Self-referenced Sensing in Microring Resonators

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Introduction

With advances in medical diagnostics, there is a growing demand for biosensors to detect low concentrations ($\sim$ few nM) of specific analytes in a complex biological sample.

An **ideal biosensor** should have **high sensitivity, low limit of detection (LOD) and high selectivity.** Further, it should be **cheap, portable and easy to use.**

A **whispering gallery mode (WGM) resonator** is an ideal candidate for high performance sensor: WGM have high Q and occupies small mode volume V. Owing to the high Q/V, photons with **locally large electric field recirculates with long lifetime.** This allows enhanced interaction with analyses, ensuring **an ultra-high sensitivity of detection.**

The conventional sensing using WGM resonators are based on measuring shift in resonances, rosonance broadening or mode splitting. Indeed, in all these schemes, very **high sensitivity is achieved** [1].

The figure of merit of biosensing is the LOD, which is remarkably low for WGM detectors sensing via linear and non-linear processes. Subsequently, there have been several recent developments, which include

- multiplexed arrays, with each microresonator functionalized to respond to a specific molecule developed
- biosensing in real complex biological samples like undiluted human urine [2]

Hurdle in commercial use: Despite these remarkable advances, WGM sensors are largely confined to academic labs. Their operations require tunable laser sources or high precision spectrometers. As a result, these are expensive, bulky and require special training to use. This is the main obstacle in their commercial use.

Heterodyne sensing using a sensing and a reference cavities **does not require spectrometer or tunable laser source.** However, these are impractical as minute fabrication uncertainties can lead to unacceptable uncertainties in the reference resonances. This means, each fabricated device would have to be calibrated individually, which is not viable commercially.

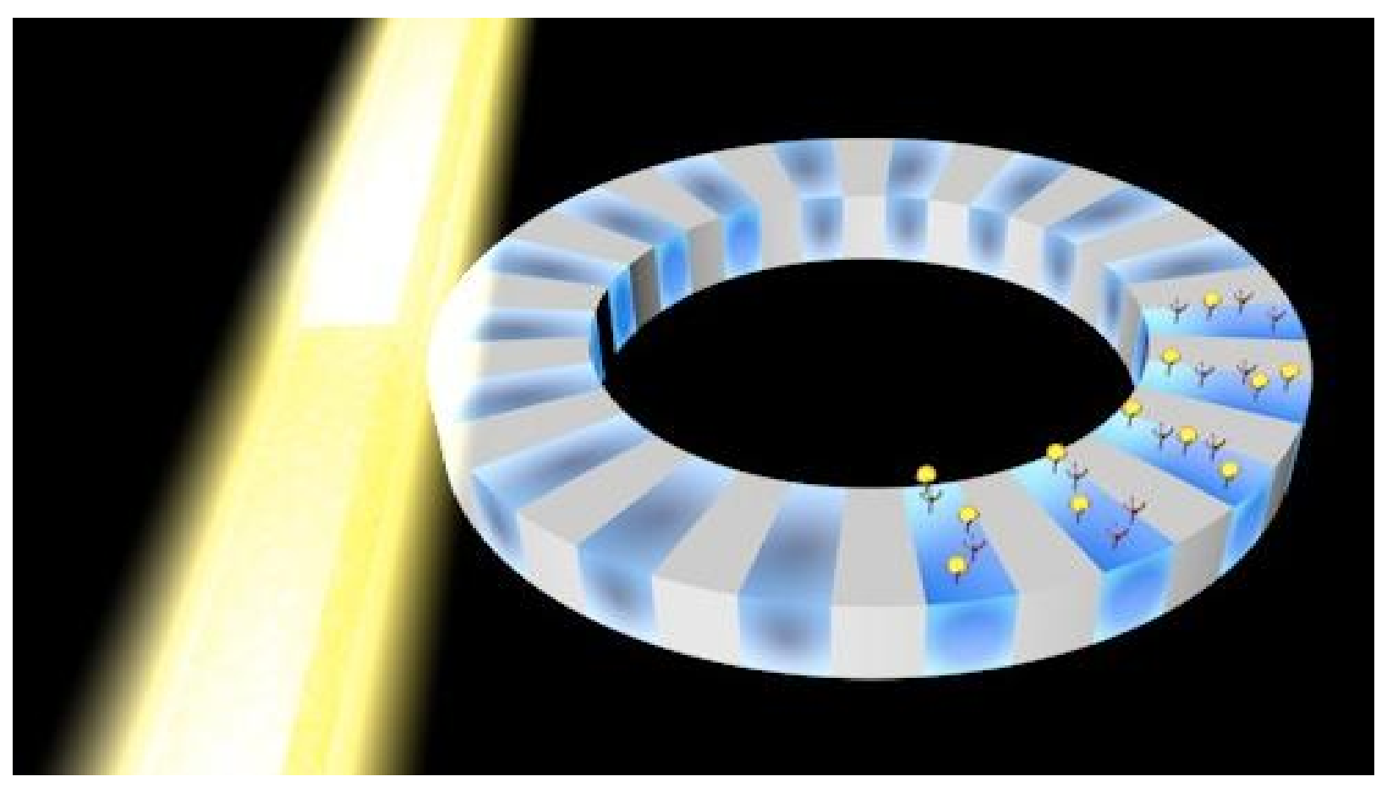
Self-heterodyne detection using a single resonator proposed in [3] is promising: single particle binding event can lead to detectable resonance splitting. The resulting low frequency beat signal can be measured by conventional electronics. However, in this case, the beat signal does not have a monotonic dependence on the number of analyte particles. Consequently, the scheme is not suitable to measure of analyte concentrations.

