Characterization of optical microring ultrasound detector by using a high frequency focused photoacoustic transmitter

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We characterize a response of optical microring resonator to high frequency focused ultrasound. To properly evaluate the response over high frequency and broadband spectrum, we use a photoacoustic concave transmitter generating and subsequently focusing the ultrasound. A detected focused profile reveals two types of spatial peaks due to the special ring-shaped detector geometry interacting with the high frequency focused ultrasound. Spectral analysis shows that those peaks are contributed by the main and the side lobes of focused ultrasound, respectively. Experimental focal widths agree with theoretical values within $\pm 2 \mu\text{m}$ error, which can be attributed to the narrow width of waveguide. © 2009 American Institute of Physics. [doi:10.1063/1.3243337]

For ultrasound detection, optical modalities such as optical microring resonators,^{1,2} Fabry–Pérot etalons,^{3,4} and Mach–Zehnder interferometers⁵ have recently attracted great attention in acoustic and photoacoustic imaging. Especially, the microring detectors have characteristics of low noise and flat wideband response.⁶ 90 MHz bandwidth (3 dB rolloff) has been reported under a plane wave incidence condition. The detector sensitivity can be improved by increasing the quality factor (Q) of ring resonator. Recently, microring resonators with $Q > 10^4$ have been demonstrated,⁷ which is about an order of magnitude higher than the previously reported. These characteristics are desirable for high frequency ultrasound imaging.

The optical microring detector has a finite dimension in its diameter and waveguide width. For high frequency ultrasound, the acoustic wavelength can be comparable or even smaller than the microring size. Such a characteristic could be manifested in the microring response. Despite its excellent bandwidth up to high frequency, spatial and temporal responses of the microring in this regime have not been properly characterized so far. Moreover, it is essential to evaluate the microring responses for applications of high spatial resolution imaging of objects in proximity of the detector.

For high resolution characterization, a spatially localized acoustic source is needed. In this letter, we use high frequency focused ultrasound generated by a photoacoustic source. Photoacoustic generation is useful to obtain high frequency and broadband ultrasound simultaneously.⁸ Such spectral feature is desirable to characterize frequency-dependent responses of detector over a wide spectral range. Light-absorbing materials such as metal, mixture of carbon black and polydimethylsiloxane,⁹ and gold nanostructure films¹⁰ have been exploited to generate high frequency ultra-

sound (> 50 MHz) by nanosecond laser pulse excitation. We introduce a photoacoustic concave transmitter capable of sharp focusing. The focusing is achieved with a thin metal layer deposited on the concave side of planoconcave glass lens. The transmitter is back-illuminated with nanosecond laser pulses through the planar glass side, which leads to positive focusing of the acoustic waves.

Polystyrene microring is fabricated on a SiO_2/Si substrate by using an imprint technique.¹¹ The microring has a diameter of $100 \mu\text{m}$ and a waveguide width of $2 \mu\text{m}$. The photoacoustic concave transmitter was fabricated by depositing a 100 nm thick Cr layer by sputtering over a planoconcave spherical glass (Newport, KPC 043; radius-of-curvature 12.92 mm; diameter 22.86 mm). Sputtering was used to obtain uniform film thickness on the curved substrate. A 6 ns and 150 mJ pulsed laser beam with 532 nm wavelength (Surelite I-20, Continuum, Santa Clara, CA) was used to illuminate the Cr film. A neutral density filter was used to attenuate the laser power. At the position of transmitter, the laser beam is 37 mm in diameter that is 1.5 times larger than the lens diameter, and the energy density is less than 0.5 mJ/cm^2 . A larger beam size is desirable to ensure a sufficiently large effective aperture as well as uniform illumination over the lens surface. The focused ultrasound profile was measured by scanning the microring using motorized motion stages. The optical detection with a probe laser beam and data acquisition processes are similar to the previously reported.⁶ An erbium-doped fiber amplifier was used to increase the optical output from a tunable laser. For ultrasound detection, the wavelength of the probe beam was fixed at the maximum slope of the resonance dip in the optical transmission spectrum. An ideal frequency spectrum of photoacoustic source can be estimated by taking the Fourier transform of the time derivative of the 6 ns laser pulse. The spectrum has a center frequency at 67.5 MHz and 3 dB rolloff at 35 and 107 MHz, respectively.

