Real-time wavefront shaping through scattering media by all-optical feedback

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Controlling light through dynamically varying heterogeneous media is a sought-after goal with important applications ranging from free-space communication to nanosurgery. The underlying challenge is to control a large number of degrees of freedom of the optical wavefront, at timescales shorter than the medium dynamics. Many advances have been reported recently following the demonstration of focusing through turbid samples by wavefront shaping, where spatial light modulators with more than 1,000 degrees of freedom were used. Unfortunately, spatial light modulator-based wavefront shaping requires feedback from a detector or camera and is currently limited to slowly varying samples. Here, we demonstrate a novel approach for wavefront shaping utilizing all-optical feedback. We show that the complex wavefront required to focus light scattered by turbid samples (including thin biological tissues) can be generated at submicrosecond timescales by the process of field self-organization inside a multimode laser cavity, without requiring electronic feedback, spatial light modulators or phase-conjugation crystals.

The ability to control light in such a way as to overcome the deleterious effects of propagation through complex, inhomogeneous media has been extensively investigated during recent decades. Adaptive-optics techniques have been used to overcome atmospheric turbulence in applications such as astronomical observations and free-space optical communications, and holography and phase-conjugation techniques have been investigated for more scattering samples, such as optical diffusers. Recently, exciting developments in the control of light in turbid media by wavefront shaping using either computer-controlled spatial light modulators (SLMs) or phase-conjugation crystals have been reported. These developments have enabled high-contrast focusing, even through turbid, nearly opaque samples, where light is scattered to complex speckle patterns with the number of scattered modes greatly exceeding the number of controlled degrees of freedom (DOFs) of the incident beam, NDOF (refs 3, 21). Following the pioneering demonstration of spatial focusing by Vellekoop and Mosk, wavefront shaping has also been exploited to surpass the diffraction limit in scattering media, for imaging and image transmission, for controlling the scattered light in both space and time, as well as manipulating its spectral and polarization properties. Unfortunately, these developments all rely on computer-controlled SLMs with electronic feedback, or photorefractive crystals, and so are fundamentally limited by relatively slow response times (ranging from tens of milliseconds to hundreds of microseconds) for addressing a single DOF. Consequently, to date, high-resolution wavefront shaping has not proven useful for focusing through samples that evolve on timescales shorter than a fraction of a second, such as live biological tissues or liquid suspensions.

Here, we present a novel all-optical approach to high-resolution wavefront shaping that is capable of focusing light scattered by rapidly varying inhomogeneous media at submicrosecond timescales, without requiring computer-controlled SLMs or electronic feedback. Our approach relies on the self-organization of the optical field inside a multimode laser cavity to generate an optimal wavefront that forms a sharp focus from the otherwise randomly scattered light. This is achieved using a reflection of a small retro-reflecting target placed at the desired focal plane as a coherent optical feedback (this target is shown as a pinhole aperture and cat’s eye reflector in Fig. 1a). This coherent reflective feedback is used to initiate lasing through the medium in a lasing state that focuses the maximum light power on the reflecting target. The reason for the formation of the tight focus on the target is that the lasing process naturally selects the lasing state with minimal lasing threshold, that is, the state with minimal loss. This lasing state is the optical field with a complex wavefront that compensates for the scattering properties of the medium and that is focused on the target with minimal loss. In the presence of the target’s feedback, all other lasing modes are suppressed via the process of mode competition in the laser cavity.

The physics behind this field-generation mechanism is intimately related to lasing in random media and, in particular, to the role of mode competition and coherent feedback in random lasers. Specifically, in our experimental implementation (Fig. 1a), the coherent feedback to the lasing state with a tight focus on the target dominates over the incoherent feedback from other scattered modes. We note that a coherent reflective feedback is used for focusing through inhomogeneous media in iterative time-reversal techniques in acoustics and self-phasing antenna arrays. However, in such cases, focusing is achieved through phase conjugation, a completely different physical mechanism.

