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Ring ultrasound transducer based miniaturized photoacoustic imaging system

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Abstract

In recent years photoacoustic microscopy systems have attracted significant attention from biomedical researchers due to its ability to provide label-free imaging of hemoglobin (vasculature), lipids, and melanin with high spatial and temporal resolutions even from deeper (> 1 mm) depths inside biological tissue. This work reports the development of a low-cost and miniaturized photoacoustic (PA) imaging device for microscopy applications. A ring ultrasound transducer with 2.5 mm outer diameter and 0.5 mm inner diameter is fabricated using a 150 μ m thick PZT element as the piezoelectric layer. The ring ultrasound transducer is integrated with a pulsed laser diode with integrated optical fiber which is coaxially fed through the transducer. Raster scanning of the integrated device is used to obtain 3 dimensional images of a tissue-mimicking phantom.

Keywords

Photoacoustic Imaging; Ultrasound; Ring Ultrasound Transducers; Pulsed laser diode

I. INTRODUCTION

Photoacoustic Imaging (PAI) is a hybrid imaging modality wherein thermo-elastic expansion of light absorbing molecules of tissue when illuminated with short nanosecond light pulses generate wideband acoustic pulses. These photoacoustic waves are then detected by ultrasound transducers to form photoacoustic images providing optical absorption based molecular contrast of the tissue[1], [2]. The imaging depth and spatial resolution are scalable with optical and ultrasound parameters to suit a particular imaging application. Multi-scale photoacoustic systems have been reported over the last decade to image microscopic, mesoscopic and macroscopic features. In particular, photoacoustic microscopy (PAM) provides label-free 3D imaging of vasculature with high spatial and temporal resolutions from even deeper (> 1 mm) depths [3], [4]. PAM has been widely applied in several pre-clinical applications such as identifying cancer biomarkers and mapping neural activity[5].

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However, most PAM systems are bulky table-top setups, mainly due to complicated arrangements of ultrasound and optical beam engineering involved to obtain confocal arrangement of the optical and acoustic spots[1], [6], [7]. Miniaturized PAM systems that can be integrated as a catheter are highly desirable for multiple endoscopy and surgical applications[8], [9]. A few successful attempts on miniaturization of PAM systems to the form factor of a typical catheter have been reported in past[10]–[16].

In this work, we present a forward-looking catheter (~3 mm diameter) sized low cost photoacoustic transducer realized using a simple integration of a custom made miniaturized ultrasound transducer and a multimode optical fiber connected to a low-cost laser diode. PZT is chosen as the piezoelectric element considering its high piezoelectric coupling and ease of processing. The ultrasound transducer is characterized using pulse-echo measurements. The ring ultrasound transducer, assembled with a ferrule-optical fiber system is then characterized as a photoacoustic transducer. The overall PA system can be housed within a match-sized box, thus making it low-cost and portable. In future, the forward looking single element system will be further developed into an intra vascular photoacoustic imaging system by using a multi-element micromachined ultrasound array for intravascular imaging applications.

II. MATERIALS AND METHODS

A. Architecture of the proposed photoacoustic transducer

A schematic diagram of the proposed miniaturized photoacoustic device architecture is shown in Fig. 1. A ceramic ferrule with inserted optical fiber is used as the base for the device. A 2.5 mm ring ultrasound transducer consisting mainly of the thin piezoelectric layer and a few millimeter thick backing layer is mounted on top of the ferrule. The inner diameter of the transducer, 0.5 mm, is designed to have a matching hole to the ferrule to allow light delivery through the center. For the present work our ring ultrasound transducer has an outer diameter of 2.5 mm and an inner diameter of 0.5 mm. We use 150 μm thick PZT as the piezoelectric element. A 400 μm core diameter multimode optical fiber is fitted through the hole of the ring ultrasound transducer. A coaxial cable connected to the ring transducer sends the returning photoacoustic signals to a data acquisition system, where the signals are then processed and reconstructed into photoacoustic images.

