Ultra-widely tunable photonic microcavities through evanescent field perturbation

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Abstract: Evanescent perturbation is examined as a means of tuning photonic microcavities over large wavelength ranges. 27nm reversible tuning is achieved through nanometric control of a silica perturbing body in the near-field of a microring resonator.

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The field of integrated optics promises to provide a practical and scaleable means of routing and switching light for applications ranging from telecommunications networks to sensing and spectroscopy. However, a key barrier to the development of dynamic integrated optical circuits is the lack of a practical means of enabling large changes in waveguide *effective-index* (Δn_{eff}). Large Δn_{eff} is critical for the development of widely tunable filters and for scaling active components to smaller size. Currently, thermo-optic tuning is the only widely implemented means of producing a Δn_{eff} in optical circuits [1-3], but it has insufficient range and is slower than desired for many applications.

In this paper we demonstrate ultra-wide tunability through evanescent perturbation of a large free-spectral-range (FSR) micro-ring resonator. Geometrical tuning mechanisms, such as evanescent tuning, have the distinct advantages that they are material-system independent and that they enable large Δn_{eff} with small power dissipation. In what follows, a 1.7 % frequency shift is demonstrated (or 27 nm tuning near 1565 nm) in a microring resonator without significant distortion of the cavity resonance. Furthermore, complete recovery of the resonance is found when the perturbing body is removed. Experiments are carried out with a novel silica-fiber probe which provides access to the evanescent field of an air-clad high-index-contrast (HIC) ring-resonator mode. As the probe is advanced toward the ring resonator, the probe-ring distance is found through simultaneous nanometric distance calibration and force measurements.

For the purposes of this study, a silicon-rich silicon-nitride ring resonator of the type described in Ref. 4, but of first order, is considered. The ring resonator was designed for operation at 1.5 μm wavelengths, with an FSR of 27 nm. The mode of the air-clad ring resonator has an evanescent field extending outside the guide in the direction normal to the plane of the ring. Consequently, a dielectric body can be placed above the ring such that it uniformly penetrates the evanescent field of the ring (see inset of Fig. 1(b)). This produces an increase in effective index of the mode, resulting in a shift of resonance frequency. If the perturbing dielectric is comprised of silica, a maximum theoretical tuning range of 29.9 nm at an operating wavelength of 1565 nm is possible. The tuning closely approximates an exponential as a function of distance z from the ring, with a decay length of $1/\alpha \cong 91.6$ nm, making it evident that a high degree of positional control is required.

The major challenge in a laboratory implementation of the geometry shown in Fig. 1(b) is the high degree of angular alignment required between the perturbing body and the ring resonator (typically microradians). This alignment issue is addressed through a novel probe design illustrated in Fig. 1(a). It utilizes a fiber-taper near the end of the probe, which allows the fiber end to lie parallel to the surface when in contact with the substrate of the ring resonator. The fabrication process for this probe is outlined in the inset of Fig. 1(a). First, the fiber is tapered to several microns, forming a flexible joint. Then the face of the probe (used to perturb the ring resonator) is formed by a fiber cleave, and annealed until a small amount of glass reflow occurs, ensuring an ultra-smooth surface.

The apparatus used to perform evanescent perturbation experiments can be seen in Fig. 1(a). It consists of the silica fiber probe (described above), which is mounted on a cantilever having a force constant of ~5000 N/m. The probe-cantilever assembly is advanced with a distance-calibrated piezo translation stage such that it can be brought in and out of contact with the ring-resonator device. Motion of the cantilever and probe relative to the device is monitored with an interferometer, one end of which is formed by the cantilever. Position is read through rapid interrogation of the interferometer with white light from an erbium-doped fiber amplifier (EDFA) and an optical spectrum analyzer (OSA). Force experienced by the probe can be precisely measured from the cantilever deflection. Broadband EDFA light is also coupled into and collected from the ring resonator device with lensed fibers to measure the micro-ring response. Experiments were performed by simultaneously measuring the ring resonator drop response, cantilever position, and forces of probe-sample interaction.

