Coherent enhancement of optical remission in diffusive media

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Remitted waves are used for sensing and imaging in diverse diffusive media from the Earth’s crust to the human brain. Separating the source and detector increases the penetration depth of light, but the signal strength decreases rapidly, leading to a poor signal-to-noise ratio. Here, we show, experimentally and numerically, that wavefront shaping a laser beam incident on a diffusive sample enables an enhancement of remission by an order of magnitude at depths of up to 10 transport mean free paths. We develop a theoretical model which predicts the maximal remission enhancement. Our analysis reveals a significant improvement in the sensitivity of remitted waves to local changes of absorption deep inside diffusive media. This work illustrates the potential of coherent wavefront control for noninvasive diffuse wave imaging applications, such as diffuse optical tomography and functional near-infrared spectroscopy.

Significance

Waves propagate diffusively through disordered media—such as biological tissue, clouds, or Earth’s crust—due to random scattering. Although most waves are reflected, only a tiny fraction carry information from deep inside the medium. These remitted waves are widely used to noninvasively probe disordered systems: from seismic interferometry to diffuse optical tomography and functional near-infrared spectroscopy. The meager signal-to-noise ratio of remitted waves eventually limits the depth that can be probed. By tailoring the spatial wavefront of a laser beam, the remitted signal can be enhanced by an order of magnitude, while increasing its sensitivity to local changes inside an optical diffusive medium. This work illustrates the potential of coherent wavefront control for noninvasive diffuse wave imaging applications.

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The authors declare no competing interest.

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**Experimental Setup**

In order to monitor wave transport inside the diffusive medium, we fabricate two-dimensional (2D) disordered structures on a silicon chip and observe the internal light distribution from the third dimension (Fig. 1A) (39). The remission matrix $\mathbf{R}$ is introduced to relate input fields within a finite region of the interface to remitted waves from another region displaced from the injection site, on the same interface. We measure $\mathbf{R}$ for different separations from $3\ell$ to $25\ell$, find the maximum remission eigenstates, and investigate their spatial structures.

The 2D diffusive system has a slab geometry (width $W = 400 \mu m$, thickness $L = 200 \mu m$) and open boundaries on all four sides (Fig. 1B). Inside the slab, air holes of 100-nm diameter are randomly distributed, with a filling fraction of 2.75%. The transport mean free path is $\ell = 6.4 \mu m$ at (vacuum) wavelength $\lambda_0 = 1.55 \mu m$ (40). With slab dimensions $L$ and $W$ much larger than $\ell$ but still smaller than the 2D localization length, light transport is diffusive. Out-of-plane scattering is treated as loss, corresponding to a diffusive dissipation length of $\xi_a = 56 \mu m$ (SI Appendix, section 1A).

A spatial light modulator (SLM) shapes the phase front of the monochromatic laser beam, which is then coupled into a multimode waveguide etched on a silicon-on-insulator wafer. The waveguide delivers light of $\lambda_0 \approx 1.55 \mu m$ to a 2D slab on the same chip via 56 guided modes. The field distribution across the entire slab is measured in an interferometric setup. We scan the input wavelength to obtain different configurations.

First, we generate random illumination patterns using the SLM, and map diffusive light transport inside the slab. Fig. 2A shows the ensemble-averaged intensity distribution $\langle I_{\text{rand}}(y, z) \rangle$. The injection site centered at (0, 0) has a width $W_1 = 15 \mu m$. Away from the injection site, the intensity of the remitted light drops quickly. Along the front boundary $z = 0$ of the slab, the diffusive intensity decreases quadratically with distance $|y| = d \gg W_1$.

The probability of photon migration from the injection site $(0, 0)$ to the remission site $(d, 0)$ via the position $(y, z)$ inside the slab equals the product of the probability of migrating from $(0, 0)$ to $(y, z)$ and that from $(y, z)$ to $(d, 0)$. The former is proportional to $\langle I_{\text{rand}}(y, z) \rangle$, and the latter is proportional to the average intensity distribution $\langle I_{\text{rand}}(d, y, z) \rangle$ for light injected at $(d, 0)$, according to optical reciprocity (13). With random incident wavefronts, the maximum probability of photon migration is found within a banana-shaped region connecting (0, 0) and $(d, 0)$. While increasing injection–remission separation enhances the penetration of the light, it comes at the price of a rapidly reduced signal strength.

