Piezoelectric tuning of a suspended silicon nitride ring resonator

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***Abstract* – A novel piezoelectric actuator is fabricated on a suspended silicon nitride ring resonator to tune the optical resonance via mechanical deformation. Fabricated devices exhibit tuning across a full free spectral range by applying 16 V across the piezoelectric.**

INTRODUCTION

The silicon nitride (Si_3N_4) waveguide with silicon dioxide (SiO_2) cladding provides extremely low loss waveguides for photonic integrated circuit applications [1]. These materials are available in a silicon (Si) CMOS foundry, providing a high-performance photonic platform at a low cost. Examples of integrated photonics based on Si_3N_4 include RF beam-forming networks and time delay devices [2-3]. Low waveguide propagation loss allows for practical realization of high-Q resonant cavities [4]. By means of heterogeneous integration, active materials can be incorporated with passive nitride resonators to create broadband, tunable, and narrow-linewidth lasers [5].

A major limitation of this platform is the lack of an effective phase tuning mechanism. Thermally tuned devices require a constant power dissipation on the order of 300 mW to tune across a full free spectral range (FSR) and suffer from thermal crosstalk between adjacent devices [3-6]. The dielectric nature of the waveguides precludes a carrier injection-based approach as has been demonstrated in the Si platform [7]. Stress-optic approaches show promise, but demonstrations of this effect require both high voltage and large device size to achieve tuning across a full FSR [8-9].

In this work, a novel tuning mechanism is demonstrated with pure mechanical deformation via a piezoelectric thin film deposited on a suspended Si_3N_4 waveguide. By physically deforming the ring resonator, the length of the cavity is reduced, thereby shifting the resonant wavelength. The minimum static power consumption of this tuning mechanism is expected to be limited only by the leakage current through the capacitor dielectric of the piezoelectric actuator.

DEVICE FABRICATION

The waveguide consists of an SiO_2 lower-cladding formed by thermal oxidation, and a low-pressure chemical vapor deposition stoichiometric Si_3N_4 core. The waveguide structures are patterned with deep ultra-violet lithography and etched by an inductively coupled plasma (ICP) reactive ion etch (RIE) with $CHF_3/O_2/CF_4$ gases. An upper cladding of SiO_2 is formed by a plasma enhanced chemical vapor deposition (PECVD). Following a chemical-mechanical polishing of the upper cladding, the actuator fabrication proceeds by deposition of a lower electrode (35 nm thick titanium dioxide and 100nm thick platinum), 1 μm thick layer of lead zirconate titanate (PZT) via chemical solution deposition, and a 100 nm thick platinum (Pt) top electrode. The entire actuator stack is subsequently etched by an ion-mill to form a concentric ring on top of the Si_3N_4 resonator. Finally, the ICP-RIE is used to etch deep trenches through the SiO_2 cladding layers adjacent to the waveguides, and a gaseous xenon difluoride (XeF_2) dry etch of the underlying Si substrate is performed as schematized in Fig. 1.

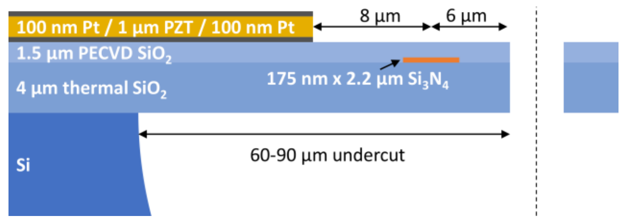

Fig 1. Cross-sectional schematic of ring resonator with PZT. The dotted line represents the symmetry of the cladding and substrate due to the isotropic XeF_2 etch

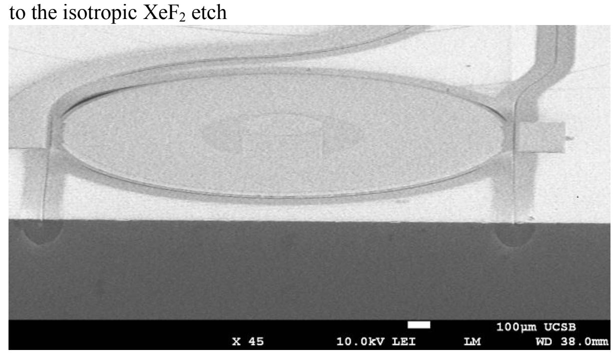

Fig 2. SEM of suspended nitride resonator with PZT actuator

The Si_3N_4 ring resonator is free to deform, independent of the silicon substrate. When a voltage bias is applied to the PZT actuator, it transfers compressive stress to the released waveguide, causing it to deform both radially inwards, and vertically upwards in a manner analogous to a flexural cantilever. The radius of the ring resonator is 580 μm. The distances separating the trench and the actuator from the waveguide core were chosen to minimize optical losses due to scattering from the vertical trench, and absorption from the electrodes, respectively. A scanning electron micrograph (SEM) is presented in Fig. 2 of the fabricated device.

