

Focusing through dynamic disordered media using a MEMS spatial light modulator

Thomas Bifano^{1*}, Chris Stockbridge¹, Yang Lu¹, John Moore¹, Samuel Hoffman¹
Kimani Toussaint², Richard Paxman³

¹*Boston University Photonics Center, 8 Saint Mary's Street, Boston MA, 02215*

²*University of Illinois at Urbana-Champaign, 1206 W. Green St., Urbana IL 61801*

³*Paxman Consulting, 9228 Sunset Lake Dr., Saline, MI 48176*

Corresponding author: tgb@bu.edu

Abstract: Experiments demonstrating controlled optical propagation through a dynamic, highly scattering medium are described. The phase of a coherent beam is controlled both spatially and temporally using a reflective, 1020-segment MEMS spatial light modulator.

OCIS codes: (290.4210) Multiple scattering; (010.1080) Active or adaptive optics; (110.0113) Imaging through turbid media; 230.6120 Spatial light modulators; 230.3990 Micro-optical devices.

Summary

Adaptive optics has become indispensable in certain high-resolution imaging and beam-propagation systems as a way to compensate unavoidable wavefront aberrations. For the most part, applications of this technique have succeeded only when the aberrations are both measurable and constrained within a relatively thin slice of the optical path, allowing phase conjugation with a deformable mirror or spatial light modulator. Controlled imaging or beam propagation through highly disordered, extended dynamic media is considerably more challenging. Over the past five years, a number of research groups have demonstrated focusing and controlled propagation through static scattering media [1-7] and through dynamic biological media [8] using liquid crystal spatial light modulators (SLMs) to modulate phase using an optimization algorithm based on feedback from a sensor on the far side of the scattering medium. More recently, one group has demonstrated focusing through a dynamic scattering medium using a binary intensity modulation and off-axis holography [9].

The work presented here describes experimental results on optical transmission through nearly opaque media and focusing using a microelectromechanical system (MEMS) reflective spatial light modulator SLM (Boston Micromachines Corporation kiloSLM®) [10], which can speed optimization rates, enabling robust focusing at intensities up to several hundred times the background level. This SLM has been used previously in a variety of applications requiring control of dynamic aberrations containing high spatial and/or temporal frequencies [11-19]. It is comprised of 1020 controllable mirror segments in a 32×32 array (with immobile mirror segments at the four corners of the array). Each segment measures $300\mu\text{m}$ square and $3\mu\text{m}$ thick and can be translated in a surface-normal direction using voltage control to an underlying electrostatic actuator. Each segment translation is controllable over a range of $\sim 1.5\mu\text{m}$. The SLM was pre-calibrated using a surface mapping interferometer (Zygo NewView 6300), to allow subsequent direct phase control with ~ 0.01 wave accuracy at the laser wavelength of 532nm . The SLM can be updated at a frame rate of $\sim 30\text{kHz}$. In the experiments reported here, the 32×32 pixel CMOS sensor used for optimization feedback limited the overall system control frequency to be $\sim 350\text{Hz}$.

A schematic representation and a photograph of the experimental setup are depicted in Figure 1. The phase of a collimated beam can be controlled over a full wavelength at each of spatially distributed, independent mirror segments. The SLM optical plane is reimaged onto the front surface of a scattering medium using a lens and a microscope objective, and scattered light exiting the medium is projected by a second objective onto a CMOS camera sensor. The objective of the optimization algorithm is to enhance the intensity of a single speckle grain at the center of camera sensor plane. The optimization algorithm employed in this work is based on coordinate descent using a set of orthogonal Walsh functions as a basis set [20, 21]. Details of the algorithm have been reported previously [22].

A number of different scattering media were used, including a 12 μm thick film of fixed dry titanium dioxide paint on a glass slide, a dilute mixture of paint and paint extender (i.e. a dilution medium), and a 5mm thick slab of tissue from a chicken breast.