Experimental set-up

To experimentally investigate, in a controllable manner, the potential of the proposed all-optical approach for controlling light propagating through highly scattering media, we used a unique self-imaging (‘degenerate’) laser cavity design (Fig. 1a, Supplementary Fig. S4). This cavity design supports many thousands of transverse lasing modes and allows flexible control of the coupling between the different modes (see Methods). The experimental cavity was composed of a flash-lamp pumped Nd:YAG gain medium, two flat cavity mirrors and two lenses in a 4f telescope.
arrangement ($f = 400$ mm). The 4f telescope ensures that any electric field spatial distribution will be reimaged onto itself after completing a round trip in the cavity, so any field is an eigenmode of the degenerate cavity. A pinhole placed at the focal plane of the telescope and at the centre of the cavity served as the target for light focusing. The target’s effective reflective feedback and loss to unfocused modes was controlled by varying the pinhole diameter (see Methods). To monitor the intensity pattern at the target plane a small portion of the light impinging on the target was output coupled and measured by a charge-coupled device (CCD) camera, located outside the cavity. To test if a tight focus on the target could be formed through a scattering sample, we placed the sample inside the laser cavity, close to one of the cavity mirrors. The naturally occurring phenomenon of mode competition then selected the lasing state with minimal losses, that is, the field with the appropriate spatial amplitude and phase distributions that is tightly focused through the pinhole aperture after passing through the scattering sample. In this manner, focusing is achieved by the laser itself and occurs on submicrosecond lasing timescales, without any further manipulation.

It is important to note that other degenerate cavity designs would perform equally well as the one used in our experimental verification, with some of them more suited than others for different applications (see Discussion and Supplementary Fig. S4).

**Focusing through a static scattering diffuser**

As a first experiment, we placed an optical diffuser adjacent to the back cavity mirror. Simple focusing of a reference plane wave from an external continuous-wave (c.w.) laser source through the diffuser resulted in a random speckle pattern at the target plane, with no appreciable unscattered, ballistic component (Fig. 2a). In contrast, our laser operates in a lasing state that forms a significantly enhanced intensity peak through the diffuser, refocusing the scattered light on the target (Fig. 2b). Interestingly, the lasing and the refocused intensity peak were stable and insensitive to transverse shifts of the diffuser or to tilts of the adjacent cavity mirror within the diffuser scattering angle, whereas without the diffuser the cavity required precise and careful alignment to achieve optimal lasing. Quantitatively, comparing the intensity cross-sections of the lasing pattern to that of the reference plane wave focusing gives a relative intensity enhancement factor of $\eta \approx 80$ on the target area $A_{\text{target}}$ (Fig. 2c). As explained in the next section, taking into account the estimated number of speckles that are contained within the target area and whose intensities are simultaneously enhanced, $N_{\text{enh}} \approx 15$, these results suggest that our system simultaneously frequency- and phase-locks more than 1,000 independent lasing modes ($N_{\text{DOP}}$, see equation (1)).

**Focusing dependence on system parameters**

To understand the physics behind the mechanism by which the all-optical feedback is used to focus light in our experiments, it is constructive to draw a comparison with the conventional approach to wavefront shaping using SLMs (Fig. 1a, inset). In the latter, the signal from a small detector placed behind a scattering medium (for example, from a single pixel of a camera) is used as the feedback signal for an iterative optimization algorithm. These algorithms aim to maximize the detected intensity by manipulating the spatial phases of a monochromatic laser beam using the SLM pixels. Each pixel represents a single DOF. In analogy, the complex-patterned laser beam impinging on the scattering sample in our scheme can be decomposed into an array of localized laser modes, each with its own independent phase (Fig. 1b), which effectively act as independent lasers. Following this analogy, the array of independent laser modes mimics the array of controllable pixels used in conventional SLM-based wavefront shaping. This analogy is of course not perfect, as it neglects the fact that the random spatial phase modulation induced by the scattering medium also alters, locally, the cavity’s optical length, giving rise to frequency shifts of the different laser modes. As a consequence, focusing the light through the random medium inside the cavity is achieved by simultaneously locking of both the relative phases and frequencies of the array of laser modes (Fig. 1b). In this laser-array analogy, the focus is
formed by a state of mutual coherence, that is, phase-locking, among the laser modes. The modes are able to phase-lock as result of the coupling between them, which is governed by the diffraction from the small reflecting target aperture. Specifically, after each round trip in the cavity, every individual localized mode energy is diffracted over an area that is inversely proportional to the pinhole dimensions, causing light to couple from this laser mode to its neighbours, thereby frequency- and phase-locking them through the process of frequency pulling\(^34\). It is important to note that a circular aperture provides long-range coupling\(^35\). This enables the locking of a large number of modes within only a few round trips in the cavity, reducing the time required for focusing. Mode competition will phase- and frequency-lock the modes to produce a complex multimode lasing state with maximal reflectivity from the target, thus focusing the optical power on the target, which effectively serves as the front cavity mirror of the laser array.

