MEMS-Actuated Microdisk Resonators With Variable Power Coupling Ratios

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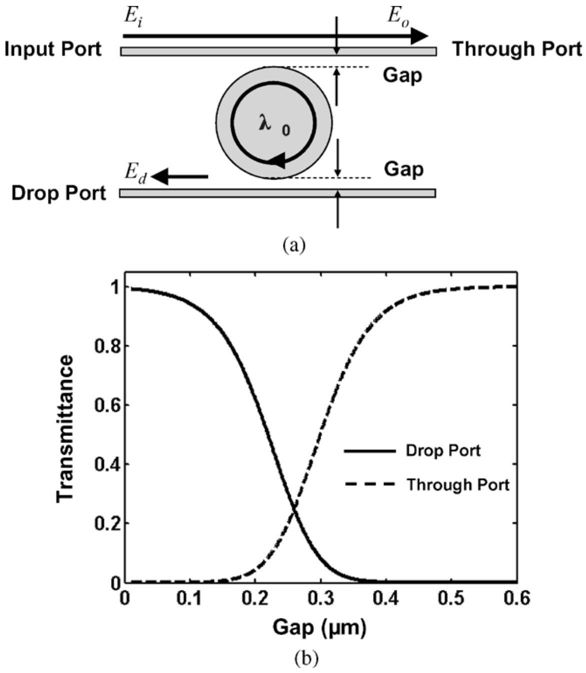
***Abstract*—A novel tunable microdisk resonator with microelectromechanical-system (MEMS)-actuated deformable waveguides is demonstrated for the first time. The deformable waveguide enables us to continuously vary the power coupling ratio of the microdisks. A laterally coupled device with a quality factor of 7700 is fabricated on silicon-on-insulator substrate. An optical notch filter with variable attenuation at the resonant wavelength is successfully demonstrated, with an extinction ratio of 9 dB. The MEMS-actuated tunable microdisk is a basic building block for many dynamic wavelength-division-multiplexing circuits.**

***Index Terms*—Microdisks, microelectromechanical devices, microresonators, optical resonators.**

I. INTRODUCTION

MICRODISK and microring resonators have shown great promise to dramatically reduce the footprint of most wavelength-division-multiplexing photonic integrated circuits, including wavelength filters and add–drop multiplexers, optical delay lines, and group velocity dispersion compensators [1]–[4]. The ability to tune the microresonators is desirable because it enables us to dynamically reconfigure their optical functions. Two types of tuning mechanisms have been reported. The resonant frequency can be varied by local heating [5] or electrical carrier injection [6]. Alternatively, the unloaded quality factor (Q) of the cavity can be spoiled by attaching a lossy material, such as metal film, on the resonator [7], or in case of III–V microdisks, by electroabsorption [8]. The former is useful for tunable filters, while the latter has applications in reconfigurable optical add–drop multiplexers (ROADM).

In addition to the resonant frequency and the unloaded Q, the optical response of microresonator circuits also depends on the coupling between the waveguides and the resonator. Almost all of the microfabricated disk and ring resonators reported to date have fixed power coupling ratios. Recently, we reported the first tunable microdisk resonators with variable power coupling ratios [9]. The ability to change the coupling between the microresonator and the input–output waveguides enable us to operate the microresonators in under-, critical, and over-coupling regimes. In addition to ROADMs and wavelength-selective switches, such tunable resonators can also be used to construct tunable optical delays and dynamic dispersion compensators. Previously, variable coupling was achieved only in bulk optical setup [10] or large resonators with multimode interferometer couplers [11].



(a)

(b)

Fig. 1. (a) Schematic of a microdisk add–drop multiplexer. (b) The calculated transmittance of the through and the drop ports at resonance versus the gap spacing between waveguide and microdisk.

The coupling coefficient can be varied over many orders of magnitude without degrading the unloaded Q by physically changing the gap spacing between the resonator and the waveguides. Microelectromechanical-system (MEMS) actuators are ideal for moving or deforming the waveguides. They have very small footprints and low power consumption. In this letter, we report on the design, fabrication, and testing of a laterally coupled microdisk resonator with deformable waveguides. Continuous tuning of resonant peaks with an extinction ratio of 9 dB is achieved at an actuation voltage of 61 V. To our knowledge, this is the first MEMS-actuated microresonator with variable power coupling ratio.

