Dual-microring-resonator interference sensor

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Dual-microring-resonator interference with the microrings on separate arms of a Mach–Zehnder interferometer is shown to provide the basis for high-performance sensors. The output spectrum, which depends on the overlap of the resonances of the two microring resonators, depends sensitively on the resonance shift of one of the microrings due to the presence of an analyte. The sensitivity and detection limit are obtained theoretically and found to be as large as 0.31 nm overlap resonance shift according to $2 \times 10^{-6}$ refractive index units for Si-based sensors.

Microring resonators (MRs) are widely deployed for high-sensitivity chemical detection applications in part due to their compact scale combined with their compatibility with common technological materials such as silicon, group III-nitrides, and polymers. MR sensor function is typically based on one of two schemes. The first is to detect the MR-resonance-wavelength shift; the other is to detect the intensity variation at fixed wavelength. The underlying commonality of the two sensing schemes is that the spectrum is shifted according to the effective refractive index shift caused by the analyte. The performance of MR sensors can be quantified by the sensitivity and detection limit. Since the detection capability of experiments is frequently limited by signal noise, attention has largely focused on improving the sensitivity, which relies on high quality factor ($Q$) MR resonators. The highest $Q$ reported is $\sim 10^8$; such high values of $Q$ necessitate precise control of the fabrication.

In this paper, a sensing scheme is proposed based on a dual MR, as showed in Fig. 1. One of the MRs acts directly to sense the analyte, while the other’s resonance is stable and serves as a reference MR. In the absence of the analyte, the resonances of the two MRs mutually interfere through the Mach–Zehnder (MZ) effect. The spectra of the two MRs differ due to their different radii. Because the two MRs are designed so that one specific resonance of each microring occurs at the same wavelength $\lambda_0$ in the absence of the analyte (called the overlap resonance), their combined resonance in the MZ geometry forms a central resonance in the symmetric transmission dips associated with the nonoverlapping resonances of the individual MRs (see below, Figs. 3 and 4); it is this specific feature associated with the overlapping resonance dip that provides the means of sensing the analyte. Namely, the presence of the analyte shifts the resonances of the sensing ring; thus altering the spectral properties of the overlapping resonance of the pair of MRs in the device. The mechanism for the single-MR resonance shift is as follows. One of the MRs is sensitive to an analyte that shifts the background refractive index. This in turn shifts the resonance of that MR, leading to a shift with respect to the unchanged resonance of the reference MR. Consequently, the combined resonance in the MZ geometry, which involves interfering light propagating through the two arms of the device, is altered. It is shown below that the spectral change for the dual-MR sensor in the MZ geometry due to the analyte can be considerably greater than that for a comparable single-MR sensor, which means higher sensitivity can be realized.

The sensor consists of two MRs, one coupled to each arm of a MZ interferometer with each MR having a different radius. We will analyze the MZ-based sensor as follows. We consider the light propagation through each arm separately and then consider the interference upon combining the light from the two arms. In doing so, we neglect the back coupling of light from one arm to the other. Ring I is the sensing MR, while ring II is the reference MR. The radii of the rings are $R_1$ and $R_2$, respectively, with $R_1 > R_2$. The resonance conditions for the two MRs may be expressed as

$$2\pi R_1 n_{\text{eff}1} = m\lambda,$$
$$2\pi R_2 n_{\text{eff}2} = n\lambda,$$ (1)

where $n_{\text{eff}1}$ and $n_{\text{eff}2}$ express the effective refractive indices of the two MR waveguides, respectively, and $m$ and $n$ are integers and $\lambda$ is the free-space optical wavelength, which will correspond to an overlapping resonance at wavelength $\lambda_0$ of the two MRs in the absence of the analyte, i.e., it is assumed

