A model for an Optical Ring Microresonator towards Nanoparticle Detection

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ABSTRACT

In this work, we have used an optical microring-based resonator, and developed a Multiphysics finite element model of this resonator for ultrasensitive biomolecule and nanoparticle detection. We applied an input tunable laser light at the input node of the straight form waveguide at a wavelength of 1.55 μm and monitored the transmitted light at the output node. During this process, we recorded the transmission spectrum and located the exact position of the resonance wavelengths shifted towards higher wavelength value (red shift). A linear correlation was observed, between increasing the radius of the microring and the resonance wavelength red shift. Additionally, we have shown that we could detect resonance value shifts for very small changes in the microring radius, as low as 10 nm.

Keywords: Optical Ring Resonators, Biosensors, Nanoparticle Detection, Optical Resonance

INTRODUCTION

Optical resonators have shown great potential as fundamental building blocks in a wide range of photonic devices and applications including filters, optical multiplexers, logic gates, switches, and sensors [1]. Microresonator consist of a couple of standard waveguides, one of them is of a straight form and the other is circular; and are defined by a micron-scale geometry (microsphere, microtoroid or microring).

Light can be confined even in any transparent material (e.g. classic glass) by reaching certain physical conditions. While the light is reflected within a waveguide, it affects another evanescent wave in the outer medium that is propagated tangentially to the surface and extends around 200 nm outward [2]. In the classical picture, optical resonances are coupled in a resonator, when the length of the circular light path, around the circumference, matches an integer value of the wavelength. Microresonators as photonic devices consist of the waves that circulate in the inner cavity structure. These waves are maintained by total internal reflection occurring inside of the cavity structure. The resonance is reached, when the waves return to the same point and in the same phase (modulus 2π) and creating standing waves. The resonances depend highly on geometry of the resonator cavity [3, 4]. When the microresonator reaches the resonance state, light of resonance wavelength builds up an intensity through multiple round-trips into the circular form and a part of the remained light travels to the output bus waveguide, performing the detection port (photodetector). Inside of the microresonator closed-loop, only some of the specific wavelengths will contribute to the resonance of the light. In a ring resonator, the resonance can be identified by a sharp dip in transmission spectra, typically obtained by delivering tunable laser light to the resonator via a tapered optical fiber positioned close to the resonator. The resonance dips can be observed by measuring the transmission spectrum, while sweeping the laser wavelength. As the wavelength of the laser matches the resonance wavelengths of the ring, light couples from the optical fiber to the microring, resulting in an intensity drop in the transmission spectra monitored at the output of the waveguide [5].

Sensing recently have seen a tremendous development. In general, clinical diagnostics mostly rely on sensing molecular nanoparticles based on biochemical assays, as for instance enzyme-linked immunoassays (ELISA), radiolabeled immunoassays, or polymerase chain reactions (PCR). Another detection is reached by utilizing of any biorecognition element such as an antibody or similar bioagent [6]. All of these diagnostic methods mentioned above need chemical amplification as well as labeling of the analyte in order to give any detectable signal. In addition, all of them require biochemical and physical procedures for amplification and labeling the analyte, by following many procedures. These detection methods require skilled personnel and trained professional workers [7]. Moreover, well-equipped laboratories and the cost for all these staff reach in very high values. For most of the reasons stated above, there is a need for a lower cost, automated, real-time, portable and cost effective techniques in health care [8, 9]. Therefore, one of the best candidates for biodetection to meet the above requirements with high sensitivity is optical microring resonator [5]. Low cost is one of the advantages due to the small arrays and resonators can be fabricated on a small chip. Ultimately mass-produced, as their fabrication process requires standard technology [10]. Figure 1 shows a schematic representation of a microresonator biosensor.

