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用于纳米粒子检测的双环谐振器

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摘 要:设计了一种可以探测单个纳米粒子的光学传感器结构,该结构由双环、双环间耦合区的通孔和直波导构成,并引入了 Fano 效应,进一步增强了粒子在光场中出现时的光耦合场变化.当纳米粒子穿过两个微环间的通孔时,其耦合系数和输出端的光强均发生变化,提出了一种基于双环谐振器结构的高精度耦合系数传感方法,通过检测双环谐振器耦合系数和输出端光强的变化对单体纳米粒子进行精确检测和计数.理论计算结果表明,在损耗为 1dB/cm 的情况下,与单环结构相比,双环结构的灵敏度提升了两个数量级.该双环结构在减小波导损耗的同时有效提升了检测灵敏度.

关键词:光电子器件;光子传感器;微环谐振器;耦合系数;纳米粒子检测
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Dual-microring Resonator Sensor for Nanoparticle Detection

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Abstract: An optical sensing structure was designed to detect the single Nanoparticle. The structure consists of a dual-ring, a nanopore in the coupling area and a straight waveguide, and the Fano effect is introduced. The proposed structure could further amplify the change of coupling effect due to the presence of nanoparticle. Nanoparticles flowing through a nanopore between microrings could change both the coupling coefficient and the optical intensity at the output. An ultrahigh precision method for coupling coefficient sensing was proposed based on a dual-microring resonator structure. The counting and sizing of nanoparticle could be achieved by detecting the change of optical intensity and coupling coefficient. The theoretical results show that the sensitivity of the dual-ring design is calculated to be around two orders of magnitude greater than a single-ring design under 1dB/cm loss condition. The propose structure can improve the sensitivity effectively with reducing the waveguide loss.

Key words: Optoelectronic device; Photonic sensor; Microring resonator; Coupling coefficient; Nanoparticle detection
OCIS Codes: 230.5750; 230.4000; 040.1880; 040.6040; 130.0250; 130.3120

0 Introduction

Nanoparticle detecting is of great importance in areas such as nanotechnology, virology, disease diagnosis and biomedical research[1-2]. An amount of methods have been proposed for the nanoparticle detecting such as microring resonators and slot structure[3-5]. Particle sizing by using Electron microscopes such as Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM) is a mature method, but the devices are expensive and bulky. Dynamic laser scattering is a much simpler way for measuring the particle size which is down to the order of 10nm, however, this method requires relatively large sample concentration.

The optical whispering-gallery mode has been

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under intensive investigation for highly sensitive biomolecular detection in the past decade[6-8]. The ring resonator was also employed for nanoparticle detection, counting, and sizing[9-10]. Recently, our team proposed a single microring resonator with flow-through nanopore to detect single NP[11]. A dielectric microring resonator and an adjacent waveguide bus are embedded in a low-index medium. A flow-through nanopore is created in the coupling region between the ring and the waveguide. When a single NP of interest is presented in the nanopore, the coupling coefficient between the ring resonator and the waveguide changes, resulting in the variation of intensity at the output. The method does not require the NP to adhere to the surface of the device, avoiding the uncertain diffusion and accumulation of NPs that make it difficult to accurately detect the size of single NP. However, the sensitivity and resolution of the single-ring-resonator method is not high enough for the detection of NPs which are smaller than 20nm.

In this paper, a designing of dual-ring resonator structure was proposed for the coupling coefficient sensing. It can bring an ultrahigh sensitivity for a single nanoparticle detection. The coupling coefficient between rings is independent of waveguide loss so that the sensitivity of the dual-ring structure can be improved significantly by reducing the loss. Compared with the single-ring structure, the sensitivity is expected to be improved by around two orders of magnitude using the state-of-art low loss silicon microrings[12]. Based on Ref. [11], the scattering loss of the single NP can be neglected. The analysis will focus on the variation of coupling coefficients induced by nanoparticles. We will discuss the design and the characteristics of dual-ring structure and compare it with the single-ring structure.

