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Biochemical Sensor Based on Single-Microsphere-Coupled Mach-Zehnder Interferometer

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A cost-effective sensor based on single-microsphere-coupled Mach-Zehnder interference is theoretically investigated, which is related to the asymmetric Fano resonance line shape. Fano resonance results from interference between a resonance pathway associated with a high-Q microsphere and a coherent background pathway by introducing an extra phase shift. The sensor can be realized when the refractive index of a fiber taper changes in the nonresonance arm and that of a high-Q microsphere resonator remains constant. Besides, the gap distance between the fiber taper and microsphere can be easily tuned to achieve high sensitivity in the case of overcoupling. The spectral responses of this device in glucose solutions of different concentrations are theoretically calculated. It can produce a sharp asymmetric Fano resonance line shape related to the slope between zero and unity transmission. The gradual change in Fano line shape can be observed owing to the solution concentration change. The variations in relative intensity are approximately linearly related to low and high solution concentrations at special wavelengths. This structure can be that of the promising highly sensitive biochemical sensor owing to the high quality factor and tunable slope over the resonant frequency range.

1. Introduction

Photonic microresonators have great potential applications in highly sensitive sensors owing to their ultrahigh Q and confined microscale modal volumes. Microcavity-based biological detection and chemical detection are driven by the prospective benefits of microscopy and spectroscopy techniques.(1,2) However, they are limited by bulky and expensive instruments, long processing time, and the need for labelling. Whispering-gallery-mode (WGM) microresonators have been proposed and it is a powerful method

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of achieving label-free detection for ultrasensitive biochemical sensors.(3) New label-free optical techniques have been developed to realize inexpensive and high-resolution devices.(4–7) It mainly depends on the refractive index of microresonators. The index could be affected by biochemical molecules attached to the resonators' surface or by the surrounding environment that serves as waveguide cladding. Such refractive index is detected by monitoring the resonant wavelength shift.(8,9) This method generally has a large dynamic spectral range for the sensor. However, the spectral resolution is usually lower in low concentration than in high concentration. As an alternative, detection can also be made by measuring the output intensity change, which is related to the sharp slope between zero and unity transmission.(10) This method is more sensitive for detecting a small change in the resonance region and is cost-effective.(11)

In this letter, we propose a cost-effective sensor based on the single-microsphere-coupled Mach-Zehnder interferometer (1SMZI), which is related to asymmetric Fano resonance. Fano resonance results from interference between a resonance pathway associated with a high-Q microsphere and a coherent background pathway by introducing an extra phase shift. The sensor can be realized when the refractive index of a fiber taper changes in the nonresonance arm of 1SMZI and that of a high-Q microsphere resonator remains constant. Thus, the turbulence coming from the surrounding environment is significantly reduced and this structure still maintains high sensitivity and stability. It does not require expensive and complex fabrication procedures. In addition, the gap distance between the fiber taper and microsphere is easily tuned to achieve strong dispersion related to high sensitivity. We theoretically calculate the spectral responses of 1SMZI in glucose solutions of different concentrations. The gradual change in asymmetric Fano resonance can be observed because of the change in solution concentration. The variations in relative intensity are approximately linear as functions of different solution concentrations at special wavelengths. As a result, 1SMZI shows better performance in biochemical detection.

2. Theoretical Analysis

Figure 1 shows a sensor made from a 1SMZI. The MZI includes two paths; in one path, an optical microsphere is coupled with a fiber taper, which is called microsphere resonator (1SR); in the other path, the change in fiber taper gives rise to an extra phase shift. The taper-based microsphere resonator manifests periodically resonant properties as evanescent wave coupling. Furthermore, the distance between the microsphere and

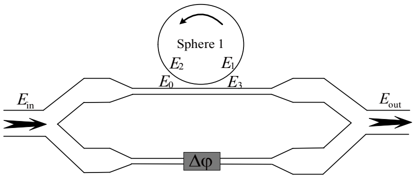


Fig. 1. Schematic of 1SMZI.

