Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2010 February 1; 7564: 75642N. doi:10.1117/12.841206.

Design and characterization of acoustic 4f imaging system by using an optical microring ultrasound detector

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Abstract

We propose an acoustic 4f imaging system by using a pair of acoustic lens and an optical microring ultrasound detector (OMUD). The system was designed to have a long range imaging, and the signal strength was enhanced by a factor of ~ 13 by using an acryl-based acoustic lens at an imaging distance of close to 10 cm. The acoustic signal had a broadband and high frequency spectrum for a given focal distance owing to the unique characteristic of the OMUD. The imaging was obtained without using any reconstruction algorithms. Several performances of the designed system have been investigated by using photo-acoustic microspheres (301 μm in diameter) which are excited by pulsed laser beam. The resolution of images were compared, which consist of full frequency spectrum and harmonic frequency components. With high frequency (10 MHz and 15 MHz), the images showed consistently better resolutions (440 μm and 370 μm) for the microsphere. Frequency analysis of a time-domain signal waveform showed that the signal spectrum of the current system extends up to 20 MHz.

Keywords

4f imaging; photo-acoustic imaging; optical microring ultrasound detector; ultrasound transducer

1. Introduction

An optical 4f imaging is capable of mapping spatial information in an object plane onto an image plane with one-to-one correspondence [1]. Due to the spatial Fourier transform property of lens, unit magnification in axial and lateral directions between the object and the image is preserved. Such a feature is very attractive for fast 3-D imaging without complex reconstruction process. A similar concept has been recently introduced for photo-acoustic imaging [2]. However, the imaging resolution in this previous work was severely limited to 3~4 mm (lateral) due to detector's performance. As the 4f imaging system adopts two focusing lenses and its imaging is based on the collection of focused point images, a small size acoustic detector is a key element to achieve high spatial resolution. Moreover, a broadband response of the detector is highly desirable for photo-acoustic imaging. A high frequency component over several tens of MHz is required for recognizing the fine feature of objects while a low frequency, < 5 MHz, is still needed for smooth parts of the structure

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[3]. However, most of piezoelectric transducers have limited bandwidths around their specified central frequency. This makes it difficult to cover both frequency regimes simultaneously. Therefore, a small size ultrasound detector with broadband response is essential to take the full benefit of a 4f imaging system for high resolution and to preserve large scale structure close to the original shape of the object.

In this work, we propose a 4f imaging system by using an optical microring ultrasound detector (OMUD) that satisfies the aforementioned requirements [3-7]. The frequency response of the OMUD is very broad and extends to high frequency where 3-dB roll off is around 90 MHz, still maintaining low noise-equivalent pressure (NEP) of 0.2 kPa over 1 to 50 MHz. We used photo-acoustic sources as imaging objects which have a broadband spectral information. The OMUD consists of polystyrene optical waveguides having a planar geometry with approximately 100 μm in ring diameter and 2 μm in waveguide width. We investigated imaging performance by using photo-acoustic sources (microspheres with 301 μm in diameter) that are excited by pulse laser beam. A broadband response was clearly confirmed for a given focal distance condition owing to the characteristics of the OMUD. The current 4f lens was designed to have a long focal depth, ~ 39 mm, and therefore the high frequency performance was limited to ~ 20 MHz, approximately.

2. Experimental Setup

2.1 Fabrication of optical microring ultrasound detector

The OMUD was fabricated by using an imprint technique. The detail process is described elsewhere [8]. Briefly, a thin polystyrene layer was spin-cast on a SiO_2/Si substrate. The polystyrene ring pattern was directly replicated from a hard mold under proper conditions of temperature and pressure. After de-molding, the residual polymer layer was removed by a dry-etching technique. The fabricated resonator consisted of bus and ring waveguides. The ring diameter was 100 μm . The cross-sectional dimensions of the waveguide are approximately 2 μm by 2 μm . The input of bus waveguide was glued to a single-mode optical fiber and the output was glued to a multi-mode fiber. An index-matching epoxy was used as a coupling medium between the waveguide end and the fibers.

