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Photo-acoustic concave transmitter for generating high frequency focused ultrasound

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Abstract

We present a photo-acoustic concave transmitter to generate and subsequently focus high frequency ultrasound. Owing to a short time-duration of pulse laser beam, high frequency acoustic waves and tight focusing can be easily achieved. The transmitter consists of a light-absorbing film coated on a concave spherical structure. For detection, we used an optical microring ultrasound detector capable of covering a broadband and high frequency spectrum of photo-acoustic source. A spot width of $\sim 44 \mu\text{m}$ was obtained at the focal plane. As the finite size and the specific shape of the microring cause a geometrical effect on the detection process, especially for high frequency components, we performed a 2-D spatial signal processing to remove this effect and extract a pure pressure distribution. The aperture for acoustic focusing could be optically controlled by changing the size of pulse laser beam.

Keywords

photo-acoustic generation; high frequency ultrasound; acoustic focusing; microring resonator

1. Introduction

High frequency focused transducers have been broadly used for high resolution imaging for acoustic and photo-acoustic applications [1]. Curved single element piezoelectric transducers or flat transducers with acoustic lens are common in most cases.

Photo-acoustic generation is useful to obtain high frequency and broadband ultrasound. Ultrasound $>100 \text{ MHz}$ can be easily generated by using nanosecond pulse laser excitation. In principle, even higher frequency (e.g. $>\text{GHz}$) can be generated by using shorter laser pulses. Moreover, the generated acoustic waveform is clearly defined in time, not involving any ringing effect commonly observed in conventional piezoelectric transducers that is associated with their resonant nature in operation. This aspect leads to better temporal resolution for the received signal. For efficient photo-acoustic energy conversion, several materials have been used such as metal, mixture of carbon black and polydimethylsiloxane (PDMS) [2], and gold nano-structure films [3]. Among these materials, the gold nano-

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structure has shown the best efficiency in terms of high frequency characteristics. This is due to very thin thickness of the nano-structure reducing the possibility of high frequency attenuation through the medium.

In this work, we present a photo-acoustic concave transmitter to generate and subsequently focus broadband ultrasound with sharp focusing owing to the high frequency components. The transmitter consists of a light-absorbing film coated on a concave spherical structure. The lens is back-illuminated with 6-ns laser pulses through the planar glass side, which leads to positive focusing of acoustic waves. The focal profiles were characterized by using an optical microring ultrasound detector with a broadband and high frequency response [4-6]. Such frequency response of the detector is necessary for proper characterization of the photo-acoustic source. For high frequency components with acoustic wavelengths smaller than the detector diameter, we performed a 2-D spatial signal processing to remove the detector geometry effect and then extract the original pressure distribution from the measured focal image. The recovered spot size was $\sim 44\text{ }\mu\text{m}$ at the focal plane. Such high resolution recovery process was possible because the microring has a narrow width of waveguide, $\sim 2\text{ }\mu\text{m}$. We also introduce a concept of optically controlling the acoustic aperture of the focused transmitter.

2. Experimental Setup

The photo-acoustic focused transmitter was fabricated by depositing a thin chromium over a concaved surface. The concave surface was replicated by molding a glass lens (Newport, KPX 010, 3.308 mm in radius-of-curvature, 6.35 mm in diameter) into a UV curable polymer. For the UV-curable polymer, we used NOA65 (Norland Product Co.), which after curing is robust and transparent in the visible range of light spectrum. After the pre-polymer was fully cured under UV irradiation, the glass lens was demolded. The chromium film (100 nm thick) as a light-absorbing layer was deposited on the curved surface by evaporation. As the photo-acoustic wave is generated by using a nanosecond pulsed laser beam, the transmitted ultrasound inherently has a broadband spectrum including high frequency components. Therefore, a detector should have such frequency response to properly characterize the transmitter. For this purpose, we used an optical microring resonator which has a broadband response up to 90 MHz (3-dB roll off) [6]. The microring resonator was made of polystyrene and fabricated by using a nano imprint technique on SiO_2/Si substrate [7]. The microring detector has 100 μm in diameter and 2 μm in waveguide width. The optical detection procedure using the microring is similar to the previously reported [6].

