64-channel fiber-optic ultrasound detector array with high sensitivity for photoacoustic imaging

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Abstract: We present a 64-channel fiber-optic ultrasound detector array with high sensitivity. The sensor can exhibit an NEP of 0.64 kPa and a wide bandwidth about 47 MHz, which gives a favorable resolution of photoacoustic imaging. © 2022 The Author(s)

1. Introduction

Photoacoustic imaging is based on the ultrasound generated by absorption of light energy and consequent thermal expansion [1]. The combination of high resolution of optical contrast and large depth of ultrasound imaging provides a novel tool for medical diagnosis and biological discovery [2,3]. There are various of ultrasound sensors, which employing mechanical, electrical and optical machinery. Optical ultrasound sensors have an edge over mechanical and electrical based ultrasound sensors due to their compact size, high sensitivity and immunity towards electromagnetic interference. Optical ultrasound sensors using micro-ring resonators [4], fiber Bragg gratings [5], Michelson interferometer [6], etc. have been reported in the literature. However, photoacoustic imaging with these sensors need to cooperate with mechanical scanning, which limits the scanning speed. And the vibration of the moving motor will affect the signal which aggravate the artifact of the reconstructed image. To overcome these, ultrasound detector array is a good alternative for they are compact, stable and very easy to detect ultrasound signal. We have demonstrated a detector array before. Due to the limited bandwidth and number of elements, the axial resolution of previous one was only 115.2 μm at depth of 4.8 mm [7].

In this paper, we demonstrate a 64-channel fiber-optic ultrasound detector array with high sensitivity applied to detect the broadband photoacoustic signal. The detector array is composed of an Fabry Perot (FP) cavity which is made by a Parylene spacer sandwiched between two dielectric mirrors. The probe exhibits a noise equivalent acoustic pressure (NEP) of 0.64 kPa and a bandwidth of 47 MHz. And assembled with a fiber bundle, the array provides a favorable axial resolution 47 μm at depth of 13.9 mm of photoacoustic imaging. The ultrasound array has parallel detection capabilities and can offer an effective way for photoacoustic imaging in the future work.

2. Experimental setup

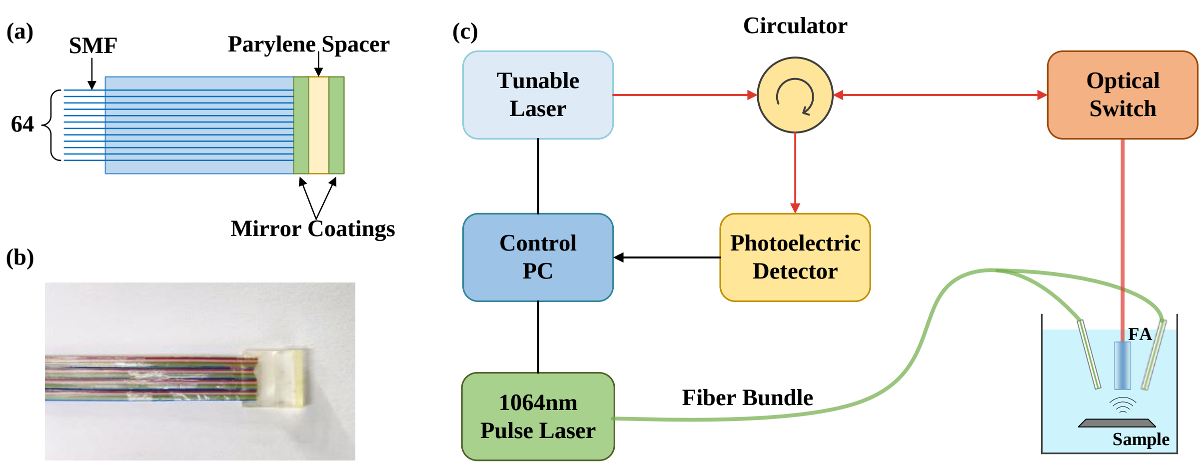

Fig.1. (a)A magnified visualization of the distal end of the fiber-optic ultrasound detector array. (b) The photograph of the ultrasound detector array. (c) Schematic diagram of the photoacoustic imaging system.

