Micromechanically Tuned Ring Resonator in Silicon on Insulator

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Abstract: Monolithic integration of a micromechanical cantilever with an optical ring resonator in silicon on insulator is demonstrated. The ring is tuned over a 120 pm wavelength range by applying 9 V, without affecting its Q-factor.

1. Introduction

Silicon microring resonators are interesting building blocks for integrated optical functions such as optical modulators, switches, and wavelength routers. These functions require a tuning mechanism. In silicon photonics, the thermo-optic, electro-optic, and mechano-optic effects can be used. The thermo-optic effect has a time constant on the order of 1 µs, but the necessary heaters require continuous power dissipation. The electro-optic effect in silicon pn-junctions can be fast with a time constant below 1 ns and very low power consumption [1], but the effect introduces noticeable optical loss due to free carrier absorption, which is a drawback for applications that require low-loss tuning over a broad wavelength range. The mechano-optic effect, where a dielectric object is displaced in the evanescent field of an optical waveguide by an electrostatic micromechanical actuator, is a potentially strong effect, requiring low actuation power and inducing low optical loss. Ultrawide tuning of a ring resonator has been demonstrated by use of an optical fiber tip as the movable dielectric object [2]. Recent results have demonstrated the interaction between the scanning tip of an atomic force microscope and nanophotonic structures [3,4]. The first integrated mechano-optically actuated ring resonator, which was limited to on/off switching, employed an aluminum microbridge that, when pulled close to the ring, inhibits the resonance due to increased optical loss [5].

For the first time, we demonstrate a ring resonator in silicon on insulator (SOI) that can be mechano-optically tuned with a monolithically integrated and electrostatically actuated microcantilever.

2. Modelling

We designed a racetrack-type optical ring resonator having a bend radius of 10 µm and straight sections of 12 µm length. The free spectral range of the ring is 6.6 nm at a wavelength of 1550 nm. The waveguide supports a single TE mode. The waveguide width and gap between the waveguides in the coupling region are 600 nm and 240 nm, respectively.

We modeled the perturbing effect of the presence of a silicon nitride cantilever with a two-dimensional modesolver to calculate the effective refractive index n_{eff} of the silicon waveguide as a function of the air gap between the cantilever and the waveguide for TE-polarized light. As expected from the exponential tail of the evanescent field, the response is strongly nonlinear, as shown in Fig. 1. In particular, the gap should be smaller than 300 nm in order to have any noticeable effect. A smaller initial gap requires a smaller change of the gap, hence a smaller actuation voltage, to obtain a given change in the effective index. Unfortunately, fabrication of the cantilevers with good yield becomes increasingly challenging for smaller initial gaps. Hence we aimed for an initial gap of 200-300 nm to obtain sufficient actuation at an acceptable yield with our technology.

An increase Δn_{eff} of the effective refractive index increases the optical path length of the ring resonator, leading to an increase $\Delta\lambda$ of resonance wavelength. For a given perturbation length (i.e. cantilever width) L_{pert} and order m of the optical ring, the wavelength shift is, to first order, given by $\Delta\lambda = \Delta n_{\mathrm{eff}} L_{\mathrm{pert}} / m$.

We designed relatively narrow, 10-µm-wide cantilevers covering most of the coupling regions, but allowing visual inspection of this critical region. With a 3D finite-difference time-domain method, we calculated the power coupling coefficient in absence of the cantilever as 0.0236; with a cantilever at 200 nm above the waveguides it increases by about 3 % to 0.02435. In the latter situation, an optical loss of 0.18 % due to the induced effective refractive index discontinuity was calculated. For the cantilever in contact with a waveguide, the induced loss was calculated to be 3.3 %.

