Optoacoustic imaging using fiber-optic interferometric sensors

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Optoacoustic imaging combines the advantages of high optical absorption contrast in biological tissues and optical spectroscopy with excellent spatial resolution of ultrasound imaging techniques. The optical absorption of short laser pulses from different tissue structures produces an instant distribution of heat sources and, owing to the thermoacoustic conversion, results in the generation of acoustic pressure pulses. The typical frequency spectrum of the optoacoustic signals covers an ultrawide range of ultrasound from \(\sim 100\) kHz to \(\sim 10\) MHz. Therefore, detection of the optoacoustic signals requires ultrawideband transducers to image different sizes of absorption regions within the body. Future success of the optoacoustic imaging as a novel medical imaging modality and the diversity of its applications depend on the development of ultrawideband ultrasonic transducers, which at present are not commercially available.

The detection technology traditionally used in conventional ultrasonic imaging is based on piezoelectric transducers, which are highly sensitive but have limited bandwidth owing to their resonant nature. The detectors based on thin piezoelectric polymer films, like polyvinylidene fluoride (PVDF), can be made sensitive within an ultrawideband using appropriate backing and front matching materials. However, their sensitivity decreases with decreasing size and the corresponding electrical capacitance. This presents a problem when considering detection of high ultrasonic frequencies where both the small thickness of the detector (required for high axial resolution) and the small width of the transducer element (required for high lateral resolution and improved image fidelity) reduce its sensitivity. Another drawback to piezoelectric sensors, which is related to their electrical nature, is that they are not immune to electromagnetic noise interference.

Optical detection of ultrasound has been studied as an alternative to piezoelectric technology for decades. We can differentiate between two kinds of ultrasound optical sensors: those that monitorize pressure-induced displacements of a membrane or resonant optical cavity and others that are based on a pressure-induced refractive index variation in or around the sensor material. In the first group the following are included: etalons [3], fiber Bragg gratings [4], and dielectric multilayer interference filters [5]. Intrinsic fiber optic interferometric sensors [6] are within the second group. All of these optical sensors, contrary to piezoelectric transducers, are not affected by external electromagnetic disturbances or any other types of electrical noise and thermal signals produced by the direct laser pulse illumination. In particular, the fabrication of intrinsic fiber optic interferometric sensors is straightforward and involves the use of low-cost materials. The sensitivity of these sensors can be improved for biomedical applications by appropriate folding or coiling of the fiber, i.e., increasing the effective surface area of the optical fiber that interacts with the acoustic field [7].

Recently, intrinsic fiber-optic Mach–Zehnder and Fabry–Perot sensors have been proposed as integrating line detectors for optoacoustic imaging [8]. High-resolution optoacoustic three-dimensional images have been obtained rotating the object and scanning in one direction with a free-space laser beam Mach–Zehnder interferometer as the line detector [9].

In this Letter we present results on the detection of optoacoustic signals using single-mode silica optical fiber (SOF) interferometric sensors, which are designed for the frequency range from 100 kHz to 5 MHz. We propose a system for reconstruction of optoacoustic images based on scanning an interferometric fiber optic ultrasonic detector with a finite aperture. We compare an image obtained by this system with an image obtained using an array of piezoelectric transducers made from PVDF [10].

The principle of operation of the intrinsic fiber optic sensor is based on the fact that an acoustic wave...
induces strain in the optical fiber that modifies the phase of the light given by $\Delta \phi = k(nl + l\Delta n)$, where $k$ is the wavenumber, $l$ is the length of the sensing segment, and $n$ is the effective refractive index of the optical fiber. At ultrasonic frequencies, the strain induced, localized on a fiber segment of length $l$, can be considered axially constrained, so the phase shift induced is mainly governed by the strain-optic effect taken into account by the factor of $\Delta n$. The phase shift can be magnified using a longer fiber segment exposed to the acoustic wave. However, the use of any large fiber arrangement causes temporal averaging of the ultrasonic signal, since at frequencies of 1 MHz the acoustic wavelength is around 1.5 mm.

Sensitivity per unit length is a key parameter for designing the fiber optic arrangement. To evaluate this we have measured the phase change induced in a segment of the optical fiber by an ultrasonic pressure wave generated by a calibrated piezoceramic (PZT) emitter using a Mach–Zehnder interferometer. The characterization setup has been described in our earlier publication [11]. The acoustic sensitivity of the SOF at 1 MHz is 0.95±0.03 mrad/kPa and at 5 MHz is 0.37±0.02 mrad/kPa. The acoustic beam diameter was close to 3.4 mm at the measurement distance; thus the sensitivity at 1 MHz per unit length is 0.28 mrad/kPa/mm. The sensor with an active fiber length of 100 mm and an interferometric system with a resolution of 5 mrad has a noise equivalent pressure of 0.18 kPa at 1 MHz.

We have compared the optoacoustic signal detection using our sensors made from a single-mode optical fiber and ultrawideband ultrasonic transducers made from PVDF. The optoacoustic signal has been produced by irradiating a large cylindrical phantom ($d=14.5$ cm, $h=8.5$ cm) made of poly(vinyl-chloride) plastisol (PVCP) [12] with pulses generated from a Nd:YAG laser (ULTRA). The phantom mimics optical and acoustic properties of biological soft tissue with an optical absorption coefficient $\mu_a = 0.12$ cm$^{-1}$, an effective scattering coefficient $\mu'_s = 5.4$ cm$^{-1}$, and an anisotropy factor of $g=0.8$ at 1064 nm. Embedded close to 20 mm below the surface of the phantom is an optically absorbing object with a rectangular bar shape of dimensions $2 \times 2 \times 0.7$ cm with $\mu_a = 0.58$ cm$^{-1}$. The Nd:YAG laser emits pulses at a wavelength 1064 nm, with energy of 75 mJ, 6 ns duration, and a repetition rate of 10 Hz.