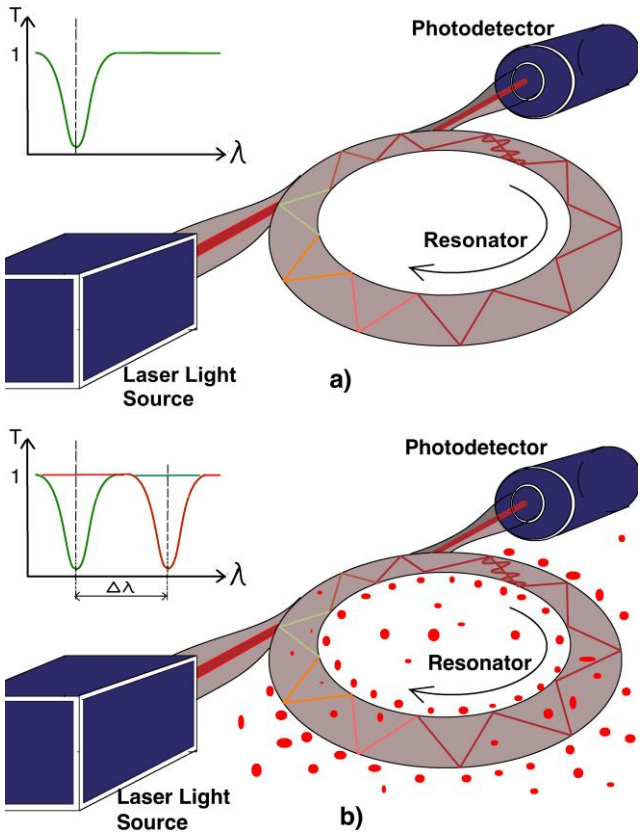

Figure 1: A schematic representation of microresonator biosensor.

We can determine the resonance wavelength of this optical ring microresonator by sweeping the wavelength of a waveguide-coupled by tunable laser source and monitoring transmission spectrum via the photodetector at the output of the fiber. In that graph of the figure 1a), the lowest value of the Lorentzian line represents the exact location of the resonant wavelength, changed by $\Delta\lambda$ after the biomolecules/nanoparticles are in the vicinity or bind to the outer ring resonator area (red tiny beads, Figure 1b). This shift represents the parameter of utilization as sensing mechanism for this model.

RESULTS AND DISCUSSIONS

Herein, we have used an optical microring-based resonator, and developed a Multiphysics finite element method for the model of this resonator as an ultrasensitive biomolecule and nanoparticle detection. We used an input tunable laser light at the input node of the waveguide at a wavelength of 1.55 μm and monitored the transmitted light at the output node. Refraction index for the *core* part of the resonator fiber was set to be 2.5; likewise, for the *cladding* part (covering material of the *core*) refraction index was set to be at value of 1.5. In our studies, we observed a linear correlation between increasing the radius of the microring and the red shift (higher value) in the wavelength resonances. Additionally, we found that we could detect resonance shifts for very small changes in microring radius, as low as 10 nm.

Furthermore, we assumed that biomolecules /nanoparticles are to bind around the ring and the graph of transmission is displayed with a resonance shift ($\Delta\lambda$). This resonance shift can be detected as shown in figure 1 (b), illustrated with the red line. In this aspect, we modeled nanolayers to mimic biomolecules and nanoparticles that would bind into the microring sensor. The maximum monolayer density of the dielectric properties to the accumulated biomolecules/nanoparticles and ring material will be similar [2]. From the optical point of view, this dielectric ring is grown in thickness. Therefore, we varied the thickness of the nanolayer modeled around the ring resonator which corresponds to different size of biomolecules /nanoparticles. Consequently, we monitored the corresponding resonance shift.

Figure 2 shows the electric field within the resonator. Gradient colored bar in the right side denotes the values for the field from the negative and positive range. The width of the tapered vertical fiber and the resonator is 2 μm each. Also, the light wave circumnavigating the outer circle of the ring with a radius of $R = 83.00\ \mu m$ and a wavelength of $\lambda = 1.550 \mu m$. The bottom part of the straight waveguide represents the tunable laser light source (down-left), and in the other side we have been monitoring values around these quantities for the aim of a higher precision. The radius of the microring was varied from 83.00 μm to 83.10 μm for our simulations to achieve a linear response. The circular form waveguide represents the ring resonator.

