# Sensitivity and detection limit of dual-waveguide coupled microring resonator biosensors

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We show that a linear relation exists between the device sensitivity and the quality ($Q$) factor of a dual-waveguide coupled microring resonator optical biosensor when the optimal conditions are satisfied. We also show that the detection limit depends on the loss coefficient and signal-to-nosie ratio (SNR) of the overall system, rather than the circumference of the ring. For a microring resonator sensor whose $Q$ factor is 20000, the detection limit is found to be about $10^{-7}$ with 30-dB SNR, which is in good agreement with reported experimental data. These results indicate that loss reduction is the top priority in the design and fabrication of highly sensitive microring resonator optical biosensors.

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Planar integrated optical biosensors have attracted much attention due to their ease of fabrication and their capability of integration. To date, sensors based on surface plasmon resonance (SPR)[1−5], Mach-Zehnder interferometers MZIs[6,7], gratings[8], Fabry-Perot cavities[9], and microresonators[10−12] have been demonstrated. As a potential solution for label-free detection, biosensors based on microring resonators are capable of detecting minute amount of analytes by virtue of their high quality ($Q$) factor and the long equivalent interaction length due to resonance. In previous works, these structures have been experimentally realized using materials such as $Si_xN_y/SiO_2$[13], silicon[14,15], low-loss Hydex material[16], and polymer[17−19]. Currently, the smallest calculated detection limit in terms of refractive index unit is $10^{-7}$[17], much higher than those obtained with SPR sensors[1−3]. Though it is commonly believed that the device sensitivity grows as the $Q$ factor increases, recent studies on the optimal conditions for biosensing indicate a more complex relation between the two parameters[20,21]. In this letter, we thoroughly investigate the sensitivity of a dual-waveguide coupled microring resonator biosensor and find a linear relation between the device sensitivity and the $Q$ factor when the optimal conditions are satisfied. In addition, the detection limit is found to be dependent on the loss coefficient and the signal-to-noise ratio (SNR) of the overall system, rather than the circumference of the ring. These results will be useful in the design and analysis of microring resonator biosensors.

In our configuration, the microring resonator is coupled with two straight waveguides that serve as input and output ports, respectively, as shown in Fig. 1. The analyte located on top of the ring waveguide causes a change in the refractive index of the cladding, which is probed by the evanescent tail of the modal field, and in turn changes the transmission behavior of the light propagating in the microring. This change can be monitored by spectral scan for resonance wavelength shift or detection of the output intensity at a fixed wavelength. Here we focus on the case based on intensity detection, because it possesses higher sensing capability[17]. The device sensitivity $S_D$ is defined as $S_D = |\mathrm{d}I_\mathrm{N}/\mathrm{d}n_\mathrm{eff}|$, where $I_\mathrm{N}$ is the normalized output intensity and $n_\mathrm{eff}$ is the effective refractive index. Previously, for a given attenuation coefficient $\sigma$, the optimum of the self coupling coefficient $t$ has been found to be $\sigma^2$[20]. $\sigma$ is determined by the half roundtrip propagation loss and can be interpreted by the circumference $l$ and the loss coefficient $\alpha$ as $\exp(-\alpha l/2)$. Moreover, for a given microring resonator, i.e., where both $\sigma$ and $t$ are fixed, there is an optimal operating wavelength $\lambda_m$ at which the device sensitivity is maximized to be $S_{D\max}$:

$$S_{D\max} = \left|\frac{\mathrm{d}I_\mathrm{N}}{\mathrm{d}n_\mathrm{eff}}\right|_{\max} = \left|\frac{(1-t^2)^2}{4t^2}\cdot\frac{\cos^2(\theta_m)}{\sin^3(\theta_m)}\cdot\frac{\pi l}{\lambda_m}\right|. \quad (1)$$

As is shown in Eq. (1), for a given ring structure, $S_{D\max}$ is achieved when the wavelength-dependent phase shift $\theta$ ($\theta$=$2\pi n_\mathrm{eff} l/\lambda$) achieves its optimal value, $\theta_m$:

$$\theta_m = \pm\arccos\left[\frac{\sqrt{\left[1+\frac{(1-t^2\sigma^2)^2}{2t^2\sigma^2}\right]^2+8}-\left[1+\frac{(1-t^2\sigma^2)^2}{2t^2\sigma^2}\right]}{2}\right], \quad (2)$$

where $\theta_m$ is determined by the attenuation coefficient $\sigma$ and the self coupling coefficient $t$, and so is the optimal operating wavelength $\lambda_m$[20]. Therefore, combining $t$=$\sigma^2$