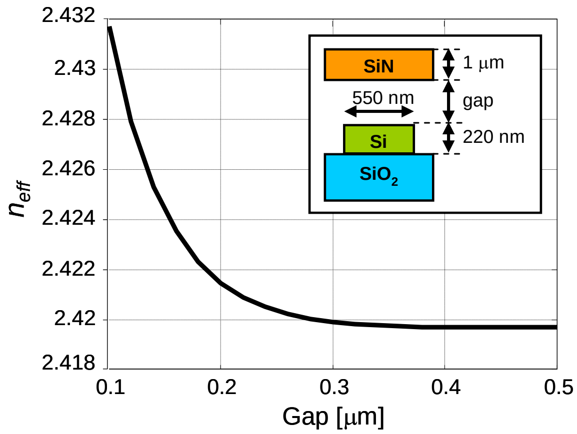

Fig. 1. Calculated effective refractive index as a function of the air gap between the cantilever and the waveguide. Inset: cross-section used in the simulation. The refractive indices used in the simulation are 3.4 for Si, 2.0 for SiN, and 1.45 for SiO$_2$.

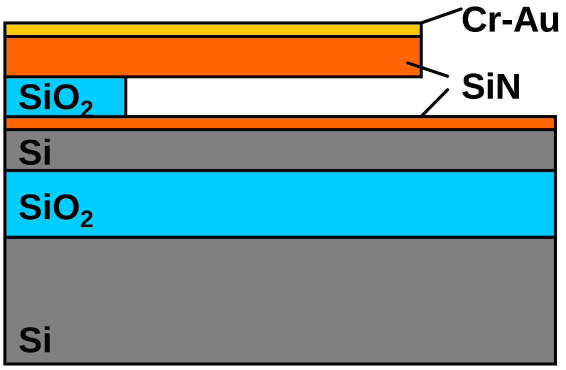

Fig. 2. Schematic cross-section of the layer stack used to fabricate the integrated device.

3. Fabrication

The ring resonators were fabricated [6] in SOI technology by etching 200 nm deep into the 220-nm-thick silicon device layer, which is on top of a 2-µm-thick SiO$_2$ layer. 10-µm-wide, 40-µm-long silicon nitride microcantilevers were then monolithically integrated on top of the optical structures. The layer stack used to integrate the microcantilever on the SOI wafer is shown in Fig 2. Firstly, a 43-nm-thick silicon nitride (SiN) protection layer was deposited onto the silicon device layer of the SOI wafer, followed by a 196-nm-thick sacrificial SiO$_2$, a 1.0-µm-thick SiN, and finally a 58-nm-thick chromium-gold top electrode layer. The bulk silicon wafer acts as the bottom electrode. We estimate this initial gap to be 290 nm, resulting from the 196-nm-thick sacrificial layer and a 94-nm upward bending of the cantilever due to tailored residual stress. A scanning electron microscope (SEM) image of the integrated device is shown in Fig. 3.

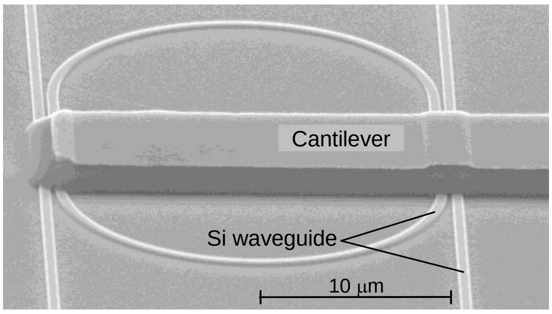

Fig. 3. SEM image of the fabricated device.

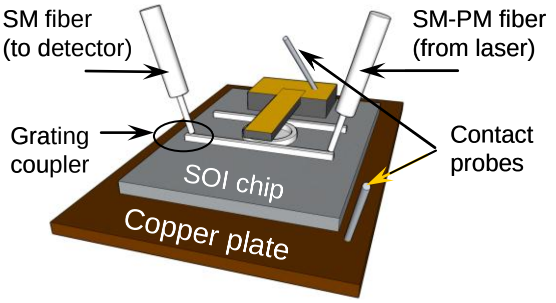

Fig. 4. Schematic of the setup used for electrostatic actuation of the cantilever and optical transmission measurements.

4. Characterization

The device was characterized using the set-up shown in Fig. 4. Light was coupled to the device using grating couplers (not shown in the figure). Contact probes connected to the contact pad on the top surface of the cantilever and to the bulk silicon of the wafer allowed for electrical actuation of the cantilever. Transmission spectra were measured using a tunable laser and a photodetector. The dynamic response was recorded by connecting the photodetector output to an oscilloscope.