The condition for reaching the resonance effect is:

$$\frac{m\,\lambda_R}{n} = 2\pi R. \qquad (1)$$

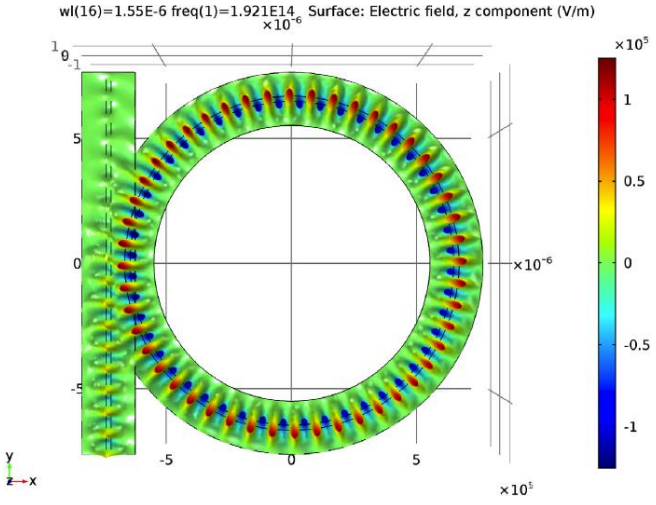

Figure 2: The out-of-plane component of the electric field for the resonant wavelength.

Where, n - represents the orbital refractive index (RI) of the ring, m - is an integer number for orbital wavelength. Regarding to this expression, the sensitivity of the resonance wavelength due to changes in radius ΔR, and by assuming similar refractive index (n), is

$$\frac{\Delta\lambda_r}{\lambda_r} = \frac{\Delta R}{R} + \frac{\Delta n}{n}. \quad (2)$$

In this study, determining the resonator radius value has been very critical. Starting from a radius of $20\mu m$, we increased to $30\mu m$, $40\mu m$, and so forth, until around $200\mu m$. Most of the obtained responses did not match the criteria of providing a linear and successive responses, in order to quantize those obtained values to use in describing the size of the nanoparticles that would bind to the resonator. Interestingly, we found that the linear successive responses for the respective resonance wavelengths, that can be acquired, are in the range between 80 μm and $90\mu m$ (for the outer circle of the microring). To be more precise, the values between 83.00 and 83.10 μm with an incremental value of 10 nm were used. According to this model, we can obtain information that can help us to determine the size of nanoparticles on the microring. Then, we use the recorded spectrum to locate the minimum position (dip) line corresponding to the exact resonance wavelength of the resonator response.

The resonance wavelength shift depends sensitively on the change of the optical length path of the travelling light, in a linear fashion. This occurs due to the binding of biomolecules around the micro-resonator at outer part of surface, or molecules positioned at the vicinity. Figure 3 shows the successive responses of the microresonator by varying the ring radius. In Fig. 3, we can determine the exact resonant position response, which in this case is starting from the first resonance value (red line) corresponding at a wavelength value of 1.5543 μm (1.5563 μm). Binding of nanoparticles with the size of 10 nm causes a shift of wavelength (to purple line position) to the corresponding value of 1.5545 μm (or 1.5565 μm). This resonance wavelength shift continues, as we increase the size of the ring.

