

A New High-Frequency Photoacoustic Sensing (PAS) Probe Using Silicon Acoustic Delay Lines (SADLs)

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ABSTRACT

In this paper, we report a high-frequency photoacoustic sensing (PAS) probe design consisting of an optical fiber for light delivery and two silicon acoustic delay lines (SADLs) for detecting/relaying the PA signals. A beveled tip is formed at the distal end of the optical fiber to overlap the illumination region with the detection zone of the SADLs. Detected PA signals are transmitted through the SADLs with low loss at frequencies up to 17 MHz. For demonstration, a prototype PAS probe using SADLs is designed, fabricated, and tested. Testing results show that the PAS probe provides superior sensitivity with considerable high-frequency improvement.

Keywords: Silicon acoustic delay line, photoacoustic sensing, high frequency.

1. INTRODUCTION

In recent years, new photoacoustic sensing (PAS) probes [1-4] have been developed to conduct localized measurements in biological tissues. Different from conventional optical modalities, PAS can detect optical absorption contrast at a penetration depth beyond the optical diffraction limit [5-8]. However, the need for both light delivery and ultrasound detection poses some challenges in the design and construction of the PAS probes, especially in terms of compactness. For *in-vivo* applications, the diameter of the PAS probe needs to be as small as possible to minimize its invasiveness. To address this issue, new probe designs based on optical-fiber acoustic delay lines (OFADLs) have been investigated [9, 10]. One or two optical fibers were used as both an optical waveguide for light delivery and an acoustic delay line for relaying the PA signal. As a result, the overall diameter of the PA probe can be significantly reduced. As an additional benefit, after transmitting through the delay line, the PA signal will arrive at the transducer after all interference signals diminish and therefore can be easily distinguished and recorded for data processing.

Due to low acoustic velocity (e.g., ~5000 m/sec [11]) and high acoustic attenuation of fused silica, the maximal single-mode transmission frequency and bandwidth of OFADLs are typically limited to a few MHz. The low acoustic transmission frequency and bandwidth result in poorer depth resolution of PA detection. It can also limit the detection sensitivity because the peak amplitude of the PA signal oftentimes occurs at much higher frequencies.

To address this issue, we report a new PAS probe design based on SADLs. Compared with fused silica, single-crystalline silicon has much higher acoustic velocity (e.g., ~8400 m/sec [12]) and lower acoustic attenuation, and is compatible with different micromachining methods. Therefore, it is possible to make SADLs with high acoustic transmission frequency. For demonstration, a prototype PAS probe using SADLs is designed, fabricated, and tested with different concentrations of dye solutions and biological tissues with an embedded target.

2. EXPERIMENTAL PROCEDURE

2.1 Probe Design and Construction

Fig. 1 shows the schematic design of the PAS probe, which consists of one optical fiber, two SADLs, and a homemade ultrasound transducer. The optical fiber (FT200UMT, 0.39NA, Thorlabs, Newton, NJ) for light delivery is located at the center of the probe. The 200- μ m core diameter allows the transmission of μ J laser pulses without damaging the fiber tip [13]. The SADLs are laid in parallel with the optical fiber. Their acoustic time delay is longer than the duration of the interference signals, such that the real PA signal from the target can be easily distinguished. The micro linkers hold the

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optical fiber and the SADLs in position while providing acoustic isolation between them. Because the optical fiber and the SADLs are arranged side by side, this causes an offset of the light delivery and PA detection, resulting in lower PA detection efficiency [14, 15]. To address this issue, the distal end of the fiber is polished at an oblique angle (42°) to form a beveled-tip for deflecting a larger amount of light toward the center of the two SADLs. A “hollow” ultrasound transducer consists of a flat piezoelectric substrate with a drilled hole to allow the optical fiber to pass through. The diameter of the hole is slightly larger than that of the optical fiber, such that the ends of the surrounding SADLs can have good contact with the ultrasound transducer.

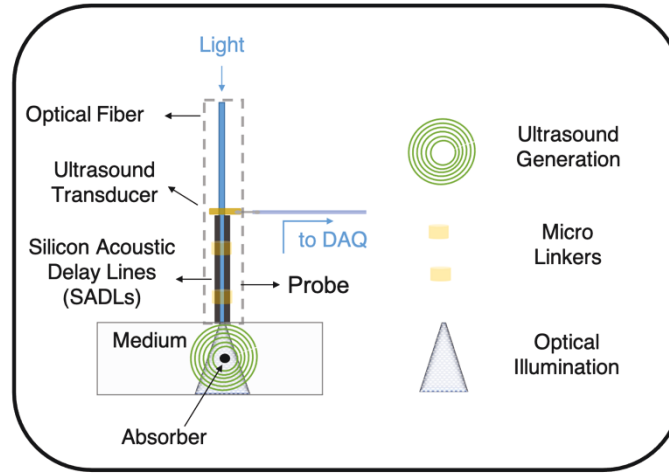


Figure 1. a) Schematic of the PAS Probe Design.