3. Results and Discussion

As the optical microring detector has a finite size and a specified shape, the imaging result is affected by such geometrical effect where the acoustic wavelength is smaller than or comparable to the detector dimension. For low frequency where the wavelength is much larger than the detector size, the microring works close to a point detector because the acoustic wave slowly varies in phase over the detector. Therefore, for high frequency detection, a proper step of spatial processing is required to remove the detector geometry effect. At each temporal frequency, the measured image in the experiment is the result of

spatial convolution of the original pressure distribution with the detector geometry. Here, we assume that the microring detector has a 2-D shape as the waveguide height (2 μm) is sufficiently smaller than the acoustic wavelengths. Then, the 2-D spatial convolution process is described as

$$P(x, y) \otimes D(x, y) = Q(x, y) \quad (1)$$

where $P(x, y)$ is the 2-D distribution of original pressure, $D(x, y)$ is the geometry of microring detector, and $Q(x, y)$ is the measured image. Using eq.(1), we could extract $P(x, y)$ by deconvolving $Q(x, y)$ with $D(x, y)$.

For a photo-acoustic concave transmitter, the focal point is formed at the center of spherical curvature because the generated pressure has a complete spherical wavefront. Fig. 1(a) is an image on the focal plane (at a distance of the lens radius). In Fig. 1, we show the measured image, the 2-D profile of microring used in the calculation, and the recovered image of the focused pressure distribution. The measured image in Fig. 1(a) contains the effect due to the microring geometry. This effect caused two types of peaks in the focal plane: a main peak at the center and a shoulder peak around the center. The location of shoulder agrees with the location of microring waveguide. This behavior depends on acoustic frequency. For low frequency with larger wavelength than the detector size, only a single peak is observed as expected. For high frequency, two peaks are observed and resulted from different mechanisms [8]. Briefly, the central peak is due to the integration effect of the sidelobe of focused ultrasound over the whole circumference of microring detector. The shoulder peak is the result of the focused ultrasound mainlobe directly overlapping with the part of microring exposed in that focused mainlobe. In Fig. 1(a), the measurement resolution was 4 μm in both x - and y -directions. In Fig. 1(b), the microring geometry was represented in 2 μm resolution. For the microring calculation, we assumed a spatial domain amplitude of 1 at the location of microring waveguide and 0 elsewhere. The waveguide was described approximately as a single line in the figure as the width of microring waveguide is $\sim 2 \mu\text{m}$. For spatial signal processing, both Fig. 1(a) and Fig. 1(b) should have the same resolution in space. To meet this condition, the resolution in Fig. 1(a) was improved to 2 μm by interpolation. We inserted an interpolated value between adjacent pixels (*i.e.* an average value between two neighbors). The shape of the microring would have been more circular if we had used a higher resolution grid. However, we avoided it because more interpolation steps are required to the original data. Higher resolution scanning ($< 2 \mu\text{m}$) in the original measurement is possible but this requires long measurement time ($\sim$ several hours) as the number of pixels increases. However, such long time measurement was not desirable due to a thermal stability issue in the detector. In Fig. 1(c), the deconvolution result is shown. Based on the spatial processing method, we extracted the spot width of the photo-acoustic concave transmitter, $\sim 44 \mu\text{m}$. In Fig. 2, the 1-D profiles across the center of focal spot (in y -direction) are compared. A clear single peak after deconvolution is shown while it is difficult to determine the exact focal width from the measured profile. In the measured profile, the left and right shoulder peaks were not completely symmetric in amplitude. This is possibly due to a slight misalignment in the axial direction of the focusing geometry.

