A compound optical microresonator design for self-referencing and multiplexed refractive index sensing

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We propose a novel self-referencing and multiplexed refractive index (RI) sensor consisting of Fabry-Pérot (FP) resonators and microring resonators. The transmission spectra show resonant features superimposed on a background defined by the FP oscillations. The resonances have asymmetric Fano-like non-Lorentzian shapes used as the sensing peaks and the FP oscillations used as the reference peaks for the internal self-referencing. The sensing peaks shift linearly with increasing RI of the cladding of the microring resonator while FP peaks stay constant. The proposed sensor concept is simple, easy-to-fabricate, self-calibrating and can be used for simultaneous measurements of different samples.

Introduction

Optical refractive index (RI) sensors are becoming promising tools in bio-sensing, environmental monitoring and medical diagnostics [1-3]. For their wider deployment, the future lab-on-a-chip RI sensors would have multi-channel operation, low-cost production and an internal calibration mechanism. Integrated-optical RI sensors are in particular attractive by being compact, low-cost and rugged, which are also partially addressing above-mentioned requirements. Several integrated-optical RI sensing schemes have been investigated [3-5]. Among them, microcavity resonators have the advantage of high quality factors and small mode volumes. However, optical sensors are in general prone to adverse effects, and their detection limit and sensitivity are limited by the environmental noise caused by temperature fluctuations and variations in the bulk RI of the sample. Different solutions have been proposed [6-8] but most of them require advanced manufacturing technologies, which would reduce their reproducibility and mass production potential. On the other hand, there are only a few examples in the literature demonstrated the multiplexed sensing operation for integrated-optical sensors [9].

In this paper, we propose a new type of self-referencing and multiplexed integrated-optical RI sensor that is comprised of Fabry-Pérot (FP) microcavity resonators evanescently coupled with microring resonators. An optical microring resonator is a cavity known as an excellent transducer for optical sensing due to its interferometric nature. An advantage of coupled cavities is the generation of asymmetric Fano-like resonances, due to the complex interference effect. The sharp slope in Fano resonance provides more sensitive detection of small changes in resonance. Here, we form the on-chip FP resonator with Sagnac loop mirrors, making the resonator design more flexible and easy to optimize compared to using end-facet reflections. Figure 1 shows the schematic of the two-mirror based compound resonator. The transmission spectra of the proposed structure consist of Fano resonances that are superimposed on a background defined by the FP oscillations. With the RI of the cladding layer of the microring resonator increasing, the Fano resonances shift linearly while FP oscillations stay unchanged, which are used as the reference peaks for the self-referencing operation. For the two-mirror FP cavity resonator coupled to a single microring resonator, we achieved a sensitivity 220 nm/RIU and a maximum figure of merit (FOM = S/FWHM, where FWHM is the full-width at half maximum of the Fano resonance) 4400 RIU^{-1}. It is possible to multiplex several sensors by adding more microring resonators to the sensor layout. The proposed RI sensor concept is simple, easy-to-fabricate, multiplexed and free of environmental effects, which holds great promise for medical and environmental applications.

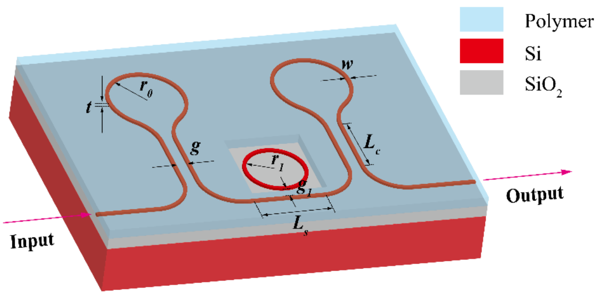

Fig. 1. Schematic of the compound resonator consisting of a microring resonator and a Fabry-Pérot resonator formed using two Sagnac loop mirrors. Definition of design parameters: t is the waveguide thickness, w is the waveguide width, r_0 is the radius of the loop mirror, g and L_c are the gap and length of the directional coupler, respectively, r_1 is the radius of the microring resonator, and g_1 is the gap between the straight waveguide and the microring, L_s is the length of the straight waveguide between the loop mirrors.