New Self-heterodyne Sensing Scheme:

We propose a new self-heterodyne sensing scheme based on mode splitting which varies monotonically with analyte concentration [4]. The proposed scheme has following features:

- The proposed 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, the cavity supports doubly degenerate modes on either side of the edge of the Brillouin zone.
- **As analyte molecules bind, the degeneracy lifted and leads to mode splitting.**
- When the split modes are simultaneously excited, **low frequency beat signal is produced, which can be recorded by off-the-shelf electronics.**

Schematically, the situation is depicted below:



Theory

We consider a microring resonator 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. The eigenmodes of the cavity are $\psi_\ell(r,\theta,z)$. For TE modes $\psi_\ell(r,\theta,z) = E_z^\ell(r,\theta,z)$ and for 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.**

Near the edge of a Brillouin zone, $\ell_c = \pi/d$, the eigenmodes on the two branches can written as

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

$\Phi_\ell(r,z)$ is the transverse spatial dependence, which is same (leading order) for all ℓ in the vicinity of ℓ_c.

Note that the modes $\psi_{\ell_c+p}^\pm$ and $\psi_{\ell_c-p}^\pm$ have the same frequency for any $p \in \mathbb{Z}$. Consequently, there is a **two-fold degeneracy in the spectra.**

To illustrate the sensing scheme, let us focus on the modes

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

which have **identical frequency**.

When analytes bind on a fraction of the ring (say, $-\theta_0 \le \theta \le \theta_0$):

- In the exposed region, the refractive index changes: $n_1 \to n_1 + \Delta n'$ and $n_2 \to n_2 + \Delta n'$
- The change in the refractive index induces a polarization $\mathbf{P} = \alpha\mathbf{E}$, where $\alpha \propto \Delta n'$
- This leads to a **differential shift** of the wavelengths $\delta\lambda_1$ and $\delta\lambda_2$ of the modes χ_1 and χ_2

In the spectrum, **the degeneracy is lifted in the presence of the analytes and the mode splitting is given by $\Delta\lambda = \delta\lambda_1 - \delta\lambda_2$:**

