Noise-tolerant wavefront shaping in a Hadamard basis

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Abstract: Light can be focused inside scattering objects by spatially shaping the wavefront of the incident light. We presented a new algorithm of wavefront shaping to improve the tolerance to noise over existing feedback-based algorithms.

Scattering and diffusion of light are the main limitations for optical imaging. However, wavefront shaping techniques make it possible to shape the incident wavefront so that it exactly matches the scattering properties of the object, and form a focus through or inside the object [1].

Wavefront shaping is based on the fact that light scattering is linear and deterministic. Light transmission through any object can be described by

\[ E_b = \sum_{a}^{N} t_{ba} E_a \]  

(1)

where \( a \) is the indices of modes of the incident field \( E_a \), and \( b \) is the indices of the components of the transmitted field \( E_b \). The transmission elements \( t_{ba} \) describe scattering in the sample. Feedback-based wavefront shaping algorithms search for the optimum incident field that maximizes some feedback signal, such as transmission into a specific output mode [2]. The task of finding the optimum wavefronts for multiple targets (output modes) is equivalent to measuring the transmission matrix rows \( (t_{ba}) \) of the scattering medium, up to an unknown phase factor for each row of the matrix [3].

A common procedure to find the optimum incident field with a phase-only spatial light modulator (SLM) is using the stepwise sequential algorithm (SSA) [2]. In this algorithm, the SLM is divided into segments, and the phase of each individual segment is varied between 0 and \( 2\pi \) consecutively while keeping the phase of all other segments fixed. Due to interference between light originating from the controlled segment and light originating from all other segments, the feedback signal will respond sinusoidally. By fitting these sinusoids, the transmission matrix (TM) is reconstructed [2]. The drawback of the SSA algorithm becomes apparent when many segments are used. In this case the contribution of each segment is small compared to the reference field coming from the rest of the segments, giving a low interferometric visibility of the feedback signal. This results in a low signal to noise ratio (SNR) in the measured TM elements.

This low SNR is especially noticeable when the photon budget for the measurements is limited, such as in high-speed wavefront shaping [4], and in microscopy.

A method that was introduced by Popoff et al. [5] organizes the segments in a Hadamard basis. The feedback signal is measured for each Hadamard vector, allowing the TM to be reconstructed. In this method, always a large fraction of the segments is modulated, increasing the visibility of the interference signal, and consequently improving the SNR [5]. However, this technique requires part of the incident light to remain unmodulated serving as a reference field for the measurements. Since part of the light is not modulated, the contrast of the final focus is not optimal.

A different way to increase the SNR for a given photon budget is by performing a pre-optimization [6,7]. In pre-optimization schemes, one first performs an optimization with part of the SLM segments and uses that solution as a starting point for a second optimization step. With pre-optimization, the feedback signal in the second optimization step will be higher, causing the second step to be more robust to noise in most cases [6].

A special case of pre-optimization was developed by Tao et al. [7]. In the first step, half of the segments is modulated using a Hadamard-based algorithm while the other half is used as a reference. Since the number of controlled segments is equal to the number of reference segments, this approach leads to an optimally balanced interference of modulated and reference field. In the second step, the optimized half of the wavefront is displayed on the SLM. The roles of modulated and reference segment are now switched, and the other half of SLM segments is optimized.

The method of Popoff et al. can be used to simultaneously find the wavefronts to focus light to multiple targets, or even to project arbitrary images through the scattering medium. In effect, this method measures multiple rows of the TM simultaneously. Unfortunately, pre-optimization approaches cannot be used for this purpose. After the pre-
optimization step, one has to choose what wavefront to use as a starting point for the next step, so the procedure can only be used on one point at a time.

In this work, we present a new algorithm, called dual reference, which is a combination of the methods used by Popoff et al. [5], and Tao et al. [7]. We take advantage of the optimal balanced interference of the modulated and reference field as in Tao et al., while keeping the ability to measure all rows of the TM simultaneously, as in Popoff et al.

We compare the experimental results of the performance of the proposed method with the existing feedback-based wavefront shaping methods for various photon budgets. The measured enhancement for the dual reference algorithm, shown as the blue solid curve in Fig. (1), confirms that using this method gives us higher enhancement for multi-target optimization compared to SSA (black dash-dot curve) and Popoff’s method (green dash curve).

The measured enhancement for Tao’s method, shown in the red dot curve in Fig. (1), is higher than the other algorithms due to the pre-optimization step. However, finding the corrected wavefronts for all 100 targets took 100 times longer than the other three algorithms.

In conclusions, our algorithm achieves the maximal interferometric visibility during the measurements for simultaneous multi-target wavefront shaping, resulting in an optimal SNR. Moreover, there is no need to reserve segments for the reference beam. We have experimentally demonstrated that this method enables us to perform simultaneous multi-target optimization with a higher enhancement than the popular methods used by Popoff et al. [2010] and Tao et al. [2017] (for multi-target) for a wide range of photon budgets.

We envision that the presented method could be beneficial to the experiments having the transmission matrix measurement involved, especially when the photon budget is limited.

Fig. 1. The measured averaged enhancement versus the total photon budget for dual reference algorithm (blue solid curve), SSA (black dash-dot curve), Popoff et al. [5] (green dash curve), and Tao et al. [7] (red dot curve). Bars represent the standard error of the measurement set.

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