Grating engineering for self-referenced Al_2O_3 microring resonator sensors

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Microring resonators can be used in biosensing applications. Including a Bragg grating in the resonator results in frequency splitting of the resonances, creating a self-referenced sensor. The grating has to be designed such that the reflectivity is uniform. In that case, changes in the frequency splitting can be ascribed solely to the presence of biomarkers. To achieve this behaviour, the grating design is optimized by chirping and apodization. The resulting resonance splitting is constant over a bandwidth of 5 nm. The RIU sensitivity of this sensor is 209.22 pm/RIU, with a limit of detection of $\sim 7 \cdot 10^{-6}\ RIU$.

Introduction

Microring resonator sensors are a promising candidate for biosensing applications [1]. A microring resonator (MRR) sensor is a device that can sense changes in the environment of the device by measuring shifts in the resonance spectrum. The resonances shift when the optical path length of the MRR changes, which happens as a result of external perturbations to the system. In the case of a biosensor, the MRR is typically covered with acceptor molecules, that selectively bind to a particular biomarker [1]. The biomarker is a molecule found in bodily fluids, blood or tissue that is a sign for a specific disease. The optical path length of the MRR changes as biomarker molecules attach to acceptor molecules. As a result of the changed optical path length, the resonances shift.

In biosensing applications, one would often try to show the presence of a specific biomarker molecule. It would seem straightforward to do so by recording shifts of the resonances. However, more parameters influence the effective refractive index of the waveguides, for instance, temperature fluctuations and bulk refractive index changes. To ascribe changes in the resonance spectrum to the presence of biomarker molecules, referencing can be used to distinguish between different signal sources. Typically two transducers are used, of which one is sensitive to the biomarker and one is not. This however leaves uncorrelated noise contributions. To compensate for the uncorrelated noise contributions, a self-referenced MRR can be designed.

The self-referenced MRR consists of a Bragg grating inside the path of the MRR. The resonances of the MRR with Bragg grating now occur as resonance doublets. The frequency splitting, the frequency separation between the two resonances in the doublet, is directly related to the grating reflectivity [2]. Therefore, by recording the amount of frequency splitting, any signal that causes a change in the grating reflectivity can be measured. When the periodicity of the Bragg grating is filled with (or alternatively formed by) acceptor molecules, the reflectivity of the Bragg grating changes upon adhesion of biomarker molecules. Furthermore, since the splitting is much less sensitive to temperature and bulk refractive index variations than the MRR resonances, the MRR with Bragg grating exhibits self-referencing behavior. Figure 1 (b) depicts the splitting of the resonances in resonance doublets.

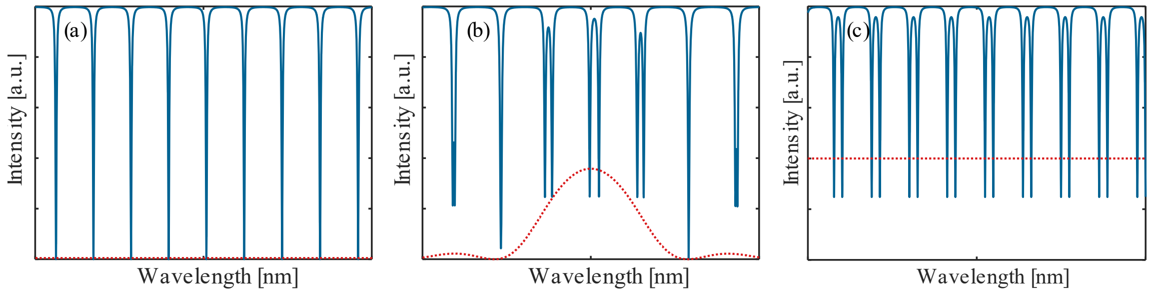

Figure 1 Transmission spectrum of (a) a MRR without a grating, (b) a self-referenced MRR, c) self-referenced MRR with idealized grating. In all cases, the blue line represents the transmitted power and the red line represents the reflectivity of the Bragg grating

Grating Engineering

The working principle of the Bragg grating can be understood as follows. The Bragg grating lifts the degeneracy between the clockwise and counterclockwise propagating modes in the MRR. A standard single periodicity and fill factor Bragg grating will have a frequency response as indicated by the red line in figure 1 (b). A flat response is required, shown in figure 1 (c), to ascribe changes in the frequency splitting to the presence of biomarker molecules. If the grating response is not flat, any shift of the MRR resonance will change the encountered grating reflectivity as shown in figure 1 (b). The amount of frequency splitting in this case remains sensitive to temperature and bulk refractive index changes.

