Self-referenced Sensing in Microring Resonators

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ABSTRACT

Ultra-sensitive detection of analytes can be performed using whispering gallery mode resonators. However, monitoring the small changes in the resonances requires a bulky and expensive spectrometer or a tunable laser source. This limits the use of these efficient sensors within specialized labs. In response to this issue, we propose a self-heterodyne sensing scheme using a microring resonator that is (1) covered with a Bragg grating and (2) functionalized only over two opposite quarters of its perimeter. As the analyte binds to the functionalized area, a limited set of modes near the edge of the Brillouin zone undergo splitting. With increasing analyte concentration, the splitting grows monotonously. With currently available Q factors, this splitting can be small enough to be monitored by conventional electronics. On the other hand, the high sensitivity and low limit of detection seen in more conventional schemes are preserved.

Keywords: Whispering gallery mode resonators, Bragg grating, self-referenced biosensing, resonance splitting

1 INTRODUCTION

In the domain of medical diagnostics, there is a strong need for biosensors capable of detecting ultra-low concentrations (typically, in nM range) of specific analytes in complex biological samples. In this context, an ideal biosensor should have high sensitivity, low limit of detection and high selectivity towards the target molecules. Further, it should be cheap, portable, and easy to use. The health care providers should be able to perform the test on the spot and prompt results will save their valuable time and labour. The whispering gallery mode (WGM) resonators, which have very large quality factor Q and support modes occupying very small volume V, have emerged as ideal candidates as high-performance sensors. Owing to the large Q/V ratio, the photons remained confined in these cavities with long lifetime and the small mode volume V amplifies the local electric field of the recirculating photon. When any analyte is present, the enhanced light-matter interaction in these cavities ensures an ultra-high sensitivity of detection [1]. Indeed, the potential of WGM cavities as extremely sensitive label-free sensors has been demonstrated in the shift of the resonance frequency when analytes are present [2]. Besides that, sensing has been realized by resonance broadening [3] and mode splitting [4]. The figure of merit of a bisosensor is its limit of detection (LOD), which can be remarkably low for sensing via linear [5] and non-linear processes [6]. More recently, multiplexed arrays, with each microresonator functionalized to respond to a specific molecule, have been developed and biosensing have been experimentally demonstrated in real complex biological samples like undiluted human urine [7]. Despite these remarkable advances, the use of WGM sensors have remained confined mostly to specialized academic labs. The operation of the sensors in conventional detection schemes requires a tunable laser source or a high precision spectrometer, which is expensive, bulky and requires special training to use. This necessity is an important obstacle in their mass production and use at the point of care. Heterodyne sensing using a sensing cavity and a reference cavity would appear to solve this issue but is in fact impractical. Indeed, even the smallest fabrication uncertainties can lead to unacceptable uncertainties in the reference resonant frequencies. Thus, to implement this sensing strategy, each and every fabricated device would have to be calibrated individually.

More promising was the self-heterodyne detection scheme using a single resonator presented in [5], where single particle binding event can lead to detectable resonance splitting. The resulting low frequency beat signal can be measured by conventional electronics. However, the beat signal does not have a monotonic dependence on the number of analyte particles, making the measure of analyte concentration problematic. Here, we propose a new self-heterodyne sensing scheme that is again based on mode splitting, but where splitting varies monotonically with analyte concentration [8]. The proposed sensor architecture consists of a Bragg grating imprinted on a microring resonator and only a fraction of the ring is functionalized for molecular attachment. In absence of the analyte molecules, the microring with the grating supports doubly degenerate modes on either side of the edge of the Brillouin zone. As analyte molecules bind to the functionalized fraction of the resonator, the degeneracy between some modes is lifted, which is observed as a mode splitting in the spectra. When a broadband source simultaneously excites two split resonances, it produces a low frequency beat signal, which can be recorded by off-the-shelf electronics. We demonstrate, both analytically and using COMSOL simulations, that the beat frequency increases monotonically with the concentration of the analyte and that the highest sensitivity is achieved when two opposite quarters of the ring are functionalized. We show that the proposed sensing scheme has very high sensitivity to environmental perturbations and a very low limit of detection can be achieved.