1 Theory

1.1 Dual-microring structure

The dual-ring resonator sensor scheme is shown in Fig. 1. In this sensing structure, there are two bus waveguides and two microrings in which three couplings exist: coupling between ring A and the top bus waveguide, coupling between ring B and the bottom bus waveguide, and coupling between ring A and ring B. A nanopore exists in the coupling region between the rings, allowing NPs in the liquid to flow through. The coupling coefficient changes when a NP is presented in the nanopore. Sizing and counting of the NPs can be realized by detecting the intensity of the transmitted light at the output port.

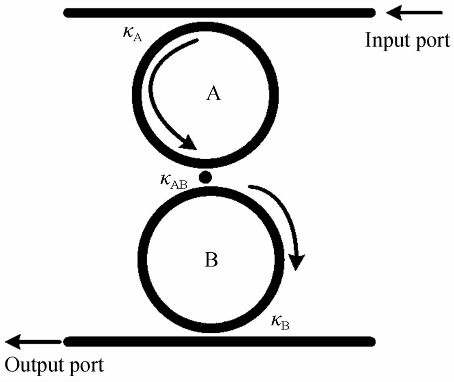


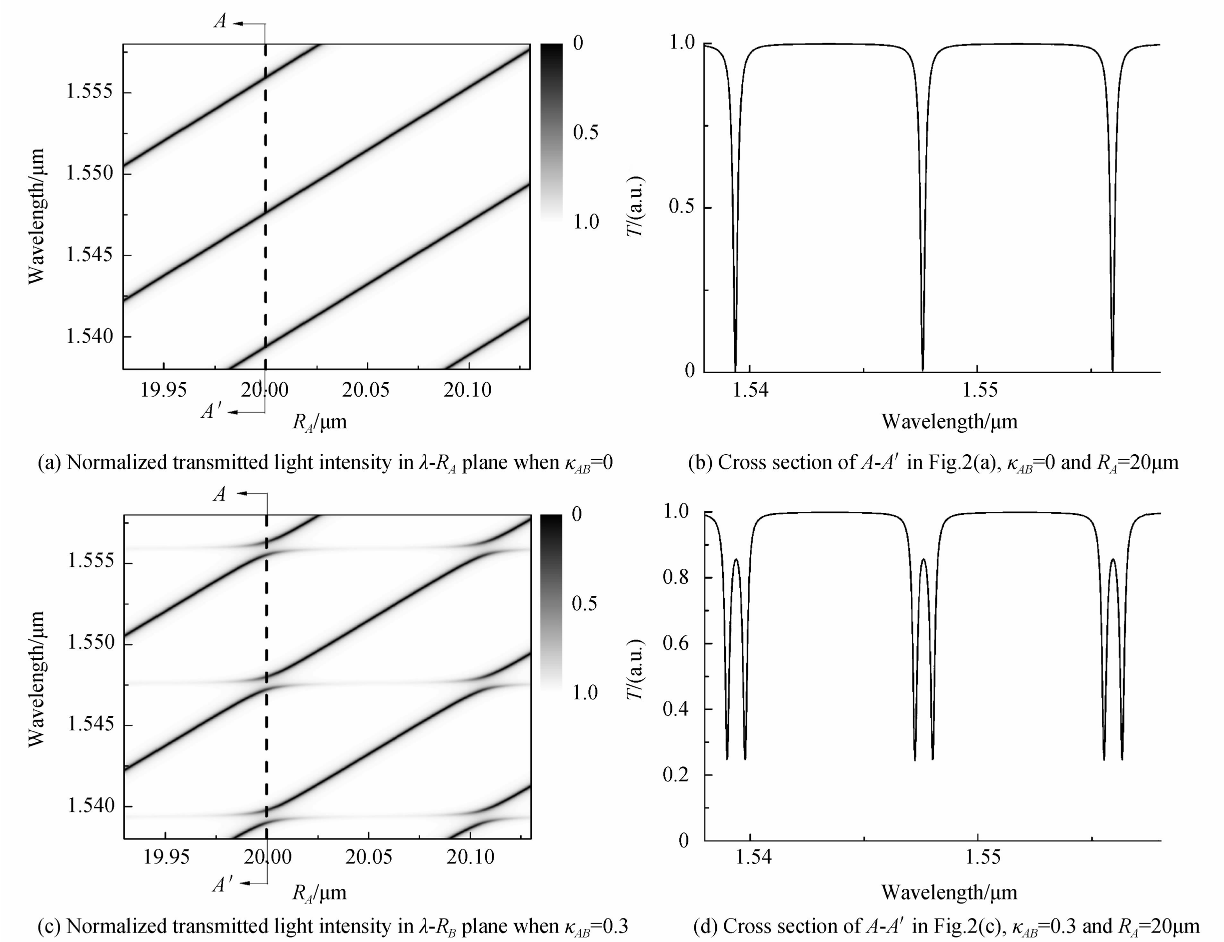
Fig. 1 The structure of dual-ring resonator sensor device