II. DEVICE DESIGN AND FABRICATION

Fig. 1(a) shows the schematic of a microdisk add–drop multiplexer. The coupling coefficient between the microdisk and the waveguide varies exponentially with the gap spacing. For materials with high index contrast, such as Si, more than five orders of magnitude change in coupling coefficient can be achieved by moving the waveguide over a distance as small as 1 μm. Fig. 1(b) shows the calculated transmittances of the through and

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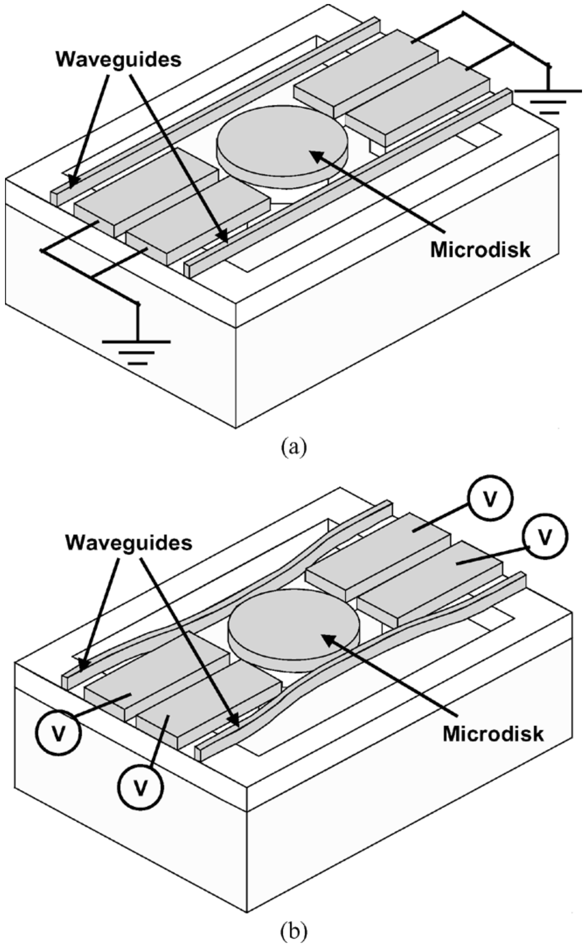


Fig. 2. Schematic structure of the microdisk resonator with deformable waveguides. (a) At zero bias, the microdisk is completely uncoupled since the suspended waveguides are far away from the microdisk. (b) With voltage applied on the electrodes, the waveguides are bent toward the microdisk, increasing the coupling between the waveguides and the disk.

the drop ports at resonant wavelength versus the gap spacing. The calculation is based on coupling-of-modes formalism in time domain [1]. Complete switching from through to drop port is attained by reducing the gap from 0.6 μm to near contact. The calculation assumes a Q of 10^6 for the microdisk.

The schematic of our device is shown in Fig. 2. A fixed microdisk is sandwiched between two suspended deformable waveguides, which can be pulled toward the microdisk by four electrostatic gap-closing actuators. The device is fabricated on a silicon-on-insulator (SOI) wafer. The microdisk, waveguides, and the MEMS actuators are patterned by a single lithographic and etching step and are inherently self-aligned. The MEMS electrodes are separated for independent control of the input and output coupling. The radius of the microdisk is 10 μm and initial gap spacing is 1.4 μm. To avoid the pull-in instability in gap-closing actuators, the actuator spacing is designed to be three times larger than the disk-waveguide spacing. Using this design, the coupling gap can be continuously reduced until physical contact without experiencing instability.

It should be mentioned that laterally coupled microresonators in high-index contrast materials, such as Si–air, usually require electron-beam lithography to pattern the submicron ($0.1 \sim 0.2$ μm) gaps. Here, since we are able to control the gap by deforming the waveguide, the initial gap spacing is large and can be patterned by standard optical lithography.

