Single Optical Fiber Photoacoustic Sensing Probe

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ABSTRACT

In this paper, a novel photoacoustic (PA) sensing probe design consisting of single optical fiber is reported. The same optical fiber is used for light delivery, which also serves as an acoustic delay line to relay the PA signal. As the key feature of the design, the ultrasound transducer is made optically-transparent to allow excitation light to pass through. This probe design provides three major benefits, including miniaturization, co-registered optical excitation and acoustic detection, and clear separation of PA signal from interference signals. Testing results show that PA probe provides good sensitivity and high linearity.

Keywords: Photoacoustic sensing, optical fiber, transparent ultrasound transducer, acoustic delay line.

1. INTRODUCTION

For biomedical applications, photoacoustics (PA) has become a useful technique that combines both rich optical absorption contrast and good acoustic penetration depth beyond optical diffraction limit [1, 2]. Although better than conventional optical methods, the penetration depth of PA sensing and imaging in tissues is still limited by the maximal allowable laser fluence, the optical absorption and acoustic attenuation in tissues [3]. In recent years, new PA sensing probe [4-6] or guided biopsy needles [7-9] have been developed to conduct localized measurements. Different from conventional optical sensing probes [10] (which would consists of a single optical fiber for both light delivery and reception), the need for light delivery and ultrasound detection poses some challenges to the design and construction of PA sensing probes, especially in terms of compactness. For in-vivo applications, the sensing probe needs to be as compact as possible to minimize its invasiveness.

To address this issue, we have demonstrated a new PA sensing probe design using two optical fibers [11]. One optical fiber serves as the optical waveguide for delivering excitation laser pulses onto the target. The second optical fiber functions as an acoustic delay line to detect and transmit the generated PA signal from the target to an outside ultrasound transducer, while creating a desirable amount of acoustic time delay. With the transducer located outside, the PA probe consists of only two optical fibers placed closely to each other to provide a small probe diameter. In addition, by adding an extra time delay, the PA signal will reach the transducer after all interference signals diminish and therefore can be easily distinguished and recorded for data processing. Still, with the use of two optical fibers, the PA sensing is not as compact as many optical sensing probes with only single optical fiber. In addition, the light delivery and the ultrasound detection areas are offset with each other, resulting in a non-ideal PA signal detection configuration.

In this paper, we report a new PA sensing probe design using a single optical fiber for both light delivery and ultrasonic detection. This is made possible by the development and use of an optically-transparent ultrasound transducer, which allows the excitation light to pass through and travel along the optical fiber to reach the target. In return, the transducer senses the generated PA signal transmitted through the optical fiber. For demonstration, a prototype probe was designed, fabricated, and tested with different concentration of dye solutions.

2. EXPERIMENTAL PROCEDURE

2.1 Probe Design and Construction

Fig. 1a shows the schematic design of the PA sensing probe. It consists of one single optical fiber laid out along the probe, which is housed inside a polyimide tubing. The polyimide tubing provides good structural protection and also

Photons Plus Ultrasound: Imaging and Sensing 2019, edited by Alexander A. Oraevsky, Lihong V. Wang,
Proc. of SPIE Vol. 10878, 1087846 · © 2019 SPIE · CCC code: 1605-7422/19/$18 · doi: 10.1117/12.2508008

acoustic insulation for the optical fiber [11]. A hollow needle can be used to provide better stability for the fiber tip of the probe. During the operation of the probe, the optical fiber can easily contact with surrounding tissue or media.

Fig. 1b illustrates the operation principle and signal conversion/flow of the PA sensing probe. First, the optical fiber serves as an optical waveguide to transmit the excitation pulses from the laser to the target. Excited media in the target generate PA signals due to thermoelastic generation of ultrasound. Next, the optical fiber serves as an acoustic delay line to transmit generated PA signals from the target to the transducer. To accomplish the optical and acoustic transmissions through the fiber, the transducer is made optically-transparent. The PA signals sensed by the transparent transducer are amplified and displayed by the amplifier and the scope, respectively. Finally, the amplified PA signals are stored on computer in data acquisition (DAQ).