FIG. 1. MZ coupled dual-MR sensor. Ring I coupled to one arm of the MZI is a sensing MR, while ring II coupled to the other arm is a reference MR.
that $R_1$ and $R_2$ are such that a convenient $\lambda_0=\lambda_n$ may be chosen so that both equations in Eq. (1) are satisfied for some pair of integers $m$ and $n$. The free spectral range (FSR) of a MR resonator

$$\text{FSR} = \frac{\lambda^2}{2\pi R n_{\text{eff}}},$$

(2)

where $\lambda$ is the average free-space wavelength in the operating range of the device, is the wavelength separation between successive resonances. Due to the difference of $R_1$ and $R_2$, the FSRs of the two MRs differ, and are denoted FSR$_1$ and FSR$_2$. We define the FSR difference

$$\Delta\text{FSR} = \text{FSR}_2 - \text{FSR}_1.$$  

(3)

Let $\lambda_0$ be the wavelength where the resonances of interest of the two rings coincide. In order to discuss the radius effect on the sensing, the ratio of the two ring radii is defined as

$$a = \frac{R_2}{R_1},$$

(4)

where by assumption $a < 1$. Thus, using Eq. (2), $\Delta\text{FSR}$ can be rewritten as

$$\Delta\text{FSR} = (1-a)\text{FSR}_2.$$  

(5)

In sensing applications, the change of refractive index shift $\Delta n_{\text{eff}}$ induced by the analyte to be detected is in practice $\leq 10^{-5}$ refractive index units (RIU), which is much smaller than $n_{\text{eff}}$ itself. Moreover, $n_{\text{eff}}$ is essentially wavelength independent in the narrow sensing window. Therefore, $R_{\text{eff}}$ is taken to be independent of wavelength in the sensing discussion.

In a conventional single-MR sensing scheme, the resonance-shift wavelength $\Delta \lambda$ follows from the effective-index variation. According to Eq. (1), the resonance shift of a single MR due to $\Delta n_{\text{eff}}$ can be expressed as

$$\Delta \lambda = \frac{2\pi R_1 n_{\text{eff}}}{m} \
\text{ due to } \Delta n_{\text{eff}}$$

(6)

In the dual-MR sensing scheme, the reference MR is not affected by the surrounding changes. Thus, its effective index remains the same in the presence of the analyte, which means that the resonance spectrum of the reference MR is stable during sensing. In contrast, the spectrum of the sensing MR shifts depending on the effective refractive-index shift due to the analyte. The spectrum of the dual-MR sensor, however, exhibits this shift through the (near) overlap of a fresh pair of single-MR resonances at $\lambda_0$ (as in Fig. 2, where $h=1$)

$$\lambda_0' = \lambda_0 + h \cdot \text{FSR}_1 + \Delta \lambda,$$

for some small integer $h$. Also the fresh overlap wavelength satisfies

$$\lambda_0' = \lambda_0 + h \cdot \text{FSR}_2.$$  

(8)

Thus, the change in the overlap resonance can be expressed as

$$\lambda_{\text{shift}} = \lambda_0' - \lambda_0 = h \cdot \text{FSR}_2,$$

(9)

where $h=\Delta \lambda / \Delta\text{FSR}$ is an integer. If, however, there is no small integer $h$ such that satisfies Eq. (9), then we say, the overlap wavelength is off-resonance. The minimum possible shift $\Delta\text{FSR}$ occurs for $h=1$. Once the effective index change $\Delta n_{\text{eff}}$ is less than the detection limit, the overlap resonance cannot be detected. The discreteness of the overlap resonance shift means the sensing modality of the analyst is discrete too. The discrete characteristic will be discussed later. The sensitivity of the dual-MR sensor is defined as the ratio of $\lambda_{\text{shift}}$ to the variation of the effective index $\Delta n_{\text{eff}}$ due to the analyte,

$$S = \frac{\lambda_{\text{shift}}}{\Delta n_{\text{eff}}} = \frac{\Delta \lambda}{\Delta n_{\text{eff}}} = \frac{\Delta \text{FSR}_2}{\Delta \text{FSR}_1} \frac{1}{1-a} \Delta \lambda.$$  

(10)

According to Eq. (10), the sensitivity of dual-MR sensor is $1/(1-a)$ of an otherwise comparable single-MR sensor. When $a$ approaches 1, i.e., $R_1 \approx R_2$, the sensitivity of the dual-MR sensor may be orders of magnitude higher than that of the single-MR sensor; however, limitations associated with finite $Q$ (see below) also come into play.

