All optical fiber combined-imaging system of photoacoustic and optical coherence tomography

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ABSTRACT

We present an all optical fiber combined-imaging system that integrates non-contact photoacoustic tomography (NPAT) and optical coherence tomography (OCT) to simultaneously provide PA and OCT images. The fiber-based PAT system utilizing a Mach-Zehnder interferometer with a fiber laser of 1550 nm measures the photoacoustic signal at the sample surface. For the generation of a PA signal, a pulse train from a bulk type Nd:YAG laser illuminates the sample via a large core multimode optical fiber. The fiber-based OCT operating at a center wavelength of 1310 nm allowed is combined with the fiber-based PAT system by sharing the same optical fiber probe. The two lights from the fiber laser and the OCT source are guided into the probe through each port of a 2 by 2 optical fiber coupler. The back-reflected lights from the sample are guided to respective imaging systems by the same coupler. With these both NPAT and OCT images could be co-registered without physical contact with the sample. To demonstrate the feasibility of the proposed system, a phantom experiment has been carried out with a phantom composed of a black PET fiber and a fishing wire. The proposed all fiber-optic combined-imaging system has the potential for minimally invasive and improved diagnosis.

Key words: multi-modal imaging, non-contact photoacoustic tomography, optical coherence tomography, fiber imaging system.

1. INTRODUCTION

As a noninvasive imaging modality, a photoacoustic tomography (PAT) imaging system can visualize the distribution of light-absorbing elements or their structures in a biological sample [1–3]. As a hybrid technique of optical and ultrasound imaging system, PAT can provide a good optical contrast and high ultrasonic resolution at depths of up to several centimeters [2]. It utilizes the photoacoustic effect that makes conversion between light and acoustic pressure waves through the thermal expansion induced by the localized absorption of short optical pulses. When a short pulsed laser illuminates a biological sample, a portion of the optical energy is locally absorbed and converted to heat rapidly, leading to thermal expansion, which generates broadband acoustic waves within the sample.

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The generated acoustic waves (referred to PA waves) propagate to the tissue surface, and they are detected by either a mechanically scanned single-element ultrasonic transducer or an array-type ultrasonic transducer in a water tank or through an impedance matching agent. After recording the PA waves, the photoacoustic image corresponding to the distribution of absorbers within the sample is reconstructed. With this technique, various biological studies from organelles to organs such as cells, blood vessels, small animal brains, and full organs have been reported. Their results have provided the useful information pertinent to specific diseases and cancers also [1–3].

Recently, several attempts have been made to combine the photoacoustic imaging system with other optical imaging systems to enable simultaneous measurements in biomedical applications. For examples, there have been a combined photoacoustic microscopy (PAM) and spectral domain optical coherence tomography (OCT) [4], a photoacoustic and fluorescence confocal microscopy [5], an integrated diffuse optical tomography and photoacoustic tomography (DOT/PAT) [6], and a multimodal photoacoustic and optical coherence tomography (PAT/OCT) [7]. Although the reported systems can provide the complementary information such as anatomical and functional information of biological samples, a number of instrument design challenges exist in the configuration of systems. Due to different detection mechanism of respective imaging systems, the overall configurations of the combined systems are complicated and restrict in-line detection of multi-modality system. Also, a PA imaging system usually needs contacting piezoelectric transducers for detecting the ultrasonic waves. This contact detection induces some limitations in some applications such as burning diagnostics and ophthalmic applications. As an alternative to the ultrasound transducers, optical methods have been reported to detect the ultrasonic waves [7-10]. However, these techniques are difficult to be combined with other imaging modalities due to the use of bulk optics and complicated components, and still they require physical contact with samples.

In this study, we propose the fiber-optics-based dual-modal imaging system that combines non-contact photoacoustic tomography (NPAT) and optical coherence tomography by using a common fiber optic probe. This can provide PA and OCT images at the same time, which gives complementary information of samples; optical absorption and scattering distribution. For implementing the common fiber optic probe, a commercial optical fiber coupler, a homemade fiber lens, and a large core multimode fiber are used. To evaluate the performance of the proposed system, a phantom experiment is carried with the sample composed of a black PET fiber and a fishing wire.