2.2 4f lens and measurement setup

The 4f lens was made of acryl having a bi-concave shape where the concave surface has 18 mm in radius-of-curvature and 35 mm in aperture diameter (Fig. 1). This provided a wide aperture angle, $\sim 153.3^\circ$. The distance from the edge of lens rim to the focal plane was 25.1 mm. The acryl was chosen as a lens material because it provides low acoustic attenuation and has high transmission coefficient (~ 0.94) at the interface of acryl and water. The focal length of the lens is given by lens maker's formula,

$$\frac{1}{f} = (n - 1) \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

where f is the focal length, n is the acoustic refractive index, and r_1 and r_2 are the radii-of-curvature for front and back surfaces. Here, the focal length $f = 38.98$ mm in the water was

obtained by taking $r_1 = 18$ mm and $r_2 = \infty$. The sample is located at the front focal plane (object plane) and the detector at the back focal plane (image plane) (Fig. 1). The 4f imaging system gives an image which is spatially reversed to the object at the image plane. Therefore, it eliminates the need of an image reconstruction step after data acquisition, which is typically required in conventional imaging systems. Moreover, the current configuration allows 3-D imaging in principle as elevation information can be obtained by converting time-of-flight of ultrasound into the corresponding axial distance.

Two black polymer microspheres with 301 μm in diameter (Thremo Scientific Inc., Waltham, MA) were used as light-absorbing objects. The microsphere has a polystyrene-based copolymer structure including a light-absorbing group which is uniformly distributed in the sphere. The microspheres were fixed onto an epoxy-coated glass substrate by UV-curing process. The epoxy (NOA 61, Norland Products Inc., Cranbury, NJ) is optically transparent giving a high optical contrast against the microspheres. Approximately, half of the microsphere was embedded in the epoxy layer while the other half was exposed to water.

Fig. 1 shows an experimental schematic for 4f imaging system based on OMUD. 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 objects. The 4f image profile was measured by scanning the OMUD at the back focal plane using motorized motion stages while the objects were fixed at the front focal plane. The optical detection with a probe laser beam and data acquisition processes are similar to the previously reported [7]. The probe laser beam (8168A, Hewlett Packard) is amplified up to 50 times by an erbium-doped fiber amplifier (EDFA), which is fiber-connected to the device input. The output fiber of OMUD is connected to an amplified GaAs photodiode (1811-FC, New Focus, San Jose, CA). The photodiode has a bandwidth of 25 kHz~125 MHz, ac gain of 4×10^4 V/A and dc gain 10^3 V/A. The photo-acoustic signal is monitored in time-domain by using a digital oscilloscope (WaveSurfer 432, LeCroy, Chestnut Ridge, NY). Each signal was obtained by averaging 10~30 sweeps. The quality factor (Q) of the microring resonator was about 5000. For ultrasound detection, the wavelength of probe laser beam is fixed at the maximum of the resonance slope.

3. Results and Discussion

A long-range 4f image measured by the OMUD is shown in Fig. 2. Two microspheres with 301 μm in diameter were ~ 1.4 mm apart from each other. The image was obtained by taking peak values of time-domain signals in each pixels. The total imaging time depends on the number of pixels, the number (10~30) of signal averaging in each pixel, and the sweeping time of xy -manipulator over the imaging range. The experiment was carried to obtain a 2-D image including ~ 1600 pixels. In Fig. 2, the image amplitudes between the two microspheres were different (*i.e.* the bottom one is brighter than the upper in Fig. 2(a)) due to the non-uniform spatial intensity distribution of pulsed laser beam. The 300 μm contour lines are also shown. In this full spectrum image, the detected signal is dominated by low frequency range < 5 MHz (shown in Fig. 4(b)). As a result, the image is broader than the nominal size of the microsphere. Two microspheres were distinguished more clearly in the high frequency image shown in Fig. 2(b) and (c). To obtain these images, we first obtained a frequency spectrum of the time-domain signal in each pixel of Fig. 2(a), and then chose the

amplitude of a specific harmonic component to construct the pixel image. This process was applied for all pixels. Here, the images for 10 MHz and 15 MHz are shown as examples. The image size becomes close to the contour of the bead because the sharp boundary of the beads is characterized by high frequency components. For >20 MHz, the image contrast was rapidly degraded to <3 (the ratio of the peak value to the background noise). The 1-D cross-sectional profiles across the center are shown in Fig. 3. Full-width half-maximums (FWHMs) for the images of the full spectrum, the 10 MHz and the 15 MHz harmonic components were $\sim 1330\text{ }\mu\text{m}$, $440\text{ }\mu\text{m}$ and $370\text{ }\mu\text{m}$, respectively.