The pressure signals generated with this setup from the absorbing object in our phantom have presented peak-to-peak amplitudes of about 1 kPa. It was necessary to coil the optical fiber 20 times to achieve sufficient sensitivity to measure pressure at that level. The total width of the sensor was 5 mm. The contact area length was limited to 5 mm to avoid excessive spatial integration of incoming acoustic signal. The finite area of the sensor implies a directivity of $\pm5^\circ$ for an optoacoustic signal coming from a sphere of 3.5 mm of radius.

Figure 1(a) shows the fiber optic Mach–Zehnder interferometer sensor experimental setup. The light source is a linearly polarized He–Ne laser at a wave-length of 632.8 nm. In the reference arm a phase modulator is used to stabilize the interferometer, thus compensating temperature drifts and low-frequency vibrations. The interference visibility is optimized by matching the polarization at the output of each fiber arm using polarization controllers. The interferential optical signal is measured using an avalanche photodiode (APD) module (Hamamatsu C5331) and monitored using a digital oscilloscope. The bandwidth of this optical detector is 100 MHz and has a lower cutoff frequency of 4 kHz.

The PVCP phantom was placed over an array of 64 PVDF ultrawideband detectors arranged in a concave arc [Figs. 1(b) and 1(c)]; this forms part of an optoacoustic probe supplied as a component of the Laser Optoacoustic Imaging System (LOIS) provided by Fairway Medical Technologies [10]. Each sensor of LOIS has an average sensitivity of 1.66 mV/Pa at a frequency of 1.5 MHz after two stages of 20 dB amplification. The fiber optic sensor is placed directly opposite the PVDF transducer, which is located in the center of the arc-shaped array. The phantom was positioned such that the absorber was located approximately equidistant between the PVDF and optical fiber sensors.

Figure 2(a) depicts a typical optoacoustic signal detected from an absorbing object with a rectangular bar shape and positioned at an angle to a sensor channel of the PVDF array. The voltage signal obtained was deconvolved to pressure by using the known impulse response of the PVDF detector [10]. Figure 2(b) shows the interferometric signal of the intrinsic fiber optic sensor. Comparing Figs. 2(a) and 2(b), a similar pulse shape and time of flight as detected with two different sensors can be observed. The temporal width of the pulse is related to the spatial dimension of the absorber in the direction perpendicular to the sensor surface. A sharp negative pulse at the origin in the fiber optic sensor signal was due to the scattered light from the Nd:YAG laser pulses incident on the APD photodetector. This pulse...
constructed images using both systems [Figs. 3(b) and 3(c)] depicts a LOIS image. The optoacoustic imaging in the phantom [Fig. 3(a)] and the energy [10]. Figure 3 shows the position of the ab- pressure signals into monopolar signals of absorbed wavelet filter that simultaneously converts bipolar signals detected by our optical fiber sensor were filtered using a nine-scale filter with cut off frequencies of 30 kHz and 2 MHz. The optoacoustic signals, de-
ected using signals of LOIS system detected from the pressure signals measured by the optical fiber sensor and PVDF transducers from the LOIS array. To reconstruct a two-dimensional image, the fiber optic sensor was placed on the top of the PVCP phantom, which was rotated by 58 different positions thereby forming the total scanned array aperture of 178°. The phantom was illuminated using an optical parametric oscillator laser (Vibrant 355, OPOTEK, Inc.) tuned to 480 nm, which delivers, at a distance of 125 cm, an elliptical spot with a major axis of 2.4 cm and minor axis of 0.8 cm and a fluency of 20 mJ/cm². The second optoacoustic image was reconstructed using signals of LOIS system detected with 64 piezoelectric PVDF transducers occupying the total angular aperture of 174°. In this case, the phantom was illuminated with the Nd:YAG laser pulses. In both cases we have used the filtered radial backprojection algorithm for the reconstruction of the optoacoustic images [13]. Digitized optoacoustic signals detected by our optical fiber sensor were filtered using a bandpass filter with cut off frequencies of 30 kHz and 2 MHz. The optoacoustic signals, detected with LOIS, were filtered using a nine-scale wavelet filter that simultaneously converts bipolar pressure signals into monopolar signals of absorbed energy [10]. Figure 3 shows the position of the absorbing object in the phantom [Fig. 3(a)] and the reconstructed images using both systems [Figs. 3(b) and 3(c)] depicts a LOIS image. The optoacoustic images generated by both systems are in good agreement with dimensions, shape, and location of the embedded object. Also, based on shape of resolved corners, both systems possess similar spatial resolution.

There are two main artifacts that reduce the con- trast of the reconstructed images. The first one appears in the form of shadowed areas near the object and outside the area enclosed by the arc, owing to an incomplete data set. The second is due to the strong optoacoustic signals generated by the incident laser beam on the surface of the phantom; this produces a blurred light area on the right of the object in the case of the fiber sensor image reconstruction and slightly above the object in the LOIS image.

In summary, an ultrasonic sensor based on an optical fiber interferometer has been designed, developed, and calibrated. The system is capable of detecting optoacoustic signals in the range of 0.1 to 5 MHz. Further improvement of the system sensitivity can be obtained by using polymer optical fibers in place of silica optical fibers as the sensing element [11]. Two-dimensional optoacoustic images of a large phantom simulating breast tissue reconstructed using signals detected by our optical fiber sensor and PVDF transducers presented good agreement between the systems. Results from our experiments encourage further development of optical fiber sensors for utilization in future optoacoustic imaging systems.

References