

Biochemical sensors based on polymer microrings with sharp asymmetrical resonance

Chung-Yen Chao and L. Jay Guo^{a)}

Solid-State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109

(Received 12 May 2003; accepted 27 June 2003)

Photonic microresonators have great potential in the application of highly sensitive sensors due to high Q -factor resonances and steep slopes between zero and unity transmission. A microring resonator with increased resonance slopes is proposed by introducing two partially reflecting elements implemented by waveguide offsets. This configuration produces a Fano-resonant line shape and can greatly enhance the sensitivity of the sensor. Polystyrene microring resonators were fabricated by the nanoimprinting technique, and the optical spectra were measured in glucose solutions of different concentrations. The shift in resonant wavelength and variation of the normalized transmitted intensity are linearly related to the concentration of the glucose solution. © 2003 American Institute of Physics. [DOI: 10.1063/1.1605261]

Microdisk and microsphere resonators have been proposed as sensitive chemical sensors¹ and biosensors due to their large Q factors of resonance.² These sensors rely on accurate measurement of the effective refractive index change due to the presence of biomolecules on the surface of sensing areas, or the presence of a solution surrounding the devices.^{3,4} Boyd and Heebner proposed that sensing can also rely on the optical absorption of molecules attached on microdisk surfaces.⁵ In all these examples, detection is made by measuring resonance shifts. As an alternative, detection can also be made by measuring the output intensity change from the microresonator at a fixed wavelength. The latter scheme is especially useful for detecting very small concentration of analytes.

Theoretically, the resonance line shape of a traditional microdisk or microsphere resonator is symmetrical with respect to its resonant wavelengths. In this letter, we propose a microring resonator structure that incorporates two partially reflecting elements in the waveguide that couples the microresonator. This structure can produce a sharp asymmetric Fano-resonance line shape, in which the slope between the zero and the unity transmission is greatly enhanced compared with that of a conventional microring resonator. Such a Fano-resonance scheme was proposed by Fan to improve the optical switching characteristics of microresonator-based devices.⁶ For the sensor application that we consider in this letter, the sharply asymmetric line shape of the Fano resonance provides greatly improved slope sensitivity. We further propose use of a polymer core and air cladding for the microring waveguides because they could allow surface modification for specific biomolecule attachment. As a proof of concept, we fabricated a polystyrene microring resonator by the nanoimprinting technique and used it to measure the glucose concentration in aqueous solutions.

A microring resonator consists of a ring, or racetrack, waveguide that is closely coupled to a straight waveguide, as shown in Fig. 1(a). In the proposed configuration two offsets

are added in the straight waveguide [Fig. 1(b)], which cause partial reflection of propagating optical waves. To analyze the behavior of this configuration, we use the scattering matrix introduced in Ref. 6 to obtain the transfer matrix, T_s , that relates the incoming and outgoing optical field components at the left port (a_1 and b_1) to those at the right port (a_2 and b_2):

$$\begin{aligned} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} &= \frac{1}{i\sqrt{1-r^2}} \begin{bmatrix} -1 & -r \\ r & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\delta} & 0 \\ 0 & e^{-i\delta} \end{bmatrix} \\ &\times \begin{bmatrix} 1 - \frac{i\gamma}{\omega - \omega_0} & \frac{-i\gamma}{\omega - \omega_0} \\ \frac{i\gamma}{\omega - \omega_0} & 1 + \frac{i\gamma}{\omega - \omega_0} \end{bmatrix} \times \begin{bmatrix} e^{i\delta} & 0 \\ 0 & e^{-i\delta} \end{bmatrix} \\ &\times \frac{1}{i\sqrt{1-r^2}} \begin{bmatrix} -1 & -r \\ r & 1 \end{bmatrix} \times \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} \equiv T_s \times \begin{bmatrix} a_1 \\ b_1 \end{bmatrix}. \quad (1) \end{aligned}$$

Here ω is the angular frequency of incident light, r the amplitude reflection coefficient at the waveguide offset junctions, ω_0 the center angular frequency of a selected resonance, γ the half width of this resonance, and δ the phase shift that the waveguide mode acquires as it propagates a length of L [see Fig. 1(b)]. The transmission spectrum near one resonance can then be calculated using Eq. (1). Figure 1(c) shows calculated spectra for configurations with and without the partially reflecting elements. Compared with a conventional microring resonator where waves propagate in one direction, the added partially reflecting elements introduce backward propagating waves that can perturb the phase of the wave transmitted and hence lead to complex interference. Such interference produces an asymmetric Fano-resonant line shape.⁷ As can be seen in Fig. 1(c), Fano resonance greatly increases the slope between the zero and the unity transmission compared with that of symmetric resonance exhibited in a traditional microring resonator, and this characteristic can be used for the sensitive detection of the resonance shift.

