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Robust highly stable multi-resonator refractive index sensor

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A B S T R A C T

Here we show that a serial array of three evanescently coupled microring resonators can achieve detection limits for refractive index changes in the surrounding environment that are more than 40% better than a single resonator. The improved performance of the three rings occurs when only the central resonator is exposed to the refractive index change and is due to the narrower linewidth that results from the off-resonant coupling to the adjacent resonators. Unlike a single resonator sensor that is usually operated close to critical coupling to maximize the sensitivity, the three resonator configuration is able to achieve superior detection limits over a wide range of inter-resonator couplings. We use this to show that random variations of the couplings resulting from manufacturing variations has a minimal impact on the performance of the three ring system.

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1. Introduction

Integrated microring resonators are one of several optical devices being developed as refractive index (RI) sensors [1–8] for the detection of biochemical analytes. The resonant wavelengths of the resonator are determined by the effective index of refraction, which itself is dependent on the index of refraction in the material surrounding the resonator waveguide due to the evanescent field of the resonator mode. The presence of an analyte, either in a bulk aqueous solution surrounding the resonator or attached to biorecognition elements on the resonator's surface, alters the index of refraction in the vicinity of the resonator. This leads to a shift of the resonant wavelength that can be detected with a tunable wavelength laser and spectrometer [9,10]. These micro-optical RI sensors have several advantages compared to more traditional detection techniques such as fluorescence including being cheaper, easier to operate, and label free [9].

Typically only a single ring resonator evanescently coupled to a waveguide in an all-pass configuration has been used. Moreover, the detection limit of the resonator decreases rapidly when the coupling to the waveguide deviates significantly from the critical coupling strength. Although the theoretical limit for the detection limit using a single resonator is $10^{-9}\,RIU$ (refractive index units), the best experimentally measured detection limit is only around $10^{-7}\,RIU$ [9]. By contrast, multi-resonator systems have found use as filters [11] and delay lines [12] due to the ability to control the shape and width of their transmission band as well as the phase delay using the inter-resonator evanescent couplings. The formation of transmission bands in arrays of coupled resonators would appear to preclude them from RI sensing where it is desirable to have the narrowest possible transmission resonance. However, when one or more of the resonators have resonance frequencies incommensurate with the rest of the resonators, transmission resonances form that can be narrower than achievable by the lone resonator [13]. Unfortunately determining the parameters needed to achieve these narrower resonances is not straightforward.

For the work detailed in this paper, we theoretically model and analyze three microring resonators in series coupled evanescently to each other as represented by the fabricated device shown in Fig. 1 for RI sensing. The device in Fig. 1 serves only as a model for our theoretical analysis. Only the first resonator to the left is coupled to a waveguide through which the optical transmission is measured. The central resonator alone is exposed to the surrounding environment with the analyte and used to detect RI changes. The radius of the central resonator and its couplings to the adjacent resonators were treated as free variables that were optimized using a genetic algorithm to find a transmission resonance that maximizes the RI detection limit. We found that the three ring system is able to achieve a detection limit 41% better than the critically coupled single ring. However, what is also significant is the robustness of the three ring system to variations in any of the couplings since there exists a large range of values for the couplings that lead to performance better than a single ring RI sensor. We numerically simulated manufacturing defects by randomly varying the coupling coefficients of both the optimized three ring system and the single ring and showed that the three ring system's performance

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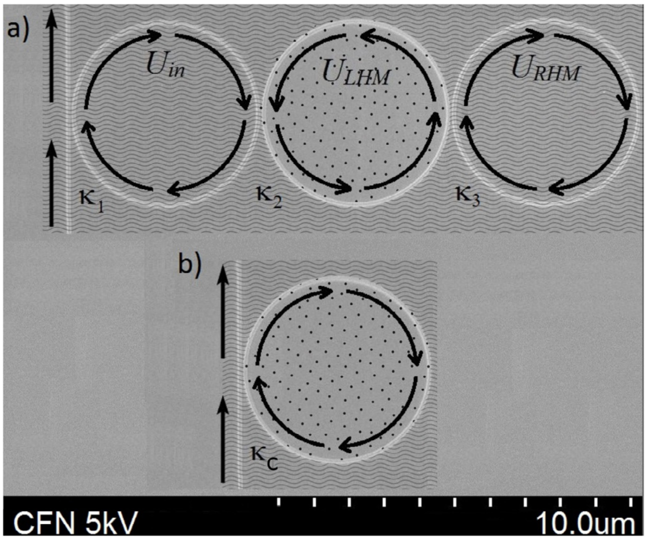

Fig. 1. (a) Three ring RI sensor in which only the central resonator is exposed to the analyte solution. The central resonator is evanescently coupled on both left and right sides to two additional resonators while only the leftmost resonator is coupled to a waveguide through which the transmission is measured. (b) Single micro-ring resonator RI index sensor coupled to waveguide in all pass geometry. Note the areas in waves are cladded and ones with dots are exposed to the analyte.

is less affected by the defects than the single ring and in most instances continues to show better detection limits than the optimized single ring.