fiber taper could be adjusted easily for producing effective coupling and consequently, high Q factors. We use the directional coupling transfer matrix theory to describe the resonant properties of 1SR and 1SMZI. The total output power, which is associated with incoming and outgoing optical field components, is expressed as(12)

$$T = \left|\frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}\right|^2 = \frac{1}{4}\left[1 + 2\left|\frac{E_3}{E_0}\right|\cos(\varphi_S + \varphi_0 - \Delta\varphi) + \left|\frac{E_3}{E_0}\right|^2\right], \tag{1}$$

where $\varphi_S = \arctan\left(\dfrac{-a_1(1 - r_1^2)\sin\varphi_1}{r_1(1 + a_1^2) - a_1(1 + r_1^2)\cos\varphi_1}\right)$ is the effective phase shift, which accounts for the phase difference due to coherent effects between the microsphere and the fiber taper when optical field components pass a single resonator and $\left|\dfrac{E_3}{E_0}\right| = \left|\dfrac{r_1 - a_1\exp(i\varphi_1)}{1 - a_1 r_1\exp(i\varphi_1)}\right|$. E represents the electric field envelop. In that case, the coupling coefficient r_1 and transmission coefficient k_1 are related by $r_1{}^2 + k_1{}^2 = 1$. r_1 is relative to coupling strength. a_1 is the attenuation factor, which accounts for the intrinsic loss in 1SR. $\varphi_1 = n\omega L/c$ is the roundtrip phase shift, where n is the refractive index of the microsphere, ω is the single-mode monochromatic field of angular frequency, and c is the velocity of light. L is the perimeter of the microsphere. φ_0 is the global static phase shift between two arms. The extra phase shift $\Delta\varphi$ in this system is introduced by artificial factors. The sensitivity of 1SMZI can be approximately expressed as

$$S = \left|\frac{\mathrm{d}(\varphi_S - \Delta\varphi)}{\mathrm{d}\varphi_1}\cdot\frac{\mathrm{d}\varphi_1}{\mathrm{d}n}\right| = \left|\frac{\mathrm{d}(\varphi_S - \Delta\varphi)}{\mathrm{d}\varphi_1}\right|\cdot\left|\frac{\mathrm{d}\varphi_1}{\mathrm{d}n}\right| \approx \left|\frac{n_g}{n}\right|\cdot\left|\frac{\mathrm{d}\varphi_1}{\mathrm{d}n}\right|, \tag{2}$$

where n_g is the group refractive index of 1SR. The sensitivity of 1SMZI includes two terms: one is the dispersion response $\mathrm{d}\varphi_s/\mathrm{d}\varphi_1$ and the other term is the phase change in the resonator induced by the measured variable n.

3. Discussion

For simplicity, we assume that the two paths have the same physical length $\varphi_0 = 0$. If there is no change in the MZI structure ($\Delta\varphi_0 = 0$), we could obtain the symmetrical resonant line shape. Figure 2 shows spectral response as a function of frequency detuning and couple coefficient. In this case, the loss coefficient is fixed at $a_1 = 0.999965$ and the couple coefficients are set as $r_1 = 0.999666$, 0.999756, and 0.99986. If external factors are applied to the tapered region ($\Delta\varphi = 0$), the spectral responses of this structure will change correspondingly, resulting in output transmission change.

For the application of biochemical detection, optical microcavity-based sensors rely on the accurate measurement of the refractive index change owing to the presence of biomolecules on the surface of sensing areas, or the presence of a solution surrounding the devices. If the taper's surrounding environment changes, the refractive index of the taper will change accordingly. It causes an extra phase shift. Owing to the extra phase

