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A LOW-POWER MEMS TUNABLE PHOTONIC RING RESONATOR FOR RECONFIGURABLE OPTICAL NETWORKS

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ABSTRACT

We experimentally demonstrate a low-power MEMS tunable photonic ring resonator with 10 selectable channels for wavelength selection in reconfigurable optical networks operating in the C band. The tuning is achieved by changing the geometry of the slot of a silicon slot-waveguide ring resonator, by means of vertical electrostatic parallel-plate actuation. Our device provides static power dissipation below 0.1 μ W, a wavelength tuning range of 1 nm, and a narrow bandwidth of 0.1 nm, i.e. 10 nW static power dissipation per selectable channel for TE mode tuning.

INTRODUCTION

The current exponential increase in data communication, with annual growth rates up to 90% [1], follows from the ever-increasing demand for capacity in communication networks. This demand cannot be fulfilled by traditional copper networks due to fundamental limits in data transmission, making optical networks a requirement. A promising solution to further increase optical network capacity is to add spatial multiplexing on top of existing optical wavelength multiplexing [1].

Spatial multiplexing requires optical add/drop filters. Following the introduction of reconfigurable optical add/drop multiplexers (ROADMs) in 2003, the demand for flexibility and scalability in the communications network resulted in the progressive substitution of the traditional fixed optical add/drop multiplexers (FOADMs) with ROADMs. The currently available ROADMs systems are based on free space optics. Light is launched into free space from a fiber input towards a diffractive grating where the channels are spatially separated and directed towards an optical switching array. After switching and redirecting, the channels are recombined with a second grating and coupled back into the fiber system. Current switching arrays are formed by either MEMS mirrors or liquid crystals [2]. However, free-space-based ROADMs have a number of disadvantages such as large size, high insertion losses, and fabrication complexity, which translates directly to high costs. Key features for a future ROADM are good optical performance, high number of channels, low insertion loss, flexible channel plan, and low cost [2].

A promising approach to fulfill these requirements is the use of matrixes of single-wavelength reconfigurable add-drop filters (Fig.1). Silicon photonic ring resonators are excellent candidate building blocks for this scheme, due to their compactness and high optical quality factor (Q). Constant bandwidth filters are preferred, to maintain equal channel spacing. Furthermore, the number of available communication channels is determined by the filter bandwidth and its tuning range.

Resonance wavelength tuning in ring resonators can be achieved by using physical effects such as carrier

injection, thermo-optic tuning, electro-optic materials, and MEMS actuation. Several approaches to tunable ring resonators have been presented. Wavelength tuning by free carrier injection enables high-speed modulation [3], but the optical loss induced by the interaction between photons and free carriers makes the method impractical for reconfigurable optical networks. Thermo-optic tuning yields long tuning ranges and constant bandwidth [4, 5]. However, for ROADM applications, power dissipation from thermally tuned rings causes thermal crosstalk, resulting in communication errors and thus limiting integration density. Integration of electro-optic materials can provide ring resonator tuning with low static power dissipation. However, with the electro-optic materials used so far, the devices show either low optical Q due to scattering from the tunable material [6], short tuning ranges [7], tuning instability due to resonance drift [8], or optical interference due to fabrication complexity [8, 9].

Figure 1: Matrix of reconfigurable ring resonators for optical wavelength band selection to several output ports. The use of such spatial multiplexing in reconfigurable optical networks has the potential to meet the currently increasing demand for data communication capacity.

MEMS-based optical tuning has been achieved by a suspended dielectric cantilever on top of a ring resonator. In this configuration, the small separation of cantilever and waveguide necessary for wavelength tuning sets the actuator operation close to pull-in, resulting in a controllable wavelength tuning range of only 120 pm [10]. A constant bandwidth and long tuning range were achieved by tuning the diameter of a silicon ring. The ring consisted of two suspended U-shaped waveguides optically connected by directional couplers. One of the waveguides is displaced by a comb drive actuator, changing the diameter of the ring and thus resulting in a shift in resonance wavelength [11]. However, the use of fully suspended waveguides makes anchoring necessary, which results in poor optical performance due to reflections caused by waveguide discontinuities at the anchors.

In this work, we use vertical parallel-plate actuation of an SOI cantilever containing the inner part of a slot-waveguide ring resonator. This locally changes the effective refractive index of the resonant optical mode, resulting in a shift in resonance wavelength. The novel vertical actuation introduced in this work yields a discontinuity-free optical path, while setting the actuator operation point far from the pull-in state. A key advantage of electrostatic tuning of MEMS cantilevers is the low-power wavelength tuning, which results in negligible cross-talk between adjacent rings. Moreover, the perfect elasticity of the single-crystalline silicon cantilever provides a stable and hysteresis-free tuning [12]. A schematic of the device is shown in Fig. 2.

Figure 2: A schematic of the MEMS tunable ring resonator. Parallel-plate actuation (indicated with open arrow) of a free-standing cantilever (indicated in orange) that contains part of the inner rail of a slot-waveguide ring resonator changes the waveguide geometry. This locally affects the effective refractive index of the resonant optical mode, resulting in a shift in resonance wavelength. The inset shows the simulated optical mode.

FABRICATION

Our MEMS tunable ring resonator was fabricated by a very simple SOI-based process (Fig. 3) with two dry etch steps for the silicon device layer (resulting in two heights) and a wet SiO_2 under-etch. The first lithography step defines the ridge waveguides that form the ring resonator and the grating coupled bus waveguide. The second lithography step and the wet under-etch define the free standing cantilever. The cantilever is delimited by the fully etched slot waveguides, and its free suspended area is determined by the placement of etch holes.