2. MATERIALS AND METHODS

2.1 Miniaturized fiber-optics probe

In the proposed dual-modal imaging system combining fiber-optic NPAT and OCT, an optical fiber coupler working at 1310 ~ 1550 nm was used to integrate the interrogating light beams from both systems. For the effective focusing of probe beams, a homemade fiber lens was used, which allowed to achieve a compact probe design and common detection of two interrogating beams.

Figure 1 describes the fabrication of the fiber lens. A single body fiber lens was fabricated with a single mode fiber (SMF) and a coreless silica fiber (CSF). A short piece of CSF was fused at the tip of SMF, and then a lens curvature was formed on the end of the CSF piece by electric arc discharging [11]. The lens curvature was controlled by adjusting the arc discharging duration and the arc power. In order to achieve a compact fiber-optics probe, the fabricated fiber lens was placed next to a large core multimode fiber as shown in the photograph of Fig. 1. Through the large core multimode fiber, the excitation beam of the NPAT system was delivered.

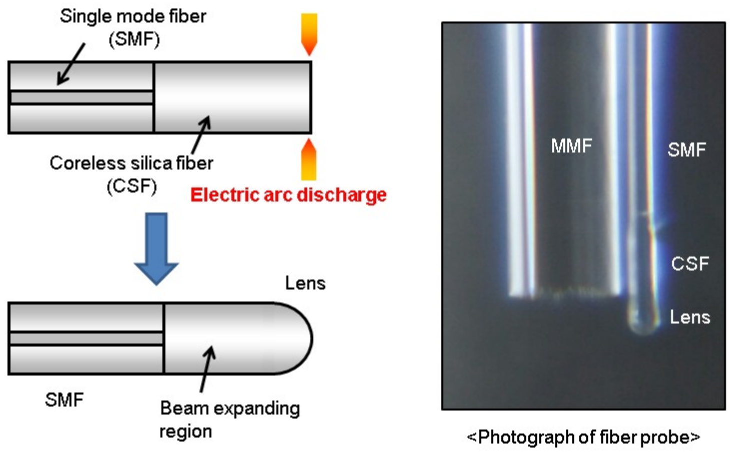

Figure 1. Fabrication process of the common fiber probe. Schematic of the fiber lens (left) and a photograph of implemented fiber probe (right). SMF (Single mode fiber) and CSF (coreless silica fiber) is fused, and the lens curvature is formed by electric arc discharging. The fiber lens is attached to a large core multimode fiber.

2.2 All-fiber-based NPAT and OCT system

Figure 2 describes the schematic of the fiber-optics-based combined NPAT and OCT system using fiber-optics probe. The blue lines and the red lines in Fig. 2 indicate the optical fiber nets of the NPAT and the swept-source OCT, respectively. The configuration and principle of the NPAT system based on a heterodyne interferometer has been described in a previous work [9]. Briefly, the heterodyne interferometer consists of a single frequency laser (1550 nm wavelength) for interrogating PA signals, single mode fiber couplers, an acousto-optic modulator (AOM; 80 MHz driving frequency), AOM driver, a polarization controller, an optical circulator, a balanced photodetector (BPD), and an IQ demodulator. A Q-switched Nd:YAG laser (Quantel, Brilliant ultra 50), to excite ultrasound waves, is guided through the large core multimode fiber. It emits a train of 8 ns duration pulses at a 532 nm wavelength with a repetition rate of 20 Hz and a maximum energy of 50 mJ. The beam back-reflected from the sample surface is delivered back to fiber lens, optical fiber coupler and optical circulator (Cir_3); and then interfered with the reference beam passing through AOM. The interference signal is detected by the BPD and demodulated by an IQ demodulator. Finally, the demodulated signals are digitized and processed to photoacoustic signal.

OCT consists of a fiber-based Mach-Zhender interferometer as is illustrated with red lines in Fig. 2. A swept source laser (HSL-2000, Santec) is used as the OCT light source, which is divided into the reference and the sample arms. The reference arm incorporates a collimator, a ND (Neural density) filter, a lens and a mirror. The sample beam shares the same optical fiber which is used as the sample arm of the PAT system, passing through an optical fiber coupler (FC1310-70-50-APC, Thorlabs). Then, the OCT sample beam is focused onto the sample with the fiber lens. The interference between the reference and the sample beams is detected by a dual balanced photodetector (BPD) and record by a digitizer. The OCT image is reconstructed by taking Fourier transform and imaging processing.