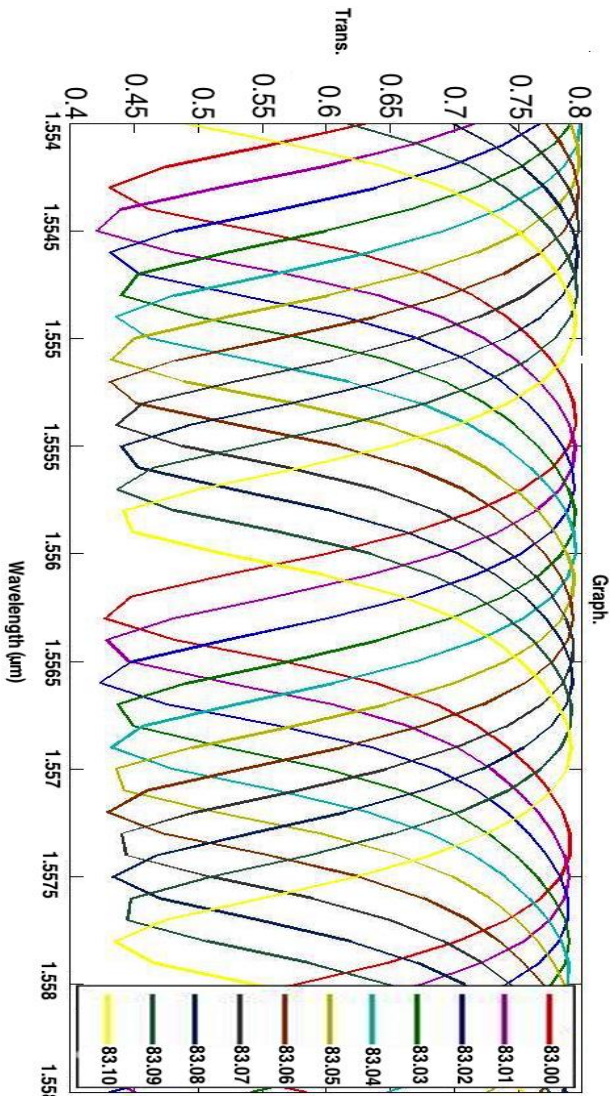

Figure 3: Linear successive responses, compiled for the simulations of the microresonator by varying the ring radius from 83.00μm to 83.10 μm with 10 nm increments.

For example, the last resonance shift (yellow line) consists of a shift caused by biomolecules with the size (radius curvature) of 100 nm and the resonance wavelength value for this case corresponds to value of 1.5559 μm (or 1.5579 μm). Our studies suggest that these series of responses continue to follow this trend even for larger sizes, beyond 100 nm. We accomplished the simulations up to the value of 220 nm.

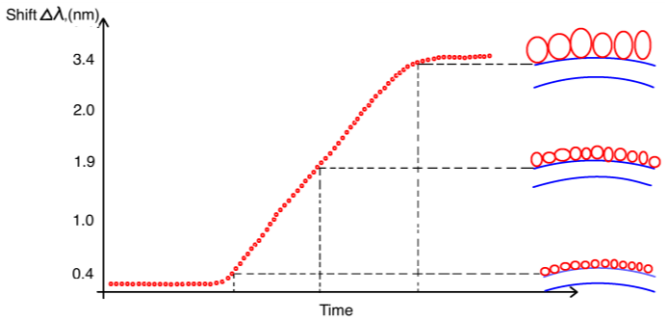

Figure 4: Sensitivity estimation regarding to the size of the binding biomolecules/nanoparticles.

Figure 4 shows the resonance wavelength shift as a function of the size of the binding biomolecules. It is taken from the spectrum in Fig 3. In the beginning, the shifting curve starts from zero. For the size of around 10 nm, there is a shift value of 0.4 nm. The second case shows a shift value of 1.9 nm, corresponding to the molecule size of 40 nm. Similarly, a shift of 3.4 nm corresponds to the molecule size of 100 nm.

CONCLUSIONS

We have conducted this study with the aim of exploring the operation and working principle of microring resonator as label-free analysis platforms towards biomolecules and nanoparticle detection. In our efforts, we have developed a model platform to simulate the optical ring resonator. The principal work is based on the resonant frequency shift as a function of microring size. Light adsorption by the individual nanoparticles, enable us the opportunity to use it as a relevant mechanism to produce discrete changes in resonance frequency/wavelength of optical ring resonator. A linear correlation was observed, between increasing the radius of the microring and the resonance wavelength red shift. Additionally, we have shown that we could detect resonance shifts for very small changes in the microring radius, as low as 10 nm.

Furthermore, optical microresonators have shown a great potential for possibility of commercialization with superior sensitivity, even for a single particle detection. Another advantage of microresonators consists of the effective way of delivering the sample material in to the sensing place, which enbales us the reduction of clinical analysis time. Therefore, ring-shaped microresonator biosensors are foreseen to have a bright future in clinical diagnostics, since they are label-free analytic detectors and they enable the possibility for integration on a chip-scale device.

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