

Optimal control of light propagation through multiple-scattering media in the presence of noise

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Abstract: We study the control of coherent light propagation through multiple-scattering media in the presence of measurement noise. In our experiments, we use a two-step optimization procedure to find the optimal incident wavefront that generates a bright focal spot behind the medium. We conclude that the control of coherent light propagation through a multiple-scattering medium is only determined by the number of photoelectrons detected per optimized segment. The prediction of our model agrees well with the experimental results. Our results offer opportunities for imaging applications through scattering media such as biological tissue in the shot noise limit.

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1. Introduction

Spatial inhomogeneities in the refractive index of a material such as paper, white paint or biological tissue cause multiple scattering of light. Light propagates diffusively through such materials, which makes the control of light propagation through these kind of materials impossible with conventional optics. A multiple-scattering medium has for a long time been considered as a barrier to optical propagation. It has been theoretically predicted that a multiple-scattering medium can act as a high-precision optical device such as a thin lens, mirror, polarizer or Fourier analyser [1]. The first optical lens made of multiple-scattering medium was demonstrated by manipulating the incident light field, which starts a new research topic in optics called wavefront shaping [2].

Many applications of wavefront shaping have recently been demonstrated in advanced optics, biophotonics, nanotechnology, and biomedical imaging [3]. Optical pulse compressors have been realized using wavefront shaping [4–6]. It has been shown that a multiple-scattering medium can be used as a high numerical aperture lens [7] that enables sub-100 nm optical resolution [8]. Recently, wave plates and spectral filters made of multiple-scattering media have been realized [9–12]. Fluorescence imaging inside biological tissue has been demonstrated by scanning the optical focus guided by acoustic focus [13, 14]. In addition, a non-invasive imaging technique was reported, in which a fluorescent biological object hidden behind a scattering medium was imaged [15].

Transforming a multiple-scattering medium into a high-precision optical device requires a high degree of control of light propagation through the medium. Control over the propagation of light through a multiple-scattering medium is quantified by a figure of merit that is given by the intensity enhancement. The enhancement is equal to $\eta = I_{\text{opt}}/\langle I_A \rangle$ where I_{opt} is the intensity in the target after optimization and $\langle I_A \rangle$ is the ensemble averaged intensity in the target before the optimization [16].

Many wavefront shaping methods have been reported to focus light through multiple-scattering media [16–25]. All of these wavefront shaping methods are essentially based on the measurement of a part of the transmission matrix, which is the complex field response of the medium in the transmission to a set of input field bases. Using the information in the transmission matrix, one can synthesize the optimum field to focus light through the medium. It has been shown that the enhancement depends linearly on the number of degrees of freedom that are controlled until it reaches a saturation where practical limitations become prominent [2]. Therefore, we compare the maximal enhancements reported from various wavefront shaping and transmission matrix experiments. In early wavefront shaping experiments it was shown that one row of the transmission matrix gives the information to focus light through to a particular position behind the multiple-scattering medium resulting in an enhancement up to $\eta = 1000$ [2] using 3228 segments. An enhancement $\eta = 54$ has been reported by Popoff *et al.* using 256 segments [17]. In their experiment, the transmission matrix of a multiple-scattering medium was measured and the information of the transmission matrix was used to create a focus through the medium on any selected position [17]. Using the transmission matrix approach, the transmission of an image is demonstrated through a multiple-scattering medium [26]. Cui reported an enhancement $\eta = 270$ using a parallel optimization method with 441 segments [22]. An enhancement $\eta = 454$ has been reported by Conkey *et al.* using 1024 segments [24]. Park *et al.* reported an enhancement $\eta = 400$ using 1681 segments [9]. The optimal enhancements reported here range from 50 to 1000. It remains an open question what the cause of the wide variation of the enhancement in different experiments is. In addition, genetic algorithms have been used for wavefront shaping, and they appear to produce enhancement values in the same range [10, 23] suggesting they may be subject to similar limitations. However, non-linear algorithms such as genetic algorithms [27, 28] are not within the scope of this paper and investigation of the fundamental limitation of the enhancement factor using genetic algorithms is an interesting subject for further research.

It has been suggested that measurement noise causes phase errors in the optimization (such as noise causes phase errors in phase contrast imaging techniques [29]) which limit the enhancement [16]. To our knowledge the effect of measurement noise on the enhancement factor has not been investigated. Therefore we present in this paper an experimental and theoretical study of the influence of the noise on the enhancement factor using linear algorithms. We show a two-step sequential optimization algorithm that leads to the optimal enhancement using a linear algorithm in the presence of noise. The optimal enhancement in this case is found to be given by basic physical principles, namely quantum noise in the photodetection process.