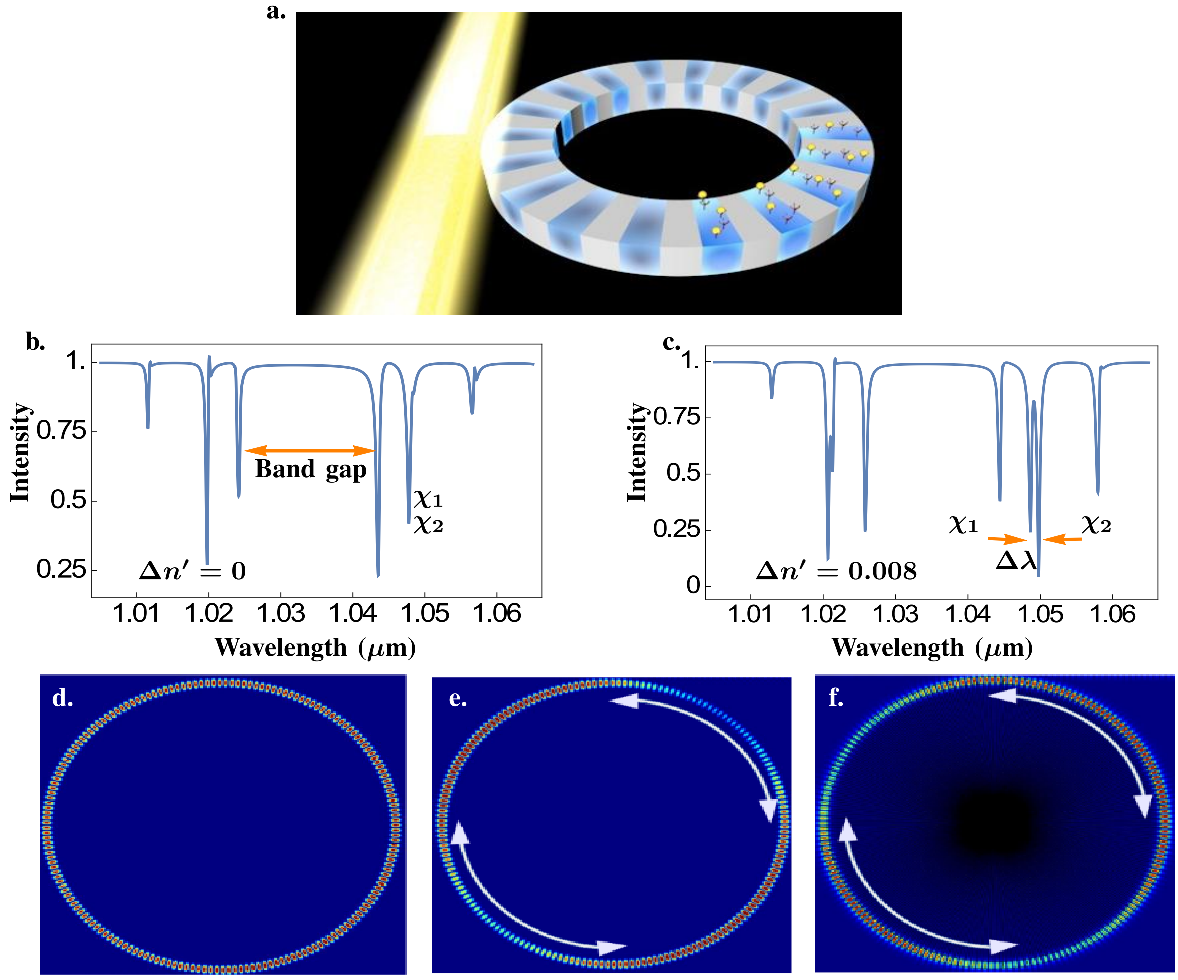

Figure 1. a. Schematic of a ring resonator with a grating that is partially functionalized for molecular attachment. b. The spectra in absence of the analyte ($\Delta n' = 0$). c. The splitting of the resonance when molecules are present ($\Delta n' \neq 0$). The difference in the resonant wavelength of the two split resonances is denoted by $\Delta\lambda$. In the simulations, we used Al_2O_3 ring with inner and outer radii of 9.75μm and 10.25μm. The Bragg grating consists of 180 periods and the refractive index alternates between $n_1 = 1.6$ and $n_2 = 1.65$. The analytes bind to two opposite quarters of the ring. d. The electric field in the ring corresponding to the unperturbed mode χ_1. e.The electric field for the perturbed mode χ_1. f. The electric field for the pertubed mode χ_2. In d. and e., $\Delta n' = 0.012$ and the functionalized quarters are designated by white arrows.

2 THEORY AND NUMERICAL SIMULATIONS

We consider a microring resonator of radius R with a Bragg grating imprinted on it. The grating, of period d, comprises of periodic step variation of refractive index between n_1 and n_2 in the ring. The eigenmodes of the cavity are $\psi_\ell(r,\theta,z)$ where (r,θ,z), are the cylindrical coordinates and ℓ is the azimuthal number. For transverse electric (TE) modes $\psi_\ell(r,\theta,z) = E_z^\ell(r,\theta,z)$ and for transverse magnetic (TM) modes $\psi_\ell(r,\theta,z) = H_z^\ell(r,\theta,z)$. For the ring with Bragg grating, there is a gap $\Delta\omega$ in the frequency spectrum, with modes on two branches. The gap $\Delta\omega$ is proportional to $\Delta n = n_2 - n_1$. Near the edge of a Brillouin zone, $\ell_c = \pi/d$, the eigenfrequencies $\omega_\pm(\ell)$ on either side of the gap are approximately given by $\omega_\pm(\ell) \approx \omega_0(\ell_c) \pm \sqrt{v_g^2(\ell-\ell_c)^2/R^2 + \Delta\omega^2/4}$. The corresponding eigenmodes on the two branches can be well approximated by

$$\psi_\ell^\pm(r,\theta,z) \approx \Phi_{\ell_c}(r,z)\left(e^{i\ell\theta} \pm e^{i(\ell-2\ell_c)\theta}\right) \tag{1}$$

where $\Phi_\ell(r,z)$ is the transverse spatial dependence, which is same to the leading order for all modes in the vicinity of ℓ_c. Importantly, the modes $\psi^\pm_{\ell_c+p}$ and $\psi^\pm_{\ell_c-p}$ have the same frequency for any $p \in \mathbb{Z}$ and hence there is a two-fold degeneracy in the spectra. To illustrate the sensing scheme, let us focus on the modes

$$\chi_1 = \psi^\pm_{\ell_c+1} + \psi^\pm_{\ell_c-1} \approx 4\Phi_{\ell_c}(r,z)\cos(\ell_c\theta)\cos\theta, \qquad \chi_2 = \psi^\pm_{\ell_c+1} - \psi^\pm_{\ell_c-1} \approx 4i\Phi_{\ell_c}(r,z)\cos(\ell_c\theta)\sin\theta \tag{2}$$

which have identical frequency. When analytes bind on a fraction of the ring (say, $-\theta_0 \leq \theta \leq \theta_0$), the refractive indexes of the Bragg grating in the exposed region changes to $n_1 \to n_1 + \Delta n'$ and $n_2 \to n_2 + \Delta n'$. The change in the refractive index induces a polarization $\mathbf{P} = \alpha\mathbf{E}$, where the polarizability α is proportional to $\Delta n'$ and $\mathbf{E}$ is the electric field in the cavity. Assuming that α is uniformly distributed in the region $-\theta_0 \leq \theta \leq \theta_0$, the