The photoacoustic concave transmitter generates the acoustic waves simultaneously over the concave surface due to rapid thermal expansion of the Cr film by the absorption of pulsed laser energy. The time-domain signal measured at

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FIG. 1. (Color online) (a) Measurement schematic (ND: neutral density filter; EDFA: erbium-doped fiber amplifier). (b) Temporal waveform measured at the focal spot. The calculated waveform does not include the effect of microring bandwidth. The sound speed 1494.7 m/s in calculation is used to fit the measurement.

the focal point, i.e., the center of the concave surface, should be the coherent summation of the acoustic waves generated from each point on the spherical Cr surface. In Fig. 1(b), the temporal profile near the focal point is shown, which is similar to the time derivative of the input laser pulse with the exception of a small kink between the peaks. The peak-to-peak interval was ~ 54 ns. This interval and the broadening in each polarity agree with that of simulated pressure waveform, not including the effect of microring bandwidth. The calculation was done by integrating the acoustic pressure at focal plane over the ring geometry and taking into consideration the sound attenuation in water. We assume uniform spatial distribution of optical beam on the Cr film in calculation. The peak interval between the positive and negative polarity can be reduced by using microring with smaller diameter as confirmed by our calculation. Since the concave substrate has a 12.92 mm radius-of-curvature, the focal spot in theory should appear around 8.61–8.73 μs with the sound speed of 1480–1500 m/s in water. We used 1494.7 m/s in the calculation to fit the measured waveform in Fig. 1(b). The waveform distortion may be due to the nonperfect spherical shape of the glass substrate ($\sim 1\%$) and the misalignment of the microring in the axial direction (tilt angle $\sim 2.4^\circ$, as confirmed by the scanning along the z -axis).

Figure 2 shows the spatial profile of the focused ultrasound measured by scanning the microring at the focal plane. Each data point in the plot represents the absolute peak value of the time-domain signals measured at each spatial location. Interestingly, the one-dimensional (1D) profile of the focused ultrasound as detected by a 50 μm radius microring shows three peaks: a main peak located at the center and two secondary peaks located 50 μm from the center that coincide exactly with the position of the ring waveguide that is sym-

FIG. 2. (a) 2D spatial profile of focused ultrasound measured at the focal plane by the microring detector. (b) 1D profile measured across the focal spot. The calculated pressure profile in (b) does not include the effect of microring bandwidth.

FIG. 3. (Color online) Normalized spatial profiles reconstructed by the amplitudes of harmonic frequency components 10, 30, and 50 MHz from Fig. 2(b). The dotted profiles were calculated by spatially convolving the side lobes of the focused ultrasound with the microring geometry. Only the first order side lobe was used in (b), and the second order in (c). The widths of the experimental main peaks agree with those of the dotted profiles.

metric from the center. The full-width at half-maximum (FWHM) of the central peak was 41 μm . This result implies that the microring detector may be able to measure objects whose size is smaller than its diameter. In Fig. 2(b), we also show the simulated pressure profile. The microring responses were relatively weak at the shoulder peak positions than at the center. It will be shown that the detector at these locations has more attenuation over high frequency components (the section of Fig. 4).

