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Novel ultrasound detector based on small slot micro-ring resonator with ultrahigh Q factor

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ABSTRACT

An ultrasound detector based on a novel slot micro-ring resonator (SMRR) with ultrahigh Q factor and small size is proposed in this study. The theoretical Q factor of SMRR can be approximately 8.34×10^{8} with bending radius of merely 12 μm. The ultrahigh Q factor leads to an enhanced sensitivity that is approximately two orders of that of state-of-the-art ultrasound detector based on polymer micro-ring resonator. Moreover, the 3 dB bandwidth of the ultrasound detector is approximately 540 MHz, thereby leading to an ultrahigh axial resolution of 1.2 μm. The proposed detector is also CMOS compatible and can be easily and extensively integrated to be maximized in photoacoustic microscopy.

1. Introduction

Photoacoustic imaging is a non-invasive imaging modality and has been extensively investigated in the medical field because of their advantages of rich optical contrasts and high resolution of ultrasonic imaging [1]. For this reason, ultrasound detectors play an important role in biomedical imaging and scientific research, and novel detectors capable of enhancing the resolution and sensitivity attract great interest in ultrasonic community. Currently, the dominant available ultrasound detectors are based on piezoelectric technology, which are well-performed in the low ultrasonic frequency region. However, the piezoelectric technology has significant challenges as the frequency increases to above 20 MHz [2]. Accordingly, great efforts are made to overcome various obstructions in biomedical photoacoustic imaging, such as low detection sensitivity and small signal-to-noise-ratio (SNR) limited by the piezoelectric transducers in a high-frequency range [3]. Ultrasound detectors based on etalons [4,5], Bragg grating waveguide [6], microtoroid resonator [7], and micro-ring resonators [8,9] were proposed to address the aforementioned obstacles. These detectors offer high sensitivity, large SNR and high-element density without compromising the frequency limitation arising from the RF interference in the piezoelectric transducers. Among these detectors, integrated optical micro-cavities are preferred due to the advantages of CMOS compatibility, small feature size and high quality factor, which are important in determining the sensitivity of ultrasound detectors. To obtain a strong interaction between the ultrasonic and optical fields, optical microcavities based ultrasound detectors generally utilize polymers with low Young's modulus (~GPa). However, the low refractive index contrast limits their performance when the device is considerably small. Unfortunately, for the sake of high-frequency ultrasound detection, the small feature size is required and should be below 0.5 or 0.8 times the wavelength of the ultrasound wave in the photoacoustic imaging system [2]. For instance, the acoustic wavelength is approximately 30 μm for high-frequency ultrasonic signal with central frequency of 50 MHz. As a result, the radius of the micro-ring should be on the order of 15 μm. Meanwhile, a smaller size of micro-ring resonators is universally desirable for ultrasonic imaging applications, such as providing high resolution and high contrast over a large imaging region, minimizing the spatial averaging effect for high-frequency acoustic waves, producing high-density array for 2-D or 3-D high-frame-rate real-time imaging, and so on [7].

This study utilizes a slot waveguide-based micro-ring resonator (SMRR) to achieve high sensitivity with a small feature size. The slot waveguide maximizes the continuity of the electromagnetic field on the boundary between different materials. Accordingly, the SU8 polymer is adopted to embed the slot and encapsulate the silicon strips as cladding. Through careful design process, the optical field with a relatively high mode refractive index can be localized in the SU8 slot zone. Subsequently, the stress imposed on SU8 by ultrasound will affect the optical mode of the slot waveguide; the influence accumulates during the circulation of the light wave along SMRR. The modified optical field can be detected through a photodiode and the ultrasonic signal can be

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subsequently demodulated.

2. The Principles of SMRRs

The schematic and structure of SMRR is illustrated in Fig. 1(a). The slot waveguide is constructed with two adjacently placed silicon strips with the gap embedded by the SU8 polymer, which also serves as upper cladding. The bottom layer is silicon dioxide and serves as the buffer layer. The bus waveguide is a silicon strip waveguide, which is serving as light input and output ports. To achieve high coupling efficiency from the bus waveguide to the slot ring, the strip width is designed to be slightly smaller than common silicon nanowires [9]. After the light is injected to the input port of bus waveguide, it will couple into the micro-ring in the form of evanescent wave and circulate along the slot. As an illustration, the optical field distribution in the micro-ring resonator is shown in Fig. 1(b). Then, the transmission can be calculated as follows:

$$T = 1 - \frac{(1-\gamma^2)(1-\tau^2)}{(1-\gamma\tau)^2 + 4\gamma\tau\sin^2(\phi/2)}, \quad (1)$$

where γ represents the attenuation of the slot ring waveguide and is defined as $\gamma = e^{-\pi R \alpha_R}$, $\phi = \frac{2\pi}{\lambda}2\pi R n_{eff}$ is the phase shift after one-circle travel along the slot ring, and τ is the amplitude transmission coefficient.