1.2 Design for coupling coefficient between ring A and ring B

The nanoparticle presented in the nanopore changes the normalized field distribution in the coupling region, inducing the variation of the coupling coefficient. Larger evanescent field in the coupling region results in a larger coupling coefficient and a higher susceptibility to particle disturbance. According to Ref. [11], for the same nanoparticle of interest, the ratio between the variation of coupling coefficient $\Delta\kappa$ and the initial coupling coefficient κ remains the same, no matter how the gap between ring A and ring B changes. As a result, a nanoparticle can induce a larger $\Delta\kappa$ when κ becomes larger. Thus the value of , the coupling coefficient between ring *A* and ring B, is a direct factor influencing the sensitivity of dual-ring structure.

The transmission characteristic of the dual-ring structure is analyzed firstly. Fig. 2(a), (b) show that the transmitted light intensity varies with λ and R_A when $\kappa_{AB}=0$. In this condition, the dual-ring structure is equivalent to a single ring structure, whose resonances have a redshift with the increasing of R_A. In Fig. 2(c), (d), the resonance peaks split, and κ_{AB} is set to be 0.3. Mode splitting occurs near the wavelength which sets both ring A and B in resonance. The splitting varies with value of κ_{AB}.

As shown in Fig. 3, the splitting distance between resonance peaks increases with the increasing of κ_{AB}. Therefore, a particle passing through the nanopore which changes κ_{AB}, can induce a resonance shift. At a given wavelength near the resonance, the resonace shift can result in a significant variation of the transmitted light intensity. As a result, nanoparticles can be detected by measuring the transmitted light intensity. In order to make the dual-ring structure eligible for resonance shift, the operating wavelength should be chosen at the split resonance peaks. For example, in the case of Fig. 2(d), the resonance at 1 548 nm occurs when $\kappa_{AB}=0.3$



(a) Normalized transmitted light intensity in λ-R_A plane when κ_{AB}=0

(b) Cross section of A-A' in Fig.2(a), κ_{AB}=0 and R_A=20μm

(c) Normalized transmitted light intensity in λ-R_B plane when κ_{AB}=0.3

(d) Cross section of A-A' in Fig.2(c), κ_{AB}=0.3 and R_A=20μm

Fig. 2 λ-R_{A} and T-λ curve in different conditions

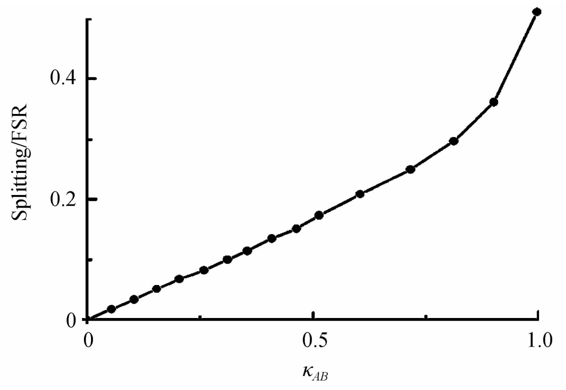


Fig. 3 Splitting distance between two resonance peaks normalized by the FSR(The FSR of dual-ring structure is noted in Fig. 2 (d))