A pull-in phenomenon occurs if the cantilever deflection exceeds a critical value above which the restoring elastic force can no longer compensate the electrostatic force. We measured that pull-in occurs at about 9.5 V, corresponding to a critical tip deflection of 150 nm. This phenomenon was irreversible.

Figure 5 shows the measured transmission spectra for three different applied voltages, 0 V, 8.5 V, and 9.0 V. The resonance wavelength shifts as the cantilever moves closer to the waveguide. The quality factor of the resonance remained high, i.e., the presence of the cantilever does not significantly increase the propagation loss in the resonator, as could be expected from the small calculated increase in coupling strength and loss. However, when the cantilever was pulled in at 9.2 V, hence touching the waveguide surface, a noticeable change of the quality factor Q from 10000 to 5000 was observed.

Figure 6 shows the measured resonance wavelength shift as a function of actuation voltage [7]. As expected from the dependence displayed in Fig. 1 and the approximately quadratic dependence on voltage of the cantilever displacement, the response is strongly nonlinear, with 20 pm wavelength shift obtained for a voltage change from 8 V to 8.5 V.

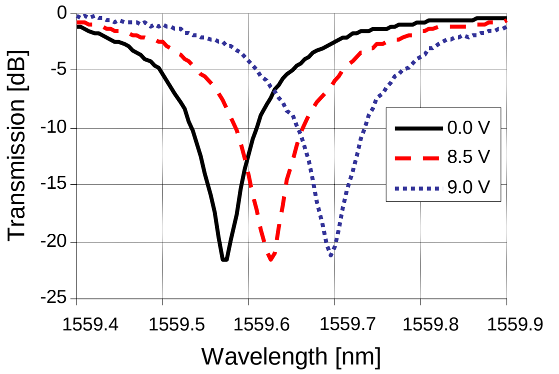

Fig. 5. Transmission spectra of a ring resonator measured for 0 V, 8.5 V, and 9.0 V actuation voltage.

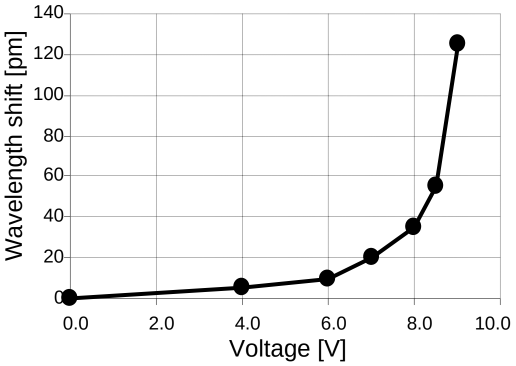

Fig. 6. Measured resonance wavelength shift as a function of actuation voltage.

As the device is actuated electrostatically, no continuous power is dissipated. The energy needed to tune the device over its reversible range can be estimated as the energy needed to charge its capacitance, which is about 1 pF (mostly determined by the electrical bond pads; the capacitance of the cantilever itself is only 10 fF). The energy required for 50 pm resonance wavelength shift due to a 0 V to 8.5 V actuation signal is 36 pJ.

The mechanical resonance frequency of a 40-µm-long cantilever was found to be 805 kHz and its rise time was ~2.5 µs, as measured by a laser Doppler vibrometer. Dynamic measurements of the electro-mechano-optical modulation by applying a 4.0 V square-wave peak-to-peak voltage to the electrodes of a 100-µm-long cantilever showed a ~16 µs rise time, consistent with its resonance frequency and quality factor. These results suggest that modulation in a bandwidth of 805 kHz with a rise time of a few µs is feasible with 40-µm-long cantilevers.

The tuning range can be extended by using wider cantilevers. By optimizing the fabrication process, the initial gap can be reduced to approximately 100 nm, thus increasing the modulation strength by a factor of 2-3.

5. Summary

We demonstrated the feasibility of monolithically integrating a power-efficient nanomechanical actuator with a planar optical device. The low requirements on actuation power and small footprint make these devices interesting for application in arrays, for example in read-out systems for optical sensor networks, or protection switches in optical communication networks.

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