The results of a tuning experiment can be seen in Figs. 1(c)-(e). Fig. 1(c) shows the ring resonance frequency as a function of the cantilever height measured by the interferometer. Each data point (circle) represents the resonant

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wavelength obtained from measurements of the drop port of the ring resonator. The force and force derivative experienced by the probe over the same range of cantilever displacement are displayed in Fig. 1(d-e). In Fig. 1(d) two trends can be seen: (1) for smaller positions (i.e. position ≤ 1270 nm) an exponential change in resonance wavelength covers a 25 nm tuning range; (2) for positions larger than 1270 nm (indicated by the vertical dashed line) there is a very gradual change in ring resonance frequency. In interpreting these two tuning regimes, the forces of interaction between the probe and sample (seen in Fig. 1(b)) provide insight. For the evanescent tuning regime attractive forces (negative in sign) are experienced by the probe, which are due to a combination of capillary and Van der Waals interactions as the probe approaches flush contact [5]. Snap-down of the probe can be seen at 1270 nm most clearly through a sharp increase in the derivative of the force, corresponding to the maximum in the exponential portion of the tuning curve. After this point, the probe remains flush with the device resulting in compression of the probe, which is seen as a large positive slope in the force curve.

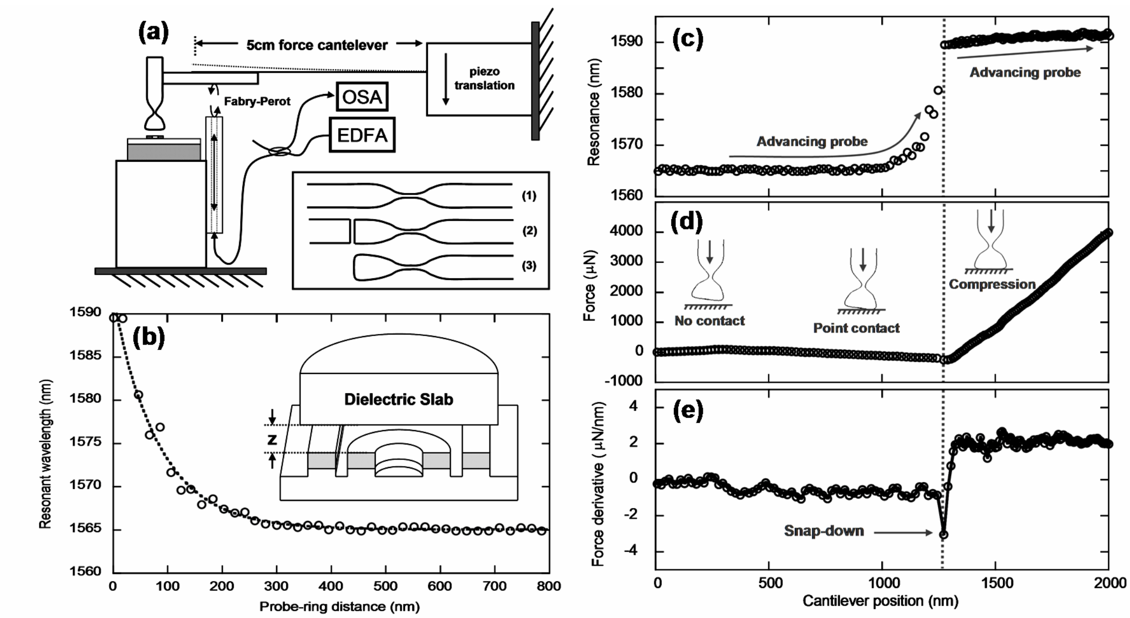

Fig. 1. (a) Tuning apparatus and (inset) probe fabrication process; (b) measured resonance wavelength of microring vs. distance of probe from ring surface (inset – schematic of tuning geometry); (c,d,e) resonance wavelength, force and force derivative vs. cantilever position.

Through an analysis of the force and force derivative measurements, the probe-ring distance can be placed on an absolute scale and compared with theory, as seen in Fig. 1(b). An exponential fit of the tuning versus probe-ring distance reveals a decay length of 87 ± 4 nm and a maximum tuning of 24.8 nm, which agrees with the theoretical decay length of 91.6 nm and maximum tuning range of 29.9 nm. Tunings as large as 27 nm were obtainable by contacting the ring using unique points of the probe face, indicating that conformation of the probe surface plays a role in limiting the maximum possible perturbation. High-speed acquisition of spectra shows that throughout the tuning process the resonance shape appears to be preserved. Additionally, when the fiber is raised again the unperturbed resonance is fully recovered, demonstrating a negligible degree of hysteresis, which suggests no material exchange between the probe and ring.

In conclusion, high-fidelity reversible tuning was demonstrated over 1.7% frequency range through evanescent tuning. In this experiment, a uniform silica perturbing body was used, although it should be noted that with higher-index perturbing structures, upwards of 3% tuning could be implemented through the same range of motion. Furthermore, higher index-contrast waveguides (such as silicon) can tolerate stronger perturbation before coupling to radiation modes occurs, which should further enhance tuning ranges.

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