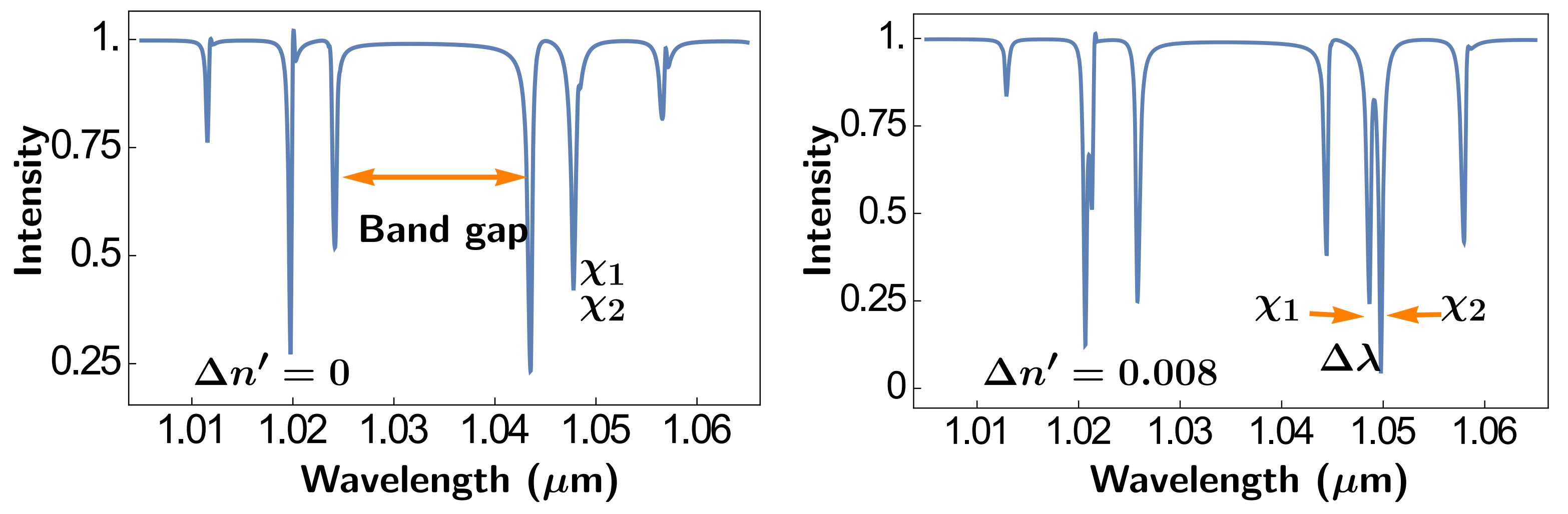
$$\frac{\Delta\lambda}{\lambda} = \frac{\delta\lambda_1 - \delta\lambda_2}{\lambda} = \frac{2\iint \mathbf{E}_{\ell_c}^* \cdot \alpha\mathbf{E}_{\ell_c} r dr dz}{\pi\iint |\mathbf{E}_{\ell_c}|^2 r dr dz}\int_{-\theta_0}^{\theta_0} \cos^2(\ell_c\theta)(\cos^2\theta - \sin^2\theta)d\theta, \tag{3}$$