The structure of the fiber ultrasound detector array is illustrated in the Figure.1(a). The detector array comprised 64 sensing elements with the spacing of approximately 127 μm. Each element is a single mode fiber (SMF) with a resonant cavity. The FP cavity located at the distal end of the fiber array. It comprised by an Parylene-C spacer of thickness 15 μm sandwiched between two dielectric mirror coatings with ~98% reflectivity. One coating was deposited directly onto the fiber array at normal incidence; the other, on the distal surface of the Parylene spacer. The photograph of the fiber ultrasound detector array is presented in Fig. 1(b).

The sensing principle of the detection system is based on the interaction of the acoustic and optical fields. The cavity length is modulated by the deformation of spacer when ultrasound waves generated by an illuminated sample hit on the surface of a sensor. The change in thinness influences the optical phase, and thus regulates the total reflected power.

The photoacoustic imaging system based on optical ultrasound detector array is shown in Fig.1(c). The sensor was interrogated using a continuous-wave, tunable laser operating in the wavelength range 1400-1600 nm. A photoelectric detector with direct current (DC) and alternating current (AC) output is connected at the return port of the circulator to detect the reflected light. The DC output is connected to an analog-to-digital card for recording the interferometer transfer function. The AC output is connected to a 100Ms/s acquisition card for recording the time-varying reflected light power modulation generated by the incident ultrasound wave. A MEMS optical switch at a rate of 250 Hz is used to scan the 64-channel FP detector array.

A Nd: YAG laser system with wavelength of 1064nm and pulse duration of 10ns was used for photoacoustic excitation. The pulsed light output was coupled to a customized Y-shaped fiber bundle consisting of 420 fibers. The bundle exhibits a light coupling efficiency of 65% approximately. A tungsten wire is placed in the center of the holder in a water tank. The imaging performance is evaluated by reconstructing images from the multi-channel signals without mechanical scanning.

3. Experimental Results

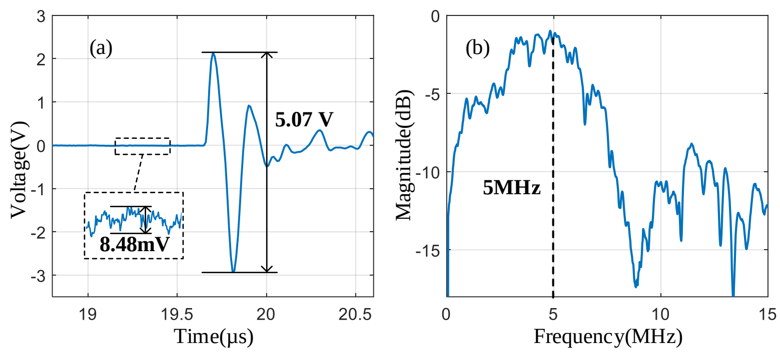

Fig. 2. (a) Temporal response of a detector. (b) FFT of the detected ultrasound signal with central frequency of 5MHz.

The sensitivity of a fiber ultrasound detector of the array is evaluated in terms of NEP. The ultrasound source used in the evaluation is a calibrated 5 MHz transducer with its output of 384 kPa. The detector array was placed at a distance of 3cm from the transducer. The NEP over a 5 MHz bandwidth were recorded and shown in Figure.2(a), presenting a peak-to-peak amplitude of 5.07 V and the root mean square noise of the detector is 8.48 mV. Indicates that the NEP of the array unit is 0.64 kPa. Fast Fourier transform (FFT) is used to convert the time-domain signal to frequency-domain. The frequency response is shown in Fig.2(b), which shows the center frequency of 5 MHz.

