High speed light focusing through dynamic turbid media

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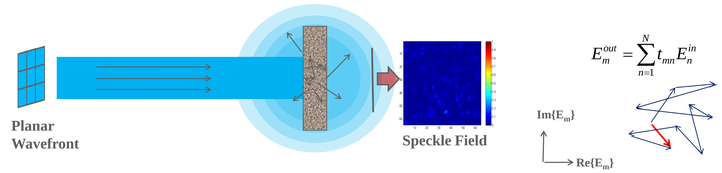
Abstract

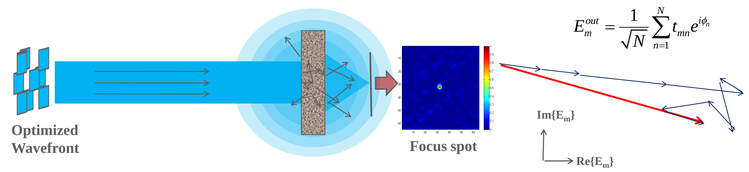
We demonstrate a high speed technique for focusing light through turbid media. The system generates holograms implemented via a deformable mirror device (DMD), enabling high speed transmission matrix (TM) measurements. The measured TM of a scattering material determines the hologram required for focusing through the scatterer. We demonstrate this technique measuring a TM with 256 input modes and a single output mode in 33.8 ms and creating a focus with a signal to background ratio of 160. We also demonstrate focusing through a dynamic, strongly scattering sample.

Introduction

Random scattering distorts incident wavefront



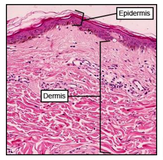
Wavefront optimization for focusing



- Focusing through turbid media has been achieved by optimizing wavefronts to overcome the effects of multiple scattering [1]
- Divide the incident wavefront into N spatial input modes and optimize the phase of each mode [1,2]
- Most current techniques use a liquid crystal – spatial light modulator (LC-SLM) for phase modulation

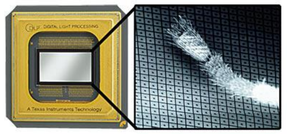
Motivation

- Focusing light through tissue could improve many biomedical applications:
  - Photodynamic therapy
  - Optical trapping
  - Fluorescence imaging
  - Neuron excitation and imaging



[3]

- Turbid biological tissues have structural changes on the millisecond timescale
  - LC-SLMs are too slow, 10-500 Hz
  - Need faster focusing technique
  - Use TI-DLP DMD array, 24kHz



[4]

Binary Amplitude Lee Hologram

Allows for phase modulation using binary amplitude modulator

- Encode the phase, $\varphi(x,y)$, into the transmission hologram, $t(x,y)$, then threshold [5]
- This places the information of $\varphi(x,y)$ in -1st diffraction order

$$t(x,y) = 0.5\left[1+\cos\left(2\pi(x-y)\alpha - \varphi(x,y)\right)\right]$$

$$h(x,y) = \begin{cases} 1; t(x,y) \geq 0.5 \\ 0; t(x,y) < 0.5 \end{cases}$$

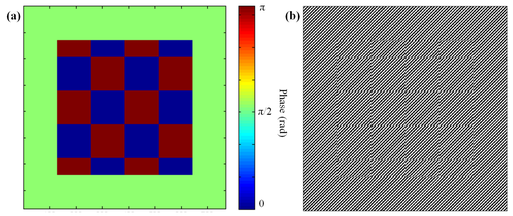
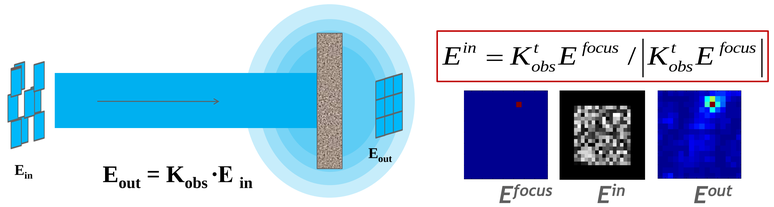


Figure: (a) The desired phase distribution, $\varphi(x,y)$, showing a Hadamard basis element surrounded by a reference phase. (b) The binary amplitude Lee hologram, $h(x,y)$, which encodes $\varphi(x,y)$.