**Remission Matrix and Eigenchannels**

Our aim is to utilize the spatial degrees of freedom in the coherent illumination pattern to improve the remitted signal strength. To find the optimal input wavefront, we measure the remission matrix $\mathbf{R}$, and find its associated eigenstates. In a standard DOT setup, light is delivered onto a diffusive sample by a waveguide, and the remitted signal is collected by another waveguide. The incident field $\mathbf{E}_{\text{in}}$ and remitted field $\mathbf{E}_{\text{re}}$ are decomposed into $M_1$ and $M_2$ flux-carrying modes of the waveguides. In a linear scattering medium, they are related by the remission matrix $\mathbf{R}$ as

$$\mathbf{E}_{\text{re}} = \mathbf{R} \mathbf{E}_{\text{in}}.$$
\[ \mathbf{E}_{\text{re}} = \mathbf{R} \mathbf{E}_{\text{in}}. \]  

Singular value decomposition of \( \mathbf{R} \) gives the remission eigenchannels. The one corresponding to the largest singular value has the highest possible remittance.

While the waveguide mode basis is used in Eq. 1, any orthogonal basis is sufficient. In our experiment, instead of using a waveguide to collect the remitted light, we directly measure the field at the front boundary of the slab at a distance \( d \) from the injection waveguide. More specifically, we sample the fields at \( 20 \times 20 \) spatial positions within a \( 10 \mu m \times 10 \mu m \) square (SI Appendix, section 1D). By displaying orthogonal phase patterns on the SLM, we construct the remission matrix \( \mathbf{R}_{\text{SLM} \rightarrow d} \). Singular value decomposition of \( \mathbf{R}_{\text{SLM} \rightarrow d} \) provides the remission eigenchannels and associated input vectors. Since our SLM can only modulate phase, not amplitude, it will not excite a pure eigenchannel. Alternatively, we can use the experimentally measured matrix \( \mathbf{R}_{\text{SLM} \rightarrow \text{SLAB}} \) that connects the incoming fields to the field everywhere inside the slab. The field distribution across the entire slab is obtained by multiplying \( \mathbf{R}_{\text{SLM} \rightarrow \text{SLAB}} \) by the input vector of a remission eigenchannel.

Fig. 2B shows an example high-remission eigenchannel profile \( \langle I_d(y, z) \rangle \). The remission region (white square) is located at \( d = 17.2\ell \) from the input waveguide. \( \langle I_d(y, z) \rangle \) shows that the diffuse light is steered toward the detector through the banana-shaped region, which is obtained by tracing the maximum photon migration probability under random illumination (SI Appendix, section 1C). The steering is further illustrated by the difference \( \langle I_d(y, z) \rangle - \langle I_{-d}(y, z) \rangle \) in Fig. 2C. The positive (red) or negative (blue) intensity pattern reveals light is directed toward the remission site at \( (d, 0) \) or \( (-d, 0) \). In both cases, the optical energy in high-remission eigenchannels is redistributed along the banana-shaped region connecting the injection and detection sites.

We vary the injection–detection distance \( d \) and plot the difference between high-remission eigenchannel profiles \( \langle I_d(y, z) \rangle \) and random input patterns \( \langle I_{\text{rand}}(y, z) \rangle \) for \( d = 12.5\ell, 18.8\ell, \) and \( 25.0\ell \) in Fig. 3. The positive (red) and negative (blue) intensity-difference areas demonstrate that high-remission eigenchannels redistribute the optical energy inside the system compared to random inputs, increasing the remitted signal. Furthermore, the positive (red) intensity difference regions in Fig. 3 are concentrated in the banana-shaped region (green line). Therefore, it is possible to directly photon migration deep inside diffusive systems by coupling into high-remission eigenchannels. The penetration depth of the remitted signal, however, does not change as a result of the remission enhancement.