^{a)}Electronic mail: guo@eecs.umich.edu

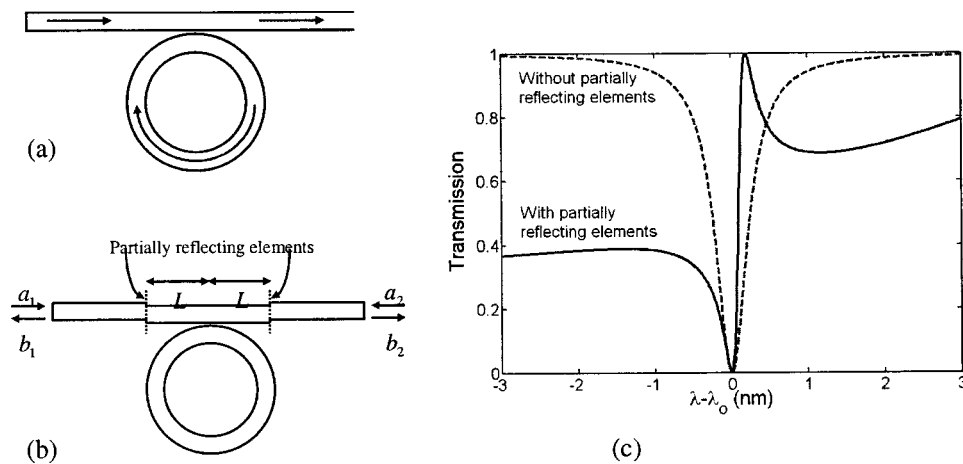


FIG. 1. Schematic configuration of (a) a conventional microring resonator and (b) a microring resonator with two partially reflecting elements that are implemented by waveguide offsets. (c) Symmetric resonance spectrum of a conventional microring resonator (dotted curve) and asymmetric Fano resonance of one with the reflecting elements (solid curve). The parameters used are $\lambda_0 = 1550$ nm, $L = 15.565$ μm and $r = 0.5$.

We chose polymer material to fabricate the microring resonator because of its rich surface functionality as well as low cost and simple processing. We have developed a process to fabricate polymer microring resonators using a direct imprinting technique,⁸ which is applicable to a large number of polymer materials. Details of the fabrication process can be found in Ref. 8. Briefly, a silicon mold with microring or microracetrack patterns was first fabricated by a combination of electron-beam lithography, nanoimprinting,⁹ and reactive ion etching (RIE). A thin polystyrene (PS) film was spin coated onto an oxidized silicon substrate. Then the mold was imprinted into the PS film under pressure of 900 psi and temperature of 175 °C. After cooldown and separation of the mold from the substrate, PS waveguides with microring resonators formed. Any residual PS layer was subsequently removed by RIE, and the oxide underneath the PS waveguide was isotropically wet etched. The latter step was taken to create a pedestal structure beneath the waveguide, which not only enhanced light confined within the waveguide but also increased the surface area of the device that can interact with analytes. Figure 2 shows scanning electron microscopy (SEM) micrographs of a typical PS microring resonator and a cross-sectional view. Notice that the two offsets in the upper waveguide act as the partially reflecting elements to produce the desired Fano resonances.

The transmission spectrum was measured with a tunable laser (Santec TSL-220). Polarization of the incident laser beam was controlled by a half-wave plate and a polarizer. The laser beam was coupled into PS waveguides and collected by objective lenses. The spectrum (Fig. 3) of a microring resonator with waveguide offsets obtained clearly shows periodic resonances with the expected Fano-resonant line shape.

The resonant wavelengths of a microring resonator depend on the effective refractive index of the waveguide mode. This index can be affected by, e.g., biomolecules attached to its surface, or by a refractive index change of the surrounding environment that serves as waveguide cladding. Sensitive detection of such an effective index change can be made by either monitoring the shift of resonant wavelengths or by measuring the change of light intensity from the output at a fixed wavelength. The former method allows a large dynamic range for the sensor, while the latter provides more sensitive detection of small changes in resonance by virtue of the large slope sensitivity of the spectrum.

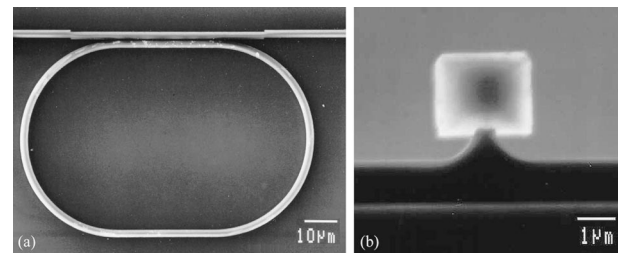


FIG. 2. (a) SEM of a PS microring resonator with waveguide offsets. (b) Cross-sectional SEM of a PS waveguide on top of a silicon oxide pedestal structure.