The time-domain signal at the center of microsphere image is shown in Fig. 4(a). The waveform is the result of mixed acoustic signals from two microspheres, aberration in the lens system, and possible misalignment. In Fig. 4(b), the corresponding frequency spectrum for the time domain signal for Fig. 4(a) is shown. High frequency information (> 15 MHz) in the signal was strong where the object and the image were placed around the focal points. The spectrum has a peak around 3~4 MHz and extends up to 20 MHz, covering both low and high frequency spectral ranges. The frequency response (especially, the high frequency components) and the system resolution were limited by the following loss mechanisms: attenuation in the lens medium (6.4 dB/cm at 5 MHz [9]), boundary reflections at both front and back lens surfaces ($\sim 6\%$ each), and absorption in water (0.05 dB/cm at 5 MHz).

As the 4f imaging system adopts two focusing lenses, acoustic signal at the focal plane is significantly enhanced by the lenses. We compared this value obtained by the 4f lens with the case in the same distance but without the lens (Fig. 5). Each dot in Fig. 5 represents a peak value of measured signal waveform. It is shown that the acoustic signal is rapidly decreased without the lens. However, with the 4f lens, the amplitude (at the center of microsphere image) was enhanced by a factor of ~ 13 at the same distance.

In the current configuration of 4f imaging system, the available frequency spectrum of measured signal was limited to ~ 20 MHz. This is mainly because the imaging system was originally designed to have a long detection depth (*e.g.* intending the breast cancer detection application). However, if we consider high resolution short-range imaging, the system needs to be modified to reduce the signal loss in high frequency. This can be done by using high frequency acoustic lenses based on ZnO and Al_2O_3 which are typically used for scanning acoustic microscopes. These lenses are commercially available and can easily allow transmission up to several hundreds MHz. In that range of spectrum, the acoustic wavelength can be smaller than the OMUD diameter. However, we expect that the OMUD can still work in this range because the OMUD has the narrow width of waveguide ($2\text{ }\mu\text{m}$) [10], which is smaller than or comparable to the acoustic wavelength in this frequency. A proper spatial signal processing will be required in this case.

4. Summary

A 4f imaging system has been proposed using the OMUD and the acryl-based acoustic lens, and imaging results were obtained with broadband and high frequency information. The current system was designed for long range imaging (focal distance $\sim 39\text{ mm}$ in water). The 4f images for two $301\text{ }\mu\text{m}$ polymer microspheres were obtained at the focal plane. Two

microspheres were clearly distinguished by using the high frequency harmonic components of the detected signal. The FWHM of the image obtained at the 15 MHz frequency was $\sim 370 \mu\text{m}$, which is close to the nominal size of the microsphere. The spectral analysis for the time-domain signal showed that the image consists of frequency components up to 20 MHz. However, the image contrast was degraded as the frequency goes beyond 20 MHz. With the 4f lens, the enhancement factor in the signal strength was ~ 13 . We believe that the high frequency transmission and enhancement factor can be significantly improved by using a proper lens material with high transmission. This will be also useful for a short range 4f imaging capable of very high resolution and fast image acquisition.

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Fig. 1.

Schematic of 4f imaging setup. The microspheres and the OMUD are located at the front and back focal planes, satisfying the 4f imaging condition. The probe laser beam, the digital oscilloscope, and the xyz-motion stage are controlled by computer.

Fig. 2.

2-D image of two black polymer microspheres with $301 \mu\text{m}$ in diameter. These are 1.4 mm apart. Each pixel size is $100 \mu\text{m} \times 100 \mu\text{m}$: (a) 4f image measured by the OMUD. The contour for the original sphere size is shown as the black circle, (b) and (c) the images obtained by harmonic frequency components of 10 MHz and 15 MHz . The image in (c) becomes sharper while the background becomes more noisy.

Fig. 3.

1-D spatial profiles across the center of the bottom microsphere shown in Fig. 3. Three traces are obtained from Fig. 2(a), (b), and (c). Each trace is normalized to its peak amplitude. The FWHMs were 1330 μm , 440 μm , and 370 μm , respectively. For the 15 MHz case, the background noise is increased, which makes the signal peak-to-background noise ratio ~ 3 .

Fig. 4.
(a) Time-domain waveform at the peak position of spatial image, and (b) the corresponding frequency spectrum.

Fig. 5.

Pressure amplitudes along the axial direction without a 4f lens. Black dots at left: experimental data, solid line: the expected $1/r$ decay of the pressure amplitude normalized to the first dot value. These amplitudes are compared to the enhanced value by the 4f focusing lens (the red dot at right indicated by arrow). The signal strength was enhanced by a factor of ~ 13 with the 4f lens.