A flat grating response, as shown in figure 1 (c), can be achieved by engineering the Bragg grating response. Two ways of manipulating the spectral response of a Bragg grating are chirping and apodization [3, 4, 5]. By chirping, the grating period of the Bragg grating increases along the grating length indicated in figure 2 (a). As a result, the bandwidth of the reflection increases. Apodizing the grating changes the duty cycle of a grating period along the length of the grating, as indicated in figure 2 (b). By changing the duty cycle, the grating strength is varied along the length of the grating. Apodization causes the reflectivity to flatten over the bandwidth.

The gratings are placed on top of a MRR that has a circumference of 3384 µm. The Al_2O_3 waveguides have a height of 0.4 µm and a width of 1.6 µm. In total, the length of the PMMA grating is 200 µm, while the thickness of the PMMA layer is 250 nm. For this thickness, the overlap of the fundamental TE mode with the PMMA grating is 22.86%. The chirp parameter is set to 600 $\mu m/m$ and the grating is apodized with a hyperbolic tangent duty cycle apodization profile [4] with parameters $D_a = 1.8$ and $D_b = 2.9$. Using the grating parameters, the self-referenced MRR sensor is fabricated.

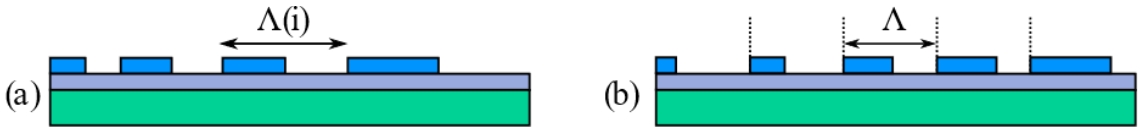

Figure 2 Schematic depiction of (a) chirped PMMA grating, and (b) apodized PMMA grating.

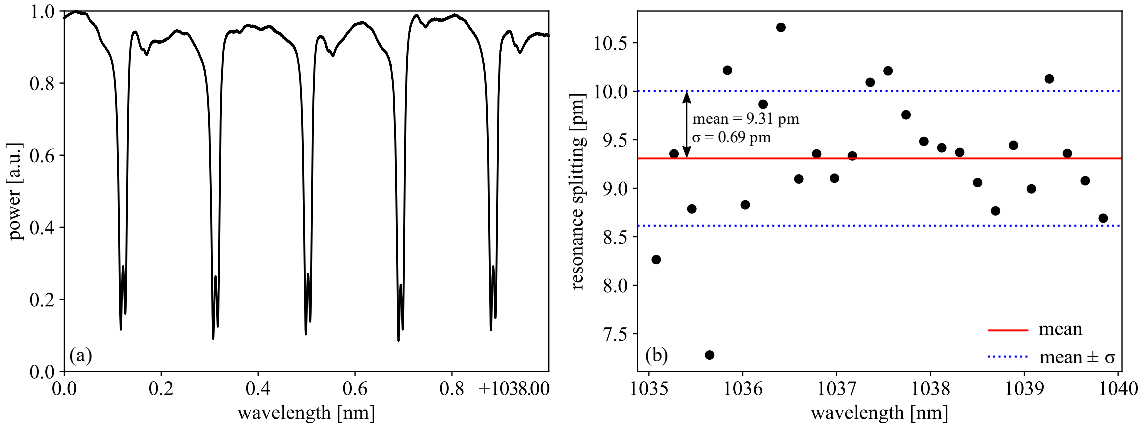

Figure 3 Transmission spectrum of (a) a self-referenced MRR with a DI water cladding, and (b) the resonance splitting of each resonance doublet in the wavelength range 1035 – 1040 nm.

Characterization device

In order to characterize the self-referenced MRR, the transmission spectrum is studied. The transmission of light of different wavelengths is measured with a photodetector. A TOPTICA CTL 1050 source allows scanning over a wavelength range of 1020 to 1070 nm. The light is guided through single-mode polarization-maintaining (PM) fibers. These fibers are butt-coupled to the end facets of the chip using index matching fluid.

In order to introduce aqueous samples, the device is equipped with a PDMS pool. The PDMS pool allows for the introduction of different fluids, to have a controlled bulk refractive index. Furthermore, the device is placed on top of a heater, that is controlled with a PID controller, to keep the temperature of the sensor as constant as possible. The resonance spectrum is measured with a DI water cladding at a temperature of 22 °C. A small section of the transmission spectrum is shown in figure 3 (a). This figure shows that the resonances are split into resonance doublets.

In figure 3 (b), the resonance splitting is shown for each of the resonance doublets in the wavelength range of 1035 to 1040 nm. The resonance splitting is determined by finding the minima of the measured power. Since the wavelength resolution of the transmission spectrum is limited, the resonance splitting can only be determined with limited accuracy in this method. The mean resonance splitting is found to be 9.31 pm, with a standard deviation of 0.69 pm. The standard deviation is identical to the wavelength resolution of the transmission spectrum. In other words, within the detection limits, the resonance splitting is constant over a 5 nm bandwidth.