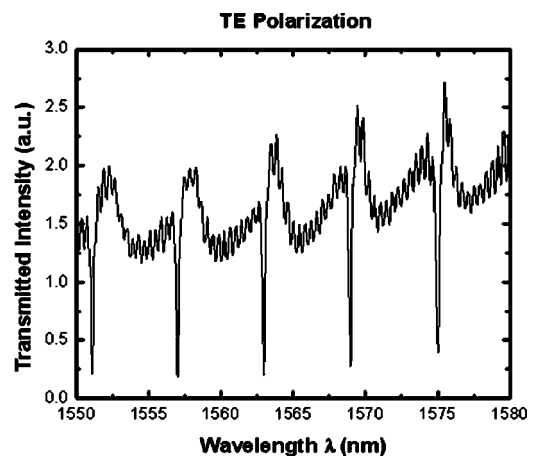


FIG. 3. Measured transmission spectrum of a PS microring resonator showing periodic resonances with a Fano-resonant line shape.

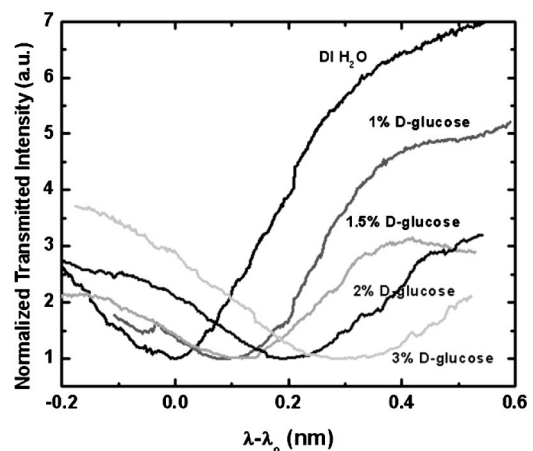


FIG. 4. Spectra measured when the resonator is immersed in DI water and in 1%, 1.5%, 2% and 3% glucose solutions.

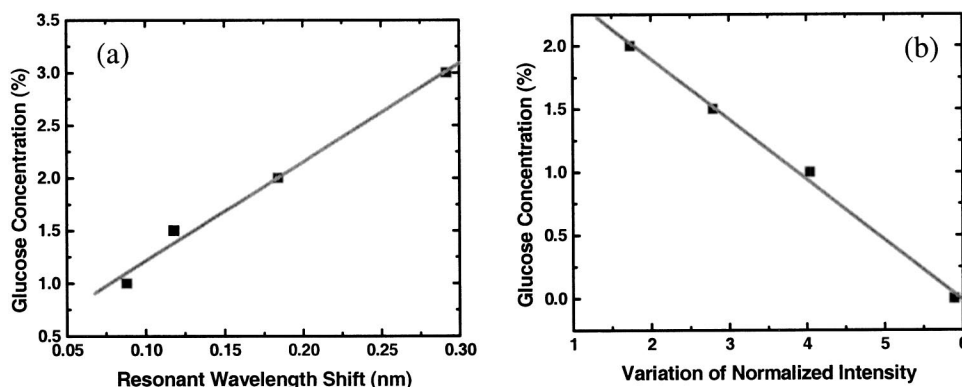


FIG. 5. (a) Concentration of the glucose solution as a function of the resonant wavelength shift. (b) Glucose concentration as a function of the normalized variation in transmitted intensity at fixed wavelength of 1569.29 nm.

We performed the experiment to detect the concentration of glucose in an aqueous solution by using a fabricated PS microring resonator. We measured the change in the spectra of the device near one of its resonances ($\lambda_0 = 1568.97$ nm) when it was immersed in glucose solutions of different concentrations. To avoid possible experimental inaccuracy, the reference spectra of the device in de-ionized (DI) water were measured each time before immersion into a glucose solution. The measured device spectra at different glucose concentrations are shown in Fig. 4. The curves shift consistently toward higher wavelength with an increase of the glucose concentration. The wavelength shift of the resonance is shown in Fig. 5(a) as a function of the concentration of the glucose solution, for which a linear relationship can be observed. Based on Fig. 4, the variation of the normalized transmitted intensity at a fixed wavelength (1569.29 nm) is plotted in Fig. 5(b) as a function of the glucose concentration, which also shows a linear relationship. We noticed that this relationship becomes nonlinear when the selected wavelength is outside the linear regime of the spectra. Since the smallest variation of transmitted intensity that can be detected with our current setup is 10 nW, we deduce that the minimum detectable concentration change of glucose solution is $\sim 0.024\%$, or 24 mg/dl. By increasing the Q factor of the resonator, the slope becomes steeper and the sensitivity can be further enhanced.

In conclusion, we proposed use of a polymer microring resonator that exhibits sharp asymmetric Fano resonances as a possible biochemical sensor. We demonstrated that the resonant wavelength of a polystyrene microring resonator is very sensitive to the concentration of glucose solution, and the resonance shift has a linear relationship with the glucose concentration. By measuring this shift, the concentration of glucose can be determined. More sensitive detection can be achieved by measuring the intensity change at a fixed wavelength, which is made possible by the significantly enhanced slope sensitivity in the sharp Fano resonances. For biosensor applications, the use of polymers may allow easy surface chemical modifications for binding of specific biomolecules on the resonator surface. This property offers potential for fabricating multiple sensors for various types of biomolecules on a single chip.

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