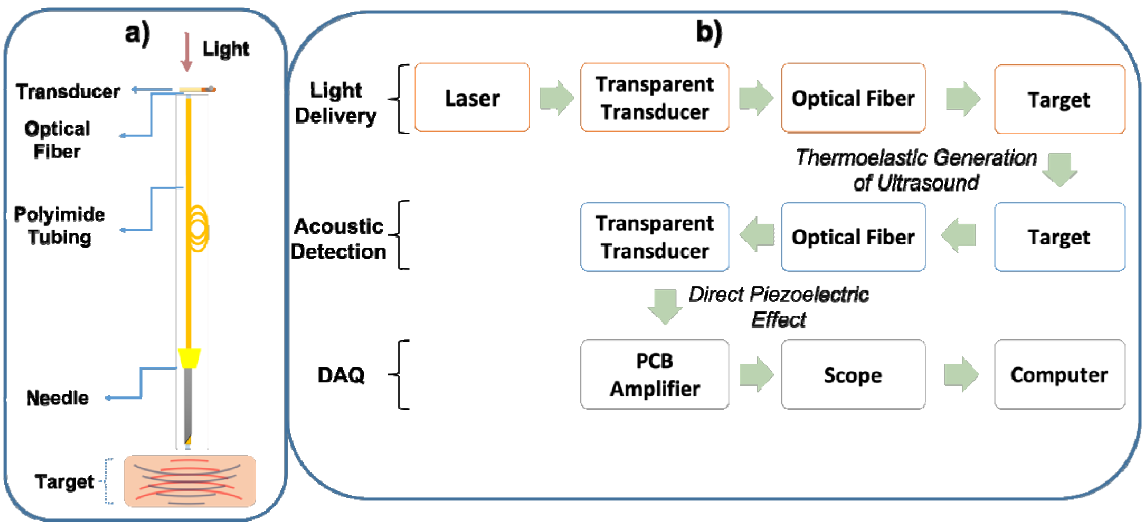

Figure 1. a) Schematic of PA Sensing Probe Design and b) Operation Principle of the PA Sensing Probe

A single multimode optical fiber (FT400UMT, 0.39NA, Thorlabs, Newton, NJ) with a core diameter of 400 µm was used to provide a good balance of both optical and acoustic performances [12]. The 400–µm core diameter allows the transmission of µJ-mJ laser pulses without burning the fiber tip. At the same time, the non-dispersive single-mode transmission frequency limit of the optical fiber is around 0.1~0.2 c/d, where c and d are the acoustic velocity and diameter of the fiber core, respectively [13]. It allows to cover the peak frequency components of PA signals generated under unfocused illumination conditions. At 1~2 MHz, the acoustic attenuation of the 400–µm fused silica optical fiber is very low, especially after the jacket layer is removed [11]. Therefore, the length of the optical fiber can be selected based on the need of actual applications as long as it is long enough to provide sufficient acoustic time delay to separate the real PA signal from the source or interference signals during the laser excitation [13, 14].

As the key feature of the new design, a piece of single crystalline PMN-PT ($Pb(Mg_{1/3}Nb_{2/3})–PbTiO_3$) substrate (HC Materials Corporation, Bolingbrook, Illinois, USA) was used to make the transparent transducer due to its good optical transparency and piezoelectric property. It has 27-33% PT content and a piezoelectric constant ranging from 2000 pC/N and 3000 pC/N with <001> poling [15, 16]. The thickness of the PMN-PT substrate was 0.6 mm, which provides a resonance frequency of ~3.5 MHz in the thickness mode [15]. The central frequency of the optical fiber (1.85 MHz) and its effective bandwidth were matched within the PMN-PT transducer's frequency spectrum. The surface area ($4.95 \times 1.74\ mm^2$) of the PMN-PT transducer was kept small to reduce the parasitic capacitance to the transducer. No matching layer was added between the PMN-PT transducer and the optical fiber because their acoustic impedances are close to each other. Both top and bottom surfaces of the PMN-PT substrate were first polished and coated with ITO (indium-tin oxide) films to form the transparent electrodes. Two Chromium/Copper pads were formed to facilitate wiring. PMN-PT transducer was mounted onto glass holder with silver epoxy and connected to an SMA adapter.

The optical transmission efficiency of the PMN-PT transducer was characterized. For polished PMN-PT transducer with 0.6–mm thickness and ITO coating, the output laser power measured with and without the transducer was 1.464 mW and

5.88 mW, respectively, which corresponds to an optical transmission efficiency of 24.9%. The thickness and the surface conditions of the PMN-PT substrate play a significant role in the optical transmission efficiency. In general, the optical transmission efficiency increases significantly when the thickness and surface roughness are reduced.