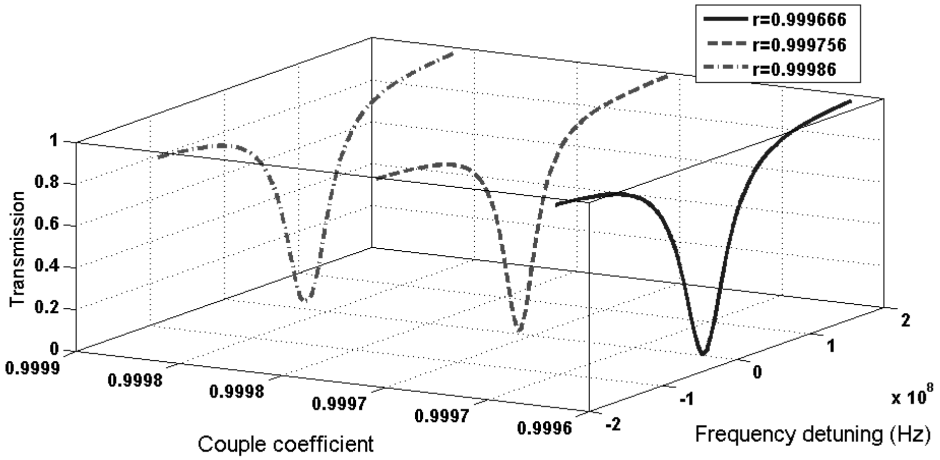


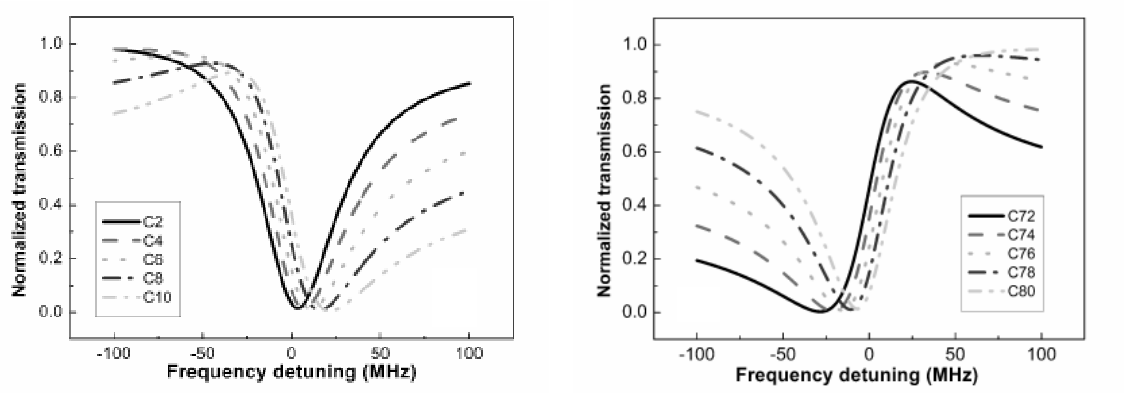
Fig. 2. Transmission as a function of frequency detuning and couple coefficient.

shift, the slope between zero and unity transmission is markedly enhanced compared with that of the conventional MZI structure. It will result in an asymmetric Fano resonance line shape. It is obvious that one can build biological and chemical sensors based on this microsphere-coupled MZI structure. As a proof of our concept, we theoretically calculate the spectral responses varying with the glucose solution concentration. In general, the refractive index related to the solution concentration can be expressed as(13) $\Delta n = 1.328 + 0.00184C$, where C is the solution concentration. We theoretically choose glucose solutions of different concentrations to act on the taper's refractive index. It causes a change in the extra phase shift. The extra phase shift is expressed as

$$\Delta\varphi = 2\pi \Delta n L_{in}/\lambda, \tag{3}$$

where the interaction length L_{in} is along the fiber taper; λ is wavelength ($\lambda_0 = 1550$ nm). The diameter of a microsphere, the couple coefficient and loss coefficient are set as $d_1 = 110$ μm, $r_1 = 0.999756$, and $a_1 = 0.999965$, respectively. We define effective refractive index $n = 1.458$ and interaction length $L_{in} = 200$ μm. In Fig. 3, we present a typical transmission of our structure, which is calculated using eq. (3). The spectral responses are simulated at different solution concentrations. This structure causes the interference between a direct channel and an indirect channel associated with high-Q microsphere resonance. Such interference theoretically produces an asymmetric Fano resonant line shape by introducing an extra phase shift. The observed asymmetric characteristics at resonance could be attributable to the interference effect similar to the Fano effect.(14) Such a Fano resonance scheme was proposed by Fano to improve the optical switching characteristics of microresonator-based devices. The Fano resonance markedly increases the slope between zero and unity transmission compared with the symmetric resonance.

The continuous changes in Fano resonant line shape can be observed in low concentrations (2, 4, 6, 8, and 10%) and high concentrations (72, 74, 76, 78, and 80%) in Figs. 3(a) and 3(b), respectively. Thus, it is convenient to realize tunable Fano resonance



(a) (b)

