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High-speed Photoacoustic-guided Wavefront Shaping with a Real-valued Intensity Transmission Matrix

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Abstract: We report the development of a high-speed and non-invasive method for focusing light through scattering media using photoacoustic guidance. We demonstrated light focusing through an optical diffuser within $\sim$ 300 ms.

1. Introduction

Focusing light through biological tissue is highly desired for various biomedical applications such as deep tissue optical microscopy, optogenetics and micro-manipulation. In the past decade, photoacoustic (PA)-guide-star-based wavefront shaping has been a promising non-invasive solution that maximises the strength of the optically excited ultrasound signals received by a focused ultrasound transducer as feedback so that the light converges into the focal region of the ultrasound transducer [1–6]. However, it usually took several minutes to several hours to form a light focus due to the use of iterative algorithms and low-repetition-rate light modulators. In this work, we propose a fast implementation of a PA guide-star-based wavefront shaping using a non-iterative algorithm and a high-rate digital micromirror device (DMD).

2. Methods

2.1. *The real-valued intensity transmission matrix algorithm*

Our algorithm employs a real-valued intensity transmission matrix (RVITM) to characterise light intensity change from the DMD to the target position and determines the optimal DMD pattern for light focusing accordingly [7,8]. Since the generated PA signal amplitude is proportional to the light intensity within the ultrasound focus, we can model the relationship between incident light and the resulting photoacoustic pressures as:

$$[I^1, I^2, \cdots, I^{2N}] = \frac{1}{\alpha}[P^1, P^2, \cdots, P^{2N}] = RVITM_r \bullet [H_1, H_2], \tag{1}$$

where $[H_1, H_2]$ is the set of binary Hadamard patterns displayed on the DMD (a Hadamard matrix H $\in$ (-1, +1) with dimensions of N x N was used to construct two binary matrices $H_1 = (H+1)/2$ and $H_2 = (-H+1)/2$), I^k and P^k are the light intensity and the PA pressure within the acoustic focus of the ultrasound transducer, respectively. A Hadamard matrix H $\in$ (-1, +1) with dimensions of N x N was used to construct two binary matrices $H_1 = (H+1)/2$ and $H_2 = (-H+1)/2$. As $[H, -H]^T = [H, -H]^{-1}$ owing to the Hadamard matrix properties, we can obtain the value of the RVITM as:

$$RVITM_{PA} = \left[2P^1 - P^1, 2P^2 - P^1, \cdots, 2P^{2N} - P^1\right] \bullet [H, -H]^T, \tag{2}$$

where we define $RVITM_{PA} = \alpha RVITM_r$, that connects the light intensities from all the input positions to the PA signal amplitude at the target location. So, a positive $RVITM_{PA}$ value means that the corresponding micromirror contributes positively to the optical intensity. Thus, in the focusing step, an optimal DMD pattern was determined by switching 'ON' all the DMD micromirrors that corresponded to positive $RVITM_{PA}$ values for focusing light at the target location.

2.2. *Experimental setup*

To demonstrate the feasibility, PA-guided light focusing through an optical diffuser was performed as illustrated in Fig.1. A pulsed laser was reflected from the DMD and projected onto an optical absorber (black tap) through an optical diffuser, whilst the excited ultrasound pressures were captured by a focused ultrasound transducer and recorded by a data acquisition card after the amplification.

