Ultrasonically encoded light as feedback to iterative wavefront shaping for focusing into random media

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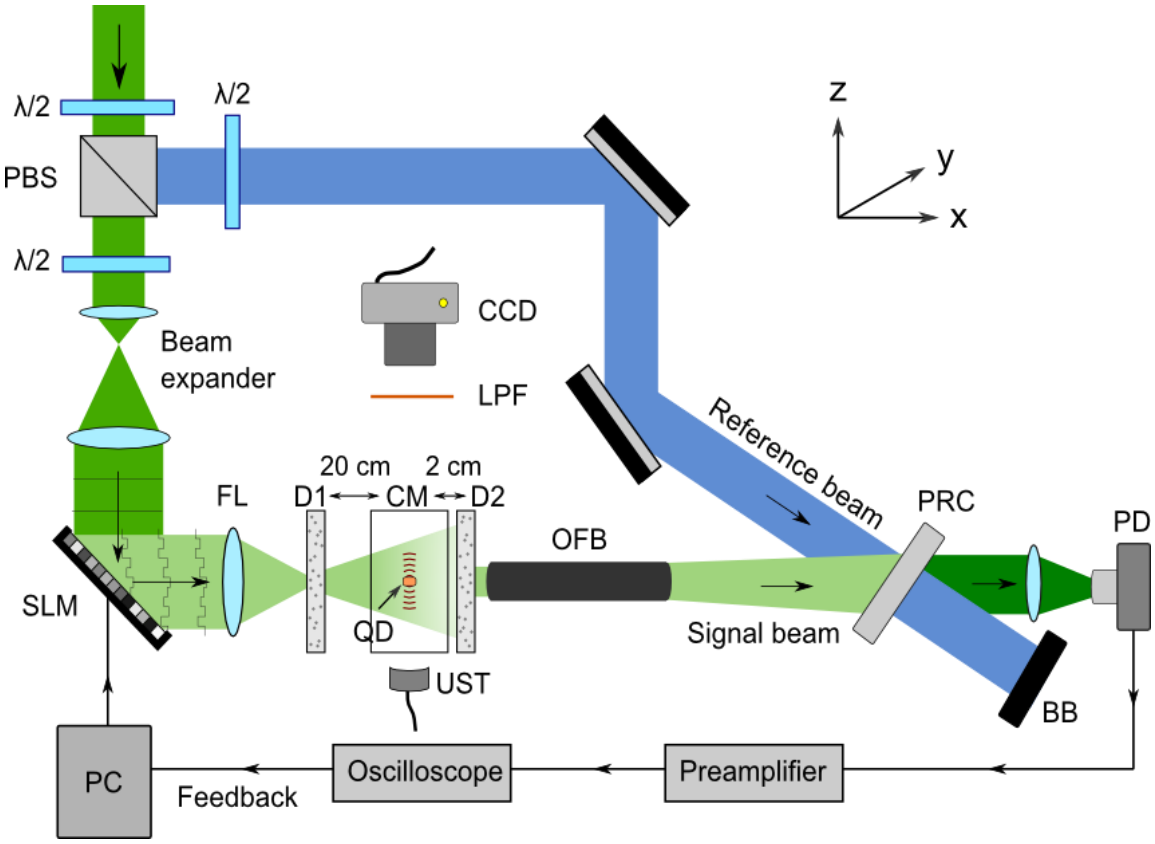
Supplementary material

