

Noninvasive nonlinear focusing and imaging through strongly-scattering turbid layers: supplementary material

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In this supplementary material to “Noninvasive nonlinear focusing and imaging through strongly-scattering turbid layers,” <http://dx.doi.org/10.1364/OPTICA.1.000170>, we supply a more detailed description of the optical system and show dynamical data demonstrating the action of the optimization algorithm. © 2014 Optical Society of America

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Experimental Setup.

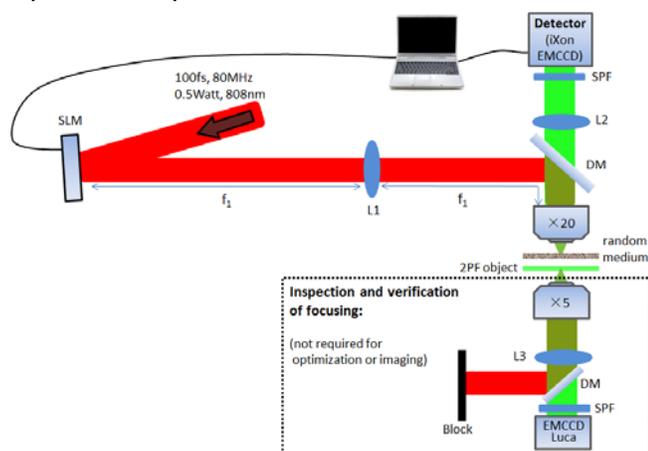


Fig. S1. Experimental setup for focusing through a scattering medium in epi-illumination and detection: the optimization is obtained by controlling the phase-only SLM (Hamamatsu), which is divided to 1200 (40 by 30) square segments, to optimize the total 2PF signal collected by a wide-area detector, utilizing a standard epi-detection two-photon microscope. The detector was implemented by integrating the total optical intensity measured by an Andor iXon EMCCD camera, imaging the scattering layer's surface. To fully exploit the memory effect for scanning the SLM is carefully imaged on the scattering layer using a 4-f telescope ($f_1=175\text{mm}$). The fluorescence screen used in Figure 1 was made of disodium fluorescein in ethanol. The distances between the diffuser and the 2PF sample was 2-10 mm. In our proof-of-concept experiments, an additional imaging system (inspection and verification

block in the figure), is used to prove that indeed the pulse has been focused on the target object. DM - dichroic mirror (Semrock), SPF - short-pass and bandpass filters (Chroma). L2, L3 - achromatic lenses with $f_2=100\text{mm}$, $f_3=200\text{mm}$ focal distances.

Media S1. (see the primary document) The video shows the progress of the optimization procedure that leads to the results of Fig. 1 in the main manuscript. It shows the two-photon fluorescence image of the screen as captured by the inspection camera, as well as the total signal measured in epi-geometry, as the genetic algorithm attempt to maximize this total fluorescence signal.

Experimental parameters. The total optimization process in this experiment (Figure 1) was approximately 2.5 hours. However, more than 75% of the total experimental time was spent on various system latencies (waiting for SLM refresh, camera and SLM communications delay, etc). A total of 650 generations of the genetic algorithm were ran in this experiment, in each of which 30 different phase-patterns were displayed on the SLM and the total 2PF signal was measured. The integration time of the camera for each of the measurement was 100ms.

In the experiment of Figure 2, 650 generations of the genetic algorithm were ran, using a camera integration time of 2ms, lasting a total of 45 minutes.

In the experiment of Fig.4 (focusing through the 1mm-thick brain tissue), 650 generations of the genetic algorithm were ran, using a camera integration times of 50ms to 13ms (integration time was adaptively lowered with signal enhancement), lasting a total of 50 minutes.

Before starting the optimization in each experiment, optimal conventional focusing was attained by displaying a set of parabolic phase-masks on the SLM, effectively converting the scattering medium to a focusing lens, having the proper focal length.

Numerical simulation parameters. The propagation of the field through the scattering layer was simulated using the angular spectrum method. The waist of the Gaussian impinging beam on the diffusing surface was 0.3mm. The diffusing layer had a scattering angle of $\sim 11^\circ$. The simulated nonlinear medium had a rectangular cross-section of $50 \times 50 \mu\text{m}$, and a thickness of $0 \mu\text{m}$, $140 \mu\text{m}$ and $280 \mu\text{m}$, and was placed such that its center is at a distance of 1mm from the scattering layer. For each thickness of the nonlinear medium, 10 optimizations were ran at 10 different random realizations of the scattering diffuser.

Expected optimized signal enhancement for a planar fluorescent object. In the simple case where no temporal pulse distortions are present, the expected focused intensity enhancement factor at the focal spot is $\eta = (\pi/4)N_{\text{SLM}}$, where N_{SLM} is the number of controlled SLM segments¹. For an N^{th} order nonlinear signal the expected enhancement would be η^N (e.g. $N=2$ for 2PF). As the optimized signal in our experiment is the sum of the signals from this focused intensity enhanced speckle, but also of the additional $(N_{\text{speckles}}-1)$ unoptimized speckle grains that initially illuminate the fluorescence object and act as largely unmodified background, the optimized signal enhancement is expected to be N_{speckles} times lower. This relationship is derived straightforwardly assuming that the total laser power transmitted through the scattering sample, P_{laser} , remains largely unchanged:

$$\frac{P_{\text{opt}}}{P_{\text{initial}}} \approx \frac{\left(\eta \frac{P_{\text{laser}}}{N_{\text{speckles}}}\right)^N + (N_{\text{speckles}} - 1) \left(\frac{P_{\text{laser}} - \eta \frac{P_{\text{laser}}}{N_{\text{speckles}}}}{N_{\text{speckles}}}\right)^N}{N_{\text{speckles}} \left(\frac{P_{\text{laser}}}{N_{\text{speckles}}}\right)^N} \approx \frac{\eta^N}{N_{\text{speckles}}} \quad (1)$$

where the first term of the numerator is the nonlinear signal originating from the optimized focal spot, and the second term is the signal originating from the rest $(N_{\text{speckles}}-1)$ unoptimized speckle grains. The denominator is the initial total nonlinear signal measured prior to the optimization procedure.

References

1. I.M. Vellekoop, and A.P. Mosk, Opt. Lett. 32, 2309-2311 (2007).