Device design and simulation results

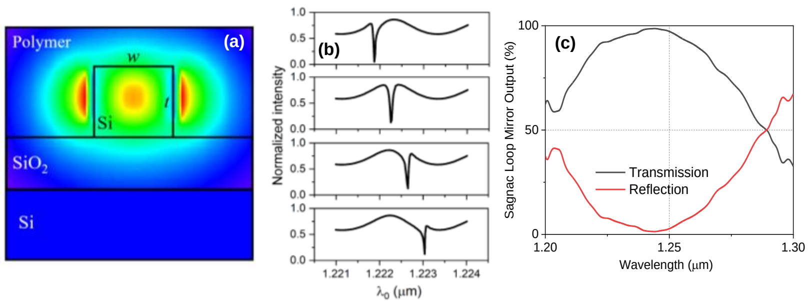

Fig. 2. (a) The waveguide geometry and the mode profile. (b) Transmission spectra of the compound resonator for different resonant wavelengths, λ_0, of the microring resonator. Note that when the resonant frequency does not coincide with a maximum of the FP oscillations, the transmission exhibits asymmetric Fano-like line shape. (c) Transmission and reflection versus wavelength values of the Sagnac loop mirror used in the compound resonator design, where $L_c = 7$ μm and $g = 0.4$ μm.

The material system of the proposed sensor is 150-nm-thick Si on a thermally-oxidized silicon wafer. The oxide thickness is 8 μm with a RI of 1.449, and the RI of Si is 3.5 at 1.3 μm central wavelength. A polymer layer (fluorinated ethylene propylene (*FEP*)) with a RI of 1.33 was used as the top cladding. A channel waveguide geometry was chosen for its excellent tolerance to fabrication variations. Single mode channel waveguides with waveguide width of 250 nm were designed. For the transverse electric (TE) polarization, the effective RI of the waveguide was calculated to be 1.6 via beam propagation method simulations. The mode profile of the waveguide is given in Fig. 2a.

The self-referencing operation is demonstrated in the structure shown in Fig. 1. Except the central wavelength of 1.25 μm where there is almost zero reflection, the FP oscillations will be observed in the rest of the spectrum. r_0 and r_1 were set as 7 and 6 μm, respectively. g_1 was optimized as 400 nm through FDTD simulations.

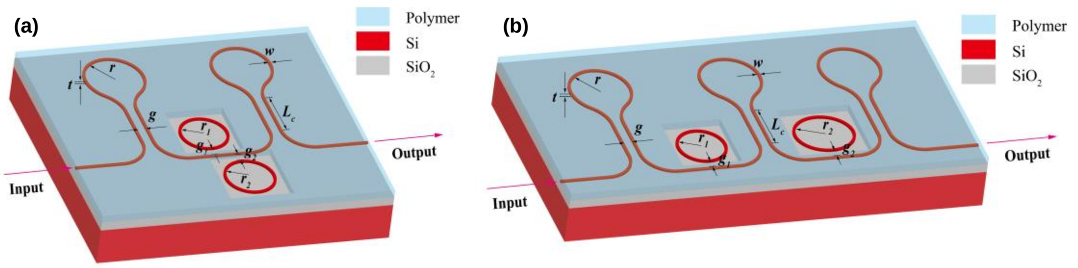

Fig. 3. Schematic of the multiplexed sensor formed by two microring resonators with radius of r_1 and r_2, and (a) two Sagnac loop mirrors and (b) three Sagnac loop mirrors.

Different multiplexing schemes are possible for the proposed sensor and two of them are shown in Fig. 3. Generally, more cavities coupled to each other could result in a more complex transmission response. Multimirror FP resonators readily generate multipeaked spectral orders and thus the transmission response of the three-mirror FP cavity shows double peaks in contrast to two-mirror FP cavity case. r_1 = 5 μm and r_2 = 6 μm were slightly different for differentiating the contribution of each microring resonator. The FP resonances stay constant, making self-referencing possible for this configuration. Compared with most of other multiplexing schemes, only one light source and a detection unit will be sufficient to detect different samples in parallel in our design, which makes it more cost-effective. The design given in Fig. 3a consists fewer mirrors and thereby can be more compact. In addition, with the design given in Fig. 3b, several FP cavities with different cavity lengths can be designed easily.

