Interferometric approach to solve microring resonance splitting in biosensor applications

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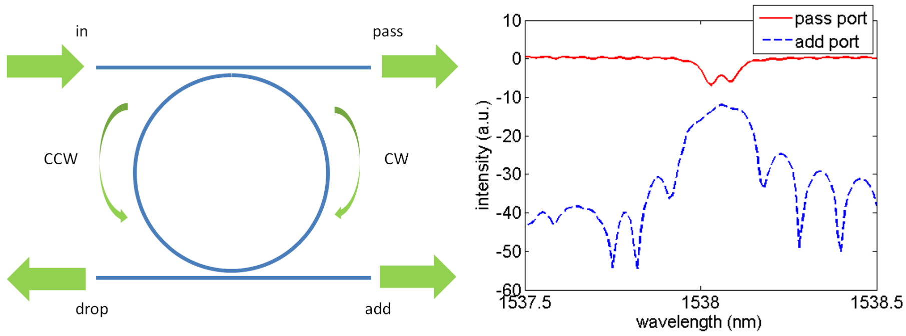
Silicon-on-insulator microring resonators have proven to be an excellent platform for label-free nanophotonic biosensors. The high index contrast of the silicon-on-insulator platform allows for fabrication of micrometer size sensors. However, it also limits the quality of the resonances by introducing an intrinsic mode-splitting. Small deviations from perfect symmetry lift the degeneracy of the normal resonator modes. This severely deteriorates the quality of the output signal. The quality of the resonances is of utmost importance to determine the performance of the microrings as a biosensor. We suggest an integrated interferometric approach to give access to the unsplit, high-quality normal modes of the microring resonator.

Introduction

Silicon-on-insulator (SOI) microring resonators have proven to be an excellent platform for label-free nanophotonic biosensors. The high index contrast of the SOI-platform allows for fabrication of micrometer size sensors. The small sensor size makes microring resonators excelent candidates for highly multiplexed assays [1]. It also allows for integration of a sensor on an optical fiber tip, opening the door to in-vivo applications [2]. By combining microrings in advanced sensing configurations, it is also shown that their sensitivity can be improved significantly [3]. The high index contrast of the SOI-platform causes high confinement of the optical fields in the waveguides, which makes the microrings very sensitive to changes on the waveguide surface. This explains their very high sensitivity, but at the same time, waveguide roughness causes scattering of the guided light. This degrades the quality factor of the resonances and can ultimately lead to splitting of a resonance [4]. Because the detection limit of a microring biosensor is directly related to the quality of the ring resonance, a high Q-factor is of primordial importance in sensing applications [5]. In this paper, we present an integrated interferometric approach to resolve the resonance splitting of a microring resonantor on a single chip. Resulting in a significant improvement of the resonance quality.

Origin of resonance splitting

A perfectly symmetric microring resonator mode is twofold degenerate. Both clockwise (CW) and counterclockwise (CCW) propagation are possible in the microring and both modes are uncoupled. This degeneracy is lifted when the CW-mode and CCW-mode become coupled. Surface roughness on the waveguide edges and the proximity of bus waveguides for microring interrogation form deviations from circular symmetry. These deviations cause forward propagating light to scatter back into the opposite direction, exciting a CCW-mode from a CW-mode and vice versa. Standing-wave modes as a symmetric and antisymmetric superposition of the traveling waves can be considered as the new eigenmodes of the system. They will however, no longer be degenerate as a consequence of the symmetry breaking coupling [6]. If the linewidth of the resonance is small enough to distinguish both modes, the resonance splitting will be visible in the output signal. This occurs for high quality resonances. Evidence of this effect is provided in figure 1, which shows both the pass-port and add-port spectrum of a microring in add-drop configuration. Only the input port is excited, so ideally, no power is present in the CCW-mode and the add-port remains dark. The measurement shows that backscattering in the microring waveguide cannot be neglected, resulting in significant power in the add-port and resonance-splitting in the pass-signal.



(a) (b)

Figure 1: (a) Microring resonator in add-drop configuration (b) Measured spectra showing resonance splitting and backscattered power

Integrated interferometric circuit

As demonstrated in [7], an interferometric approach can be used to access the normal modes of the microring resonator in an output signal. We have implemented this in an integrated circuit on a single SOI-chip. A layout of the circuit is provided in figure 2. Vertical grating couplers are used to couple light from a tunable laser lightsource into

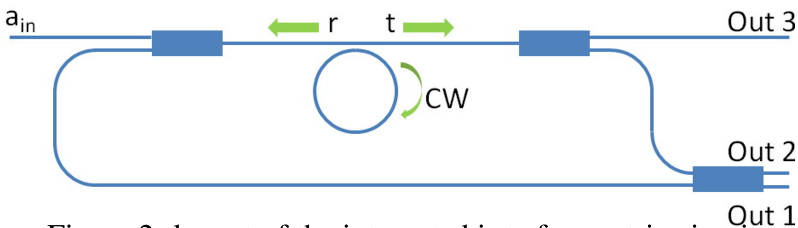


Figure 2: layout of the integrated interferometric circuit

the circuit and collect the power at the output. The input light excites a CW-mode in the microring resonator, a CCW-mode is excited as a consequence of mode-coupling. The normal modes of the microring are a symmetric and antisymmetric superposition of the CW and CCW-mode, so we can express them as follows:

$$a_{\pm} \quad = \quad \frac{1}{\sqrt{2}}(a_{CW} \pm a_{CCW}) \tag{1}$$

If the coupling per unit time between the bus waveguide and the microring is represented by κ, the fields transmitted and reflected by the resonator are

$$t = \frac{1}{\sqrt{2}} a_{in} + \kappa a_{CW} \quad \text{and} \quad r = \kappa a_{CCW} \tag{2}$$