2. The experimental setup

Our experimental setup is shown in Fig. 1. The light source is a He-Ne laser with wavelength $\lambda = 632.8$ nm, output power 5 mW, noise level of 0.2% and a long term power drift of 6%. We intentionally use a laser with a high noise and drift. A half wave plate sets the polarization and the beam is expanded to a diameter of 20 mm by a beam expander. The light is transmitted through a polarizing beam splitter and illuminates a spatial light modulator (Holoeye LC-R 2500). The spatial light modulator (SLM) consists of a twisted nematic liquid crystal cell which couples phase and polarization modulation. We used a multipixel modulation method described

in reference [30] to obtain independent phase and amplitude modulation with a single SLM. The two lenses and the pinhole after the polarizing beam splitter are a spatial filter used for the amplitude and phase modulation method. The modulated light is reflected by the polarizing beam splitter and focused on the scattering layer of the sample by a lens with a focal length of 125 mm. The sample is made by spray coating of ZnO nanoparticles on a glass cover slide with a thickness of 170 μm . The scattering ZnO layer has a mean free path of 0.65 μm and a thickness of 10 μm . The Fourier plane of the backside of the sample is imaged on a CCD camera (Allied Vision Technologies Dolphin F-145B) by a lens with a focal length of 125 mm. A polarizer before the CCD camera selects a single polarization. The CCD signal is read out in counts, where we determined that 1 count corresponds to 1.7 photoelectrons. The CCD camera has a read-out noise with a variance of 10 (count^2).

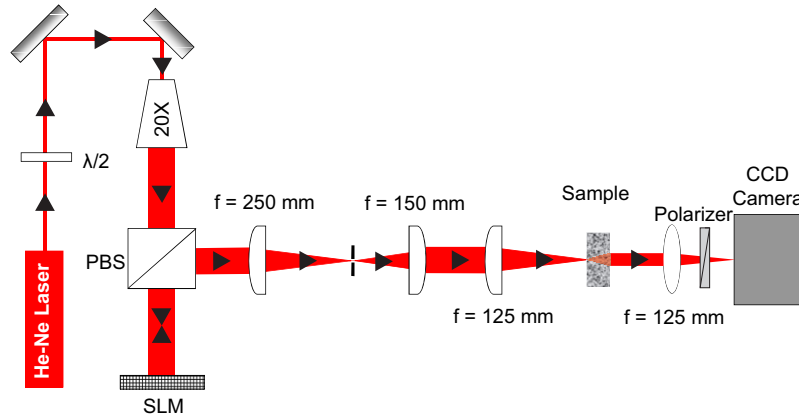


Fig. 1. The experimental setup for wavefront shaping. Laser light reflected by the SLM is focused on a white ZnO sample. The light transmitted through the sample is detected by a CCD camera. Abbreviations used, SLM: Spatial light modulator, PBS: polarizing beam splitter, $\lambda/2$: half-wave plate, CCD: charge coupled device, 20 $\times$: 20 $\times$ beam expander.

3. The enhancement factor in the presence of noise

In the wavefront shaping experiment, the SLM surface is divided into a large number of segments N . We choose $N = 850$ in all experiments described here. Each segment contains several pixels. The first selected segment is phase modulated in quadrant steps between $\Delta\theta = 0$ and $\Delta\theta = 2\pi$. We monitor the target signal I_0 by integrating the intensity in a disk shaped target area on the CCD with the same size of a single speckle spot while modulating the phase, which results in a sinusoidal signal on top of a background. A sketch of the measured signal during one phase cycle is shown in Fig. 2. We find the optimal phase for the maximal target signal for the corresponding segment, however we do not immediately display the optimal phase on the SLM. The same procedure is applied to all N segments one by one, which yields one row of the transmission matrix. In the end of the measurement of all N optimal phases, we display all N optimal phases on the SLM. We see in Fig. 2 that the target signal on the CCD camera during the phase modulation of a single segment in the presence of noise is

$$\begin{aligned} I_0 &= I_A + I_B + 2\sqrt{I_A I_B} \cos(\Delta\theta + \phi) + \sigma \\ &= B + S \cos(\Delta\theta + \phi) + \sigma, \end{aligned} \quad (1)$$