Two straight silicon wires with a length of 25-mm and a cross-section of $100\ \mu\text{m} \times 100\ \mu\text{m}$ are used as SADLs to receive the PA signals and add an acoustic time delay of $\sim 3\ \mu\text{s}$ (assuming an acoustic velocity of $\sim 8400\ \text{m/s}$ for silicon), which is longer than the typical duration of the interference signals during excitation [9, 10]. For wire-type acoustic delay lines, the non-dispersive longitudinal single-mode transmission frequency is usually around $0.1 - 0.2\ c/d$, where c and d are the acoustic velocity and the cross-sectional dimension, respectively [16-18]. With a $100\ \mu\text{m} \times 100\ \mu\text{m}$ cross-section, the highest single-mode transmission frequency of the SADLs is estimated to be $\sim 17\ \text{MHz}$. For receiving the PA signals through the SADLs, a 160- μm -thick PZT ceramic disc (Type VI, APC International Ltd., Mackeyville, PA) is used as the piezoelectric substrate of the ultrasound transducer, which has a thickness-mode resonance frequency of $\sim 13\ \text{MHz}$. The alignment hole diameter is about 430- μm , which is slightly larger than the diameter of the optical fiber (core + cladding). To facilitate the wiring, the PZT substrate is fixed onto a glass pad (also coated with two matching electrodes). Transducer mounting is completed by connecting the SMA connector to the glass-transducer assembly. No matching layer is added between the PZT transducer and the SADLs because the acoustic impedances of silicon and PZT are close to each other. Two micro linkers are used for fixing the optical fiber and two SADLs together in a stable position (Fig. 2). To achieve the required resolution, a high-resolution 3-D printer (NanoScribe Photonics Professional GT2, Germany) is used for printing the micro linkers with a resolution of $5\ \mu\text{m}$. The overall diameter and length of the micro linker are 700 μm and 2 mm, respectively.

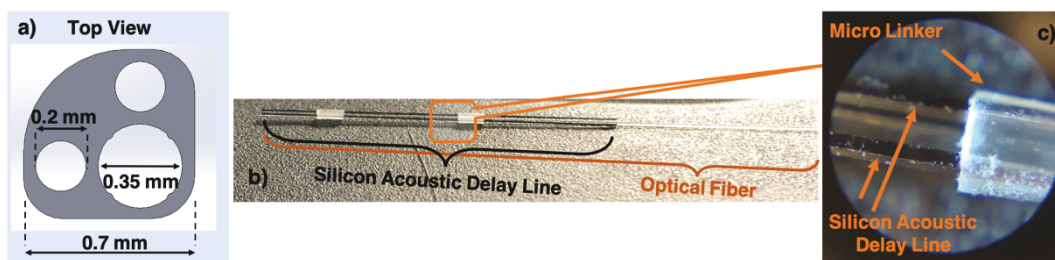


Figure 2. PAS Probe Assembly: a) Cross-Section View of the Micro Linkers, b) Photo of the Assembly, and c) Zoom-in View of Micro Linkers and the SADLs.

2.2 Ultrasound Transmission Through SADL

A two-port ultrasound testing is conducted to evaluate the acoustic transmission of the SADL (Fig. 3). Two 20-MHz contact ultrasound transducers (V250, Olympus NDT, Waltham, MA, USA) are used to transmit and receive the ultrasound signals, respectively. The SADL is placed between the two ultrasound transducers. Mineral oil is applied onto the contacts between the ends of the SADL and the surfaces of transmitting & receiving transducers to enhance coupling efficiency and minimize unwanted reverberation. The pulser/receiver (5073PR, Olympus NDT, Waltham, MA, USA) is set to the transmission mode, which sends a driving voltage pulse to the transmitting transducer to generate ultrasound signals and also amplifies signals detected by a receiving transducer. To improve the signal-to-noise ratio (SNR), the received ultrasound signals are averaged 16 times and recorded on a digital oscilloscope (TDS2002C, Tektronix Inc., Beaverton, OR, USA) to determine their peak amplitude and acoustic time delay.