 

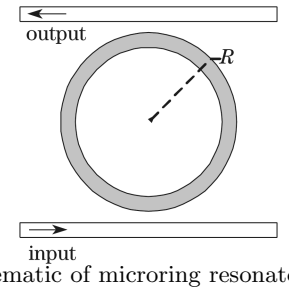


Fig. 1. Schematic of microring resonator biosensor.

with Eqs. (1) and (2), the optimal device sensitivity $S_{D\mathrm{opt}} = S_{D\max}|_{t=\sigma^2}$ for a given $\sigma$ can be obtained.

On the other hand, the $Q$ factor is defined as the ratio of central resonance wavelength $\lambda_0$ and 3-dB linewidth of the spectrum $\Delta\lambda_{3\mathrm{dB}}$[17] and can be written as

$$Q = \frac{\pi l n_{\mathrm{eff}}}{\lambda_0 \arccos\left[2 - \frac{1}{2}\left(t^2\sigma^2 + \frac{1}{t^2\sigma^2}\right)\right]} \tag{3}$$

Similarly, when the self coupling coefficient $t$ has been adjusted to the optimal condition for a given $\sigma$, the $Q$ factor achieves its optimum $Q_{\mathrm{opt}} = Q|_{t=\sigma^2}$.

The ratios of $S_{D\mathrm{opt}}$ to $Q_{\mathrm{opt}}$ for different microring resonators, i.e., $D = S_{D\mathrm{opt}}/Q_{\mathrm{opt}}$, are shown in Fig. 2, demonstrating that $D$ is independent of $l$. Since $\lambda_m$ is close to the resonance wavelength $\lambda_0$ for a high-$Q$ resonator[20], the effect of operating wavelength on $D$ can be canceled through taking the ratio of Eqs. (1) and (3) when $t = \sigma^2$. Moreover, as indicated in Fig. 2, $D$ decreases as the effective refractive index increases. However, if we define $D_1$ as $D1 = n_{\mathrm{eff}} S_{\mathrm{opt}}/Q_{\mathrm{opt}}$, it can be seen from Fig. 3 that $D_1$ remains at 0.577 for various $n_{\mathrm{eff}}$. Therefore, for a given attenuation coefficient $\sigma$, the relation between the device sensitivity and the $Q$ factor under the optimal conditions can be written as

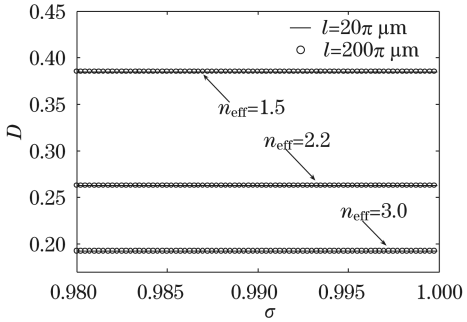


Fig. 2. $D$=$S_{D\mathrm{opt}}/Q_{\mathrm{opt}}$ as a function of attenuation coefficient $\sigma$.

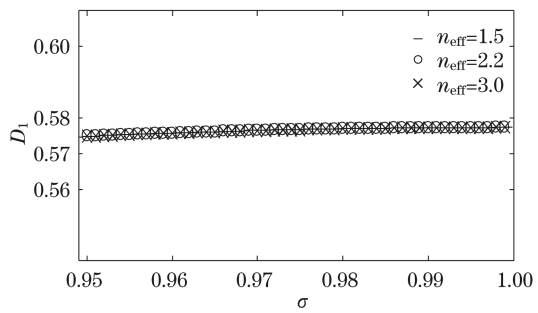


Fig. 3. $D_1$=$n_{\mathrm{eff}} S_{\mathrm{opt}}/Q_{\mathrm{opt}}$ as a function of attenuation coefficient $\sigma$.