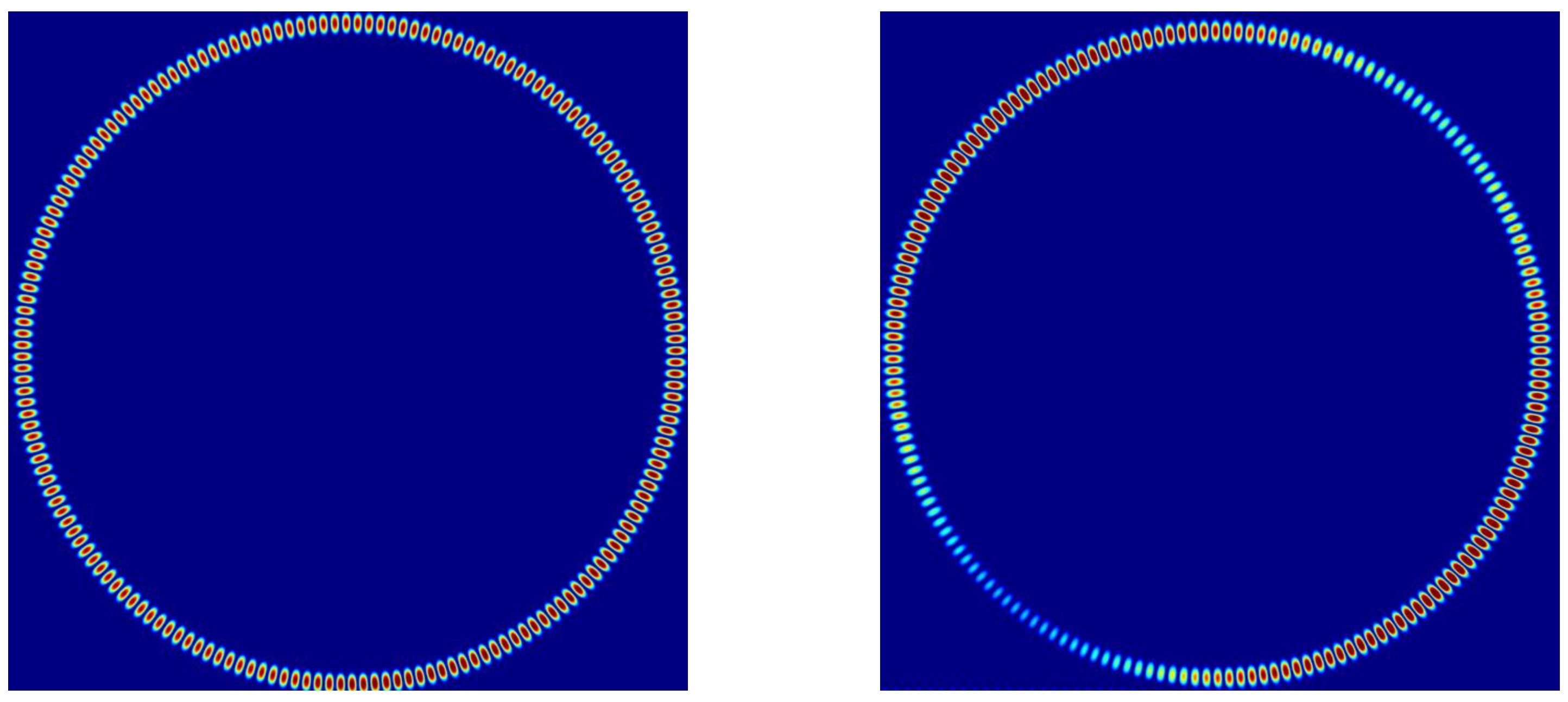
Simulations and Results

To verify the above theory, we have simulated a Al_2O_3 microring resonator using **COMSOL**.

In the simulations, we used a ring with 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 $n_2 = 1.65$.





Results:

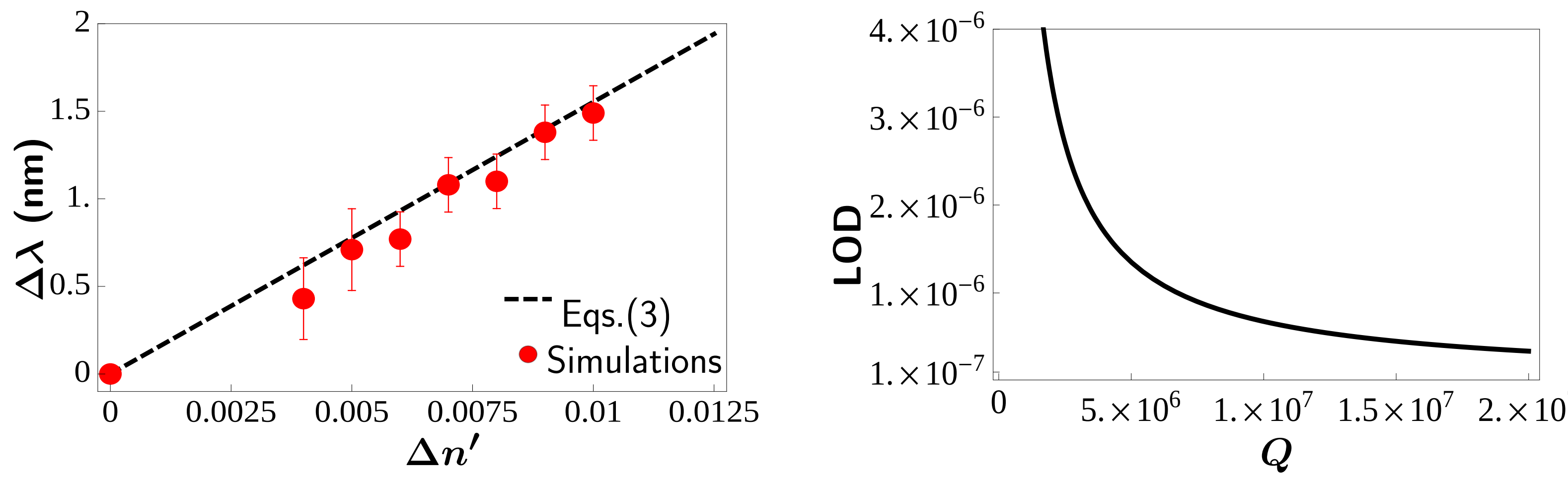
- **Our simulations confirm that when analyte is present ($\Delta n' > 0$), the modes of the cavity on either side of the band gap splits.**
- **For a fixed $\Delta n'$, we found that the splitting is maximum when two opposite quarters of the ring are functionalized.**
- Further, the splitting **$\Delta\lambda$ monotonically increases with $\Delta n'$.**
- There is an **excellent agreement between** our simulations and the estimates from Eqs.(3).

Sensitivity and Limit of detection:

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** $\sim 10^{-6} - 10^{-7}$.

The value of S and LOD are comparable with the best reported values in the literature.



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.

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