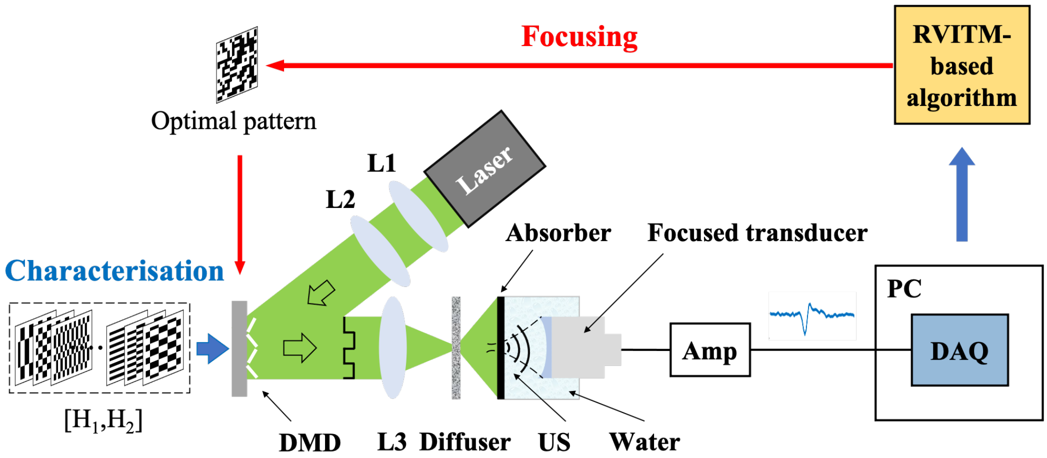

Fig. 1. Schematic illustration of the experimental setup and principle. AWG, arbitrary waveform generator; Amp, amplifier; DAQ, data acquisition canrd; L1-L3, convex lenses; Laser: 532 nm, 2 ns; Diffuser, 220 Grit. DMD, uninterrupted mode, 47 kHz; Focused transducer: 50 MHz, f = -25 mm; After the implementation of light focusing, the absorber and the transducer were replaced with a camera and a convex lens to capture the optical speckle patterns. This figure is adopted from Ref [4] with permission.

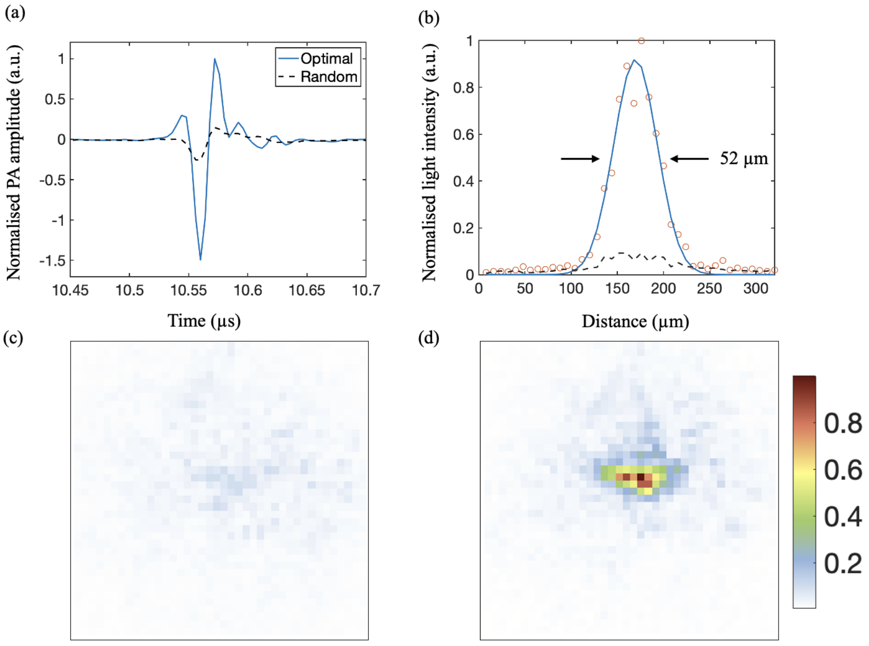

Fig. 2. Focusing light through an optical diffuser. (a) Comparison of photoacoustic (PA) signals generated with random DMD patterns and an optimal DMD pattern. (b) Lateral profile of the light focus. (c) and (d) are speckles with random DMD patterns and an optimal DMD pattern.

3. Results and discussion

Experimental results are shown in Fig. 2. When the optimal DMD pattern was displayed, the PA amplitude increased by 6.67 times compared to that with a random DMD pattern [Fig.2(a)]. The lateral profiles of the light speckle with a random and with the optimal DMD pattern are shown in Fig. 2(b). The dimensions of the optical focus, indicated by the full width at half maximum values of the Gaussian fits to the intensity profiles with the optimal DMD pattern were ($\sim$56 μm $\times$ 40 μm), which were consistent to the diameter of the US transducer' focus ($\sim$49 μm).

The input DMD patterns ($[H_1, H_2]$) were uploaded onto the memory of the DMD before the characterisation step. The display of these DMD patterns at a rate of 47 kHz cost the most time (175 ms), while PA signals were acquired at the same time. Then another 66 ms was taken to transfer the PA signals from the DAQ card to PC memory. The calculation of $RVITM_{PA}$ values and the following optimal DMD pattern cost only 58 ms using a custom script implemented in MATLAB, while it cost 7 ms to upload and display the optimal pattern on the DMD for light focusing. As a result, the total system run-time time was 306 ms.

The total system runtime for light focusing was 306 ms, the system runtime for optimising each input mode is 75 µs, which is a significant improvement in speed compared to other PA-guided wavefront shaping methods in literature. With high-speed characterisation algorithms and spatial light modulators that are continuously being developed [9–12], the proposed method could be potentially useful in various non-invasive applications such as microscopy, optogenetics, micro-manipulation, and microsurgery.

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