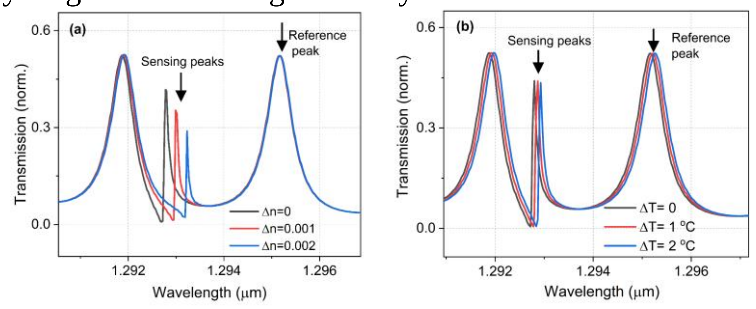

Fig. 4. Transmission spectra of the two-mirror FP resonator coupled with a microring resonator when (a) the RI of the microring cladding layer is changed by steps of $\Delta n = 10^{-3}$ and (b) the temperature of the sensor changed by steps of ΔT = 1 °C.

The FP resonances that are sufficiently away from the Fano peaks stay constant as the cladding RI of the microring resonator increases in Fig. 4a. We achieved a sensitivity 220 nm/RIU. We also used FOM to estimate the performance of the sensor more comprehensively and in Fig. 4a, they are 1692, 2444 and 4400 RIU^{-1}, respectively. In Fig. 4b, the sensing and reference peaks shifted linearly at the same rate, which means the distance between reference and sensing peaks will be constant and the changes in cladding RI can be measured independent of the temperature.

Figures 5a and 5b show the transmission response of the sensor shown in Fig. 3a with different RI of the covering layer of the second microring and both microrings, respectively. The transmission response of the first microring has double Fano-like resonances and at certain parts resonance splitting was observed. The resonance peaks associated to each microring resonators are spatially separated, which is essential for parallel measurements. Only the peaks associated with the second microring shifted linearly in Fig. 5a and the resonance peaks of each microring resonator shifted linearly at the same rate in Fig. 5b. The sensitivity was 220 nm/RIU for both microring resonators.

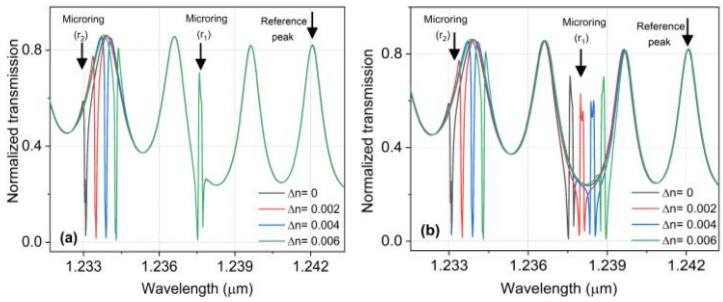

Fig. 5. Transmission spectra of the multiplexed sensor device when the RI of the covering layer of (a) the first microring (*r1*) and (b) both microrings is changed with $\Delta n = 2\times10^{-3}$ steps.

Conclusion

A novel self-referencing RI sensor based on a compound resonator concept is designed and simulated. A sensitivity value of 220 nm/RIU and a maximum FOM value of 4400 RIU^{-1} were achieved with a single microring resonator coupled to the FP resonator. The multiplexing potential of the proposed sensor concept has been investigated in two different schemes by placing two microring resonators with different radii in two- and three-mirror FP cavity resonators. We differentiated the contribution of each cover RI change separately by changing the RI of the overlay layer of the microring resonators, proving that the proposed sensor can be used in a multiplexed format to measure multiple samples simultaneously. Moreover, only one light source and a detection unit will be sufficient to perform parallel measurements, which will make this sensor cost-effective. In conclusion, the proposed RI sensor points the way to inexpensive, easy-to-fabricate and inherently self-calibrating devices for medical and environmental sensing.

References

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