2.2 Photoacoustic (PA) Testing Setup

Fig. 2 shows the PA testing setup. Excitation light was provided by a Nd:YAG laser (SPOT-10-200-532, Elforlight Ltd, Northants, UK) operating at the wavelength of 532 nm, a pulse duration of 1.75 ns, and a repetition rate of 1 kHz. The maximum output energy was 20 µJ/pulse. To provide the maximal power efficiency, the optical fiber was aligned to the focused point of the light. Acrylic spacers and the polyimide tubing were used to fix the optical fiber in a stable position. The focused light travels through the transducer and the optical fiber to reach a black tape target. A home-made PCB amplifier was used to amplify the acoustic signal coming from the transparent transducer with an amplitude gain of 23 dB. In order to receive higher PA voltages, contact conditions between the proximal end of the fiber & the transducer and the distal end of the fiber & the target were carefully maintained during tests.

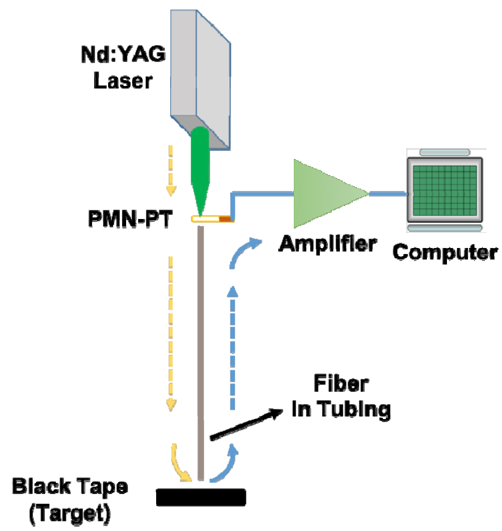

Figure 2. Schematic of the PA Testing setup with Optical (Yellow arrows) and Acoustic (Blue arrows) Transmission Paths

2.3 Dye Experiment

The PA testing setup, detailed in Section 2.2, was used to demonstrate the PA characterization of dye concentration. Instead of a black tape target, the target in the dye experiment setup was therefore a dye solution in the container. Dye solutions were prepared with red dye powders (Rit® Dye, Phoenix Brands, Stamford, CT). Powders were first dissolved in DI water and was transferred into an acrylic container. The PA sensing probe was first mounted onto a Z-stage and gradually lowered till the tip of the optical fiber just touched the surface of the dye solution. For each concentration, the PA measurement was repeated five times. The captured PA voltages were averaged to determine the overall PA response.

3. EXPERIMENTAL RESULTS

3.1 PA Testing Results

Fig. 3a shows a representative PA signal received from the black tape target after being averaged in 16 times. The excitation laser pulse energy is 5.36 µJ/pulse. The received PA signal after travelling through the optical fiber (with a length of 54 mm) encounters a time delay of 99 µs. The acoustic velocity is determined to be ~5450 m/s, which is close to the typical sound velocity of fused silica [13, 14]. The second, third, and fourth reflected signals are clearly seen at ~297 µs, ~495 µs, and ~693 µs, respectively, which are at three, five and seven times of the received PA signal delay time. This shows that the optical fiber can serve as a low-loss acoustic delay line to transmit the PA signal from the target to the transducer. A spectral analysis of the received PA signal has a center frequency of 2.1 MHz. It shows that the ultrasound transmission through the optical fiber has little dispersion or distortion.

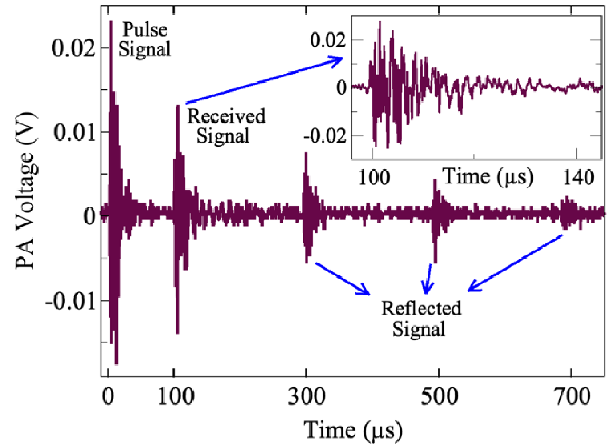

Figure 3. PA Signals Received from A Black Tape Target.