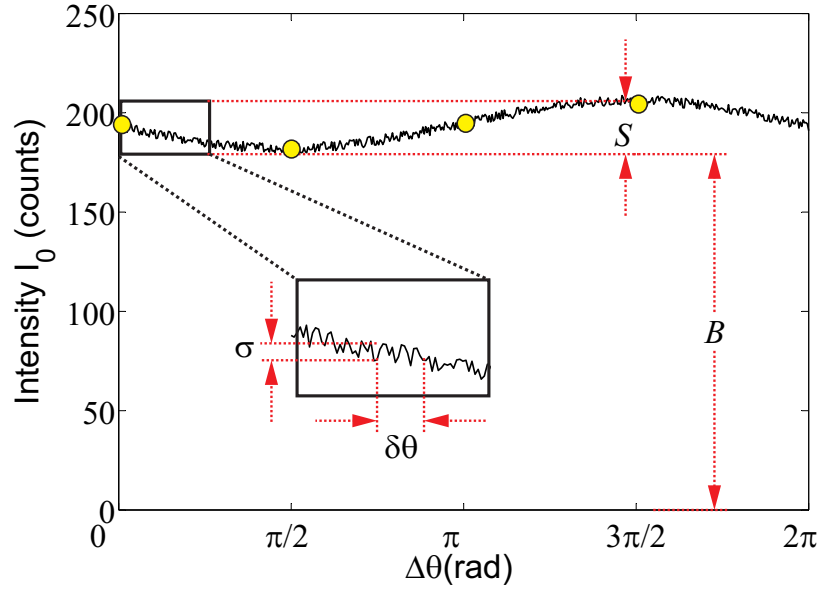


Fig. 2. Cartoon showing the effect of the noise on phase estimation. The target intensity I_0 is shown versus the phase $\Delta\theta$. The modulation signal S and the background B at the target position are shown during the phase modulation $\Delta\theta$ of a single segment. The standard deviation of the noise is represented by σ , and the standard deviation of the phase is represented by $\delta\theta$. Yellow dots represent the measurements used to construct the quadratures.

where I_A is the intensity coming from the total unmodulated SLM segments, I_B the intensity coming from the modulated single SLM segment. Here we define B as the background, S the modulation signal, $\Delta\theta$ the phase, ϕ the phase offset, and σ the standard deviation of noise. The average amplitude of the modulation signal is

$$S = 2I_A \sqrt{\frac{1}{N}}. \quad (2)$$

We use a constant area on the SLM, therefore the segment size decreases with segment number N . In Eq. (2) we see that a larger N leads to a smaller signal S .

Since we update all phase values in the end of the optimization, the signal S and the noise do not change during the optimization. For a phase determination based on quadrature phase detection (measurements 90° out of phase) we find a phase error $\delta\theta$ [31] in the measurement equal to

$$\langle \delta\theta \rangle_{\text{RMS}} = \frac{\sigma}{S}. \quad (3)$$

Here the standard deviation of noise σ and the signal S is considered for a given photon budget per optimized segment. The root mean square phase error $\langle \delta\theta \rangle_{\text{RMS}}$ is averaged over all segments and is assumed to be $\langle \delta\theta \rangle_{\text{RMS}} \ll 1$. Assuming uncorrelated phase errors, the enhancement factor η becomes

$$\eta = \frac{\pi}{4} N \langle \cos^2 \delta\theta \rangle, \quad (4)$$

which is valid for a large number of segments $N \gg 1$. For small phase errors ($\delta\theta \ll 1$) the expression simplifies to

$$\eta = \frac{\pi}{4}N(1 - \langle \delta\theta^2 \rangle). \quad (5)$$

Inserting Eq. (3) into Eq. (5) we obtain the enhancement

$$\eta = \frac{\pi}{4}N \left(1 - \frac{\sigma^2}{S^2} \right). \quad (6)$$

Eq. (6) shows that the enhancement depends both on the number of segments N and on the noise σ . Note that Eq. (6) is valid under the condition that the modulation signal S is larger than noise σ .

The modulation signal S depends on the number of segments N as $S \propto N^{-1/2}$, whereas the noise σ does not depend on N . Therefore it is useful to define a normalized signal to noise ratio R that does not depend on the number of segments N as

$$R = \frac{SN^{1/2}}{\sigma}. \quad (7)$$

We arrive at an expression for the enhancement η in which the dependence on N is explicit,

$$\eta = \frac{\pi}{4}N \left(1 - \frac{N}{R^2} \right). \quad (8)$$

It is remarkable in Eq. (8) that the enhancement is not proportional to the number of segments N . The enhancement follows a parabolic function which has a maximum equal to

$$\eta_{\max} = \frac{\pi R^2}{16}. \quad (9)$$

The maximum is obtained by selecting the optimal number of segments to be equal to $N_{\text{opt}} = R^2/2$. The only way to further increase the enhancement above this maximum is of course to improve the normalized signal to noise ratio R .