2. Model

Fig. 1 provides a schematic of the RI sensor to be studied here. The device consists of a linear array of three evanescently coupled circular micro-ring resonators of radius R_j coupled to a waveguide in an all-pass configuration. The device is completely cladded except the central resonator, which is exposed to a solution containing the analyte. The presence of the analyte perturbs the RI surrounding the resonator and subsequently the effective index of the resonator mode thereby shifting the resonant wavelength λ_r. The effective index, n_{eff}, of the central resonator can be approximated as $n_{eff} \approx \eta n_s + (1-\eta)n_c$, where η is the interaction coefficient measuring the fraction of the optical power in the evanescent field [9,10]. n_s is the index of the solution surrounding the resonator while the index of the resonator waveguide material is n_c. The presence of an analyte in the solutions will produce an index of refraction shift δn_s, which is proportional to both the concentration of the analyte and its molecular polarizability. The shift of the central resonator's resonant wavelength is then $\delta\lambda_r \approx \delta n_s(\eta\lambda_r/n_s)$ [9,10]. Note that in the numerical simulations presented below the effective index is calculated numerically using the model of an asymmetric waveguide [14].

To analyze the transmission through the waveguide coupled to the resonator array, we utilize the transfer matrix approach. As a result of phase matching, the light that is coupled from the waveguide into the clockwise (CW) whispering gallery mode of the first resonator will couple to the counter-clockwise (CCW) mode of the second resonator, which itself couples to the CW mode of the third resonator. The propagation of light in the CW and CCW directions and coupling to the nearest neighbor resonator are expressible in terms of transfer matrices [15,16]

$$U^{(1)} = \frac{-i}{\sqrt{K_1}} \begin{bmatrix} \sqrt{1-K_1}e^{i\phi_1} & -e^{i\phi_1} \\ e^{-i\phi_1} & -\sqrt{1-\kappa_1}e^{-i\phi_1} \end{bmatrix} \tag{1}$$

$$U^{(2)} = \frac{i}{\sqrt{K_2}} \begin{bmatrix} \sqrt{1-K_2}e^{-i\phi_2} & -e^{-i\phi_2} \\ e^{i\phi_2} & -\sqrt{1-K_2}e^{i\phi_2} \end{bmatrix}, \tag{2}$$

$$U^{(3)} = \frac{-i}{\sqrt{K_3}} \begin{bmatrix} \sqrt{1-K_3}e^{i\phi_3} & -e^{i\phi_3} \\ e^{-i\phi_3} & -\sqrt{1-K_3}e^{-i\phi_3} \end{bmatrix}. \tag{3}$$

The transfer matrix for a signal propagating from the in port to the through port of the waveguide is expressible as

$$U = U^{(3)}U^{(2)}U^{(1)} = \begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix}.$$

The transmission through the waveguide is given by

$$T = \left| \frac{U_{22} - U_{12}}{U_{11} - U_{21}} \right|^2, \tag{4}$$

which relates the output power in the through port to the input power at the in port, $P_{out} = TP_{in}$. In the matrices, $\phi_j = \beta_j \pi R_j$ is the propagation phase for the jth resonator with $\beta_j = \omega n_{eff}/c - i\alpha_j/2$ for light of angular frequency ω and power attenuation per unit length α_j. K_2 and K_3 are the dimensionless power couplings between the first and second and second and third resonators, respectively while K_1 is the coupling between the waveguide and first resonator. Each of the K_j represent the fraction of the power coupled between the modes of the respective elements such that $0 \le K_j \le 1$ for $j = 1, 2, 3$. It is expressible in terms of an overlap integral between the mode functions in adjacent resonators and consequently depends on the cross-sectional dimensions of the resonators' waveguides and the spacing between resonators [17,18].

It is further assumed that the waveguide is excited from a tunable wavelength laser and that the transmitted spectrum is monitored with a spectrometer. The shift of the wavelength λ_c of the linecenter of a transmission resonance affected by the presence of the analyte is then measured. The sensitivity of the transmission resonance to a change in the index of refraction of the surrounding solution n_s is

$$S = \frac{d\lambda_c}{dn_s}, \tag{5}$$

which is in units of units nm/RIU. In the case that the transmission resonance corresponds to the resonance wavelength of the central resonator, $\lambda_c = \lambda_r$ and $S \approx \eta\lambda_r/n_s$ [9]. The detection limit (DL), which is the minimum RI change that can be measured, is the ratio of the sensor resolution to the sensitivity. In our case the sensor would be a spectrometer that measures the shift of the line center of the resonance and the sensor resolution is therefore determined by both the spectral resolution of the spectrometer and any sources of noise that lead to an uncertainty in the position of the line center. Amplitude noise such as from the probing laser or thermal noise in the system will add to the resonance lineshape making it harder to identify the true extremum of the resonance representing the line center. The effect of noise on the resonance lineshape can be modeled using Monte Carlo simulations, which leads to the phenomenological equation for the detection limit described in Ref. [10],

$$\mathrm{DL} = \frac{\Delta\lambda}{4.5S(\mathrm{SNR})^{0.25}} \tag{6}$$

where SNR is the signal to noise ratio which includes amplitude noise of the probing laser, thermo-optic noise of the resonator, and detector noise, and is chosen to be SNR $=$ 80 dB for all simulations, which is equivalent to a shot-noise limited system with an input power P_{in} = 1 mW. Additionally, S is the sensitivity and $\Delta\lambda$ is the full-width at half-maximum (FWHM) of the resonances. It is worth emphasizing that the detection limit is not only determined by the sensitivity but also the linewidth of the resonance, which acts to filter the noise reducing the uncertainty in the measurement of the line center. Since the Q-factor of the resonance is $Q = \lambda_c/\Delta\lambda$ one can see that the detection limit scales as $\mathrm{DL} \sim 1/SQ$, which is equivalent to other expressions given for the detection limit [19].

The optimal parameters presented here for the three ring sensor were found using a genetic algorithm running on a Tesla K40 graphics processing unit (GPU) that minimized the detection limit. In order to

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