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A MEMS TUNABLE PHOTONIC RING RESONATOR WITH SMALL FOOTPRINT AND LARGE FREE SPECTRAL RANGE

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ABSTRACT

We demonstrate a MEMS tunable silicon photonic ring resonator with a 20 μm radius and a 5 nm free spectral range (FSR) for wavelength selection in reconfigurable optical networks. The device shows a loaded Q of 12000, and 300 pm tuning at a wavelength of 1544 nm.

KEYWORDS

Silicon photonics, ring resonator, tunable ring resonators, reconfigurable optical networks

INTRODUCTION

Silicon photonics hold great promise for future optical interconnects in information-processing systems, as the limitations of copper-based networks in terms of density, energy, and timing become more and more critical [1]. The strong light-confinement of the high refractive index contrast waveguides made in silicon enables waveguides with tight bends, and has already resulted in a drastic footprint reduction in optical networks. A key element of silicon photonic networks is the ring resonator. A ring resonator is a looped-back waveguide that supports standing wave resonances when the optical path length is exactly a whole number of excitation wavelengths. The optical path length of ring resonators depends on the geometric length of the ring and the effective refractive index of the waveguide. A small change in either of these parameters results in a shift of the resonance wavelength. By actively changing the optical path length of a ring resonator, it becomes a very sharp and precisely tunable wavelength filter (Fig. 1a) [2].

Tunable ring resonators find applications in integrated optical networks, which require accurate placement and/or active tuning of sharp wavelength filters. Examples of applications include: accurate tuning of wavelength division multiplexing (WDM) systems [3], active wavelength selection in optical routers [4] and reconfigurable optical add/drop multiplexers (ROADM) [5], broadband switches [6], and tunable lasers [7], among others. Most of these applications require small and tightly spaced rings with sharp resonances (high Q) and a long distance between adjacent resonances (large free spectral range, FSR) in order to address a large number of optical channels. Moreover, such applications require ring resonators with independent tuning, which translates into low cross-talk when tuning adjacent devices. This requirement is of major importance when using cascaded ring resonator filters for telecom applications, which need independent tuning of tightly spaced coupled resonators to achieve a flat-top spectral response (Fig. 1b and d) [8]. Figure 1 shows schematics of different ring resonator-based optical network architectures.

Figure 1: a) Photonic ring resonator add-drop filters select wavelengths from an input waveguide and transfer them to an output waveguide. b) Cascaded ring resonators yield flat-top spectral filtering, commonly required in communications networks. c), d), and e) show common architectures of ring resonator-based optical routers and ROADMs, which require a large number of tightly spaced tunable ring resonators with a long FSR and independent resonance wavelength tuning.

MEMS tunable ring resonators are excellent candidates for wavelength selection in reconfigurable optical networks, due to their low power dissipation (that translates into negligible thermal cross-talk between adjacent devices) and high optical Q. MEMS tunable ring resonators have shown FSR up to 6.6 nm [9]. However, their tuning mechanism, based on bending a cantilever on top of a racetrack ring resonator, set the operation point very close to pull-in and thus resulted in a short tuning range of 122 pm. Another approach achieved a 10 nm long tuning range in a device with an FSR of 3.3 nm [10]. But the tuning principle, based on free-standing waveguides requiring anchoring, resulted in low Q and high passband ripple due to reflections.

In our previous work, parallel plate actuation of a SOI cantilever containing part of a slot waveguide ring resonator resulted in MEMS tunable ring resonators with high Q, low passband ripple, and a 1 nm tuning range [11]. However, the FSR of the device was only 1.24 nm due to the 80 μm large ring resonator radius. This limited the maximum selectable channels to 12, and resulted in a large footprint that limits integration density.

Increasing the FSR is possible by using the Vernier effect of cascaded ring resonators [12]. However, this results in an increase in passband ripple, due to side peaks, and a several-fold increase in footprint.

In the present work, we report a MEMS tunable ring resonator with a $20\ \mu\text{m}$ radius and a FSR of 5 nm. Small rings of silicon ridge-waveguides are made possible by the enhanced light confinement provided by complete removal of the oxide layer underneath the silicon ring (Fig. 2).

Figure 2: A top view and a cross-sectional drawing of our MEMS tunable ring resonator with $20\ \mu\text{m}$ radius. Small ridge-waveguide rings are made possible by the strong light confinement resulting from the complete removal of the buried oxide layer underneath the ring (in white and bounded by dashed grey lines). Complete removal of the oxide layer is achieved by HF wet etching through etch holes (indicated in blue).

