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Critical coupling enhanced refractive index sensing in SOI slot microring resonators

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Abstract

We present a novel refractive index sensing mechanism based on slot ring resonators fabricated in the silicon platform. The sensing mechanism relies on detuning the critical coupling resonance of the ring. This new method has been realised through engineering the dispersion property of the ring directional coupler, which enables forming a narrow ring resonance spectrum with a V-shape profile. We both numerically and experimentally demonstrate that this V-shape profile can enhance the refractive index sensing operation due to following conditions: firstly, the V-shape is robust in the 1.3-1.5 refractive index range; secondly, the critical resonance peak (or bottom of the spectrum V-profile) follows a monotonically increase with the refractive index change, which results in a strong critical coupling detuning. The sensitivity of the critical peak has been measured to around 1300nm per refractive index unit with an uncertainty of the shift equal to 2 times the ring free spectral range. Different from a single resonance peak sensing, , the proposed sensing mechanism can get rid of the high losses of slot waveguides that usually spoil the ring and can target low detection limit.

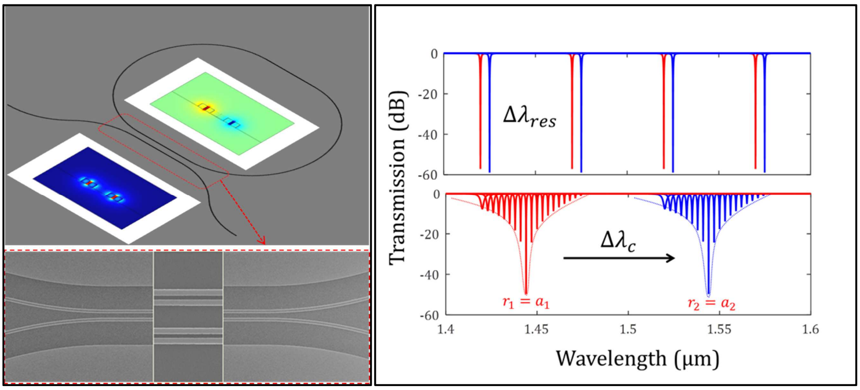
Introduction

In the context of refractive index sensing in integrated silicon photonics, ring resonators [1], [2], nano cavities [3], Mach–Zehnder interferometers [4] and Bragg gratings [5] have been proposed and demonstrated with asssed feasibilities. Complex structures, for instance, quadrabeam photonic crystal cavities [6], Vernier ring resonators [7] or ring resonator with Mach–Zehnder interferometers [8] have been proposed to increase the sensitivity and lower sensor limit of detection.

Basically, the sensing mechanism of these devices is based on the light matter interaction between the cladding material and the evanescent field out of the silicon core, which thus results in a weak optical mode perturbation. To improve and enhance light matter interaction, hollow core waveguide sensors with strong light confinement in low index active materials have been demonstrated with larger sensitivities than their standard rib-or-ridge-waveguide-based counterparts [1]. In this context, slot waveguides, which can partially confine light power up to 40-50% in low index in-slot materials, can strongly enhance the electric field in the slot region. They have been demonstrated with lots of applications such as refractive index sensing, optical manipulation of nanoparticles/biomolecules [9], all-optical signal processing [10] through nonlinear optical processes , and so on.

Experiments

In the present paper, we present a sensing method based on slot waveguide ring resonators to overcome loss limited individual resonance Q-factors. The proposed principle consists in a quick detuning of the micro-ring resonator critical coupling peak wavelength when experiencing a weak cladding index change. In this purpose, the considered slot waveguide bus-waveguide/micro-ring coupler is specially designed to increase the cross coupling ability wavelength dispersion. In the specifically studied case, geometry optimization led to a Si slab thickness of 220nm, rail width of 170nm, slot width of 110nm, and a coupler gap of 600nm. Then, relying on such a highly dispersive coupler, resonance spectra displayed distinguished critical coupling peaks [11]. In a similar configuration but with normal rail width couplers (235nm), a wider spectrum envelop is obtained, as show in Fig.2, preventing a clear identification of the critical peak.



(a) (b)

Fig. 1. (a) Optical design of dispersive coupler loaded silicon slot microring resonator; (b) Comparison between single peak sensing and critical coupling enhanced resonance comb sensing.

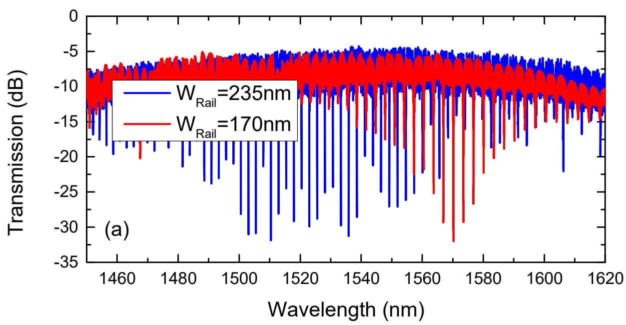


Fig. 2. Comparison of strong dispersive coupler (W_{rail}=170nm) and normal coupler (W_{rail}=170nm) loaded slot ring resonators' transmission spectra.