1.3 Sensitivity of dual-ring sensor

For simplification, we assume the two rings are identical, and $\kappa_{\mathrm{A}}=\kappa_{\mathrm{B}}=\kappa$. The normalized transmitted E-field E_{td} at the output port of the dual-ring structure can be obtained as following[13]

$$E_{\mathrm{td}}=(\alpha^2\sqrt{1-\kappa^2}+\sqrt{1-\kappa^2}\,\mathrm{e}^{\mathrm{j}2\theta}-2\alpha\sqrt{1-\kappa_{AB}^2}\,\mathrm{e}^{\mathrm{j}\theta}+\alpha\kappa^2\sqrt{1-\kappa_{AB}^2}\,\mathrm{e}^{\mathrm{j}\theta})/(\mathrm{e}^{\mathrm{j}2\theta}+\alpha^2-\alpha^2\kappa^2-2\alpha\mathrm{e}^{\mathrm{j}\theta}\sqrt{1-\kappa^2}\cdot\sqrt{1-\kappa_{AB}^2})\qquad(1)$$

where θ is the round-trip phase and $1-\alpha^2$ is the round-trip energy loss of the rings. If a nanoparticle passes through the nanopore and causes a variation of κ_{AB}, the intensity change of output port is

$$\Delta T\approx\frac{\partial T}{\partial\kappa_{\mathrm{AB}}}\Delta\kappa_{AB}\qquad(2)$$

According to Ref. [11], for the same particle, when the gap between ring A and B changes, $\Delta\kappa_{\mathrm{AB}}/\kappa_{\mathrm{AB}}$ almost remains a constant, denoted as C in this context. It describes how strongly a coupling system reacts to the perturbation of a particle. We can rewrite Eq. (2) as

$$\Delta T\approx C\frac{\partial T}{\partial\kappa_{\mathrm{AB}}}\kappa_{\mathrm{AB}}\qquad(3)$$

When we design the nanoparticle sensor without changing C, the sensitivity for nanoparticles can be evaluated by $\kappa_{\mathrm{AB}}\cdot\partial T/\partial\kappa_{\mathrm{AB}}$. In our design, we define the sensitivity of nanoparticle sensor as

$$S\approx C_0\left|\frac{\partial T}{\partial\kappa_{AB}}\right|\kappa_{\mathrm{AB}}\qquad(4)$$

where C_0 is the $\Delta\kappa_{AB}/\kappa_{\mathrm{AB}}$ induced by a nanoparticle with a lateral size of 10 nm and T is the normalized transmitted light intensity. The item $|\partial T/\partial\kappa_{\mathrm{AB}}|$ shows how sensitive the transmitted light is to the change of the coupling coefficient. The item κ_{AB} represents how large the $\Delta\kappa_{\mathrm{AB}}$ can be made by the presence of a certain particle. The goal of our design is to optimize the sensitivity of the nanoparticle sensor.

2 Structure design

The device in Fig. 1 can be fabricated on a Silicon-On-Insulator (SOI) wafer. R_A and R_B are designed as 20 μm. Fig. 4 shows the cross-section of the coupling region. The size of the waveguide cross section is 450 nm×220 nm. The effective refractive index of the waveguide mode is 2.303 at λ=1550 nm according to Finite Element Method (FEM) analysis. The gap between ring A and ring B is 250 nm and the coupling coefficient κ_{AB} is 0.1759 by Coupled Mode Theory (CMT). A nanopore is etched in the SiO_2/Si substrate. Particles in liquid solution can pass through the nanopore by controlling nanofluid system[11]. We assumed the nanoparticles have a very low density in the solution so that the single nanoparticle detection can be implemented.

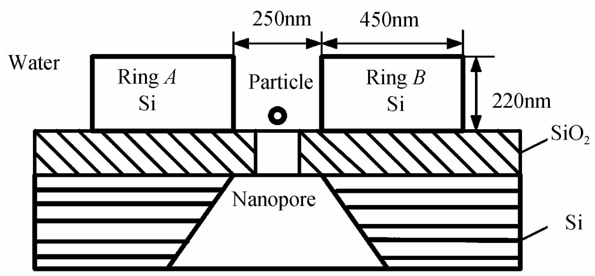


Fig. 4 The cross-section near the coupling region of dual-ring nanoparticle sensor

In order to obtain the optimized sensitivity, κ_A^2 and κ_B^2 should be equal to the round-trip loss of ring A and ring B respectively. Therefore, κ_A^2 and κ_B^2 are set to be 0.005 776, which is the round-trip loss of microrings when the loss is 1 dB/cm. In this condition, the gap between ring A and bus waveguide, as well as the gap between ring B and waveguide is 390 nm.