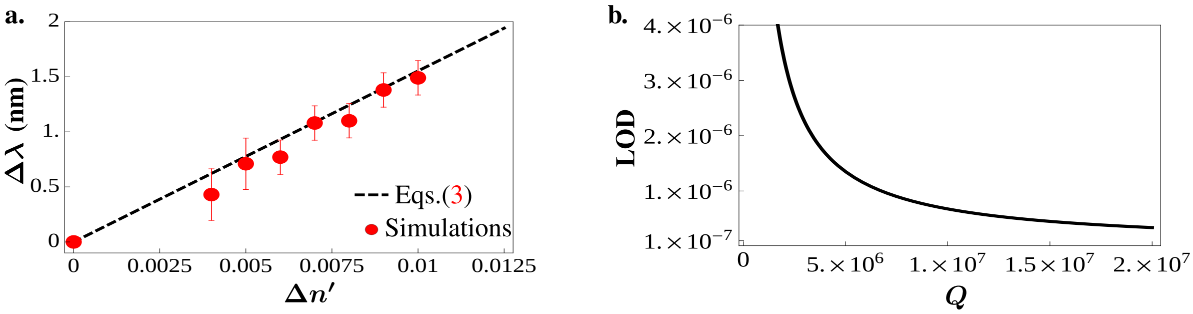

Figure 2. a. Mode splitting as a function of $\Delta n'$. The error bars correspond to the step size used to scan the spectrum in COMSOL. b. The limit of detection vs Q. The parameters are same as in Fig.1.

excess polarization perturbs the cavity modes χ_1 and χ_2 yielding a differential shift in the wavelength of two eigenmodes

$$\frac{\delta\lambda_1}{\lambda} = \frac{2\iint \mathbf{E}^*_{\ell_c}\cdot\alpha\mathbf{E}_{\ell_c} rdrdz}{\pi\iint |\mathbf{E}_{\ell_c}|^2 rdrdz}\int_{-\theta_0}^{\theta_0}\cos^2(\ell_c\theta)\cos^2\theta d\theta, \quad \frac{\delta\lambda_2}{\lambda} = \frac{2\iint \mathbf{E}^*_{\ell_c}\cdot\alpha\mathbf{E}_{\ell_c} rdrdz}{\pi\iint |\mathbf{E}_{\ell_c}|^2 rdrdz}\int_{-\theta_0}^{\theta_0}\cos^2(\ell_c\theta)\sin^2\theta d\theta. \tag{3}$$

$\delta\lambda_1$ and $\delta\lambda_2$ correspond to the shifts of the wavelength of the modes χ_1 and χ_2 and λ is their unperturbed wavelength. In the spectrum, the degeneracy is lifted in the presence of the analytes and the mode splitting is given by $\Delta\lambda = \delta\lambda_1 - \delta\lambda_2$.

To verify the above theory, we have simulated a Al_2O_3 microring resonator using COMSOL. The ring have inner and outer radii 9.75μm and 10.25μm, respectively. The Bragg grating of period $d = \pi/\ell_c$ with $\ell_c = 90$ comprise of periodic variation of refractive index between $n_1 = 1.6$ and $n_2 = 1.65$. As depicted in Fig.1, our simulations confirm that when analyte is present ($\Delta n' > 0$), the modes of the cavity on either side of the band gap splits. For a fixed $\Delta n'$, we found that the splitting is maximum when two opposite quarters of the ring are functionalized. Further, the splitting $\Delta\lambda$ monotonically increases with $\Delta n'$ and as shown in Fig.2, there is an excellent agreement between our simulations and the estimates from Eqs.(3). The sensitivity of the detection is given by $S = \Delta\lambda/\Delta n$. For our simulations, $S \approx$ 150nm/RIU (bulk Refractive Index Unit). The smallest detectable change $\Delta n'$ gives the LOD $\sim \lambda/(QS)$ where Q is the quality factor. For $Q \sim 10^6 - 10^7$, our simulations yield LOD $\sim 10^{-6} - 10^{-7}$, which is comparable with the best reported values in the literature.

3 CONCLUSION

We have proposed a new design that can be implemented with state of the art fabrication techniques. With the new scheme an ultra-sensitive self-referenced detection of analyte was demonstrated both analytically and through an extensive set of numerical simulations. This could pave the way to a portable and inexpensive microring-based sensor, which improves the performance of point-of-care and other on-field detections.

4 FUNDING

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