In conventional wavefront shaping, the relative intensity enhancement factor \(\eta\) is given by the ratio of the number of controlled DOFs, \(N_{\text{DOF}}\) (the number of controlled SLM pixels), and the number of target speckles whose intensity is simultaneously enhanced, \(N_{\text{enh}}\) (refs 13,33):

\[
\eta = \frac{\pi N_{\text{DOF}}}{4 N_{\text{enh}}} + 1 \approx \frac{\pi N_{\text{DOF}}}{4 N_{\text{enh}}}
\]

To determine if a similar relationship exists in the presented all-optical approach, we repeated the experiment of Fig. 2a–c using different target sizes (pinhole diameters), thus varying \(N_{\text{enh}}\) (Fig. 2d). The experimental results for different target sizes are presented in Fig. 2d. In agreement with equation (1), the measured product \((\eta - 1)N_{\text{enh}}\) remains constant to within \(\pm 10\%\) in the different experiments, even though the target area (and correspondingly \(N_{\text{enh}}\)) is varied by more than a factor of 5. The value of \((\eta - 1)N_{\text{enh}}\) in our experiments suggests that \(N_{\text{DOF}}\) in our system was on the order of 1,000 for this parameter range. Although in conventional wavefront shaping \(N_{\text{DOF}}\) refers to the number of independent controllable SLM pixels, in our scheme \(N_{\text{DOF}}\) indicates the number of laser modes that are simultaneously phase- and frequency-locked. Note that the total number of lasing modes is considerably larger than \(N_{\text{DOF}}\) (ref. 35), but not all of these modes can frequency-lock together due to the large random frequency detuning induced by the scattering sample. This results in clusters of phase-locked modes that share similar frequency detunings\(^32\) and \(N_{\text{DOF}}\) simply indicates the size of these clusters. To complement these measurements, we performed a detailed numerical study of the focusing performance under various system parameter changes. The results of this study are discussed below and presented in Supplementary Fig. S3 and in Fig. 2d.

As in conventional wavefront shaping through turbid media\(^34\), even though the intensity enhancement is large, only a small fraction of the total energy is focused on the target. In the results presented in Fig. 2, the laser refocuses \(\sim 10\%\) of the energy on the target, which has an area \(\sim 1,000\) times smaller than the initial spread of the beam. For the system to achieve lasing through the scattering medium, the steady-state round trip gain \(g\) has to equal the total round-trip loss. The latter is composed of the energy losses of the parts of the field that are not focused on the target, and all other cavity losses that are present without the scattering sample. Quantitatively, given a scattering sample with a total power transmission \(T\) that scatters the transmitted light evenly at an angular spread of \(\theta_{\text{scatt}}\), and is placed at the focal distance \(f\) from a retro-reflecting target of area \(A_{\text{target}}\), the round-trip gain should fulfill (assuming perfect transmission and collection efficiency of the other cavity elements)

\[
g \geq \left(\frac{A_{\text{target}}}{A_{\text{scatt}} \eta T^2}\right)^{-1} = \frac{A_{\text{scatt}}}{A_{\text{spclette}}} \frac{1}{T^2} \frac{1}{N_{\text{DOF}}}
\]

where \(A_{\text{scatt}} = (f \theta_{\text{scatt}})^2\) denotes the area at the target plane to which light is scattered, and \(A_{\text{spclette}}\) is the area of a single speckle grain at the target.
this plane. Equation (2) simply denotes the fraction of the energy that is focused on the target, which was \(\sim 10\%\) in the experiment presented in Fig. 2. The right-hand side approximation of equation (2) is obtained by using \(A_{\text{target}} = A_{\text{speckle}}N_{\text{enh}}\) and \(\eta \approx N_{\text{DOF}}/N_{\text{enh}}\) (equation (1)). An interesting result from this approximation is that the required steady-state gain does not depend strongly on the target size in the parameter range where equation (1) holds. This was the case in our experiments and numerical simulations (Fig. 2d and Supplementary Fig. S3a,b) when the target aperture contained more than a few speckle grains \(N_{\text{enh}} > \sim 10\). However, further reducing the target size required additional gain. Equation (2) also gives a bound on the required feedback level from the target for lasing with a given limited gain \(G_{\text{max}}\). For the focused lasing pattern the required feedback is simply \(1/G_{\text{max}}\), which was \(\sim 10\%\) in our experiments. For an unshaped wave focused through the sample this feedback was equivalent to \(\sim 0.1\%\) in our experiments. Note that, similar to SLM-based wavefront shaping, because the number of controlled DOFs is smaller than the number of scattered modes, lasing without a scattering medium would produce a larger intracavity energy at the same pumping conditions.