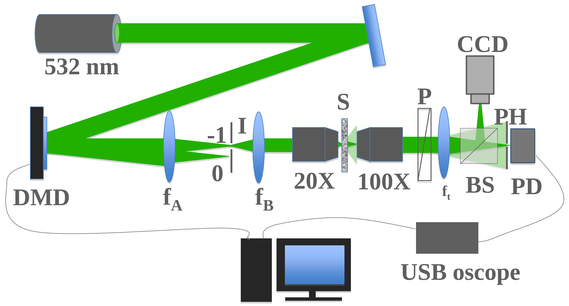
Transmission Matrix Focusing

Wavefront optimization algorithm

- Uses predefined set of masks to measure the transmission matrix between N input modes and M output modes [2]
- Allows for use of DMD at maximum frame rate
- Uses phase-only Hadamard basis set



Experimental Apparatus



Experiments

Focus through diffuse glass

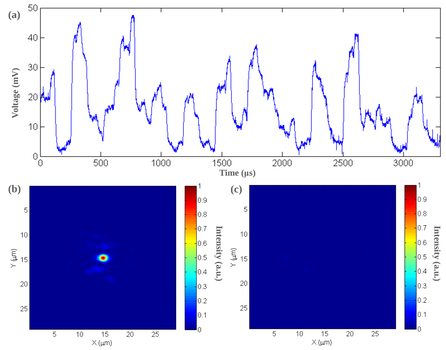


Figure: (a) 3.3 ms of data from photodetector showing the intensity of the first 25 Hadamard basis modes interfered with three phase references. (b) Focus spot with enhancement of 450 created with 1024 modes. (c) Speckle field without the optimized hologram [6].

Focus through dynamic turbid sample

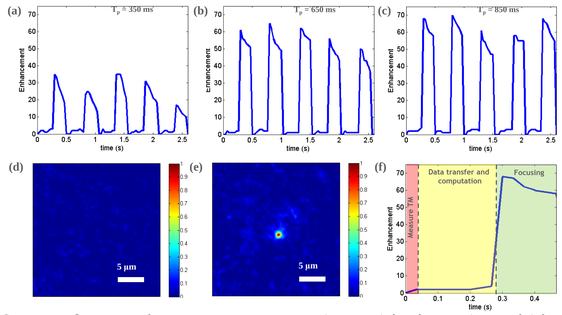


Figure: System focus enhancement versus time with dynamic turbid samples of decorrelation time: (a) 350 ms, (b) 650 ms, and (c) 850 ms. (d) Speckle field before optimization. (e) Focal spot after optimization. (f) System timing: Measure TM: 34ms (red). Data transfer and computation: 270 ms (yellow). Display optimized mask: 200 ms (green) [6].

Conclusions

- This method showed an order of magnitude improvement in measurement speed over the previous fastest method and three orders of magnitude improvement over LC-SLM methods.
- This method should have enough speed to overcome the decorrelation times of biological tissue and generate enough focusing power for a variety of biomedical sensing and imaging applications.

References

[1] I. M. Vellekoop and A. P. Mosk, "Focusing coherent light through opaque strongly scattering media," Opt. Lett. 32, 2309-2311 (2007).
[2] S.M. Popoff et al, "Measuring the transmission matrix in optics: An approach to the study and control of light propagation in disordered media," Phys. Rev. Lett. 104, 00601 (2010).
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[6] D. B. Conkey, et al, "High speed scattering medium characterization with application to focusing light through turbid media," Opt. Exp. 20, 1733-1740 (2012).