According to Eq. (1), resonances will occur when the optical path length of the micro-ring resonator is a multiple of the wavelengths, i.e.,

$$m\lambda = 2\pi R n_{eff}, \quad (2)$$

where m represents the order of the resonance mode, λ is the resonance wavelength, R is the radius of SMRR, and n_{eff} is the effective refractive index of the slot waveguide. Once the resonance condition satisfies, it will result in certain dip on the transmission spectrum, as shown in Fig. 1(c).

To characterize the performance of micro-ring resonator, one critical parameter is the Q factor, which can be derived as follows [10]:

$$Q = \frac{2\pi R n_g}{\lambda}\frac{\pi\sqrt{\gamma\tau}}{1-\gamma\tau}, \quad (3)$$

where n_g is the group refractive index and defined as $n_g = n_{eff} - \lambda\frac{dn_{eff}}{d\lambda}$. As an intuition, a large Q factor will lead to significant dips in the transmission spectrum, and the detection sensitivity will therefore be increased. According to Eq. (3), we can see that the Q factor is proportional to the ring size. To obtain SMRR with large Q factor while maintaining the small feature size, the geometry of the slot waveguide and micro-ring resonator shall be therefore optimized.

The influence of total width of the slot waveguides and the gap between silicon strips on the effective refractive index of the slot waveguides are depicted in Fig. 2. Fig. 2(a) shows that a broad gap will lead to a small effective refractive index and a large total width will pull up the effective refractive index. To obtain a small bending radius, the effective refractive index shall be large enough, thereby resulting in a small bending loss [11]. Hence, the gap should be narrow enough and the larger the total width, the better. However, the gap can't be too small and should be slightly broad to enable spinning the SU8 photoresist into the slot. In addition, a large total width of the slot waveguide will support a high order mode (see Fig. 2(d)), which will deteriorate the performance of micro-ring resonators. Thus, the gap's width and total width should be prudently determined.

Finally, the bending radius of SMRR has a significant effect on the effective refractive index and transmission loss, and the

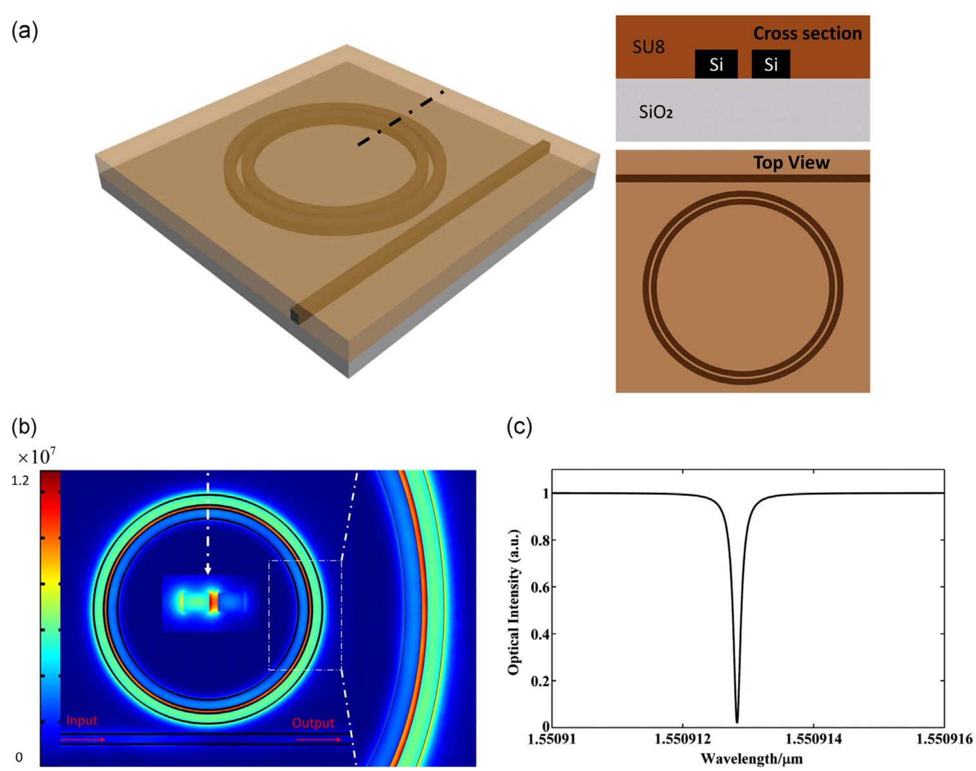

Fig. 1. (a) The schematic and structure of the proposed SMRR, (b) the optical field distribution of the SMRR when resonance occurs, in which the central inset shows the cross-section of the ring and the right-hand enlarged view depicts the details from the top view, and (c) the optical transmission spectrum of the micro-ring resonator (The gap between the bus waveguide and the SMRR is 370 nm).