3.2 Dye Experiment Results

Fig. 4a shows a representative PA signal received from 0.1g/mL concentration for red dye solution. The peak-to-peak PA voltage was 36.2 mV after being averaged in 16 times. Since the same optical fiber was used in the dye experiment, the PA signal arrived at the transducer after a delay of 99µs, the same delay time with previous experiments (Fig. 4a). Therefore, the original PA signal can be easily distinguished from the interference signals.

The change in the average PA voltage of the first peaks as a function of the red dye concentration from 0.001 g/mL to 0.1 g/mL is shown in Fig. 4b. The peak PA voltage increases with the dye concentration, showing a significant linear correlation between the dye concentration and the PA response of the probe (R^2 = 0.928). When the dye concentration was reduced down from 0.1 g/mL to 0.001 g/mL, the signal-to-noise ratio (SNR) dropped from 19.2dB to 5.63dB, the received PA waveform started to bury under the noise level. This indicates a detection limit of about 0.001 g/mL.

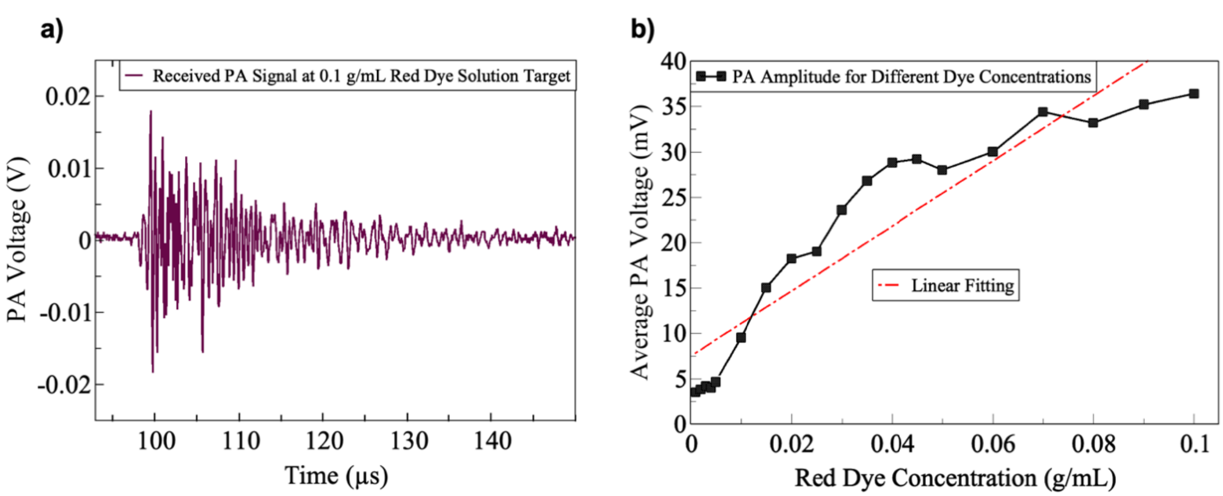

Figure 4. Dye Experiment Testing Results a) PA Signal from 0.1 g/mL Red Dye Solution and b) Average Peak-to-Peak PA Voltage vs. Dye Concentration

4. CONCLUSION

In this paper, a new PA sensing probe based on a single optical fiber acoustic delay line and a PMN-PT transparent transducer has been demonstrated. By using a single optical fiber for both delivering light pulses to the target and receiving US signals from the target, a compact and minimally-invasive probe structure can be achieved. In addition, the light delivery and the ultrasound detection are automatically aligned with each other, thereby resulting in an optimal configuration for PA signal detection. Capitalizing upon the optical transparency of the PMN-PT substrate, the transducer can be placed between the optical source and the optical fiber, allowing the light delivery and transmission of the acoustic signals through the transducer. Other optical sensing modalities can be readily integrated into the PA probe without additional optical fibers. Although the initial concept has been demonstrated, several improvements will need to be investigated in future work. First, the optical transmission efficiency can be improved by optimizing the contacts and refractive index matching between the PMN-PT substrate and optical fiber. Second, an acoustic impedance matching layer can be added onto the probe tip to improve the efficiency of PA signal collection. Third, a bundle of smaller optical fibers can be used to transmit higher frequency components of the PA signal to enhance the depth resolution of PA detection.

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