transmission from 1500 to 1580 nm; (d)-(e) DC actuation up to 12V of the actuators V_{PS} and V_{DC}, respectively, in the wavelength region around the resonance at 1535.5 nm.

III. Characterizations

In this study, ring resonators were fabricated on a SOI wafer with a 2 μm buried oxide layer using electron-beam lithography (EBL) and inductively coupled plasma (ICP) etching. The mechanical part was released by HF vapor etching.

The device transmission was measured using a tunable laser (Keysight 81940A) and optical power meter (Keysight 81633A), and the results were normalized to the reference waveguide measurement. The measured results in Fig. 2 show that the FSR is approximately 6 nm and the ER is about 26 dB at 1535.5 nm. The resonance and coupling tuning were demonstrated by tracking the resonance at 1535.5 nm, where the transmission was measured with increasing and decreasing the actuator voltage without any observed hysteresis. As the voltage of the phase shifter increased, the resonance redshifted. The linewidth broadening at high voltage was caused by an increase in phase shifter insertion loss. The effective resonance tuning range was defined as the shifted resonance with ER larger than 15 dB, and was found to be about 1.2 nm without coupling compensation. We believe that a larger tuning range can be achieved by adjusting the coupling to meet the critical coupling condition. Further systematic experimental characterizations are underway.

IV. Conclusions

In conclusion, we have proposed and implemented a MEMS-based ring resonator that allows for resonance and coupling tuning independently. The ring resonator has a 6 nm FSR and 5116 loaded Q, while still providing a low-actuating voltage of <12V.

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