In our experiment, wavefront shaping could modify the angular distribution of out-of-plane scattered light so that a larger fraction of the light would be collected by our optics with a finite numerical aperture (41). This would artificially increase the measured remission intensity. We thus resort to numerical simulations of the experimental system to quantify the remission enhancement as a function of \( d \). For this purpose, we simulate wave propagation in 2D disordered slabs using the Kwant package (41, 42), and compute the remission matrix \( \mathbf{R} \) with \( M_1 = 56 \) input channels and \( M_2 = 37 \) output channels. The eigenvalues \( \rho \) of \( \mathbf{R}^{\dagger} \mathbf{R} \) give the fraction of power remitted to the output waveguide of width \( W_2 = 10 \mu m \) when sending the associated input vectors into the slab. In Fig. 4A, we present the probability density function (PDF) of nonzero eigenvalues, \( P(\rho) \), for a broad range of source–detector distance \( d \) (larger than the transport mean free path \( \ell = 6.4 \mu m \)). The PDF decays monotonically, indicating that most eigenstates deliver little power at the remission port. However, we note that the PDF presents an upper edge \( \rho_{\text{max}} \) much larger than \( \rho_{\text{rand}} \) (the fraction of power delivered by random input illumination). For example, 10% of the total injected power can be remitted at a distance \( d \approx 8\ell \), compared to 1% for random illumination. As the distance \( d \) increases, all eigenvalues decrease, since less power is collected, and the PDF narrows. To quantify the benefit of using the eigenstate associated with the largest remission eigenvalue instead of random illumination, we represent, in Fig. 4B, the ratio \( \rho_{\text{max}} / \rho_{\text{rand}} \) as a function of the distance \( d \). Enhancement typically larger than 10 is achieved (blue color). Remarkably, the enhancement \( \rho_{\text{max}} / \rho_{\text{rand}} \) increases with \( d \), which illustrates the power of coherent wavefront control for \( d \gg \ell \). When including out-of-plane scattering loss in our simulations (purple squares), the enhancement \( \rho_{\text{max}} / \rho_{\text{rand}} \) increases slightly because dissipation has more impact on the random input propagation than on a high-remission eigenchannel (43); see SI Appendix, section 2D for the full distributions \( P(\rho) \) in the presence of loss. Moreover, increasing the scattering strength of the disordered medium through a reduction of \( \ell \) (red circles) leads to further enhancement of remission \( \rho_{\text{max}} / \rho_{\text{rand}} \), which can be as large as 20 at \( d \approx 47\ell = 150 \mu m \).

To elucidate the dependence of \( P(\rho) \) and \( \rho_{\text{max}} / \rho_{\text{rand}} \) on relevant parameters \( d, \ell, M_1, \) and \( M_2, \) we develop a theoretical model based on a combination of random matrix theory and microscopic computations of intensity fluctuations in remission. Our approach relies on the concept that any structure consisting of effective diffusive systems with comparable conductance in a series is characterized by a universal bimodal eigenvalue distribution, irrespective of the microscopic origin of scattering and the geometry of the scattering system (44). This distribution, initially put forward for transmission through diffusive wires (45), can, in principle, be used for the remission configuration, as long as input and output spatial channels do not belong to the same waveguide. However, in our setup, light propagates in an open geometry, with input/output covering only a small fraction of the total surface area. Therefore, we must also take into account the incomplete channel control of the injection and detection. We model the remission matrix \( \mathbf{R} \) as a filtered matrix of dimension \( M_2 \times M_1 \), drawn from a virtual \( M_0 \times M_0 \) matrix characterized by a bimodal distribution of eigenvalues with mean \( \bar{\rho}_0 \), and use the predictions of the filtered random matrix (FRM)
ensemble (46). The only free parameters of this model are thus $M_0$ and $\rho_0$, which can be determined from microscopic calculations of the first two moments of the distribution $P(\rho)$. Details of the full model are given in SI Appendix, section 2. Solid lines in Fig. 4 show our theoretical predictions for $P(\rho)$ and its upper edge $\rho_{\text{max}}$, which are in excellent agreement with the numerical results.