The detection limit of the single-MR sensor is typically due to the photodetector. Based on the enhanced overlap resonance shift in the dual-MR sensor, the detection limit depends on $h \approx 1$. Combining the results of Eqs. (1), (2), (5), and (6), the detection limit of the dual-MR sensor is

$$D_l = \frac{\Delta n_{\text{eff}}}{\text{FSR}_2} \frac{\Delta \lambda}{\lambda} = \frac{(1-a)}{2\pi R_2 n_{\text{eff}}}.$$  

(11)

The large shift of the overlap resonance should be an integer multiple of FSR$_2$. Reducing $D_l$ favors large rings of similar size (i.e., $|m-n|/n \approx 1$).

When the effective index change equals $D_l \times n_{\text{eff}}$, the overlap resonance is shifted one FSR$_2$. We take parameters typical of Si waveguides of height/width 220 nm/500 nm, which have effective index of 2.45. Assuming the operating wavelength $\lambda_0$ is 1.55 $\mu$m, $a=0.9$, $R_2=50 \mu$m, and the detection limit $D_l=2 \times 10^{-4}$ RIU. That means once $\Delta n_{\text{eff}}$ changes $2 \times 10^{-4}$ RIU, the overlap resonance will shift $\sim 3.1$ nm, which is easily detected. Compared to the single-MR sensor, the dual-MR sensor is much more sensitive with a large overlap resonance shift. The parameter $a$ can be chosen close to 1 to improve the performance further. As a result, the sensitivity can be enhanced by the factor of $1/(1-a)$, and the detection limit consequently can be reduced to detect weaker signals. Using $a=0.99$, $R_2=500 \mu$m with same typically parameters as below, the detection limit $D_l=2 \times 10^{-6}$ RIU, which leads to minimum overlap resonance shift $\sim 0.31$ nm. Based on similar param-
The sensing mechanism is low metric spectrum with and without analyte even for relatively MZI as in Fig. 4. The resonances overlap at symmetrical spectrum to center around overlap resonance. The coupler in MZI can split input light equally which can bring the coupling coefficients of the rings in Fig. 3, we obtain the distinguish when two such troughs are close. By decreasing resonance troughs in the spectrum, which may be difficult to be seen that high \( Q \) is not as critical. Low \( Q \) means wider resonance troughs in the spectrum, which may be difficult to distinguish when two such troughs are close. By decreasing the coupling coefficients of the rings in Fig. 3, we obtain the low-\( Q \) MR spectrum and low-\( Q \) dual MR spectrum in the MZI as in Fig. 4.

The overlap resonance appears in the center of the symmetric spectrum with and without analyte even for relatively low \( Q \). Provided \( Q \) is not too small, it is not likely to be the key characteristic of the sensor. The sensing mechanism is depending most strongly on the troughs in the spectrum and not so sensitively on the width as in the case of the single MR sensor.

In this study, we have discussed the theory of the dual-MR MZI sensor. The dramatic shift of the overlapping resonance due to the presence of an analyte is found to lead to high sensitivity of the device compared to an otherwise comparable single-MR sensor. The detection limit of the sensor depends on the FSR\(_2\) shift of the overlap resonance, which is easily detected in practice. In our simulations, the rings were chosen to have radii \( R_1=505 \mu\text{m} \) and \( R_2=500 \mu\text{m} \); the device was predicted to have a detect limit \( 2 \times 10^{-6} \text{RIU} \), \( \Delta \lambda=0.31 \text{ nm} \) overlap resonance shift. Moreover, the sensitivity is predicted to be 100 times that of the single-MR sensor. The closer \( R_1 \) and \( R_2 \), the higher the sensitivity of the device and the lower the detection limit. Meanwhile, the detection limit and sensitivity of this scheme do not depend sensitively on the width of the resonance. That means this sensor can, up to a point, circumvent conventional limits due to \( Q \). Finally, this dual-MR interference sensor is also suited for other sensing schemes, which rely on analyte-induced changes of cavity resonances.

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