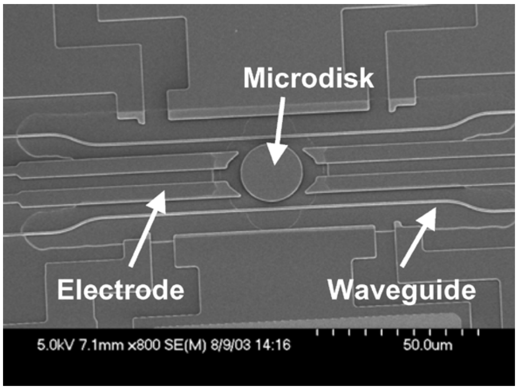


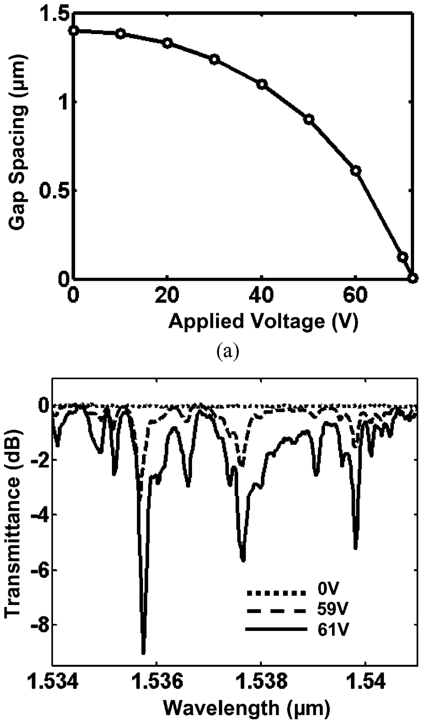
Fig. 3. SEM image of the device.

The fabrication process is described in the following. First we grow thermal oxide on the SOI wafer with a 1.2-μm-thick Si and a 1-μm-thick buried oxide layers. The waveguides, microdisks, and electrodes are patterned simultaneously using a single photomask. After this oxide layer is etched, the patterns are transferred to the silicon layer by magnetically enhanced reactive ion etch with HBr plasma. The etching process has been optimized for smooth vertical sidewalls. The as-etched waveguide is 0.8 μm wide, and the spacing between the waveguide and the disk is 0.9 μm. The dimensions of the waveguides and the thickness of the microdisks are further reduced by sacrificial oxidation, i.e., oxidizing the Si structures and then selectively etching the oxides away. To achieve more effective size reduction, the waveguides and the disks are partially released before oxidation. The oxidation also reduces the surface roughness [12]. Finally, the waveguides around the microdisks are released in buffered oxide etch through lithographically patterned photoresist windows. After releasing, the devices are cleaved into chips and antireflection coatings are applied on both facets. The final width of the waveguide is 0.35 μm after oxide is etched. The scanning electron micrograph (SEM) of the fabricated device is shown in Fig. 3.

III. EXPERIMENT RESULTS

The suspended part of the waveguide is 0.35 μm wide, 0.6 μm thick, and 150 μm long. The MEMS actuator spacing is 4.5 μm. The waveguides are grounded while voltages are applied to the biasing electrodes. We use a commercial finite-element-method simulator (ANSYS) to calculate transfer curve. The result is shown in Fig. 4(a). A voltage of 70 V is needed to achieve the maximum displacement of 1.4 μm.

The optical performance of the microdisk is characterized with one waveguide actuated. The other waveguide is left in the uncoupled state. A lensed fiber couples TE-polarized light from an erbium-doped fiber amplified spontaneous emission source to the waveguide. The output is collected by another lensed fiber. The spectral responses at various bias conditions are shown in Fig. 4(b). At zero bias, the waveguide is far from the microdisk and there is essentially no coupling. The spectral response is flat. As the waveguide is moved closer to the microdisk, clear resonance peaks are observed. There is more than one peak due to multiple transverse modes in the



(a)

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Fig. 4. (a) Simulated transfer curve of the deformable waveguide. (b) Measured spectral responses of the MEMS-actuated microresonator at various bias conditions.

vertical direction. This can be eliminated by further reducing the thickness of the microdisk and the waveguide. The dip in transmittance increases with voltage. An extinction ratio of 9 dB is achieved at 61-V bias for main peak, correspondent to a 90-nm gap spacing from the mode-coupling calculation. This is in good agreement with the calculated transfer curve of the actuator [Fig. 4(a)]. The extinction ratio is lower for higher order modes due to their smaller coupling coefficients. The full-width at half-maximum of the peak is 0.23 nm, corresponding to a Q of 7700. Because of the low unloaded Q, the microresonator is still under-coupled even at the highest bias voltage. An improved microresonator with higher Q would enable us to reach the over-coupling regime.

IV. SUMMARY

A monolithic microdisk resonator with variable power coupling ratio has been successfully demonstrated for the first time. The coupling coefficient is controlled by physically moving the waveguide with an integrated electrostatic MEMS actuator. Our device was fabricated on an SOI substrate with a single etching step. The optical resonance can be continuously tuned by voltage. A maximum extinction ratio of 9 dB is achieved at 61-V bias for our current devices. Improvement in device performance can be achieved by eliminating the high-order transverse mode in the vertical direction and increasing the Q of the microdisk.

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