The fabrication process starts with a clean SOI chip with a 220 nm crystalline silicon device layer and 2 μm buried oxide (Fig. 3A). This is a standard substrate specification used by the Epixfab silicon photonics foundries. Electron beam patterning of a 50 nm layer of a high-resolution negative electron beam resist (Hydrogen silsesquioxane, HSQ) defines the waveguide structures (Fig. 3B). The pattern is then transferred to the device layer by timed dry etch of silicon, resulting in ridge waveguide structures with 110 nm height on a 110 nm thick silicon slab (Fig. 3C). The patterned HSQ remains on the chip for the next lithography step.

Figure 3: Cross-section (A-A' from Fig. 2) of the fabrication process. A clean SOI chip (A) was spun with HSQ resist and e-beam patterned (B) to define ridge waveguides by timed dry etch of silicon (C). The HSQ resist, in combination with a second e-beam patterned positive ZEP7000 resist (D) were used for a second through dry silicon etch (E) that defines the free-standing cantilever (F). After stripping the resists, the structures are released by HF wet oxide under-etch, followed by critical point drying (G). Applied voltage between the silicon substrate and the device layer deflects the cantilever, resulting in a resonance wavelength shift.

In order to define the free-standing cantilever, we e-beam patterned a 200 nm thick layer of positive e-beam resist (ZEP7000) after alignment to the existing structures (Fig. 3D). The subsequent through dry etch of silicon was then defined by the superposition of the two e-beam masks (Fig. 3E). This allows the creation of a self-aligned etched slot in the center of the waveguide, defined by the high resolution HSQ patterning of the first lithography step. After stripping the two resists (Fig. 3F), the patterned cantilever was then released via a 50% HF wet oxide etch, followed by critical point drying (Fig. 3G).

RESULTS AND DISCUSSION

Figure 4A is a top view of the design of our MEMS tunable ring resonator. Part of the etched slot, combined with etch-holes, defines a suspended cantilever. To ensure a discontinuity-free optical path, we designed smooth refractive index transitions in the silicon ring by using strip-to-slot couplers, and in the buried oxide layer by strategic etch hole positioning for tapering the transition between suspended and supported waveguides. An SEM image of our device is shown in Fig. 4B.

For optical characterization, TE polarized light is coupled in and out of the chip through optical fibers aligned to grating couplers fabricated on-chip. At resonance wavelengths, light couples from the bus waveguide into the ring. The transmitted light from the device is then measured by a wavelength domain component analyzer (Agilent Technologies 86082A). Our device shows a free spectral range (FSR) of 1.24 nm, a 0.1 nm -3 dB bandwidth, and a loaded Q of 16200 at a wavelength of 1573.8 nm (Fig. 5).

To characterize the tuning performance of the device, the silicon substrate was grounded. A voltage was then applied by direct contact of a compliant probe needle to the device layer of the chip. The resonator was actuated by a voltage of up to 56 V, inducing a wavelength shift of up to 1 nm (Fig. 5). Considering the 0.1 nm bandwidth of the ring resonator, the number of unique selectable channels obtained for this device is 10.

Below a 30 V applied voltage, our device showed a non-linear tuning rate (Fig. 6). This is most likely caused by the static deflection of the cantilever, due to relaxation of mechanical stress of the released silicon device layer. This initial deflection results in parts of the cantilever situated above and parts below the zero deflection plane. Actuation of the cantilever then results in combined effects that may counteract depending on the cantilever initial static deflection. When the cantilever bending has overpassed the zero deflection plane (i.e. at an actuation of 30 V), blueshift prevails. Consequently, from 30 to 56 V, we observe a linear -36 pm/V tuning rate, which compares favorably to the 13 pm/V shown with integrated LiNbO₃ [9]. The bandwidth variation for our device is below 20% in the linear tuning range and shows no apparent trend, which indicates that the optical losses in the ring are not related to the wavelength tuning (Fig. 6).

Figure 4: (A) Design of the MEMS tunable ring resonator including geometrical parameters. The inset (B-B') shows the slot-waveguide cross-section. The cantilever is indicated in orange. Light couples from the bus waveguide into the ring. Half of the ring is made of a slot-waveguide with a through etched slot. A suspended cantilever is formed by the through etched slot and the etch holes. Tuning is achieved by electrostatically bending down the cantilever. (B) SEM image of a MEMS tunable ring resonator. The under-etch pattern, indicated in green, ensures a discontinuity-free optical path.

Figure 5: Transmission spectra for the device shown in Fig. 4 under a range of actuation voltages. The ring shows a Q of 16200 with an FSR of 1.24 nm. A bandwidth of 0.1 nm and a tuning range of 1 nm yield 10 selectable optical channels.

Our MEMS tunable ring resonator has static power dissipation below $0.1 \mu\text{W}$, which is orders of magnitude below the lowest reported value of 2.4 mW for thermally tuned ring resonators [5]. An optical tuning range of 1 nm and a bandwidth of 0.1 nm yield 10 selectable optical channels for our device. This results in a 10 nW static power dissipation per selectable channel.

Figure 6: Our MEMS tunable ring resonator presents a linear tuning rate of -36 pm/V (+) with bandwidth variation below 20% (*) for actuation voltages between 30 and 56 V.

CONCLUSIONS

We have shown a MEMS tunable ring resonator with a sub $0.1 \mu\text{W}$ static power dissipation and stable tuning performance using a simple silicon fabrication process.

In particular, the presented device combines the extremely low power consumption of electrostatic MEMS, a very simple high-resolution SOI fabrication process, and 10 selectable channels, i.e. the highest number reported for MEMS tunable ring resonators.

Our results suggest that the presented MEMS tunable ring resonator technology has the potential to become an important building block for combined wavelength and spatial multiplexing in future reconfigurable optical networks.

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