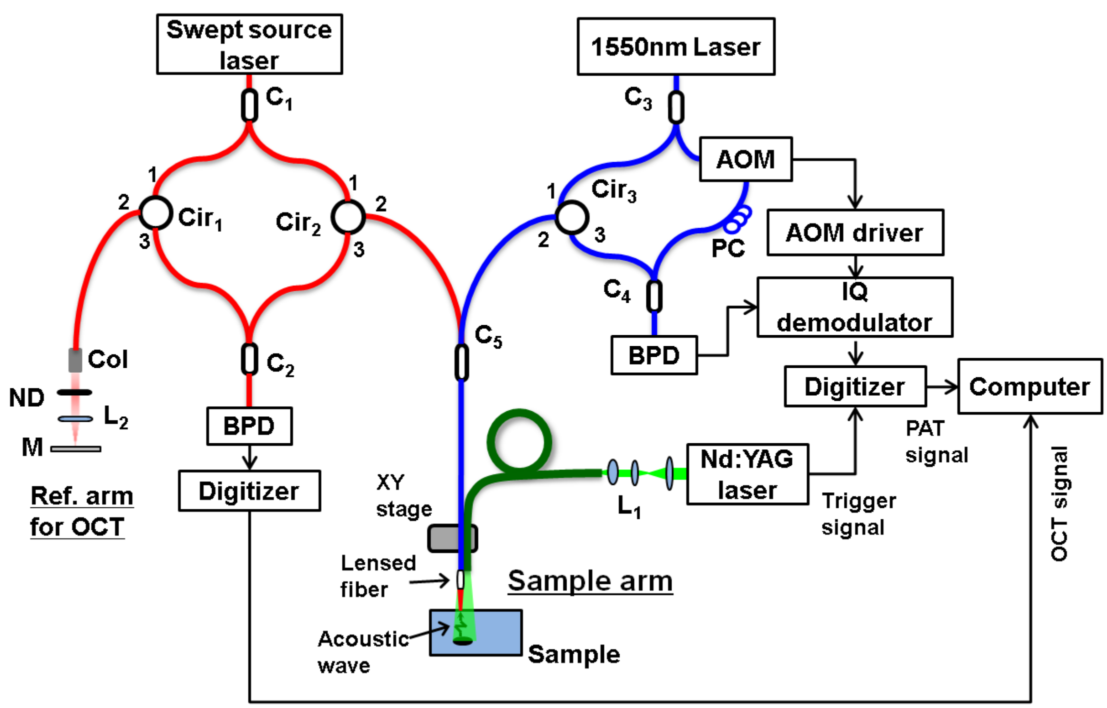

Figure 2. Schematic of the combined non-contact PAT and OCT imaging system. AOM, acousto-optic modulator; BDP, balanced photodetector; $Cir_{1,2,3}$, circulator; Col, collimator; $C_{1,2,3,4,5}$, coupler; L, lens;.

3. EXPERIMENT

3.1 Acquisition of NPAT and OCT images

For demonstrating the performance of the proposed system, a phantom experiment has been carried out. The phantom consisted of a black polyethylene terephthalate (PET) fiber and a fishing wire immersed in a petri-dish filled with a milk/water mixture. The diameters of PET and fishing wire were 200 μm and 300 μm, respectively. A schematic of the phantom is shown in Fig. 3(a). The Q-switched Nd:YAG laser illuminated the phantom through the multimode fiber, and the generated ultrasound waves were measured at the phantom surface by scanning the interrogation beam of PAT. The scanning area was 4.5 mm x 3 mm, in steps of 30 μm. While acquiring the PAT signals, the OCT signals were also obtained at the same scanning area. After obtaining the PAT and OCT signal data, a 3-dimentional (3D) PAT and OCT image was rendered. Figure 3(b) and (c) show the reconstructed OCT images along xy, and yz planes respectively, and Fig. 3(e) and (f) show the maximum intensity projections (MIP) of the reconstructed 3D photoacoustic image along xy, and yz planes, respectively. For the PA image reconstruction, a Fourier-transform reconstruction method was used [12].

Overall, the reconstructed images were clearly recognizable and agreed well with the PET fiber and fishing wire placed in the phantom. Figure 3(d) shows an overlaid 3D image of both PAT and OCT images, which confirms that excellent co-registration was made between the two images at the same site and at the same time.