To numerically study and verify the dependence of the focusing process on the various system parameters, we developed a numerical model based on the laser-array physical picture described above. In this model, we spanned the laser modes in the basis of small circular modes arranged on a tightly packed triangular lattice covering the surface of the gain aperture (Supplementary Fig. S2c). We modelled the scattering diffuser as a random phase mask with a spatial correlation length matching its scattering angle. We then calculated, for this random phase mask, the lasing steady-state solution of the entire array, taking into account the coupling between modes as well as mode competition and gain saturation. This step was accomplished by propagating the modes repeatedly through the simulated cavity until a steady-state solution was obtained (for more details see Supplementary Section S1). The numerical results for the steady-state lasing intensity cross-section at the target plane for the experimental parameters are presented in Fig. 2c by a dashed green curve. As is evident, the numerical results are in very good agreement with the corresponding experimental results. Inspection of the numerical solution for the electric field profile at the scattering medium plane shows that focusing is indeed achieved by complex shaping in both spatial amplitude and phase (Supplementary Fig. S2c,d).

Given the good correspondence between the developed numerical model and the experimental results, we used the numerical model to investigate the dependence of the focusing process on the various system parameters, beyond what is possible experimentally. The results of this study, which include the dependence on the number of lasing modes in the gain medium, gain medium diameter, target size, scattering medium properties and pumping rate (unsaturated round-trip gain), are presented in Supplementary Fig. S3. To summarize, in the range of parameters tested where the target is considerably larger than a single speckle grain \(N_{\text{enh}} \gg 1\), the intensity enhancement \(\eta\) closely followed equation (1). The enhancement did not depend strongly on the pumping rate or the diffuser scattering angle.

**Focusing through dynamic scattering samples**

To investigate the speed at which our wavefront-shaping approach can respond to dynamically varying turbidity, we replaced the static diffuser with a diffuser that was mounted on the edge of a rapidly rotating wheel. By monitoring the lasing intensity distribution at the target plane for different rotating speeds, we could evaluate the focusing temporal dynamics. Theoretically, focusing is expected to occur on timescales compatible with the phase-locking time of the coupled lasers, which is governed by the photon cavity lifetime and is tens of nanoseconds in our system. The experimental results of this investigation are presented in Fig. 3, which shows the normalized peak intensity on the target as a function of the linear speed of the diffuser, \(v\), and the corresponding phase decorrelation time for the composite cavity mode, \(\tau_{\text{corr}} \approx \sigma_{\text{corr}}/v\), where \(\sigma_{\text{corr}} \approx 50\,\mu\text{m}\) denotes the diffuser’s spatial correlation length, which is larger than the individual lasing-mode diameter. As is evident, the focused intensity peak is essentially insensitive to the motion of the diffuser to within 20\%, and tight focusing occurs even for the maximum rotation speed allowed by our experimental system, \(v > 80\,\text{m}\,\text{s}^{-1}\), which corresponds to \(\tau_{\text{corr}} \approx \sigma_{\text{corr}}/v < 620\,\text{ns}\). Such a timescale is not just considerably faster than the typical dynamics of biological samples, but is also faster than the typical pixel dwell-time in most imaging applications, including laser-scanning microscopy and optical coherence tomography (OCT). Note that, as can be observed in the insets of Fig. 3, the nominal enhancement factor in these experiments was lower than the one in Fig. 2. We attribute the lower enhancement to be the result of the experimental constraints of mounting the mechanical device at a relatively large distance from the cavity mirror, which damaged the perfect degeneracy of the cavity and lowered \(N_{\text{DOF}}\). The requirement for positioning the sample close to one of the cavity mirrors is circumvented in alternative degenerate cavity designs (see Discussion and Supplementary Fig. S4).

Finally, we applied our technique to focus light through a thin scattering biological sample. Specifically, we replaced the diffuser with a slice of \(\sim 200-\mu\text{m}\)-thick chicken breast in water and glycerol solution, placed between two microscopes slides. As with the optical diffuser, the light of an incident focused plane wave was scattered to a random speckle pattern without a noticeable ballistic component (Fig. 4a). Nonetheless, the lasing intensity pattern maintained an effective tight focus through the scattering tissue on the target (Fig. 4b).