Next, we consider limiting cases. If the number of output spatial channels $M_2$ is equal to one, the remission enhancement $\rho_{\text{max}}/\rho_{\text{rand}}$ equals the number of input channels $M_1$, regardless of the injection–remission distance $d$ and the transport mean free path $\ell$. As $M_2$ increases, the maximal remitted signal $\rho_{\text{max}}$ grows, but the enhancement $\rho_{\text{max}}/\rho_{\text{rand}}$ drops. A key quantity controlling the scaling of $\rho_{\text{max}}/\rho_{\text{rand}}$ with microscopic parameters is the non-Gaussian component of intensity fluctuations measured at the remission port and generated by random illumination from the injection port. These fluctuations are commonly termed $C_2$ (47); see SI Appendix, section 2B for their explicit calculation. When $C_2$ is small, $M_2 < 1/C_2$, the remission matrix $R$ can be approximated by a Gaussian random matrix, and the enhancement factor $\rho_{\text{max}}/\rho_{\text{rand}}$ scales as $\sim M_1/M_2$ (46, 48, 49). However, if $C_2$ is larger, $M_2 > 1/C_2$, non-Gaussian intensity correlations can further enhance the remission. In a 2D diffuse system, $C_2$ leads to an increase of $\rho_{\text{max}}/\rho_{\text{rand}}$ with both scattering strength $1/k\ell$ and injection–remission distance $d$. Indeed, in the situation $d \gg \ell$, we find that the remission enhancement depends on a single parameter: the normalized variance $\overline{\varphi(\rho)/\rho)}$ of the PDF $P(\rho)$, related to $C_2$ as $\overline{\varphi(\rho)/\rho)} = M_2 C_2 + M_2/M_1$, where $C_2 \approx \ln(d/W_1)/k\ell$ (SI Appendix, section 2B). In the limit $M_2 \gg 1/C_2$, the remission enhancement takes the form (SI Appendix, section 2C):

$$\frac{\rho_{\text{max}}}{\rho_{\text{rand}}} \approx \frac{3}{2} M_1 C_2 \times \frac{\ln(d/W_1)}{k\ell}.$$  

Unlike remission under random illumination $\rho_{\text{rand}} \approx M_2 k\ell/(kd)^2$, the high-remission eigenchannel generates a flux $\rho_{\text{max}} \approx M_1 M_2 \ln(d/W_1)/(kd)^2$ that is independent of the scattering strength $k\ell$. Ignoring the weak dependence of $\ln(d/W_1)$ on $M_1$, the enhancement factor scales linearly with the number of input channels $M_1$. Furthermore, the dependence of $C_2$ on $d$ and $k\ell$ explains the general trends beyond the above limits in Fig. 4B. We refer to SI Appendix, section 4C for a study of the continuous evolution of $\rho_{\text{max}}/\rho_{\text{rand}}$ with $M_2$.

**Sensitivity Analysis**

Given that high-remission eigenchannels improve the SNR, a natural question is whether they provide higher sensitivity to local perturbations of the dielectric constant inside a diffusive medium. The answer is important to DOT and fNIRS, which often monitor the change in remitted signal due to localized absorptive targets. The answer to this question is not straightforward, because sensitivity depends not only on the value of remission but also on the position inside the medium, as shown below. Furthermore, prior analysis of the problem, based on the diffusion equation (13), is not applicable, as the enhanced remission here is achieved through wave interference, which is not captured by diffusion theory.