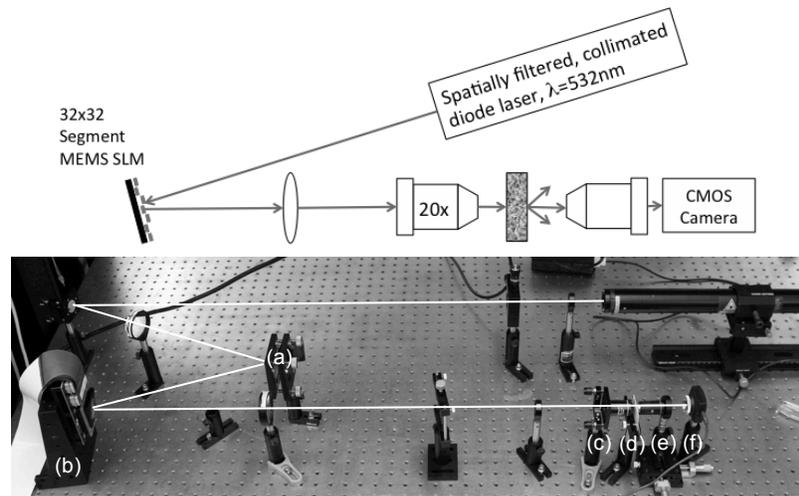


Figure 1. Schematic of the experimental apparatus. A collimated, spatially filtered laser beam, (a), reflects from the SLM surface, (b), acquiring a spatially distributed phase shift. The wavefront at the SLM is reimaged by a 45 \times telescope comprised of a 400mm focal length lens and a 20 \times , 0.4NA microscope objective, (c) onto the front surface of the scattering medium, (d). The scattering medium is a 5mm thick slab of tissue (raw chicken breast). A 5 \times microscope objective on the far side of the scattering medium, (e), projects a portion of the resulting speckle pattern onto a fixed detector, (f).

The results from focusing through chicken breast tissue are depicted in Figure 2. While the diffusion time constant of individual scatterers in such biological tissue can be as small as a few milliseconds, we found that the speckle decorrelation time was more closely linked to larger scale spatial fluctuations of the medium – essentially bulk translation of large numbers of scatterers with respect to the fixed optical system. The speckle decorrelation time constant was determined to be ~ 6.7 seconds through an ensemble average of autocorrelations of all 1024 pixels in the camera sensor before optimization. The average camera pixel intensity before optimization was recorded for use as a normalization factor in all subsequent image measurements. Optimization reached an approximately steady enhancement level (defined as the optimized final peak intensity divided by the spatial mean of the initial image intensity) of ~ 150 in approximately 15 seconds. After optimization was stopped, the SLM was held at its final optimized state and the subsequent exponential decay in intensity enhancement was recorded. The time constant for this decay was ~ 6.8 seconds.

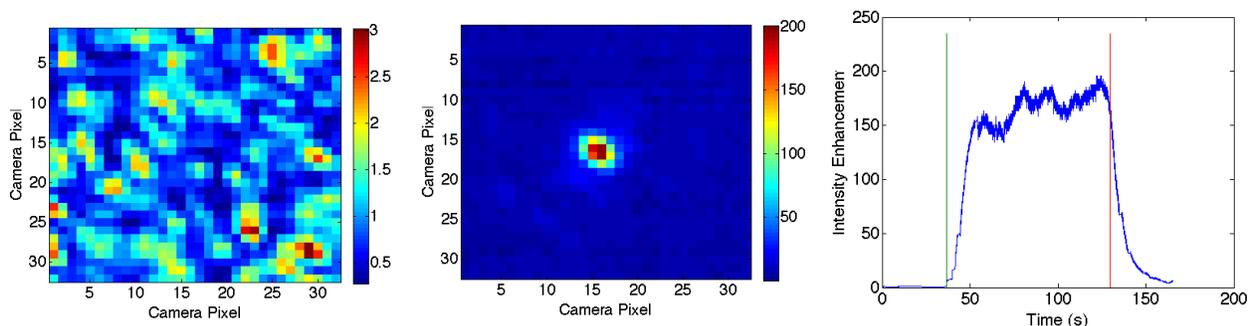


Figure 2. Optimization results for focusing through a 5mm thick specimen of raw chicken breast. Left: measured speckle pattern intensity before optimization. Middle: Optimized state, with intensity enhanced by a factor of ~ 150 . Right: Enhancement as a function of time. The first vertical line corresponds to the start time for optimization, and the second corresponds to the stop time. After optimization stops, the enhancement reduces to background level in ~ 6.8 seconds.

Thus, we have successfully focused coherent light by pre-compensating prior to encountering nearly opaque, dynamic scattering media. Whereas the experiments reported are limited by camera speed, the MEMS device will accommodate increased optimization speeds almost one hundred times faster than demonstrated here. Increased temporal bandwidth is needed to accommodate scattering media with increased dynamics, including greater rates of bulk translation and eventually scatterers that evolve on a microscopic scale. In future work we plan to increase the temporal bandwidth of our adaptive system by using high-speed sensors and improved optimization algorithms.

This work was supported by a grant from the Keck Foundation. The SLM was provided by Boston Micromachines Corporation (BMC). Professor Bifano acknowledges a financial interest in BMC.