To better understand the origin of the three peaks, we reconstructed the spatial profiles of several harmonic frequency components in Fig. 3. For 10 MHz component as shown in Fig. 3(a), only a single spatial peak is observed. This can be understood because the acoustic wavelength for < 15 MHz frequency is larger than the ring diameter. However, for higher frequency components with much reduced acoustic wavelength, the contour of the ring waveguide becomes distinct and should be reflected in the microring response. As the high frequency focused acoustic wave (i.e., with small wavelength) is scanned at the focal plane, it can intercept the ring-shaped waveguide twice, which results in two shoulder peaks. The shoulder peaks become very clear as the ultrasound frequency is greater than 20 MHz. The widths of shoulder peaks for 30 and 50 MHz are 36 and 22 μm , which agree within ± 2 μm deviation with the calculated main lobe sizes. This agreement is due to the narrow waveguide width which is much smaller than the acoustic wavelengths in the range of interest. On the other hand, the existence of the central peak may not be apparent at the first sight, as the main lobe does not overlap with the microring waveguide. We will show by calculation that it is the side lobes of the focused ultrasound interacting with the circumference of the microring waveguide that contribute to the main peak. In Figs. 3(b) and 3(c), we show the results of two-dimensional (2D) spatial convolution of the calculated side lobes with microring. In calculation, only first order side lobes were considered for 30 MHz and second order lobes for 50 MHz. All other lobes (including the main lobes) were intentionally omitted to manifest the effect of side lobes crossing the location of waveguide. The FWHM of the main peaks at these frequencies exactly agree with the spatial convolution result. This validates that the side lobe from the focused ultrasound is responsible for the appearance of the main peak. This effect can be significant because the side lobe of the focused ultrasound is integrated over the whole circumference of the ring waveguide.

The detection mechanism can be further explained by considering the frequency spectra of the signal together with the spatial profiles of focused ultrasound. Figure 4(a) shows

FIG. 4. (Color online) (a) Calculated profiles of the focused ultrasound for several harmonic frequencies at the focal plane. The location of the microring waveguide is marked at $50\ \mu\text{m}$. The side lobes of the focused ultrasound reach maxima at the location of the waveguide at 26 and 44 MHz (red), and minima at 19, 37, and 54 MHz (black). (b) The signal spectra at the location of the ring center (black, denoted as c) and the waveguide (red, denoted as w). These were obtained by Fourier transformation of the time-domain waveforms of microring output (solid) and the calculated pressure (dotted).

the calculated profiles of the focused ultrasound for several harmonic components. Because the main lobes for the harmonic components with $<19\ \text{MHz}$ are larger than the ring diameter and have direct overlap with waveguide, the detection of the focused ultrasound is primarily based on the main lobes. However, for $>19\ \text{MHz}$, it is shown that the side lobes of the 26 and 44 MHz components reach maxima at the location of ring waveguide while those of 19, 37, and 54 MHz reach minima. This effect is consistent with the experiments and is verified in the frequency spectra of measured signals in Fig. 4(b). These frequency spectra are obtained by taking the Fourier transform of the time-domain waveforms measured where the ultrasound focus is at the ring center and at the waveguide. As expected, the spectrum measured at the ring center shows pronounced enhancement around 26 and 44 MHz, which is in contrast to the spectrum at the location of ring waveguide. The spectral dips were also observed around 19, 37, and 54 MHz because the ultrasound side lobes in these frequencies have minima. We note that this spectral feature can be seen because the spatial widths of side lobes are resolved by the narrower width of ring waveguide. In Fig. 4(b), the simulated spectra for the focused ultrasound (integrated over the ring position) are also shown. At the ring center, the calculated spectrum is quite close to the measured one. But at the ring waveguide, the measured spectrum is attenuated over a broad range as compared to that of the calculated one. When the main lobe of the high

frequency ultrasound is focused to a certain section of the ring waveguide, its side lobes are simultaneously incident on the other positions of the ring. Such side lobes can have opposite polarity against the main lobe. This can cause optical modulation of the microring to be less efficient due to destructive contribution. This is contrasted to the case at the ring center where the side lobe is incident in-phase along the ring circumference, so that the constructive contribution through the whole ring maximizes the optical modulation.

In summary, the responses of optical microring detector have been characterized by using high frequency focused ultrasound. The photoacoustic concave transmitter has been used as a broadband and high frequency focused source. As the focused ultrasound is scanned by the microring in the focal plane, two types of spatial peaks are observed: (1) shoulder peaks at the ring waveguide that result from direct overlap of the main lobes of the focused ultrasound with the ring waveguide and (2) a main peak at the ring center that is contributed by both the main lobes of low frequency components and the side lobes of high frequency ones. Detection of the shoulder peaks means that even a part of the microring waveguide (several μm^2 in area) has substantial sensitivity. Therefore, a practical imaging with any features smaller than the ring diameter would require a spatial deconvolution process after measurement, which includes all the contribution over the ring circumference.

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