In practice, the microring can be covered with a cladding layer to prevent the particle attachment, which may induce resonance wavelength shift.

3 Discussion

3.1 Comparison with single-ring sensor

The single ring sensor has only one coupling between a ring and a straight waveguide[11]. A nanopore is presented in the coupling region between the ring and the waveguide. When the NP passes through the pore, κ will change as well as the light transmission intensity.

According to Ref. [13], the normalized E-field of the transmitted light of single ring structure is

$$E_t=\frac{t-\alpha e^{-j\theta}}{1-t\alpha e^{-j\theta}} \tag{5}$$

Single ring structure reaches critical coupling when intrinsic loss is equal to the coupling loss of the ring. That is $\kappa^2=1-\alpha^2$. The slope $|\partial T/\partial\kappa|$ reaches the maximum value in under-coupled region where $\kappa^2<1-\alpha^2$, as shown in Fig. 5(a). $|\partial T/\partial\kappa|$ can be improved by decreasing the loss of the ring, which refers to the waveguide intrinsic loss in this paper. However, if the loss is reduced, the κ of the maximum $|\partial T/\partial\kappa|$ in the T-κ curve decreases simultaneously. Therefore, we can't increase $|\partial T/\partial\kappa|$ and in the same time by reducing loss, which dramatically limits the sensitivity of the single ring structure.

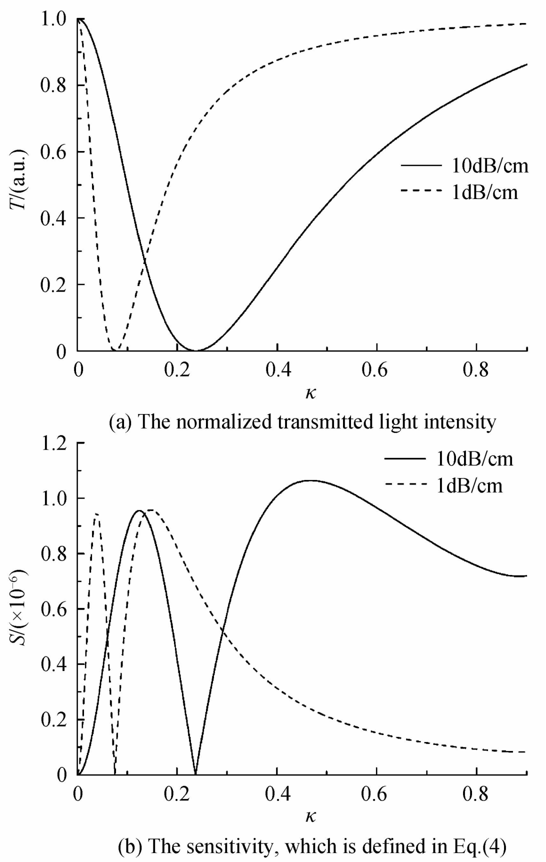
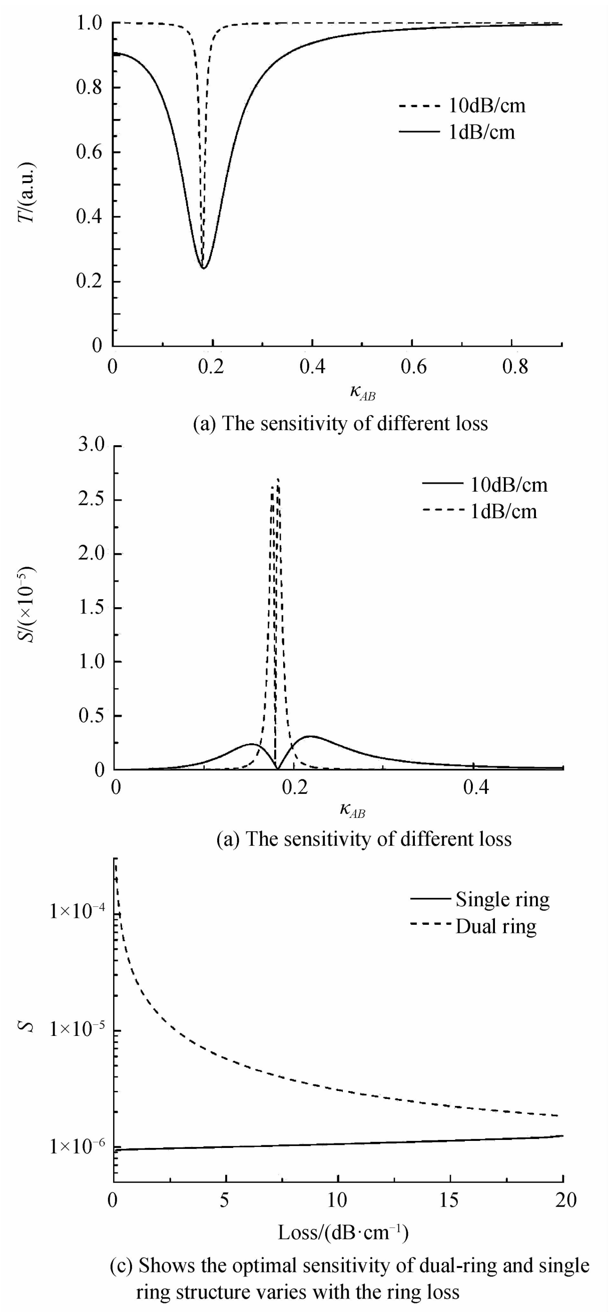