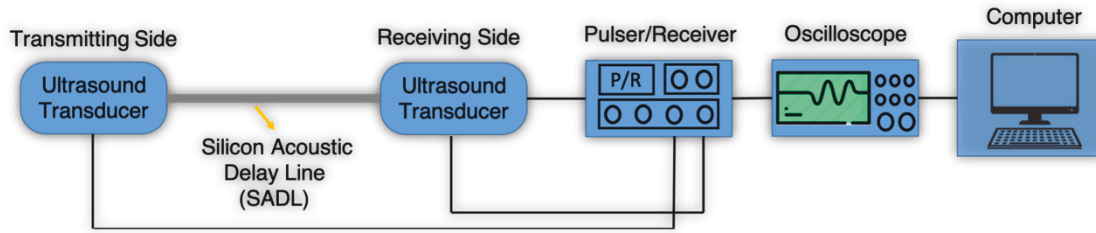


Figure 3. Two-Port Ultrasound Testing Setup with an SADL.

2.3 PA Characterization

The sensing capability of the PAS probe is characterized with a testing setup shown in Fig. 4. The light source is an Nd:YAG laser (SPOT-10-200-532, Elforlight, Northants, UK) operating at a wavelength of 532 nm. The duration of the source pulse is 1.75 ns, and the maximum output energy is 20 μJ per pulse. The pulse repetition rate is 2 kHz. The maximum excitation laser pulse energy at the probe tip is 7.77 $\mu\text{J}/\text{pulse}$. The corresponding fluence is estimated to be 19.54 mJ/cm^2 , which is below the ANSI (American National Standard Institute) safety limit of 20 mJ/cm^2 [19].

First, PA characterization of dye solution (as the PA target) with different concentrations is tested (Fig. 4). Dye solutions are prepared with black dye powder (Rit® Dye, Phoenix Brands, Stamford, CT, USA) by diluting with DI water to reach the desired concentration. The dye solution is transferred into a plastic tubing with a syringe and the 3-axis stage is gradually moved towards the tubing until the probe (mounted onto the stage) and the dye solution start to contact with each other. The PA measurement for each concentration is repeated five times. The captured PA voltages are amplified and averaged to determine the overall PA response. The detection capability of the PAS probe in biological tissues for *in-vivo* sensing is mimicked with a chicken breast tissue. A 3-D printed container is used to hold the chicken breast tissue in place. The PAS probe is contacted onto the tissue surface to detect a black-tape target buried at different depth. The chicken breast tissue consists of two layers. One layer is first laid down in the container. Subsequently, the target is placed onto this first layer and covered by the second layer.

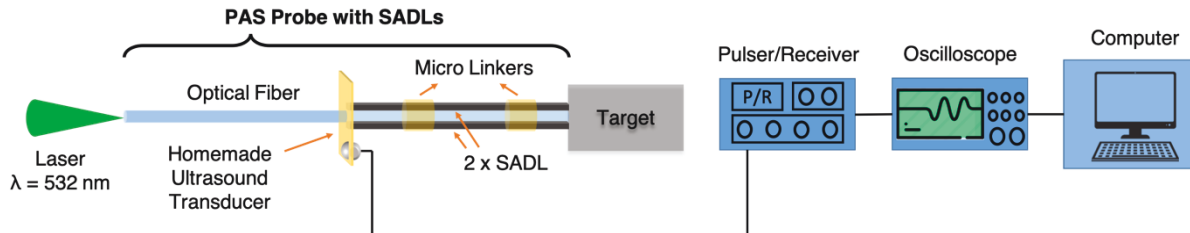


Figure 4. PA Testing Setup for the PAS Probe.

3. EXPERIMENTAL RESULTS

3.1 Ultrasound Transmission through the SADL

Fig. 5a shows a received ultrasound signal after traveling through a SADL with a length of 25 mm. The signal arrives at the receiving transducer after a time delay of 3.080 μs . The existence of the reflected signals shows that the silicon material can serve as a low-loss acoustic delay line to transmit the PA signal from the target to the transducer. The average acoustic velocity of SADLs is determined to be ~ 8120 m/s. Fig. 5b indicates the frequency spectrum of the received ultrasound signal after FFT (Fast Fourier Transformation). The peak frequency is around 14.2 MHz with 17% bandwidth. This result indicates that the coefficient of the single-mode transmission frequency (c/d) of the SADL is close to 0.2.