**Discussion**

We have demonstrated an all-optical approach for wavefront shaping light through highly scattering media at unprecedented speeds. In addition to its unmatched speed, the technique has the potential to increase the number of controlled DOFs (number of transverse modes) without a trade-off in speed as in optimization-based approaches. The main practical limitation of the technique...
is that sufficient gain should be available to overcome the scattering losses and allow lasing through the scattering medium (equation (2)). Increasing the available pumping power and reducing the illumination spot size on the sample would allow focusing through thicker and more scattering samples. Another fundamental limitation is that placing the scattering sample inside the cavity should not destroy its degeneracy (that is, self-imaging of the optical field after a cavity round trip). Any scattering sample of ‘zero’ thickness placed next to the cavity mirror preserves the cavity’s degeneracy, as its effect on the field is essentially a multiplication by a phase and amplitude mask. However, thick multiply scattering samples hold this property only for a finite angular range, given by the isoplanatic angle \( \theta_{\text{mea}} \approx \lambda/2\pi L \), where \( L \) is the sample thickness. As the numerical aperture (NA) of the cavity optics is finite (NA \( \approx 0.1 \) in our experiments), any sample that maintains isoplanatism within the cavity optics’ NA can still be effectively considered a thin diffuser and would preserve the degeneracy of the cavity. Lasing through thicker samples is possible, but would result in lower \( N_{\text{DOP}} \). An interesting point to study is the effect of the strong backscattering of such samples on the lasing process.

There are several potential attractive applications for the presented approach, from free-space optical communication through atmospheric turbulence\(^{40} \) (where the two halves of the cavity could be divided between the transmitter and the receiver) to the study of dynamic scattering samples (where the camera used in our experiments could be replaced, for example, by the input of a spectrometer, utilizing the real-time focus to couple and study a larger portion of the randomly scattered light). An attractive application in biomedical investigations is the focusing of light through a scattering layer such as the skin. One may envisage using the presented approach to perform focused lasing on microscopic-scale retro-reflecting targets implanted under the skin, such as those recently reported by Tao and colleagues\(^{41} \). This may then allow the focused probing and perhaps even therapy of tissue in the vicinity of the target. In such applications, the lasing power, which is linked to the target reflectivity, could be monitored by using the cavity mirror as an output coupler without interrupting the lasing process, similar to the monitoring of focused intensity in our experiments. Applications in imaging may be possible by monitoring the lasing power while scanning the position of the target. The use of frequency-shifting and acousto-optical tagging may allow the selective use of one out of several reflecting targets\(^{42, 43} \). Another exciting path in this field may lie in using the biological tissue itself as the gain medium\(^{43} \).

In applications where the goal is to focus inside scattering samples, no optical element can be placed between the scattering layer and the target, as was the focusing lens used in the specific cavity design of our proof-of-concept experiments (Fig. 1a). Fortunately, there are several alternative degenerate cavity designs that are better suited for such tasks\(^{31} \), and we present two of them in Supplementary Fig. 5. In the first design (Supplementary Fig. 5b), a curved rear mirror replaces the focusing lens, and the light is focused directly on the target through a scattering sample placed next to this curved mirror (the gain can be embedded in the reflecting target; Supplementary Fig. 5b). Another possible degenerate cavity design that may prove useful when the goal is to focus light through a scattering sample is the degenerate ring cavity presented in Supplementary Fig. 5c. This design allows the scattering sample to be placed at any position inside the cavity, and not just close to one of the cavity mirrors, where it is self-imaged after a round trip in the linear cavity design of our experiments. Other modifications that may extend the range of scattering samples through which focusing can be achieved include the use of higher-gain designs or different gain media that could tolerate larger losses and may increase \( N_{\text{DOP}} \) through non-linear gain-induced spatial phase modulation\(^{44} \).

Finally, it would be interesting to study and exploit the complex temporal dynamics of this system. For example, by combining a saturable absorber at the target it may be possible to achieve temporal focusing (similar to mode-locking), in addition to the demonstrated spatial focusing. One may expect increased complexity to achieve spatiotemporal focusing with this approach because, unlike with spatiotemporal focusing using SLMs or acoustic transducers\(^{8–10} \), \( N_{\text{DOP}} \) may not simply be the product of the spectral and spatial DOFs\(^{45} \). This is due to the fact that, to form an identical short pulse in consecutive cavity round trips, the different phase-locked spectral components would have to be equally spaced (as in conventional mode-locking). This may pose a limitation on the number of available DOFs.

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Author contributions

All authors contributed to designing the experiments and writing the manuscript. M.N., O.K. and E.S. performed the experiments. M.N. and O.K. analysed the results and performed numerical simulations.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to N.D.

Competing financial interests

The authors declare no competing financial interests.