Fig. 5 Sensitivity property of single ring structure

According to Fig. 5(b), the largest sensitivity of single ring structure is about 1×10^{-6} for both loss of 10 dB/cm and 1dB/cm. The 1 dB/cm curve in Fig. 5(a) has a larger slope, however the sensitivity doesn't get better because κ is lower. The dual-ring structure can solve the problem mentioned above. For dual-ring structure, the critical coupling condition depends on both κ_A, κ_B and the ring loss. κ_A^2 and κ_B^2 should approximate to the round trip loss of ring A and B respectively, but the value of κ_{AB} is independent of the loss, which contributes to the sensitivity S. In general, the sensitivity can be maximized at the critical coupling condition, however, the device can work off this condition for our design. We can adjust κ_{AB} to obtain a higher sensitivity based on Eq. (4). In fact, the sensitivity of the dual-ring structure can be improved significantly by reducing the loss, as shown in Fig. 6.



(a) The sensitivity of different loss

(a) The sensitivity of different loss

(c) Shows the optimal sensitivity of dual-ring and single ring structure varies with the ring loss

Fig. 6 Sensing property of dual-ring structure

The optimal sensitivity of dual-ring structure is about two orders of magnitude larger than the counterpart of single ring structure sensor when the ring loss is 0.76 dB/cm, which is feasible for silicon microrings[12].

3.2 Detection for nanoparticle passing through the nanopore

As mentioned above, when a single NP passes through the pore, the coupling coefficient between ring A and B change. For convenience of calculation, we assume that the particle is a cube with a lateral size of d and presented at the coupling region as shown in Fig. 4, the variation of the total coupling coefficient $\Delta\kappa$ can be calculated according to the coupled mode theory[11,14].

$$\Delta\kappa=\frac{k_0^2\,(n_{\mathrm{NP}}^2-n_{\mathrm{water}}^2)E^2(r_0)d^3}{2\beta\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E_{\mathrm{RR}}|^2\mathrm{d}x\mathrm{d}y} \tag{6}$$

where k_0 is the wave transmission constant in vacuum, β is the wave transmission constant in optical waveguide. n_{NP} is the refractive index of NPs, n_{water} is the refractive index of water, $E(r_0)$ is normalized electric at the NP's position, and E_{RR} is the normalized electric field of waveguide's cross-section. According to the Eq. (6), $\Delta\kappa$ is proportional to d^3, which is the volume of the NP.