B. Design and fabrication of ring ultrasound transducers

A pre-diced, poled, and Cr/Au sputtered PZT element (MOTOROLA 3203) is used as the piezoelectric element. The thickness resonance of the bulk transducer can be given as

$$f_0 = \frac{C_p}{2t_p}$$

where, C_p is the speed of sound in the transducer material and t_p is the thickness of the transducer. In this work we have used a 150 μm thick PZT element to develop a 13.3 MHz ring transducer with 2.5 mm diameter. The ultrasound transducer fabrication process is described in Fig. 2.

First the Cr/Au coated PZT element was mounted on a glass block using wax, and a mold of machinable ceramic was mounted around the thin piece of the PZT element after thorough cleaning of the top surface of the PZT element. A conductive epoxy (E-SOLDER 3022, Von Roll Isola Inc., New Haven CT) was cast onto the PZT element and compacted by centrifuging the epoxy filled mold at 3000 RPM for 10 minutes. Using a lathe, the mold and transducer piece was turned to a diameter of about 2.25 mm. The backing layer was then lapped to a thickness of approximately 1.5 mm. A composite polyamide casing of diameter approximately 0.25 mm larger than the diameter of the transducer was placed concentrically with the transducer. The piezoelectric element and concentrically placed polyamide casing was then filled with an insulating clear epoxy (INSULCAST 502, ITW Engineered Polymers, Montgomeryville PA). The polyamide tube was cut at ~1.5 mm length from the face of the transducer to expose the conductive backing layer. A shallow hole was made towards the edge in the backing layer and core wire of a 150 μm thick coaxial wire was inserted into this hole and fixed to the backing layer using the conductive epoxy. The shielding of the coaxial wire was soldered to the top Cr/Au layer using a very thin copper wire strand. Fig. 3. shows the fabricated 2.5 mm ring transducer mounted on a ferrule-optical fiber assembly.

C. Light source

We have used a commercially available 905 nm pulsed laser diode (PLD) (Laser Components Inc.) with 65 W peak optical power as the light source. The PLD is driven by a match-box sized high current circuit applying very short pulses (~40 ns) of high current (30 Ampere) through the PLD at 20 kHz repetition rate. The PLD is coupled to a multimode optical fiber with 400 μm core diameter. For current experiments no focusing technique was used at the output end of the optical fiber. This leaves a significant room for improvement in the imaging resolution of the photoacoustic transducer in future.

D. Pulse-echo characterization of the ultrasound transducer

The ring ultrasound transducers was characterized for its underwater pulse-echo response by using a flat aluminum block kept at 1.5 cm distance as the ultrasound reflection target. A commercial pulse-receiver (5073 pulse-receiver, Olympus Inc.) was used to give a voltage pulse input with 2 μJ energy. The received pulse with 0 dB gain shows ~80 mV peak-to-peak voltage output. The frequency response of the received pulse shows that the ring ultrasound transducer has a center frequency of 13.12 MHz with a fraction bandwidth of ~30% for -6 dB loss (see Fig. 4).

III. EXPERIMENTAL SETUP

Fig. 5 shows the schematic representation of the experimental setup used for raster scanning based imaging with the 2.5 mm diameter photoacoustic transducer. The optical fiber integrated ring transducer is mounted on a 3-axis stage (NRT-100, Thorlabs). The output from the ring ultrasound transducer is first sent to an amplifier that provides 39 dB gain. The preamplifier output is captured using a high speed (500 Msps) data acquisition system (Razormax, Gage Instruments). An on-board generated low-voltage pulse signal of the laser driver circuit is used as trigger signal for timing the acquisition and stage motion. A 3 cm

thick agar-gel phantom with 0.7 mm pencil leads embedded at ~6 mm depth in a pattern to read “PSU” is used as the imaging target.