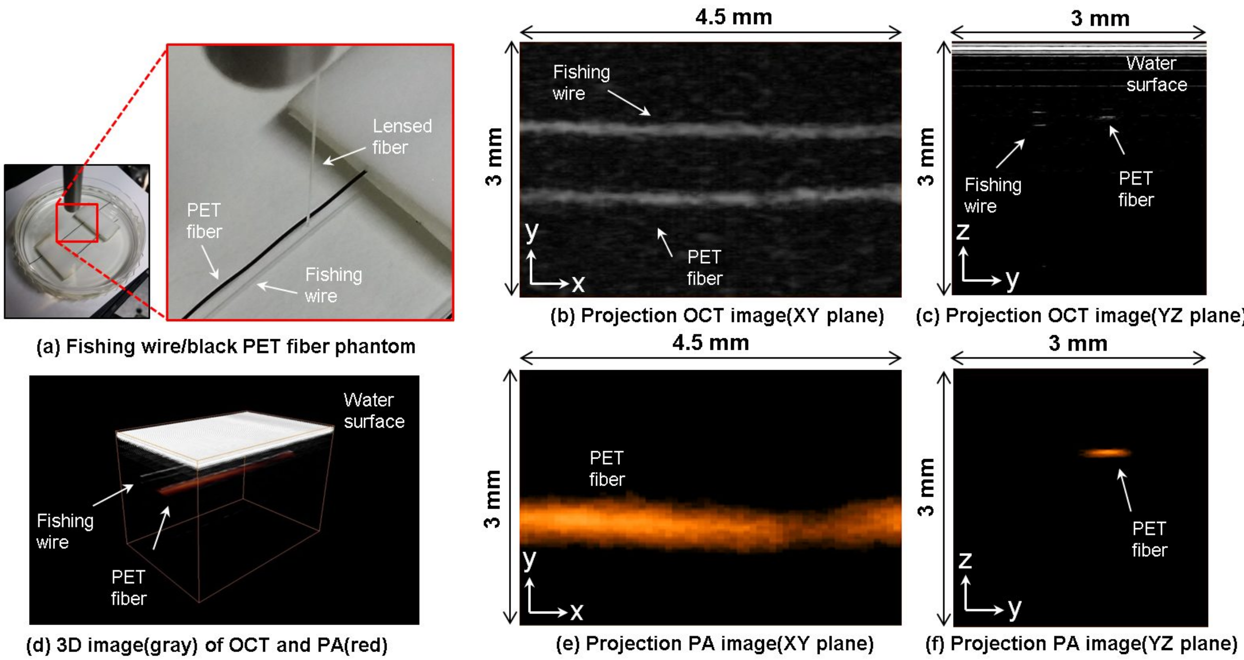

Figure 3. (a) Photograph of the phantom sample; black PET fiber and fishing wire, (b) and (c) Reconstructed OCT images along xy, and yz planes, (d) Overlaid 3D image of PAT and OCT, (e) and (f) Maximum intensity projections (MIP) of the reconstructed images along xy and yz planes.

4. CONCLUSION

We have presented all-fiber-based dual modal imaging system combining non-contact photoacoustic tomography (NPAT) and optical coherence tomography (OCT) with a compact fiber-optics probe. The dual modal imaging system was realized with fiber-optic components, therefore allowing easy combination of both modalities with one scanning probe. An optical fiber coupler and a homemade fiber lens were used for the integration of two interrogating beams for PAT and OCT signal detection. A large core multimode fiber was used for delivering the pulsed laser beam to the sample for PAT. Fiber-optic configuration of the system allows miniaturization of the system size and makes it free from optical alignments. The all-fiber probe was fabricated by fusion-splicing a short piece of coreless silica fiber (CSF) at the end of a single mode optical fiber (SMF), and a fiber lens was formed at the other end of CSF. The all fiber probe reduces unexpected back reflection thus, improving the transmission efficiently and reducing noise in measurement. In addition, it is intrinsically immune to ambient mechanical vibration. To evaluate the capability of the proposed system, PAT and OCT images were simultaneously obtained with the phantom having a fishing wire and a black PET fiber in it. The resulting NPAT and OCT images clearly matched well with the structure of the phantom.

Thus we can say that the proposed dual-modal system can provide complementary information of optical absorption and scattering distribution, and the fiber-optic configuration can be applied as a minimally invasive imaging tool in medical diagnosis also.

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