References

- [1] Vellekoop IM, Aegerter CM, "Scattered light fluorescence microscopy: imaging through turbid layers," *Opt. Lett.*, [35], 1245-1247, (2010).
- [2] Vellekoop IM, Mosk AP, "Focusing coherent light through opaque strongly scattering media," *Opt. Lett.*, [32], 2309-2311, (2007).
- [3] Vellekoop IM, Lagendijk A, Mosk AP, "Exploiting disorder for perfect focusing," *Nat Photon*, [4], 320 - 322, (2010).
- [4] Montaldo G, Tanter M, Fink M, "Time Reversal of Speckle Noise," *Physical Review Letters*, [106], 054301, (2011).
- [5] Popoff SM, Lerosey G, Carminati R, Fink M, Boccaro AC, Gigan S, "Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media," *Physical Review Letters*, [104], 100601, (2010).
- [6] Popoff SM, Lerosey G, Fink M, Boccaro AC, Gigan S, "Image Transmission Through an Opaque Material," *Nature Communications*, [1], (2010).
- [7] Lerosey G, de Rosny J, Tourin A, Fink M, "Focusing Beyond the Diffraction Limit with Far-Field Time Reversal," *Science*, [315], 1120-1122, (2007).
- [8] Vellekoop IM, Aegerter CM, "Focusing light through living tissue," San Francisco, California, USA, *SPIE*, [7554], 755430-755410, (2010).
- [9] Conkey DB, Caravaca-Aguirre AM, Piestun R, "High-speed scattering medium characterization with application to focusing light through turbid media," *Opt. Express*, [20], 1733-1740, (2012).
- [10] Bifano T, "Adaptive imaging: MEMS deformable mirrors," *Nat Photon*, [5], 21-23, (2011).
- [11] Baker KL, Stappaerts EA, Homoelle DC, Hennesian MA, Bliss ES, Siders CW, Barty CPJ, "Interferometric adaptive optics for high-power laser pointing and wavefront control and phasing," *Journal of Micro/Nanolithography, MEMS and MOEMS*, [8], 033040-033014, (2009).
- [12] Baker K, Stappaerts E, Gavel D, Wilks S, Tucker J, Silva D, Olsen J, Olivier S, Young P, Kartz M, Flath L, Kruevitch P, Crawford J, Azucena O, "High-speed horizontal-path atmospheric turbulence correction using a large actuator-number MEMS spatial light modulator in an interferometric phase conjugation engine," *Optics Letters*, [29], 1781-1783, (2004).
- [13] Kasdin NJ, Vanderbei RJ, Belikov R, "Shaped pupil coronagraphy," *Comptes Rendus Physique*, [8], 312-322, (2007).
- [14] Belikov R, Pluzhnik E, Connelley MS, Witteborn FC, Lynch DH, Cahoy KL, Guyon O, Greene TP, McKelvey ME, "First results on a new PIAA coronagraph testbed at NASA Ames," *Techniques and Instrumentation for Detection of Exoplanets IV*, San Diego, CA, USA, *SPIE*, [7440], 74400J-74412, (2009).
- [15] Belikov R, Pluzhnik E, Connelley MS, Witteborn FC, Greene TP, Lynch DH, Zell PT, Guyon O, "Laboratory demonstration of high-contrast imaging at 2 lambda/D on a temperature-stabilized testbed in air," *Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave*, San Diego, California, USA, *SPIE*, [7731], D1-D11, (2011).
- [16] Thomas SJ, Soummer R, Dillon D, Macintosh B, Gavel D, Sivaramakrishnan A, "Testing the Apodized Pupil Lyot Coronagraph on the Laboratory for Adaptive Optics Extreme Adaptive Optics Testbed," *The Astronomical Journal*, [142], 119, (2011).
- [17] Thomas SJ, Soummer R, Dillon D, Macintosh B, Evans JW, Gavel D, Sivaramakrishnan A, Marois C, Oppenheimer BR, "Testing the APLC on the LAO ExAO testbed," *Adaptive Optics Systems*, Marseille, France, *SPIE*, [7015], 70156I-70111, (2008).
- [18] Macintosh B, Graham J, Palmer D, Doyon R, Gavel D, Larkin J, Oppenheimer B, Saddlemyer L, Wallace JK, Bauman B, Erikson D, Poyneer L, Sivaramakrishnan A, Soummer R, Veran JP, "Adaptive optics for direct detection of extrasolar planets: the Gemini Planet Imager," *Comptes Rendus Physique*, [8], 365-373, (2007).
- [19] Gavel D, Severson S, Bauman B, Dillon D, Reinig M, Lockwood C, Palmer D, Morzinski K, Ammons M, Gates E, Grigsby B, "Villages: an on-sky visible wavelength astronomy AO experiment using a MEMS deformable mirror," *MEMS Adaptive Optics II*, [SPIE 6888], 688804-688807, (2008).
- [20] Wang F, "Control of deformable mirror with light-intensity measurements through single-mode fiber," *Appl. Opt.*, [49], G60-G66, (2010).
- [21] Wang F, "Wavefront sensing through measurements of binary aberration modes," *Appl. Opt.*, [48], 2865-2870, (2009).
- [22] Bifano TG, Lu Y, Stockbridge C, Berliner A, Moore J, Paxman R, Tripathi S, Toussaint K, "MEMS spatial light modulators for controlled optical transmission through nearly opaque materials," San Francisco, California, USA, *SPIE*, [8253], 82530L-82539, (2012).