Both fields are combined in a multi mode interferometer (MMI), this results in the following signals at the different output ports. ϕ denotes the phase difference between the combining waves.

$$\begin{aligned} out_1 &= \tfrac{1}{2}(\tfrac{1}{\sqrt{2}} a_{in} + \kappa a_{CW} + e^{i\phi}\kappa a_{CCW}) \\ out_2 &= \tfrac{1}{2}(\tfrac{1}{\sqrt{2}} a_{in} + \kappa a_{CW} - e^{i\phi}\kappa a_{CCW}) \\ out_3 &= \tfrac{1}{\sqrt{2}} t \end{aligned} \tag{3}$$

If we design the circuit such that the phase difference between the reflected and transmitted wave equals a multiple of 0 or π, we see that the signals in output one and two are proportional to the normal modes of the resonator. At the same time, output three is proportional to the pass-signal of the microring resonator in the all-pass configuration. This means we have access to the unsplit, high-Q normal modes of the cavity. If the detection limit of a biosensor is limited by the quality-factor of the resonance, this provides a tool to improve the detection limit significantly. Higher resonator Q-factors give rise to lower detection limits.

Experimental results

The circuit from figure 2 is designed and processed in a CMOS pilot line at imec. Using the vertical in- and outputcouplers on the waveguides, the chip can easily be measured in a fiber-to-fiber configuration. For the junction regions where waveguides are combined and splitted, MMI 2x1 and MMI 2x2 couplers are used. The coupling from the microring to the waveguide is ensured by weak evanescent coupling to a neighbouring bus waveguide. To obtain the measured spectra, a SANTEC TSL-510 Tunable laser source is used to generate the input signals. Output intensities are measured by a HP-8153 optical powermeter. The laser wavelength is swept in $10pm$ steps during recording of the power.

Figure 3 shows the recorded specta at the three outputs of the circuit. Output one and two are proportional to the normal modes of the resonator, output three returns the all-pass spectrum. We clearly see the all-pass spectrum shows severe splitting of $60pm$ in the resonance. This values is comparable to 3dB-bandwidth of the normal mode in output one. The Q-factors of the recorded resonances are listed in table 1. This result shows

Table 1: Q-factors of resonances

resonance	Q-value
output 1	$2.20 \cdot 10^4$
output 2	$1.05 \cdot 10^4$
output 3	$1.28 \cdot 10^4$

an almost twofold improvement of the resonance quality from output three to output one. Notice the distinct asymmetrical shape of the resonance in output two which makes unambiguous definition of a Q-value difficult. Additionally, the extracted normal modes do not correspond exactly with the normal modes we can distinguish in the all-pass signal. This non-ideal behaviour is a consequence of fabrication variations. The 2x2 MMI is

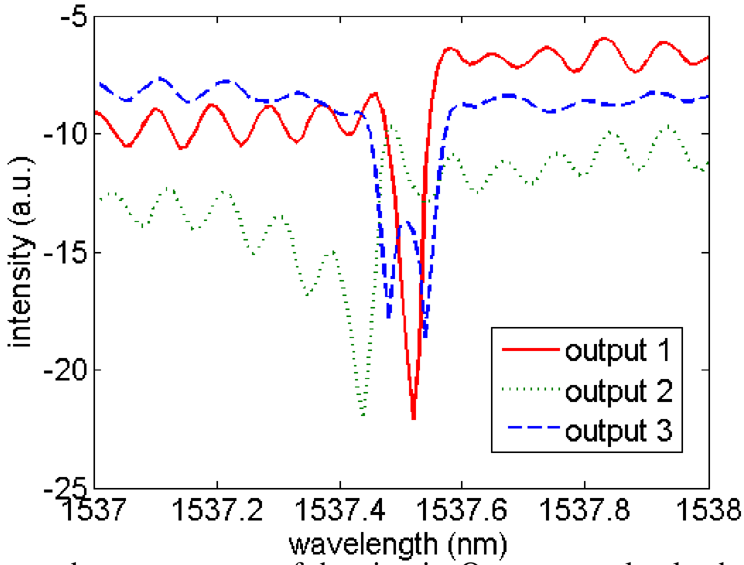


Figure 3: Measured output spectra of the circuit. Output one clearly shows the improvement of the resonance shape compared to the all-pass signal in output three.

especially sensitive to this and is not exactly balanced as a result. Also the phase relation between the reflected and the transmitted wave differs slightly from the required value of $k \cdot \pi$. This can be solved by careful tuning of the waveguide structures.

Conclusion

We have succesfully integrated an interferometric setup to resolve the resonance splitting of microrings on the SOI-platform. The access to the unsplit normal modes of the resonator allows the improvement of the detection limit of microring resonator biosensors.

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