Non-invasive Focusing Through Scattering Layers Using Speckle-Correlations

Galyla Stern¹ and Ori Katz¹ *

¹Department of Applied Physics, The Rachel and Selim Benin School of Computer Science and Engineering, The Hebrew University of Jerusalem

*Corresponding author: orik@mail.huji.ac.il

OCIS codes: (290.0290) Scattering; (030.6140) Speckle

http://dx.doi.org/10.1364/ao.XX.XXXXXX

Angular speckle correlations known as the ‘memory-effect’ have recently been exploited for non-invasive imaging through scattering layers. Here, we show how the imaging information obtained from speckle correlations can be used as a noninvasive feedback mechanism for wavefront shaping. We utilize this feedback to demonstrate guide-star free noninvasive focusing of coherent light through highly scattering layers.

When a scattering sample is illuminated by coherent light, interference of the scattered waves gives rise to random speckle patterns [5]. While speckle patterns are usually considered as a hurdle for imaging, their complex structure contains information on the incident wave. In particular, inherent speckle correlations persist even deep beyond the transport mean-free-path in scattering samples [6–9]. Such ‘memory-effect’ angular correlations were recently exploited for non-invasive diffraction-limited imaging through scattering layers, either by scanning a speckled beam on the target [10], or by a single-shot measurement of the scattered light pattern [11]. In the latter, the intensity autocorrelation of spatially-incoherent light inside the scattering medium is estimated from the scattered light distribution outside the medium. Here, we extend this approach to spatially-coherent illumination, and utilize the estimated field autocorrelation inside the sample as a feedback for wavefront shaping.

To explain the principle of the proposed approach, consider the setup depicted in Fig. 1. Figure 1 presents a simplified scenario where the goal is to use an SLM to focus a monochromatic light beam on a target placed between two highly scattering layers. As was recently demonstrated [12, 13], in the case of a fluorescently labeled target object, estimating the incoherent spatial intensity autocorrelation at the object plane is straightforward by following the principles of [11]. However, using such an approach for iterative focusing is challenging due to the long integration times required to record the low photon flux (per speckle grain) of scattered fluorescence chang2018single,hofer2018wide, and due to photo-bleaching. Our approach avoids these limitations, as well as the requirement for fluorescent labeling, by considering coherent illumination. Below we show how to estimate the coherent field autocorrelation inside the sample, and how to use it for wavefront-shaping.

In the simplified scenario of Fig. 1 a transparent target object placed between two scattering layers is illuminated through the first layer (Diffuser1) by a monochromatic spatially-coherent beam at wavelength λ. The light intensity at the second layer’s external facet is imaged on a camera. Due to the scattering of the first layer, the object is illuminated by a speckle field with complex amplitude $E_{\text{illum}}(x, y)$. The field after the object is given by $E_{\text{object}}(x, y) = E_{\text{illum}}(x, y)T(x, y)$, where $T(x, y)$ represents the thin object’s transmission. The light passing through the object propagates a distance L before impinging on the second scattering layer. If L is larger than the far-field distance (an
In the case of a realistic scattering layer with a finite thickness this simple approximation does not hold. In practice, a point illumination on a diffusive sample of thickness \( l \) would result in a speckled blob of diameter \( \sim l \) on its output facet [9, 15]. Thus, for realistic scattering layers, any features of the input intensity pattern that are finer than \( \sim l \) would not be recovered on its external facet. However, features that are coarser than \( \sim l \) can be recovered [15]. Since the camera image, \( I_{\text{camera}} \), and the estimated autocorrelation are Fourier pairs (Eq. 2), the coarse effective resolution of \( I_{\text{camera}} \) for thick layers limits the autocorrelation estimation to an angular field of view (FoV) no larger than \( \theta_{\text{max}} \approx \lambda / L \), which is, not by coincidence, the angular range of the memory effect [6, 7, 15]. This limits the target object transverse dimension to \( L / \lambda \).