Let $R$ be the total power collected at the remission port divided by the incident power for an arbitrary incident field profile $E_{\text{in}}$. With $E_{\text{in}}$ fixed, weak absorption is introduced as the imaginary part of the relative permittivity $d\varepsilon$ over a subwavelength area $A_\varepsilon$ centered at location $r_0$. This changes the collected remission by $dR$. The sensitivity is defined as $S = -dR/d\varepsilon$. Under the scalar wave equation approximation in 2D, we show, in SI Appendix, section 3, that

$$S(r_0; E_{\text{in}}) \equiv -dR\left|_{E_{\text{in}}} \right|_{E_{\text{in}}} = k_0^2 A_\varepsilon \frac{\Re \left[ E_t(r_0) E_{\text{in}}(r_0) \right]}{\int dy \operatorname{Im} \left[ E_{\text{in}}^* \partial E_{\text{in}}/\partial z \right]_{z=0}},$$  

where $k_0 = \omega/c$ is the vacuum wave number, $E_t$ is the total field given $E_{\text{in}}$ as the incident field, and $E_{\text{in}}$ is the total field with $E_{\text{in}}^*$ in the remission port as the incident field. Eq. 3 generalizes the adjoint method, commonly used in inverse designs (50), to multichannel systems. We evaluate the sensitivity $S(r_0; E_{\text{in}})$ for different input wavefront $E_{\text{in}}$ in our numerical simulation.

Fig. 5 A and B shows the ensemble-averaged sensitivity map $S(r_0; E_{\text{in}})$ computed using Eq. 3 for random input wavefronts and for high-remission eigenchannels, respectively, in a lossless system. The sensitivity map of high-remission eigenchannels has the same spatial profile as that of random inputs, with the sensitivity maximized along the banana-shaped region.

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Fig. 4. Theoretical model and numerical simulation of maximal remission enhancement. (A) Probability density $P(\rho)$ of remission eigenvalue $\rho$ for varying source–detector distance $d$ normalized by the transport mean free path $\ell = 6.4 \mu m$ in a 2D lossless diffusive slab. Analytical predictions (solid lines) agree with simulation results (dots) averaged over 2,275 disorder configurations. (B) Maximal remission enhancement $\rho_{\text{max}}/\rho_{\text{rand}}$ for three diffusive systems with different scattering strength and loss (see legend). $\rho_{\text{max}}/\rho_{\text{rand}}$ increases with $d$. Shorter $\ell$ leads to stronger remission enhancement. With loss ($\xi_a = 56 \mu m$), $\rho_{\text{max}}/\rho_{\text{rand}}$ is slightly larger than that without loss ($\xi_a = \infty$). The input waveguide has a width $W_1 = 15 \mu m$ and supports $M_1 = 56$ modes, and the output waveguide has a width $W_2 = 10 \mu m$ and supports $M_2 = 37$ modes.
of the conjugate field, remission, we separate the incident and the scattered contributions to the enhanced remission. (SI Appendix, section 2C). However, the $1/\ell$ dependence due to $C_2$ is preserved. In DOT and fNIRS, the commonly used 3D biological samples have negligible $C_2 \approx 1/\sqrt{M_1 \kappa \ell} < 1/M_2$, and the maximal remission enhancement is approximately $\rho_{\text{max}}/\rho_{\text{rand}} \simeq \left( 1 + \sqrt{M_1/M_2} \right)^2$, according to the Marcenko–Pastur law (49).

Finally, we comment that the remission matrix stands in between the transmission and reflection matrices. They are all parts of the scattering matrix. With increasing injection–detection separation, segments of the scattering matrix form a remission matrix that produces high-flux eigenchannels with deep penetration as high-transmission eigenchannels, and simultaneously large return signals (to the same side of a medium as the source) like high-reflection eigenchannels. The greatly improved sensitivity of remitted signals to local perturbations deep inside diffusive media is promising for DOT and fNIRS. An experimental implementation for biomedical imaging would involve two multimode optical fibers: one for injecting laser light into a scattering tissue, the other for collecting the remitted light. The technical challenge is that a live multicellular organism is not temporally static, which demands rapid measurement and constantly updating the remission matrix. A potential solution, beyond significant hardware improvements, is developing sophisticated algorithms or optimization techniques for obtaining an approximate high-remission eigenchannel from a small number of measurements. While the wavefront shaping is done with a continuous wave in the current experiment, short optical pulses may be explored in future studies, and adding temporal resolution can provide further control over remitted waves. As such, remission eigenstates are a nascent topic with great potential in practical applications ranging from seismology to noninvasive photomedical devices and brain–computer interfaces.

