The ‘Lord of the Rings’ of optical biosensors

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A novel optical biosensor using waveguide double-ring resonators provides high-sensitivity detection of biomolecules through intensity measurements using a low-cost broadband light source.

Sensors relying on planar optical waveguides—i.e., physical structures that guide electromagnetic waves in the optical spectrum—have attracted great interest for their potential applications in many areas. Examples include biological analysis and environmental monitoring. Unlike existing methods based on the same principle of adsorption of materials onto planar surfaces, such as surface plasmon resonance (SPR) analyzers, waveguide sensors are miniaturized and offer high-density array integration. In particular, sensors based on a single optical micro-ring resonator have been extensively investigated.\(^1\)–\(^4\)

In our previous work, we improved their sensitivity\(^5\) by combining two cascaded waveguide micro-ring resonators. These combined resonators rely on the Vernier effect, which gives high-precision measurement using a shift in the resonant wavelengths of one ring relative to the resonant wavelength of the other.\(^6\) But the benefit of these miniaturized waveguide sensors is offset by their reliance on an external tunable laser or a high-resolution spectrometer, both of which are bulky and cumbersome and increase the sensor’s overall cost. The principle of wavelength interrogation, which is the most commonly used mechanism in these sensors, may therefore not be the most suitable for practical applications.

Instead, a sensor based on intensity interrogation, measuring the change in intensity of a molecule of interest, or analyte, through a simple optical power detector, could be more appropriate. However, measuring the intensity change that occurs at a fixed wavelength near the resonance peak of a high-quality-factor (Q-factor) ring resonator would require a light source with a very accurate wavelength and a narrow bandwidth together with high stability. This is not easy to achieve in practice. To address this challenge, we have developed a highly sensitive biosensor based on the principle of intensity interrogation using two cascaded micro-ring resonators and a low-cost broadband light source.\(^7\) This method can directly derive changes in the refractive index of an analyte by measuring relative intensities without the need for spectral characterization. It also works regardless of the wavelength and power stability of the light source employed.

We tested a double-ring sensor fabricated on a silicon-on-insulator substrate. It consisted of a reference ring and a sensing ring linked by a common bus waveguide (see Figure 1). While the reference ring was covered by an upper cladding layer, the sensing ring was exposed to an analyte sample in the sensing window. We coupled the light from a broadband source such as a LED into the input port. A large portion passed straight through to the reference port, while a small portion passed through the reference ring and was coupled to the bus waveguide. This light was then further filtered by the sensing ring and subsequently exited at the signal port.

The two rings may have the same or slightly different frequency spacing of their resonator modes, also known as free spectrum ranges (FSRs). When the FSR of the sensing ring, \(\Delta \lambda_s\), was slightly different than that of the reference ring, \(\Delta \lambda_r\), we observed that the total transmission coefficient of the two rings had resonant peaks with a periodically varying envelope function. When the refractive index of the sample in the sensing window changed, the resonant wavelengths of the sensing ring shifted by

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We then tested this sensor’s ability to detect sodium chloride in several sample solutions of various concentrations. Experimental results show the transmission spectra of a solution whose concentration varied between 0 and 8% (see Figure 2). While the resonance peaks of the sensing ring shifted by only 0.327 nm, the envelope function shifted by 49 nm, with an amplification factor of 150. We then measured the normalized output power versus the sample refractive index change using a broadband source with 28 nm bandwidth centered at 1553 nm (see Figure 3). We estimated that with design optimization and improvement of the Q-factor of the ring resonators, an optical biosensor with ultrahigh sensitivity in the order of $2 \times 10^4$ dB/refractive index unit could be achieved, corresponding to a refractive index detection limit of about $5 \times 10^{-7}$.

In conclusion, we showed the feasibility of creating a biosensor based on an intensity-interrogated planar waveguide double ring resonator. This system uses a low-cost broadband light source combined with simple intensity measurements without requiring an external bulky and expensive tunable laser or spectrometer. This sensor offers many benefits, including high sensitivity, simplicity and speed of analysis, temperature insensitivity, compactness, and suitability for high-density array integration. Low-cost practical applications of planar waveguide ring-resonator biosensors will be the object of our future work.

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