With a pulse laser energy density of $\sim 0.5 \text{ mJ/cm}^2$, the microring detector output was 200~300 mV at the high-speed photo-detector. As the microring has a sensitivity of $\sim 10 \text{ mV/kPa}$, the pressure at the focus was estimated as 20~30 kPa. This value was obtained below a laser damage threshold of the chromium film. The pressure can be increased by using more efficient photo-acoustic materials. In addition, optical absorption and photo-acoustic conversion efficiency need to be optimized. Strong photo-acoustic pressure has been reported by using a mixture of carbon black and PDMS under unfocused condition ($\sim 800 \text{ kPa}$ at 10 mm distance; generated at $\sim 40\%$ of damage threshold) [2].

We now show that the acoustic aperture of the lens affects the focusing resolution. The acoustic aperture of the photo-acoustic concave transmitter was controlled by changing the size of pulse laser beam. For our concave structure, the full physical aperture angle was $\sim 120^\circ$, which was determined by the fabrication process. If the optical beam size is larger than the fabricated concave structure in diameter, the acoustic aperture of the transmitter would be the full size of the concave surface. The optical beam size, however, can be reduced simply by using a pin-hole which blocks the part of laser beam. It effectively reduces the acoustic aperture, and as a result the focusing spot becomes broad. This effect is shown in Fig. 3. Fig. 3(a) corresponds to the case of $\sim 85\%$ acoustic aperture where the optical beam size covers $\sim 85\%$ of the circular area of concave structure. Fig. 3(b) is the case of 57%. The profile of the focused pressure became rapidly broad under 50% aperture. Here, the images of Fig. 3(c) and 3(d) were obtained by using the amplitudes only at a single harmonic frequency at 40 MHz. This is shown to demonstrate that the deconvolution concept works successfully for high frequency acoustic waves (with wavelength smaller than the microring detector diameter). For typical ultrasound imaging, tight focusing is naturally preferred for high resolution. Therefore, a maximum acoustic aperture will be suitable for such purpose.

4. Summary

We proposed a photo-acoustic concave transmitter having a light-absorbing film (100 nm chromium) coated onto the concave spherical structure (3.3 mm radius-of-curvature, which is the same as the focal distance). The transmitter generated and subsequently focused high frequency ultrasound with sharp focusing. As the photo-acoustic source has a broadband and high frequency spectrum, an optical microring ultrasound detector covering similar frequency range was used to measure the focused profile. We obtained a spot width of $\sim 44 \mu\text{m}$ at the focal point, which was extracted by performing 2-D spatial signal processing on the original measured image. Because the detector has a finite size and a specific geometry, deconvolution was required to remove these effects especially for high frequency components with small wavelengths. With a pulse laser energy density of $\sim 0.5 \text{ mJ/cm}^2$, the focused pressure was estimated as 20~30 kPa. The acoustic aperture of the focused transmitter could be controlled by changing the pulse laser beam size. As expected, the focal spot size was tighter with larger acoustic aperture. We expect that the focused pressure value and the spectral characteristics can be further improved by using other photo-acoustic coating materials capable of converting the optical energy more efficiently.

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Fig. 1.

A focused ultrasound image by photo-acoustic concave transmitter. (a) An original image including the geometry effect of the optical microring detector, (b) a microring detector profile used in the deconvolution process, and (c) a recovered image of focused pressure. The pixel resolution is 2 μm by 2 μm for all cases. Note that the spatial dimensions displayed in (c) are different.

Fig. 2.

1-D profiles across the center of focal spots shown in Fig. 1(a) and 1(c). A full-width at half maximum is $\sim 44 \mu\text{m}$ for the recovered profile (black solid line).

Fig. 3.

Acoustic aperture controlled by changing the size of pulse laser beam. The images were obtained by using $\sim 85\%$ of acoustic aperture in (a) and $\sim 57\%$ in (b). To obtain the images of (c) and (d), the original images were reconstructed by using frequency domain amplitudes in each pixels. For the reconstructed images at a single harmonic frequency at 40 MHz, we performed the spatial deconvolution with the detector geometry, which leads to (c) and (d). These are shown to emphasize that the deconvolution concept works well for high frequency with smaller wavelength than the detector size. The pixel resolution is $2\ \mu\text{m}$ by $2\ \mu\text{m}$ for all cases. Note that the spatial dimensions displayed in (c) and (d) after deconvolution are different from (a) and (b).