IV. RESULTS AND DISCUSSION

In order to characterize the photoacoustic transducer for lateral imaging resolution a black light absorbing card with two white with sharp edges was used. Fig. 6a shows the black-card phantom with two 5 mm white lines (low-absorbing targets) placed 11 mm apart horizontally. Photoacoustic imaging was performed using the ring transducer assembly over the scan line region shown with dotted orange line in Fig. 6a. Fig. 6b shows the peak-to-peak photoacoustic signal amplitude plotted over the 30 mm scan line shown in Fig. 6a. The distance corresponding to reduction in the peak to peak photoacoustic signal amplitude from 75% to 25% of the maximum peak to peak signal along this 30 mm scan line gave an estimate of the spatial resolution of photoacoustic imaging with our ring transducer assembly as around 300 μm . The optical resolution can be further improved by employing a focused light source integrated with the same transducer assembly. Similarly, making the transducer focus at the required depth will also provide improved acoustic resolution for the photoacoustic imaging.

Fig. 7a shows the agar-gel phantom with 0.7 mm pencil leads placed 6 mm deep inside the phantom arranged as shown. Photoacoustic image generated by the 2D scan with the ring transducer array is as shown in Fig. 7b. The scan was performed over a region of 27 mm (along x-direction) by 12 mm (along y-direction). The step size along both directions was 150 μm . Center frequency of the 2 mm ring transducer used for this scan was 13.5 MHz. Sampling frequency was taken as 500 mega samples per second.

Current raster scan imaging can be replaced by a rotating mirror reflector based circular scanning [11] or a phased array imaging using micromachined ultrasound arrays in place of a single element transducer[8].

V. CONCLUSIONS

This work presented design, fabrication, integration and imaging results of miniaturized photoacoustic transducer device that uses a custom made ring ultrasound transducer, and a multimode optical fiber connected to a low cost laser diode. From the ultrasound echo-pulse analysis the center frequency of the fabricated ring ultrasound transducer is found to be ~13.12 MHz with ~30 % bandwidth. Photoacoustic images generated by the miniaturized microscope show ~300 μm resolution for unfocused light input. It is possible to achieve a micron scale resolution by using focused optical and ultrasound components. Targeted imaging applications of our portable microscopy system include imaging cancer biomarkers and monitoring neural activity.

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Fig. 1.

Photoacoustic transducer architecture: a ring ultrasound transducer with its inner radius matching the diameter of the light delivery optical fiber is mounted on a 2.5 mm diameter ceramic ferrule is proposed for photoacoustic imaging.

Fig. 2.

Schematic description of ring transducer fabrication process showing major steps: (a) setting up a the piezoelectric element and mold assembly, (b) filling conductive epoxy and centrifuge compacting to obtain backing layer, (c) assembly of the transducer after mold removal by turning, and (d) making contacts for a coaxial wire and drilling of 500 μm hole by using a high speed drill.

Fig. 3. Optical pictures of the 2.5 mm ring ultrasound transducers integrated with a multimode optical fiber with 400 μm diameter core.

Fig. 4. Pulse echo response of the ring ultrasound transducer shows the center frequency of the transducer at ~13.12 MHz with ~30% fractional bandwidth.

Fig. 5.
A schematic representation of the experimental setup for photoacoustic imaging is shown.

Fig. 6.

Experimental photoacoustic imaging results for a 1 D scan. (a) Top-view picture of the black-card phantom with two 5 mm white lines placed horizontally 11 mm apart. (b) Peak to peak photoacoustic signal amplitude plot for the scan line region (marked with a dotted orange line in (a)) scanned with a pitch of 50 μm over a total scan length of 30 mm.

Fig. 7.

Experimental photoacoustic imaging results for a 2 D scan. (a) Top-view picture of the agar phantom with 0.5 mm pencil lead targets arranged inside at 6 mm depth as shown. (b) Photoacoustic image reconstructed from linear 2-D scan along x-y plane (27 mm in x and 12 mm in y) with step size of 150 um along both directions.