RESULTS

The piezoelectric actuation is modelled in COMSOL Multiphysics, which includes both mechanical deformation and stress-optic coupling to the optical mode. Only the stress-optic coupling in the SiO_2 was considered, as the stress-optic coefficients for Si_3N_4 are unknown and this layer is relatively thin. For this geometry, induced strain in the radial and vertical directions are negligible, hence, the primary contribution to stress-optic tuning is from the longitudinal direction. Simulation results indicate that for the TM mode, stress-optic index tuning counteracts ~21 % of the tuning due to longitudinal compression of the waveguide. A simulation output is plotted in Fig. 3 showing the dependence of total tuning on the electric field applied across the PZT for varying amounts of undercut.

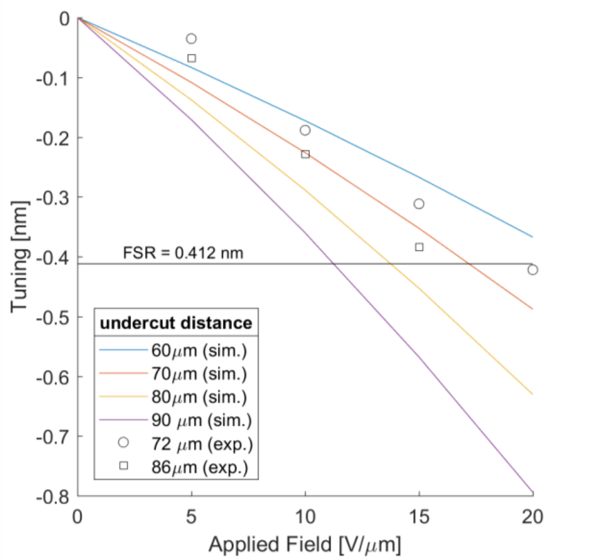

Fig. 3. Tuning vs applied electric field. Solid lines indicate simulation results. Data points indicate experimental results for varying undercut.

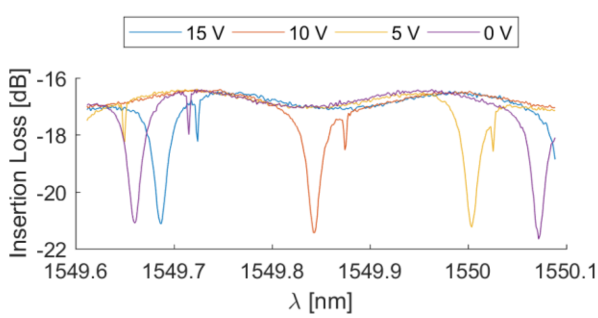

Fig 4. Ring resonator transmission spectrum for varying electrical bias and 86 μm undercut. The deeper peak corresponds to the resonance of the (designed) fundamental TM mode, whereas the shallower peak corresponds to the fundamental TE mode.

The simulations predict tuning across a full free spectral range (FSR) should be achievable with an applied bias of 20 V, given an undercut of 70 μm. However, these simulations were carried in an ideal 2D axisymmetric geometry, and likely overestimate the magnitude of tuning.

Experiments measure the ring resonant wavelengths while varying the voltage applied across the PZT. The tuning of a single device under different voltage biases and undercuts is presented in Fig. 3. The transmission spectrum of the same device at varying actuator bias points is presented in Fig. 4. A π phase shift is observed for 16 V and 86 μm of undercut.

A leakage current of 30μA was observed at this bias, corresponding to a total power consumption of 0.5mW. This magnitude of current is several orders of magnitude higher than expected. It is likely due to a gradual dielectric breakdown observed at bias of 7V/μm and above in the form of increasing leakage current versus time. We expect that improvements in PZT material quality will allow for breakdown voltages well above 25 V/μm [8,10], and leakage currents in the nA range.

The maximum undercut was limited to about 86 μm by the mechanical stability of the SiO_2 cladding. Both thermal SiO_2 and PECVD SiO_2 have an intrinsic compressive strain of 300-400MPa which can lead to buckling and failure of released structures. Our 3D structural simulations indicate, however, that optimization of the released cladding geometry may allow for undercut distances greater than 120 μm, allowing for further reductions in tuning voltage and device footprint.

CONCLUSION

A novel mechanically actuated tunable ring resonator is demonstrated in the ultra-low loss Si_3N_4 waveguide platform using a PZT transducer. The resonant wavelength is tuned by a full FSR, as required for practical applications, with a voltage of 16 V and power consumption of 0.5 mW. Improvement of PZT characteristics should provide ultra-low power tuning of Si_3N_4 ring resonator based filters and time delay devices.

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