Sensitivity analysis

The performance of the sensor is quantified by determining its sensitivity and the limit of the detection (LOD). The sensitivity of the resonance splitting to temperature variations and bulk refractive index changes is measured. Since the sensor is not yet functionalized, the grating trenches will also be filled with the different fluids that are flushed through the PDMS pool. As a result, during the sensitivity measurement, not only the bulk RIU is changed, but the refractive index contrast in the grating changes as well. The change in index contrast results in a change in reflectivity, resulting in a change in resonance splitting.

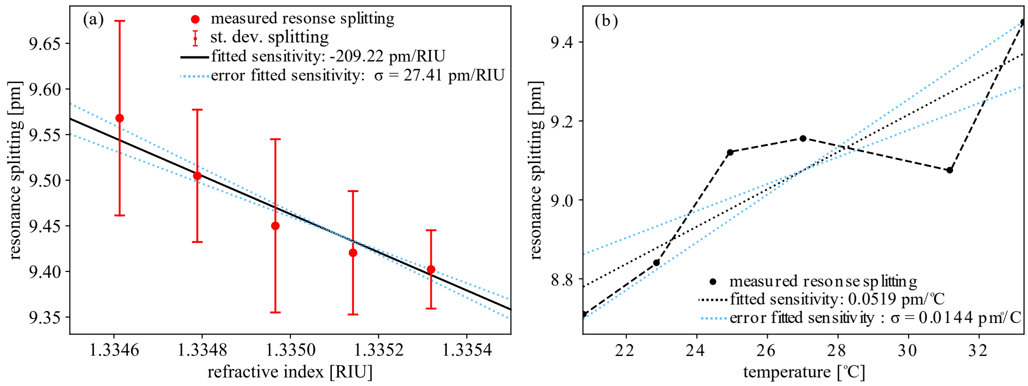

Figure 4 Resonance splitting as a function of (a) bulk refractive index and (b) temperature.

In figure 4, the measured resonance splitting as a function of the refractive index of the cladding solution and as a function of temperature are plotted. From these plots, both the bulk refractive index sensitivity and temperature sensitivity can be obtained as the slope of the linear fit. A bulk refractive index sensitivity of 209.22 ± 27.41 pm/RIU and a temperature sensitivity of 0.0519 ± 0.0144 pm/℃ were measured From these two values, the LOD can be calculated.

The LOD depends on the noise floor of the measurements. Due to the self-referencing, the noise floor is to expected to reduce significantly. Assuming that only the temperature noise contribution is to be considered for an estimation of an expected limit of detection, the LOD is given by

$$LOD = \frac{3\sigma}{S_{bulk\ RIU}} = \frac{3 \cdot S_{temperature} \cdot \Delta T}{S_{bulk\ RIU}}. \quad (1)$$

In equation (1), the parameter ΔT represents the practically achievable temperature stability, set to 10 mK. Calculating the LOD results in a value of $\sim 7 \cdot 10^{-6}$ RIU.

Conclusion

The self-referenced MRR of this work consists of a Bragg grating that is optimized to have a flat frequency response. The constant frequency response is obtained by chirping and apodizing the grating. The characterisation of the sensor shows that the resonance splitting is constant over a bandwidth of 5 nm. Additionally, a RIU sensitivity of 209.22 ± 27.41 pm/RIU, with a temperature sensitivity of 0.0519 ± 0.0144 pm/℃ were experimentally demonstrated. Combining these two sensitivities results in a limit of detection of $\sim 7 \cdot 10^{-6}$ RIU.

References

[1] M. de Goede et al., “Al_2O_3 microring resonators for the detection of a cancer biomarker in undiluted urine,” Opt. Express, vol. 27, no. 13, p. 18508, Jun. 2019.

[2] De Goede, M. et al. Mode-splitting in a microring resonator for self-referenced biosensing. Opt. Express, vol 29, (2021).

[3] A. Tehranchi et al., “Engineered gratings for flat broadening of second-harmonic phase-matching bandwidth in mgo-doped lithium niobate waveguides” Opt. Express, vol 16, Nov. 2008.

[4] I. Navruz and A. Altuncu, New trends in computer networks, Imperial College Press, ch 12, pp. 114 - 123, 2005.

[5] S. S. A. Khan and M. S. Islam, “Determination of the Best Apodization Function and Grating Length of Linearly Chirped Fiber Bragg Grating for Dispersion Compensation,” Journal of Communications, vol. 7, pp. 840–846, Nov. 2012.