$$S_{\mathrm{opt}} = 0.577 \cdot Q_{\mathrm{opt}}/n_{\mathrm{eff}}. \tag{4}$$

Figure 4 depicts the relation between the device sensitivity and $Q$ factor for a microring resonator biosensor whose radius is 10 $\mu$m. $n_{\mathrm{eff}}$ is assumed to be 2.6 at an optimal operating wavelength of 1550 nm. It can be seen that the device sensitivity does not increase monotonously as the $Q$ factor increases when $\sigma$ is fixed. This is due to the optimal condition of the self coupling coefficient[20] and similar to that in single-waveguide coupled microring resonators[21]. The straight solid line represents the optimal device sensitivity for different attenuation coefficients, which is in good agreement with Eq. (4) depicted by the circles. Since the optimal device sensitivity $S_{D\mathrm{opt}}$ is proportional to the $Q$ factor when the microring resonator is optimized, the performance of the microring biosensor can be readily evaluated by $Q_{opt}$ as Eq. (4).

The detection limit, $\delta n_{\mathrm{eff}}$, is defined as the minimal distinguishable change of the effective refractive index. It is therefore determined by the device sensitivity $S_{D\mathrm{opt}}$ along with the minimal detectable variation of normalized intensity $\delta I_{\mathrm{N}}$ as $\delta n_{\mathrm{eff}} = \delta I_{\mathrm{N}}/S_{D\mathrm{opt}}$. $\delta I_{\mathrm{N}}$ is defined as three times the standard deviation of signal noise[16], and is thus restricted by the SNR of the overall system. Consider, for example, the polymer microring resonator biosensor in Ref. [17], whose $Q$ factor is measured to be 20000. $n_{\mathrm{eff}}$ is 1.5 with the polymer serving as the core, and the optimal operating wavelength is 1569.29 nm. The SNR of the overall system is 30 dB, leading to the minimal detectable change of normalized intensity $\delta I_{\mathrm{N}}$ to be $2\times10^{-3}$. Hence, $\delta n_{\mathrm{eff}}$ is calculated to be $2.6\times10^{-7}$, which is consistent with that in Ref. [17].

Figure 5 depicts the detection limit as a function of the circumference $l$ when the loss coefficient $\alpha$ (dB/cm) is 3, 2.4[22], 1.9[15], 1.0, 0.15[16], and 0.10, respectively.

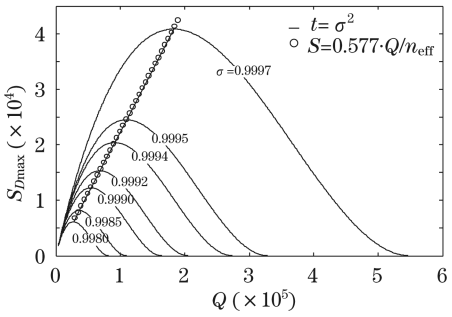


Fig. 4. $S_{D\max}$ as a function of the $Q$ factor.

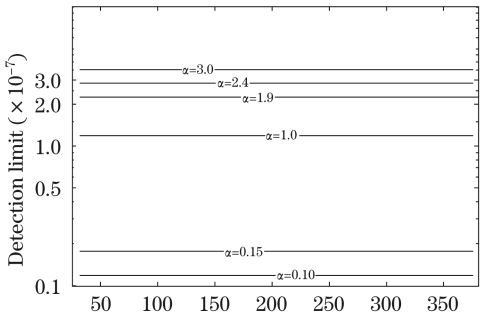


Fig. 5. Detection limit as a function of circumference.

The operating wavelength is set to be 1550 nm[14]. The SNR of the overall system is 30 dB in this calculation. The flatness of $\delta n_{\rm eff}$ indicates that the detection limit is independent of the circumference of the microring resonator for a given loss coefficient $\alpha$. Instead, $\delta n_{\rm eff}$ is determined by the loss coefficient of the waveguide and the SNR of the overall system.

In summary, we have shown that, under the optimal conditions, although the device sensitivity of a microring resonator biosensor does not increase monotonously as a function of the $Q$ factor, there exists a linear relation between the two parameters. This means that the sensitivity of an optimized microring resonator biosensor can be readily deduced from the measured $Q$ factor and the detection limit easily obtained using the SNR of the overall system. We have also found that the detection limit is determined by the loss coefficient and the SNR of the overall system, rather than the circumference of the ring, indicating that loss reduction is the top priority in the design and analysis of highly sensitive microring resonator biosensors. The predicted detection limits based on available experimental data indicate that $\delta n_{\rm eff}$ can be further reduced to a level comparable to that achieved for SPR biosensors.

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