**Data, Materials, and Software Availability.** The theoretical and numerical findings can be reproduced using the information presented in the paper or SI Appendix. The original measured data used in the experiments has been uploaded to Zenodo (https://doi.org/10.5281/zenodo.7101602) (53), and the ensuing results can be obtained by following what is presented in the paper.

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**Discussion and Conclusion**

We have shown that coherent wavefront shaping greatly enhances the remitted signal and its sensitivity to local change of absorption deep inside a diffusive medium. Our method differs from the existing method of structured illumination in optical tomography, which utilizes incoherent light and modulates only its intensity (8). While the latter improves the speed and accuracy of image reconstruction, it does not increase the remitted signal (51, 52). In our case, coherent light must be used for illumination, and both its amplitude and phase can be modulated. The phase modulation is essential to the enhancement of the remitted signal via constructive interference of multiply scattered light.

While this study is conducted on 2D diffusive systems, the method and theoretical model are applicable to 3D. The remission enhancement increases with $M_1$ but decreases with $M_2$. The 3D is different from 2D in that the maximal remission enhancement does not vary with $d$, because $C_2$ becomes independent of $d$ (SI Appendix, section 2C). However, the $1/\ell$ dependence due to $C_2$ is preserved. In DOT and fNIRS, the commonly used 3D biological samples have negligible $C_2 \approx 1/\sqrt{M_1 \kappa \ell} < 1/M_2$, and the maximal remission enhancement is approximately $\rho_{\text{max}}/\rho_{\text{rand}} \simeq \left( 1 + \sqrt{M_1/M_2} \right)^2$, according to the Marcenko–Pastur law (49).

**Fig. 5.** Sensitivity enhancement by maximal remission eigenchannel. Numerically calculated sensitivity of remission, that is, change in the remitted signal due to local absorption inside a 2D lossless diffusive system, for (A) random input wavefronts and (B) maximal remission eigenchannel. The parameters are $W_1 = 15 \mu m$, $W_2 = 10 \mu m$, $M_1 = 56$, $M_2 = 37$, $kA_1/2 = 0.65$, $\ell = 6.4 \mu m$, and $\xi_0 = \infty$. Average over 1,000 disorder realizations is performed. White dots denote the depth where the maximum sensitivity is reached for a given value of $y$, fitted by part of a circle—dashed line. The sensitivity map is identical in A and B, confirming the penetration depth is not compromised by the enhanced remission. (C) Maximum sensitivity vs. $y$ from A and B, showing an order of magnitude enhancement by the maximal remission eigenchannel. (D) Sensitivity enhancement at $y = d/2$ (circles) compared to remission enhancement (crosses) as a function of injection–remission separation $d$.

The high-remission eigenchannels improve the sensitivity up to 11 times in the banana-shaped region, as shown in Fig. 5C. We further find that the sensitivity enhancement increases with $d$, similar to the remission enhancement. Notably, the sensitivity enhancement is even larger than the remission enhancement (Fig. 5D). To illustrate that the sensitivity depends not just on the remission, we separate the incident and the scattered contributions of the conjugate field, $E_r = E_r^{\text{in}} + E_r^{\text{sc}}$, where $E_r^{\text{in}} = E_r^+ \ast$ at the remission port. The numerator of Eq. 3 has two terms: $\text{Re} \{ E_r^{\text{in}} \} \ast \text{Re} \{ E_r^{\text{sc}} \}$. A high-remission eigenchannel naturally enhances the first term, which is proportional to the remission $R \propto |E_r|^{2}$ for $r_0$ near the remission port, but it may also increase the second term to further enhance the sensitivity. Similar results are observed in systems with loss (SI Appendix, Fig. S7).

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