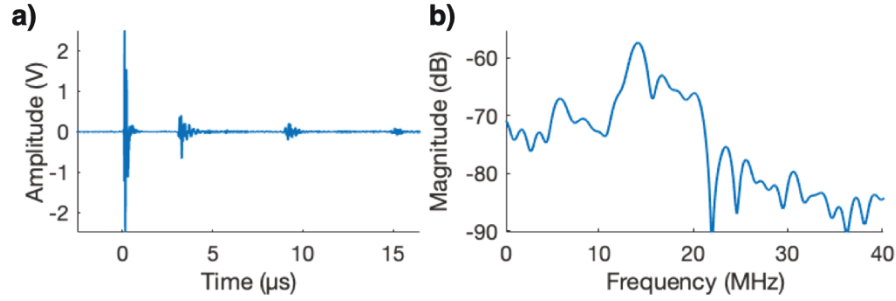


Figure 5. a) Received Ultrasound Signal After Travelling Through the SADL with a length of 25 mm, and b) Frequency Response for the Received Ultrasound Signal Through the SADL.

3.2 PA Test of the Dye Solutions

For each dye concentration, five different PA tests are performed, and the average value and standard deviation of the peak-to-peak PA amplitudes are calculated (Fig. 6). A total of fourteen concentrations are tested starting from 0.001 g/ml to 0.05 g/ml. The PA signals and the dye concentration follow an almost linear relationship ($R^2 = 0.934$). When the black dye concentration is reduced to 0.001 g/ml, the PA amplitude changes from 39.2 mV to 8.2 mV. The received PA waveform starts to bury under the noise level when the detection limit is reached. These results determine the detection limit of about 0.001 g/ml for the PAS probe in the black dye solution target.

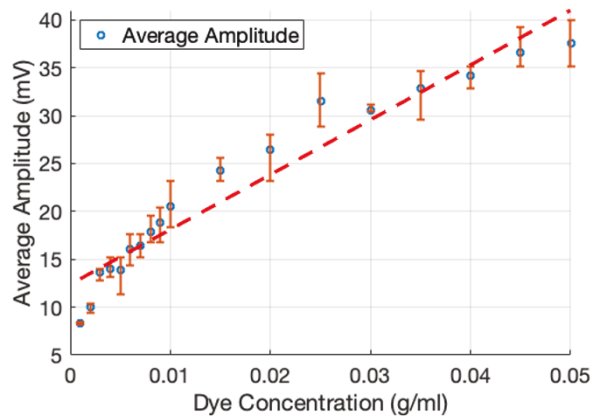


Figure 6. PA Response from Various Black Dye Concentrations: Average Peak-to-Peak PA Voltage vs. Dye Concentration (g/ml).

3.3 Target Detection in Chicken Breast

Fig. 7 shows the received PA signals from the black tape target at two different depths in chicken breast. The depths are calculated based on the first positive peak of the received PA signals. The black tape target not covered by the second layer of the chicken breast is recorded as a reference depth ($d_1 = 0$ mm). The amplitude of the PA received signal attenuates when the depth of the target increases (from d_1 to $d_{\max}$ in Fig. 7a and 7b, respectively) because there is a lower optical fluence occurred by stronger light diffusion at larger depths. After going deeper than $d = 1.51$ mm, the PA signal starts to be buried into noise, which determines the maximal detection depth under the current testing condition.

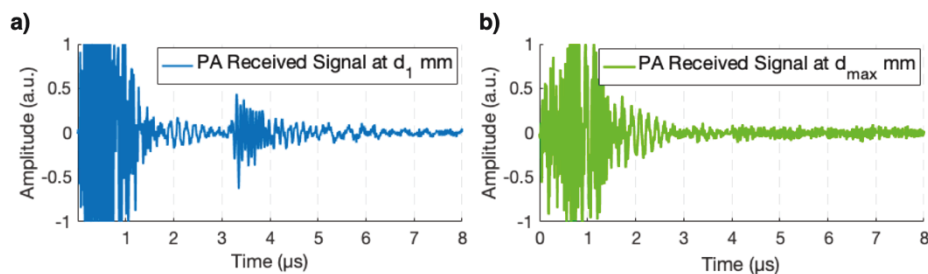


Figure 7. Received PA Signals Detected from a) $d_1 = 0$ mm to b) $d_{\max} = 1.51$ mm.

4. CONCLUSION

A novel PAS probe design using SADLs has been demonstrated. The SADLs are specially designed to allow the reception of higher-frequency PA signals while distinguishing the received PA signals from the interferences. A drilled ultrasound transducer provides unblocked optical and acoustic paths. With the high-resolution 3-D printed micro linkers, a stable and compact probe structure can be obtained without creating unwanted crosstalk. The sensing capability of the PAS probe is characterized with liquid dye solutions and demonstrated with target detection in chicken breast tissue.

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