This engineered critical coupling condition can serve as a new sensing method if compared with a standard single peak sensing scheme, as shown in Fig.1.b. In this critical coupling sensing mechanism, the deepest peak shifts are monitored instead of a single peak shift. To verify this principle and estimate the sensitivity of the optimized optical ring sensors, we realized a set of experiments by drop casting a series of commercial index liquids (from Cargille). As depicted in Fig.3, the experimentally monitored resonance spectra effectively sustain V shape profiles and clearly exhibit a nearly-single critical resonance peak (with an uncertainty range of approximately 2 micro-ring FSRs).

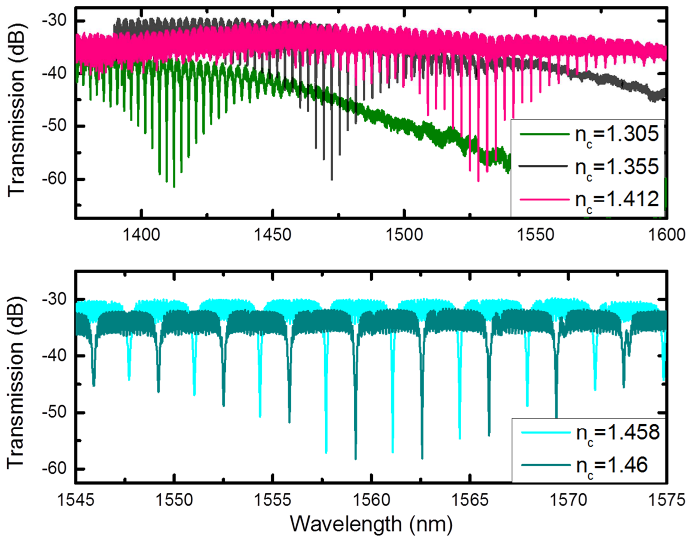


Fig. 3. Critical coupling enhanced sensing comb shifts due to cladding refractive index change.

The related monitored critical peak wavelength shift is plotted in figure.4.a. A very fast critical coupling resonance peak detuning corresponding to sensitivity (S) of 600-1300 nm/RIU is visible. This sensitivity is around 2-4 times larger than with a standard single peak resonance shift sensing approach. Such large sensitivity originates from the fact that the critical coupling condition is much more sensitive than the effective index (n_{eff}) induced resonance change. As shown in Figure.4.b, the related limit of detection defined as 2FSR/S, is here of the order of 10^{-3}. The pretty high values could be yet easily minimized by considering spiral ring resonators with FSR values down to pm levels. We thus anticipate that limit of detection down to 10^{-5} could be obtained by this approach while significantly relaxing the constraint related to high individual peak *Q* factors.

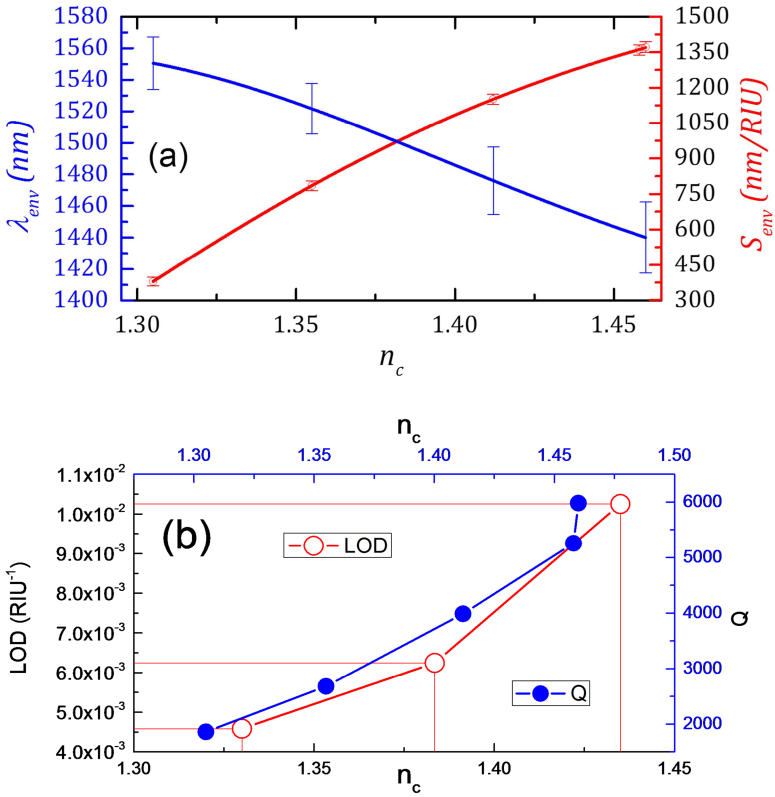


Fig. 4. (a) Critical coupling peak (λ_{env}) shift and its sensitivity (S_{env}) measured from experiments performed in Fig.3, (b) Limit of the dection (LOD) of critical coupling enhanced sensing and *Q* factor of the critical coupling peaks as function of the cladding refractive index.

Conclusion

To conclude, a critical coupling enhanced refractive index sensing approach relying on silicon slot waveguide ring resonators is proposed. The realized optical index sensor has a sensitivity of 1300nm/RIU around the water refractive index (1.33). The proposed method get rids of the necessity of high *Q* factors of the micro-ring resonators and presents a limit of detection that inversely scales with the ring length, typically scalable down to 10^{-5}.

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