In the above simplified derivation \( L \) was assumed to be larger than the far-field distance. However, this assumption can be greatly relaxed since the object is illuminated by a speckle pattern [14] or when it is diffusive. Marking the transverse coherence size of the field at the object plane by \( d_{\text{speckle}} \), where \( d_{\text{speckle}} \) is either the illumination speckle grain size or alternatively the correlation width of the diffusive object, the diffraction angle of the light propagating from the object is: \( \theta_{\text{diff}} \approx \sin^{-1}\left( \frac{d_{\text{speckle}}}{L} \right) \). The minimal propagation distance where light from opposite ends of an object mix and interfere to produce the speckles illuminating the second scattering layer is reached at \( z_0 \approx \frac{D_{\text{obj}}}{2\sin(\theta_{\text{diff}})} \approx \frac{D_{\text{speckle}}}{24} \), where \( D_{\text{obj}} \) is the transverse size of the object. For distances larger than \( z_0 \) \( (L > z_0) \) each speckle grain in the field impinging on the second scattering layer will result from interferences of all object points, and will have transverse dimensions of \( \sigma_x \approx \lambda / D_{\text{obj}} \). As in the van Cittert-Zernike theorem, the speckle size will then reflect the illuminated object dimensions \( D_{\text{obj}} \), providing the required feedback for the iterative focusing algorithm. Thus, the autocorrelation of the field at the object plane can be estimated at distances considerably shorter than the far-field distance, as is demonstrated numerically in Fig. 2.

To provide proof-of-principle experimental verification of our approach, we constructed the setup of Fig. 1. A Helium-Neon laser beam (Thorlabs HNL008LB) was expanded and shaped by a phase-only SLM (Hololume PLUTO) to illuminate a target object (a small transmission mask) placed between two scattering layers (Newport light shaping diffuser, 5° and 10°). The light on the second diffuser external facet was imaged by an sCMOS camera (Andor Zyla 4.2 plus). To inspect the focusing results, a beam-splitter (Thorlabs 45:55 (R:T) Pellicle Beam-splitter) and a second camera (Thorlabs DCU223M, not shown) were used to record the light intensity patterns at the object plane.

Fig. 3 displays an experimental result obtained with a circular target object (75 \( \mu \text{m} \) diameter pinhole). Using the proposed approach, i.e. iteratively shaping the wavefront to shrink the estimated autocorrelation width \( 3(c) \), a sharp focus with a size close to a single speckle grain was obtained \( 3(d) \), from an initially random speckle pattern \( 3(a) \). The intensity enhancement obtained after 600 iteration was \( \eta \approx 65 \).

To shrink the autocorrelation width, we have developed a simple iterative algorithm based on the random partitioning wavefront-shaping algorithm [16]: In each iteration of this algorithm, a phase is added to half of the SLM pixels, selected at random. The added phase is cycled in 6 steps from 0 to \( 2\pi \). For each phase step, the ‘width’ of the estimated autocorrelation, \( A(r) \) (Eq. 2), is approximated by its effective radius:
\[ \langle r \rangle \equiv \sum \frac{A(r) \cdot r}{\sum A(r)} \] after removing the central coherent autocorrelation peak, and cropping the autocorrelation image to a radius proportional to its width, to minimize the background effect. For each iteration, the optimization metric \[ M = \frac{1}{\langle r \rangle} \] was fitted to a cosine as a function of the added phase, and the optimum phase for the maximal \( M \) (i.e. minimal \( \langle r \rangle \)) was kept as the SLM phase pattern.

An additional experimental focusing example with a more complex object, and a comparison to conventional optimization is shown in Fig. 4. As expected, conventional optimization of the total transmitted intensity (Fig. 4(d)) shows enhancement of intensity spread on the entire object area, without forming a localized sharp focus \cite{2}. In contrast, our speckle-correlation based approach (Fig. 4(g)) forms a sharp focus.

Fig. 4(c,f,i) display the autocorrelations patterns estimated from the camera images, together with their calculated autocorrelation radius \( \langle r \rangle \) (thin red circles). Note the two peripheral peaks in Fig. 4 (c), which reflect the three peaks in the autocorrelation of the double-apertured object. In the case of a too small memory-effect range (i.e. too large object), these autocorrelation side-lobes would be impossible to estimate.