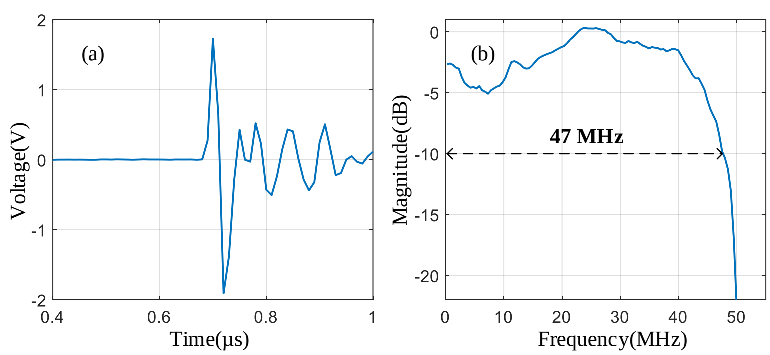

Fig. 3. (a) Broadband photoacoustic signal detected by the detector. (b) Frequency response of the detector.

To determine the frequency response, the output of a wideband photoacoustic source was measured first with a reference hydrophone and then, at the same point, with the fiber detector array. The photoacoustic signal detected by the detector array is shown in Fig.3(a). The frequency response was obtained by comparing the Fourier transforms of the time domain signal measured by each device. The normalized frequency response of the detector is shown in Fig.3(b), demonstrating broad detection bandwidth of 47 MHz at -10dB.

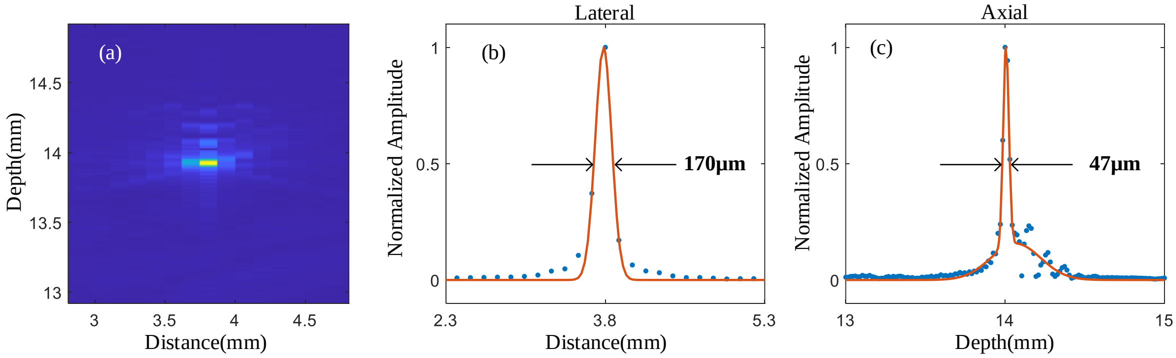

Fig. 4. (a) Reconstructed image. (b-c) The lateral and axial resolution is given by the FWHM of a Gaussian function that is fitted (orange line) to the profile.

To measure the spatial resolution of the reconstructed images, a tungsten wire with a diameter of 50 μm was used as a target to generate photoacoustic signal. The tungsten wire was perpendicular to the array translation axis and positioned at 13.9 mm relative to the array. The ultrasound waves are received by sequentially scanning the input channel of the array with an interrogation laser beam to individually address different points on the detector array. Using a synthetic aperture focusing technique, a 2D image as shown in Fig. 4(a) was reconstructed from the recorded photoacoustic signals of the 64 sensors. The resolution was defined as the full-width-at-half-maximum (FWHM) of the resulting reconstructed point spread functions, evaluated in the lateral and axial dimensions. The lateral resolution is 170 μm (Fig. 4(b)) and the axial resolution is 47 μm (Fig. 4(c)). The axial resolution is 2 times better than the previous work [7] because of the broad bandwidth and more elements.

4. Conclusion

We have proposed a 64-channel fiber-optic ultrasound detector array with high sensitivity. The detector array is composed of a FP cavity. Experimental studies show that the ultrasound detector array has a low NEP of 0.64 kPa and broad bandwidth of 47 MHz. Imaging with the optical detector array was demonstrated on a tungsten wire. The lateral and axial resolution are 170 μm and 47 μm, respectively. As a consequence, the fiber ultrasound array has a huge potential in broadband photoacoustic imaging. It has the capability of parallel detection and can realize real-time imaging by adding devices to the system.

5. Acknowledgement

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6. References

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