Experimental setup

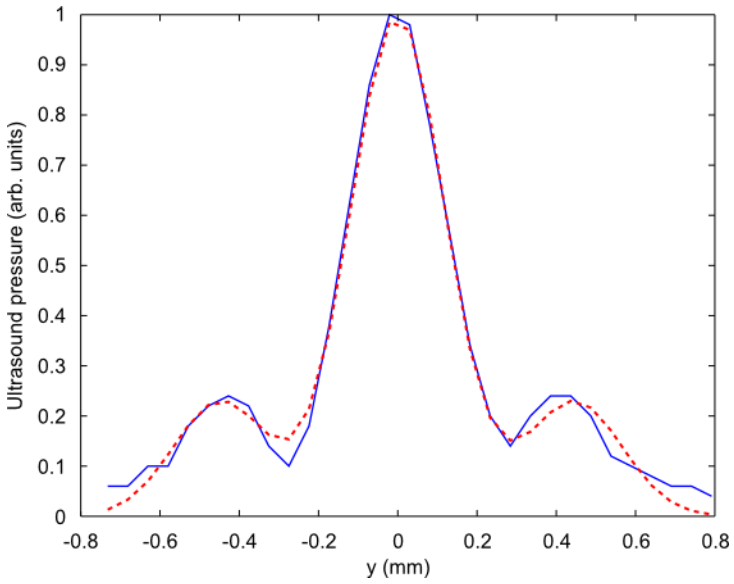


Supplementary Figure S1: Experimental setup diagram. Abbreviations: λ/2, half-wave plates; BB, beam block; CCD, charge-coupled device; CM, clear gelatin medium (10% porcine skin gelatin per volume); D1 & D2, diffusers; FL, focusing lens; LPF, optical longpass filter; OFB, optical fiber bundle; PBS, polarizing beam splitter; PRC, photorefractive crystal (BSO); PD, photodiode; QD, fluorescent quantum dot bar (QSA-600-2, Ocean Nanotech, 0.26 µM conc.); SLM, spatial light modulator; UST, ultrasound transducer.

A 1.47 W laser beam at 532 nm illuminated the sample. The incident beam was expanded to completely fill the SLM aperture. After the second diffuser D2, approximately 0.4 mW of light

was collected by the waveguide and directed to the photorefractive crystal. To detect the ultrasonically encoded light, we used a photorefractive $Bi_{12}SiO_{20}$ (BSO) crystal-based interferometer, similar to that described in [28] and [40]. The reference beam power was 28.7 mW. Both beams were directed at the same angle of approximately 10 degrees to the crystal normal.

To drive the transducer, we used five cycles of a sinusoidal wave at 6 MHz, with an amplitude of 150 mVpp before being amplified by 50 dB, and a repetition rate of 1 kHz. The transverse profile of the transducer at the acoustic focus, measured to be 400 μm using a hydrophone, is shown in Suppl. Fig. 2. The photodiode measured the signal beam exiting the photorefractive crystal. As the ultrasound pulse propagated through the medium, a dip was seen in the measured signal, which corresponded to the UE light intensity. Using a preamplifier, the signal was amplified 500 times and then high-pass filtered at 30 kHz. The oscilloscope was AC-coupled, and we inverted the signal to get a positive value. The peak of the signal minus the averaged background was used to evaluate the displayed phase pattern in the genetic algorithm described below.



Supplementary Figure S2: Ultrasonic transducer profile along the *y*-axis at the transducer focal plane. By fitting the data, the FWHM of the profile was measured (red dotted line) as 400 µm. Note that the separation between the two sidebands was about 0.85 mm.

Estimation of speckle size

The average diameter of a speckle was estimated using

$$a = 1.22\frac{\lambda L}{D} \quad (1)$$

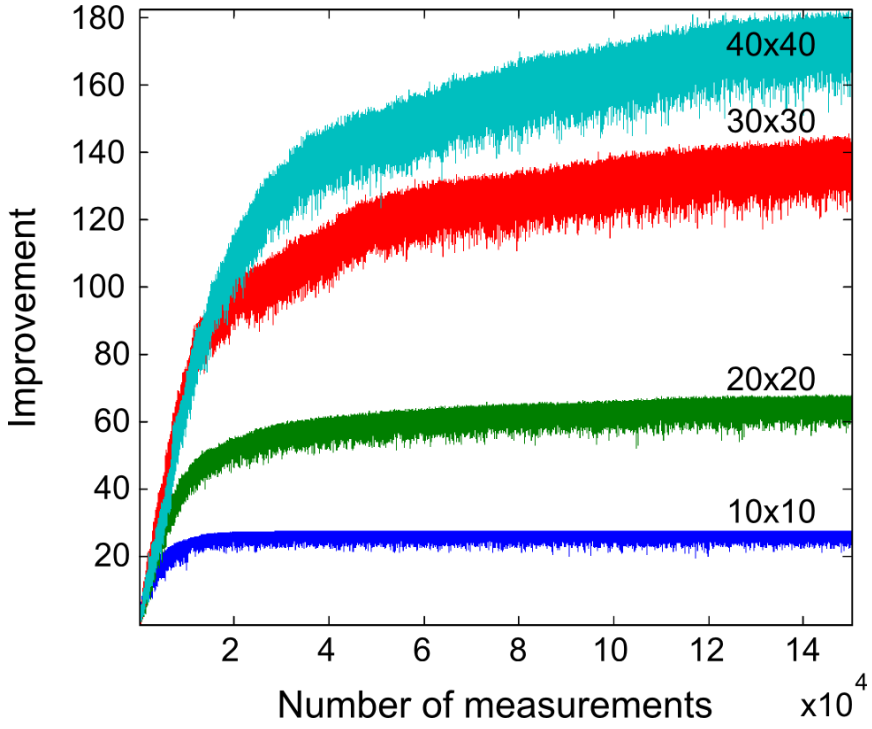
where λ is the wavelength of light, L is the distance from the exit surface of the diffuser to the ultrasound focal zone, and D is the illumination diameter at the exit surface of the diffuser. Since the diffuser was thin, we assumed that the illumination diameter at the exit was similar to that of the input. Hence, given λ = 532 nm, L = 20 cm, and D = 1 mm, the estimated mean speckle size was 130 µm.