To study the dependence of the proposed focusing approach on the problem parameters we performed a numerical study of the optimization performance for different object dimensions and the number of controlled SLM pixels. The results of the dependence on the object dimensions are shown in Fig. 5: each point represents the average enhancement obtained after 3000 iterations, averaged over 10 realizations of the scattering layers. Interestingly, for too small objects, containing only a few speckles grains, the simple proposed focusing algorithm is less effective. We attribute this to be the result of the imperfect removal of the central coherent autocorrelation peak in the simple
While sharply-localized foci with dimensions close to the speckle were not able to experimentally achieve a focus having strictly will not allow the simple algorithm to focus to a single focus. We attribute this to the relatively long timescales required for the hundreds of iterations: a typical experiment with the slow algorithm, and to an imperfect removal of the autocorrelation coherent peak. This is not a fundamental limitation, since we have verified that the autocorrelation of a diffraction limited focus, obtained with direct invasive feedback, indeed posses a smaller width than the optimized foci (not shown). Thus, more advanced optimization metrics are expected to yield improved performances.

To summarize, we have presented an all-optical guide-star free approach for noninvasive focusing through scattering layers. Unlike previous all-optical noninvasive focusing works [17–19], our approach does not require fluorescence labeling or optical nonlinearities.

We have demonstrated the approach in proof of principle experiments using thin diffusers. Our proof of principle experiments with thin diffusers should be extendable to volume scattering materials, as long as the field at the target plane is limited to the memory effect FoV. This may be relevant for anisotropically scattering soft tissues at intermediate depths [20]. For objects that are larger than the memory effect range, the information on the longer-distanced parts will not be correctly estimated, and will not allow the simple algorithm to focus to a single focus.

As any iterative optimization approach, the main limitation of the presented approach is the relatively long timescales required for the hundreds of iterations: a typical experiment with the slow refresh rate (10Hz) liquid crystal SLM used in our experiments required tens of minutes to achieve significant focusing enhancement. However, orders of magnitude faster SLMs [21–23] and faster cameras would significantly reduce the optimization time. More advanced optimization algorithms, such as genetic algorithms [24], may also reduce the number of required iterations. While sharply-localized foci with dimensions close to the speckle grain were obtained with our simple optimization algorithm, we were not able to experimentally achieve a focus having strictly a single speckle grain dimensions. We attribute this to the rela-

Fig. 5. Numerical comparison between the achieved focus intensity enhancement ($\eta$) for different (circular) object sizes. The object size (horizontal axis) is given as the ratio between its area to the speckle grain area, providing an estimate of the number of speckle grains initially contained within the object. Each point is an average of 10 realizations. Error-bars are one standard deviation. Insets: final intensity distribution at the object plane.

analysis we have used: the estimated autocorrelation width of small objects (having dimensions close to the speckle grain size) will be more affected by such simplified peak-removal procedure. However, more robust autocorrelation-width estimation algorithms can be developed for this task. On the other hand, for large objects, we observe only a near constant intensity enhancement (Fig. 5), and focus dimensions (see Fig. 5 insets). Additional simulations with a varying number of controlled SLM pixels, $N_{SLM}$, showed a linear dependence of the enhancement on $N_{SLM}$ (not shown), as in conventional wavefront-shaping with direct imaging of the target.