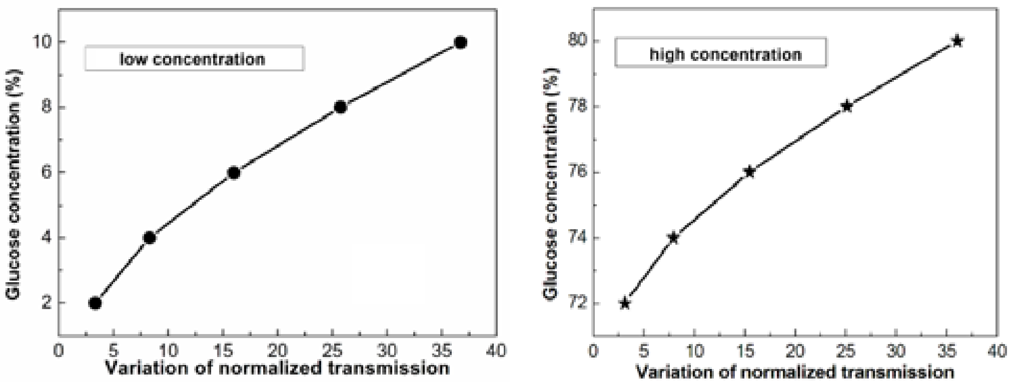
Fig. 3. (a) Fano resonance lines are observed in relation to 2, 4, 6, 8, and 10% glucose solutions. (b) Fano resonance lines are observed in relation to 72, 74, 76, 78, and 80% glucose solutions.

at different glucose concentrations. The curves shift consistently toward higher wavelength with an increase in the glucose solution concentration.

On the basis of Figs. 3(a) and 3(b), the variation of the normalized transmission at a fixed resonant frequency is plotted in Figs. 4(a) and 4(b) as a function of glucose solution concentration. An approximately linear relationship can be observed in order to detect low and high glucose concentrations. By increasing the Q factor of the resonator, the slope becomes steeper and the sensitivity can be further enhanced. This structure is that of the promising highly sensitive sensor owing to the high Q-factor resonance and steep slopes between zero and unity transmission over a very narrow frequency range.

4. Conclusions

In summary, we study a 1SMZI-based sensor. The symmetric Lorentzian line shapes appear in output spectra when there is no change in the phase shift of the nonresonance arm. For the application of the biochemical sensor, we theoretically choose glucose solutions of different concentrations to observe various spectral responses. The asymmetric Fano line shapes are produced by introducing an extra phase shift at the direct channel. The extra phase shift can tune the slope and shape of the Fano resonance. Thus, optical intensity changes in output spectra correspond to different extra phase shifts, which are relative to changes in solution concentrations. The variations in the relative intensity are approximately linearly related to low and high solution concentrations at special wavelengths. For future studies, the noise in the monitoring processes will be discussed and analyzed in detail.(15) Since the glucose solution can be easily adjusted in terms of concentration, temperature and type of molecule, 1SMZI may provide new opportunities for achieving compact sensor devices with high flexibility.



(a) (b)

Fig. 4. (a) Low glucose concentration as a function of transmission at resonance. (b) High glucose concentration as a function of transmission at resonance.

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References

1 E. Betzig, J. K. Trautmann, T. D. Harris, J. S. Weiner and R. L. Kostelak: Science **251** (1991) 1468.
2 F. Vollmer, D. Braun, A. Libchaber, M. Khoshsima, I. Teraoka and S. Arnold: Appl. Phys. Lett. **80** (2002) 4057.
3 K. J. Vahala: Nature **424** (2003) 839.
4 D. K. Armani, T. J. Kippenberg, S. M. Spillane and K. J. Vahala: Nature **421** (2003) 925.
5 F. Vollmer and S. Arnold: Nat. Methods **5** (2008) 591.
6 A. M. Armani, R. P. Kulkarni, S. E. Fraser, R. C. Flagan and K. J. Vahala: Science **317** (2007) 783.
7 J. G. Zhu, S. K. Ozdemir, Y. F. Xiao, L. Li, L. N. He, D. R. Chen and L. Yang: Nature Photonics **4** (2010) 122.
8 E. Krioukov, D. J. W. Klunder, A. Driessen, J. Greve and C. Otto: Opt. Lett. **27** (2002) 1504.
9 E. Krioukov, D. J. W. Klunder, A. Driessen, J. Greve and C. Otto: Opt. Lett. **27** (2002) 512.
10 C. Y. Chao and L. J. Guo: Appl. Phys. Lett. **83** (2003) 1527.
11 L. T. Grigorie and R. M. Botez: Trans. Can. Soc. Mech. Eng. **34** (2010) 3067.
12 Y. Lu, J. Q. Yao, X. F. Li and P. Wang: Opt. Lett. **30** (2005) 3069.
13 Z. S. Bai, Z. Q. Liu and H. Xu: J. Yanan Univ. (Natural Science Edition) **23** (2004) 33.
14 U. Fano: Phys. Rev. **124** (1961) 1866.
15 S. Ersoy and Y. Karatepe: J. Vibroeng. **13** (2011) 1392.