Genetic algorithm

The genetic algorithm used was based on [21]. We summarize the procedure briefly here:

1. An initial population of phase patterns is generated randomly.
2. The population is evaluated by displaying each pattern on the SLM and recording the signal from the oscilloscope after the PRC-interferometer.
3. New patterns are generated:
    i. Two patterns (*parents*), weighted by the value of their UE signals, are randomly selected from the current population, with patterns that produce higher UE light signals having a greater probability of being selected.
    ii. A new pattern (*child*) is generated by crossover mating, with half the pattern copied from one parent and the other half copied from the other parent, using a random binary mating template.
    iii. Some portion of the pixels in the new pattern is randomized (*mutation*). The mutation rate is reduced as the algorithm proceeds.
4. The new patterns are evaluated, and the bottom half of the previous population with lower scores is replaced (*survival of the fittest*).
5. Steps 2-4 are repeated for a set number of iterations.

Numerical simulation



Supplementary Figure S3: Simulation of signal increase with varying numbers of SLM segments, indicated above each curve.

We briefly describe the numerical simulation performed to justify our choice for the number of SLM segments used in the experiment. A model similar to that in [21] was used, except that sample decorrelation was ignored. Using matrix representation, the field after the scattering medium E^{out} is given by the matrix product of the transmission matrix of the medium T and the input field E^{in}. Assuming that the photodetector senses only a single speckle, i.e. a single element of the output field, the detected field is given by

$$E_{1k}^{out} = \sum_k T_{1k} E_k^{in}.$$

The corresponding normalized transmission matrix and input field elements are given by,

$$T_{1k} = \frac{1}{\sqrt{N}} e^{i\phi_k^{TM}}$$
$$E_k^{in} = \frac{1}{\sqrt{N}} e^{i\phi_k^{SLM}} \quad (2)$$

where the phase of the transmission matrix φ^{TM} is chosen randomly over a 2π range. We assume that the input field has uniform intensity, and that its phase is given by the phase shift imparted by the SLM φ^{SLM}. The detected intensity is then given by,

$$I_{det} = \mid E_{1k}^{out} \mid^2 . \quad (3)$$

In our simulations, we used a transmission matrix with 100×100 elements. The SLM was divided into 10×10, 20×20, 30×30, and 40×40 segments in the same manner as in the experiments. The genetic algorithm, as described above, was then used to optimize I_{det}, and the results are shown in Suppl. Fig. 3. The signal improvement was calculated by dividing I_{det} of the current pattern with the averaged intensity from the first 30 measurements. The simulation results show that the optimized intensity increases with an increasing number of SLM segments; however, the number of iterations needed to obtain a convergent value also increases. These results are similar to [21]. Hence, in the experiment, we chose the number of SLM segments based on a practical experimental time frame.

Algorithm parameters

Supplementary Table 1: Genetic algorithm parameters used in the reported experiment and simulation.

	Fig. 2 (Experiment)	Suppl. Fig. 3 (Simulation)
Number of SLM blocks	20×20	10×10 – 40×40
Population Size	30	30
Number of iterations	607	10000
Initial mutation rate	0.1	0.1
Final mutation rate	0.013	0.013
Mutation decay rate	180	180

Supplementary Video Caption

Supplementary Video: Evolution of the genetic algorithm. (a) CCD images of the fluorescent bar. The number at the top left corner indicates the iteration number of the current frame. (b) Dynamics of the ultrasonically encoded optical signal and fluorescence intensity. The markers (circle/square) indicate the current frame. (c) Fluorescence intensity along the white dotted line in (a). (d) Ultrasonically encoded optical signal amplitude.