For particles of various size, their d and $\Delta\kappa$ has the relation as shown in Table 1. For calculation near a wavelength of 1.55 μm, the refractive index of the microring $n_{RR}=3.45$, the refractive index of the bottom cladding $n_{\mathrm{M}}=1.46$, $n_{\mathrm{water}}=1.33$, $R_{\mathrm{A}}=R_{\mathrm{B}}=20$ μm, and the size of waveguide cross-section 450 nm×220 nm.

According to the data above, we can calculate the change of normalized transmitted light intensity ΔT, as shown in Fig. 7. In this case we choose several κ_{AB} and calculate the variation of light intensity caused by different NPs. It is obvious that the sensitivity is high near $\kappa_{\mathrm{AB}}=0.1759$, which was proposed in the Structure Design Section.

Table 1 Results for coupling coefficient and normalized intensity changing by different nanoparticles ($n_{\mathrm{NP}}=1.55$, $\kappa_{\mathrm{AB}}=0.1759$)

d/nm	50	40	30	20	10	5	1
$\Delta\kappa$	3.8303×10^{-5}	1.9611×10^{-5}	8.2735×10^{-6}	2.4514×10^{-6}	3.0643×10^{-7}	3.8303×10^{-8}	3.0643×10^{-10}
$\lvert\Delta T\rvert$	2.7414×10^{-3}	1.4051×10^{-3}	5.9316×10^{-4}	1.7581×10^{-4}	2.1979×10^{-5}	2.7473×10^{-6}	2.1979×10^{-8}

The state-of-the-art low noise detection system has a noise floor with a normalized standard deviation on the 1×10^{-6} level[15], allowing for detection of 10 nm nanoparticle according to Fig. 7. One advantage of our design is that the sensitivity scales with ring quality factor. With lower waveguide loss and higher quality factor, we expect that the sensitivity can be further increased, enabling detection of smaller particles below 10 nm.

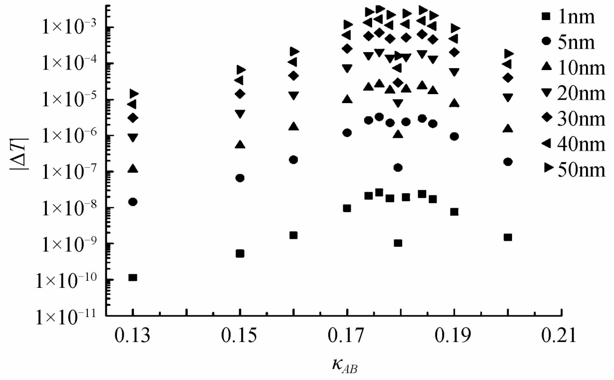


Fig. 7 Caused by particles passing through the pore

4 Conclusion

We can obtain a higher sensitivity for the nanoparticle detection by utilizing a dual-ring structure instead of the single-ring structure. The sensitivity of the dual-ring design is calculated to be around two orders of magnitude greater than a single-ring design under 1 dB/cm loss condition, taking advantage of the state-of-art low loss single microring. Compared with the single-ring structure, the dual-ring design decouples the critical coupling condition and the coupling coefficient between rings, allowing for the sensitivity to scale up with reducing the waveguide loss. It is essential to choose a proper and operating wavelength to ensure that the dual-ring structure is working at a split resonance peak as shown in Fig. 2. The loss of rings should be as low as possible by fabrication in order to reach higher sensitivity. This paper also proposes a method to evaluate the sensitivity of the nanoparticle sensors in design procedure, which is summarized in Eq. (4). Both $|\partial T/\partial\kappa_{AB}|$ and κ_{AB} influence the sensitivity S of nanoparticle sensors. For single ring structure, κ changes with the decreasing of the ring loss, thus the sensitivity of single ring structure is limited. For dual-ring structure, κ_{AB} is no longer dependent with ring loss. Its sensitivity can be improved dramatically by proper design, making it possible to detect sub-10nm nanoparticles. For future study, the micro fabrication technology is being investigated to etch nanopore in the coupling area. The current technology would cause loss to microring transmission. We hope this technology could be further improved to develop the prototype device.

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