FABRICATION

The fabrication process for the device consists of a first e-beam lithography patterning of a mask on an SOI chip (220 nm thick silicon device layer and $2\ \mu\text{m}$ buried oxide, which is a standard substrate specification used by the Epixfab photonic foundries). After a timed silicon dry etch that defines ridge waveguides and grating couplers, a second e-beam mask is patterned. Then, a dry etch through the silicon device layer defines etch holes and a slit aligned with the slot waveguide. To finalize the chip, we used HF to under-etch the buried oxide layer through the etch holes, resulting in free-standing parts after critical point drying [11].

Figure 3: A top view SEM image of the fabricated MEMS tunable ring resonator with $20\ \mu\text{m}$ radius. The under-etch (bounded by dashed lines) defines the tuning cantilever and the discontinuity free optical path, and enables strong light confinement in the ring ridge waveguides. The remaining buried oxide serves as anchor for the suspended cantilever.

RESULTS AND DISCUSSION

Figure 2 shows the design of our compact MEMS tunable ring resonator. By reducing the ring radius the footprint was reduced 16-fold compared to our previous work [11]. This reduction does not result in increased optical bend losses for the ring due to the fully under-etched ring waveguide that presents an enhanced light confinement as compared to a ridge waveguide with bottom oxide cladding. The under-etch is defined by the slot in the waveguide that is etched through the entire silicon and by additional etch holes. The under-etch results in i) a suspended cantilever for resonance tuning, ii) a discontinuity-free optical path to minimize reflections, and iii) enhanced light confinement in the suspended ring waveguide. An SEM image of our device is shown in Fig. 3.

To characterize the photonic ring resonator, we coupled light of transverse-electric (TE) polarization via optical fibers in and out of the bus waveguide through grating couplers fabricated on-chip. The transmitted light was then measured by a wavelength domain component analyzer (Agilent Technologies 86082A). Our device yields an FSR of 5 nm, a bandwidth of 135 pm, and a loaded Q of 12000 (Fig. 4). Compared to our previous work [11], this results in a 4-fold increase in FSR, which translates into 37 potential optical channels.

The tuning performance of the device was characterized by grounding the silicon substrate and then contacting the silicon device layer with a compliant probe needle and applying a voltage. An actuation voltage of up to 45 V induced a wavelength shift of up to 300 pm (Fig. 4). This wavelength shift, although comparably lower than the 1 nm of our previous MEMS tunable ring resonator [11],

compares favorably to the wavelength shift of 122 pm shown by other MEMS tunable devices with similar FSR [9].

Similarly to our previous devices, this device presents non-linear behavior at actuation voltages of below 30 V [11]. Thin film stress tests, performed by observing the static deflection of double-clamped cantilevers of different lengths within the same chip, indicate that the non-linear behavior is caused by static deflection of the ring resonator cantilever due to internal compressive stress. This static deflection results in warping of the cantilever, and yields counteracting tuning effects at the initial stages of the actuation. With applied voltages of above 45 V, the device reached pull-in and irreversibly stuck to the silicon substrate.

Figure 4: Transmission spectra for the device in Fig. 3 under a range of actuation voltages. The wide grey arrow indicates the direction of resonance wavelength shift with increasing voltage. The tunable ring waveguide shows a Q of 12000, an FSR of 5 nm, a -3 dB bandwidth of 0.135 nm, and a tuning range of 0.3 nm.

For our device the achieved linear tuning rate was -17 pm/V, which is significantly lower than -37 pm/V observed in the previously mentioned 80 μ m radius device [11]. The bandwidth variation is below 10% over the full actuation range and does not correlate with the actuation voltage (Fig. 5). We believe that both the shorter tuning range and the lower tuning rate compared to [11] can be explained by silicon residues that originated from a non-optimal first lithography and bridged parts of the slot of the tunable slot-waveguide. These bridges in the cantilever cause increased stiffness and a shorter cantilever length, thus both reducing the tuning rate and the tuning range. By further optimizing the resolution of the lithography and avoiding the unintended bridges, it should be possible to achieve increased tuning rates, as previously observed in the tunable ring resonators with rings of 80 μ m radius.

Figure 5: Our device presents a linear tuning rate of -17 pm/V for actuation voltages between 30 and 45 V. The -3 dB bandwidth of the resonator is around 135 pm and shows no correlation with the actuation voltage, which indicates absence of tuning induced optical losses.

CONCLUSION

With modest improvement in tuning rate, the demonstrated FSR of 5 nm and a -3 dB bandwidth of 135 pm, shows the potential to realize an optical communication system with close to 40 wavelength channels using this technology. The very small footprint, the large FSR and Q , and the significant tuning range of the presented device demonstrate the scalability of our MEMS tunable ring resonator technology for future reconfigurable optical networks.

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