To summarize, we have presented an all-optical guide-star free approach for noninvasive focusing through scattering layers. Unlike previous all-optical noninvasive focusing works [17–19], our approach does not require fluorescence labeling or optical nonlinearities.
1. V. Ntziachristos, “Going deeper than microscopy: the optical imaging frontier in biology,” Nat. methods 7, 603 (2010).
2. I. Vellekoop and A. Mosk, “Focusing coherent light through opaque strongly scattering media,” Opt. Lett. 32, 2309–2311 (2007).
3. A. P. Mosk, A. Lagendijk, G. Lerosey, and M. Fink, “Controlling waves in space and time for imaging and focusing in complex media,” Nat. Photonics 6, 283–292 (2012).
4. R. Horstmeyer, H. Ruan, and C. Yang, “Guidestar-assisted wavefront-shaping methods for focusing light into biological tissue,” Nat. photonics 9, 563 (2015).
5. J. W. Goodman, Statistical optics (2015).
6. S. Feng, C. Kane, P. A. Lee, and A. D. Stone, “Correlations and fluctuations of coherent wave transmission through disordered media,” Phys. Rev. Lett. 61(7), 834 (1988).
7. I. Freund, M. Rosenbluh, and S. Feng, “Memory effects in propagation of optical waves through disordered media,” Phys. review letters 61, 2328 (1988).
8. S. Rotter and S. Gigan, “Light fields in complex media: Mesoscopic scattering meets wave control,” Rev. Mod. Phys. 89(1), 015005 (2017).
9. B. Judkewitz, R. Horstmeyer, I. M. Papadopoulos, and C. Yang, “Translation correlations in anisotropically scattering media,” Nat. physics 11, 684 (2015).
10. J. Bertolotti, E. G. van Putten, C. Blum, A. Lagendijk, W. L. Vos, and A. P. Mosk, “Non-invasive imaging through opaque scattering layers,” Nature 491(7423), 232 (2012).
11. O. Katz, P. Heidmann, M. Fink, and S. Gigan, “Non-invasive single-shot imaging through scattering layers and around corners via speckle correlations,” Nat. Photonics 8, 784–790 (2014).
12. J. Chang and G. Wetzstein, “Single-shot speckle correlation fluorescence microscopy in thick scattering tissue with image reconstruction priors,” J. biophotonics 11, e201700224 (2018).
13. M. Hofer, C. Soeller, S. Brasselet, and J. Bertolotti, “Wide field fluorescence epi-microscopy behind a scattering medium enabled by speckle correlations,” Opt. express 26, 9866–9881 (2018).
14. E. Edrei and G. Scarcelli, “Optical imaging through dynamic turbid media using the fourier-domain shower-curtain effect,” Optica 3, 71–74 (2016).
15. I. Freund, “Looking through walls and around corners,” Phys. A: Stat. Mech. its Appl. 168, 49–65 (1990).
16. I. M. Vellekoop and A. Mosk, “Phase control algorithms for focusing light through turbid media,” Opt. communications 281, 3071–3080 (2008).
17. O. Katz, E. Small, Y. Guan, and Y. Silberberg, “Noninvasive nonlinear focusing and imaging through strongly scattering turbid layers,” Optica 1, 170–174 (2014).
18. J. Tang, R. N. Germain, and M. Cui, “Superpenetration optical microscopy by iterative multiphoton adaptive compensation technique,” Proc. Natl. Acad. Sci. 109(22), 8434–8439 (2012).
19. I. N. Papadopoulos, J. S. Jouhanneau, J. F. Poulet, and B. Judkewitz, “Scattering compensation by focus scanning holographic aberration probing (f-sharp),” Nat. Photonics 11(2), 116 (2017).
20. S. Schott, J. Bertolotti, J. Léger, L. Bourdieu, and S. Gigan, “Characterization of the angular memory effect of scattered light in biological tissues,” Opt. Express 23, 13505–13516 (2015).
21. G. Ghielmetti and C. M. Aegerter, “Direct imaging of fluorescent structures behind turbid layers,” Opt. express 22, 1981–1989 (2014).
22. P. Lai, L. Wang, J. W. Tay, and L. V. Wang, “Photoacoustically guided wavefront shaping for enhanced optical focusing in scattering media,” Nat. photonics 9, 126 (2015).
23. D. B. Conkey, A. M. Caravaca-Aguirre, and R. Piestun, “High-speed scattering medium characterization with application to focusing light through turbid media,” Opt. express 20, 1733–1740 (2012).
24. D. B. Conkey, A. N. Brown, A. M. Caravaca-Aguirre, and R. Piestun, “Genetic algorithm optimization for focusing through turbid media in noisy environments,” Opt. express 20, 4840–4849 (2012).