4. Pre-optimization

In order to improve the normalized signal to noise ratio R without changing the incident photon budget, we perform a two-step optimization procedure [2]. In Fig. 3, we show a schematic of this two-step optimization method. We first perform an optimization with a small number of segments N_{pre} , leading to a moderate enhancement η_{pre} (Fig. 3(b)). The phase map resulting from the pre-optimization is displayed during the whole duration of the second optimization step. As a result of pre-optimization, we obtain a higher modulation signal S on the target spot in the second step see Fig. 3(d). In addition, the pre-optimization step provides a locally constant beam profile on the target position, thereby making the measurement robust against mechanical vibrations in the second step. In the second optimization step, we use a much larger number of segments ($N = 850$) to obtain the final enhancement. We performed the same procedure with different values of N_{pre} several times to obtain different values of η_{pre} .

The target intensity detected on CCD after pre-optimization is equal to

$$I_0 = B + 2I_A \sqrt{\frac{\eta_{\text{pre}}}{N}} \cos(\Delta\theta + \phi) \quad (10)$$

where the modulation signal S becomes

$$S = 2I_A \sqrt{\frac{\eta_{\text{pre}}}{N}}. \quad (11)$$

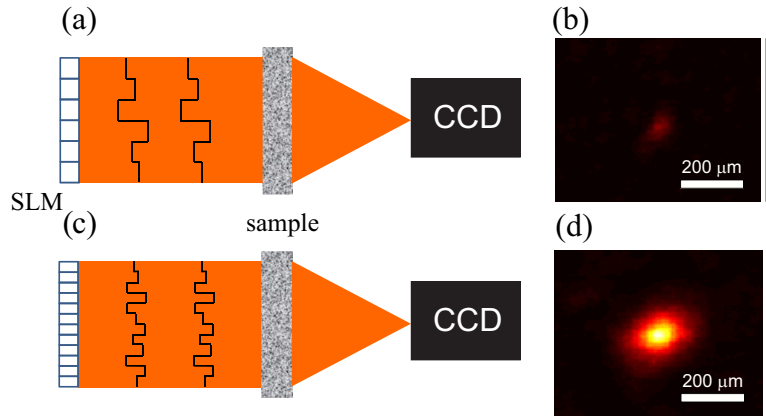


Fig. 3. Cartoon shows the phase map on the SLM after the pre-optimization (a), and after the second optimization (c). The focal spot at the target position after a pre-optimization (b), and after the second optimization (d).

As seen in Eq. (11), a pre-optimization increases S , therefore we expect to improve the normalized signal to noise ratio R .

The desired effect of the pre-optimization is to increase the modulation signal S , but it also has an effect on the noise σ . Different contributions to the noise depend on the pre-enhancement η_{pre} in a different way. In our two-step optimization, there are three different significant noise contributions which are (1) the camera read-out noise, (2) the shot noise, and (3) the laser excess noise. In Fig. 4 we show the three types of normalized noise to signal ratio versus η_{pre} for our experimental situation. The camera read-out noise is suppressed with a higher η_{pre} . The pre-optimization step improves R when the experiment is limited by the camera read-out noise. The effect of shot noise on R is independent of the pre-optimization step. A higher η_{pre} leads to a higher intensity in the target and therefore the laser excess noise, which is proportional to target intensity becomes stronger. As a result, an optimal pre-optimization step must be carefully chosen to achieve a shot noise limited signal. The best signal is found for a pre-enhancement that lies in between the low intensity regime where camera read-out noise is significant and the high intensity regime where laser excess noise reduces the enhancement.

Another approach to optimize the incident wavefront is updating each segment immediately after the measurement of optimal phase. Using this algorithm, both S and σ change during the optimization procedure. Essentially this means η_{pre} is being updated in the whole optimization procedure. This procedure has the advantage of rapidly climbing out of the low intensity region where camera read-out noise is important. However, as η_{pre} continues to increase the algorithm will leave the low noise region and enters the region where laser excess noise is significant. A two-step optimization gives us the opportunity to perform the complete second step in the optimal region of η_{pre} thereby gathering maximal information per segment measurement.

We obtain the noise parameters from independent measurements. The noise that arises from the camera read out does not depend on the number of counts on the detector and is simply equal to the variance of the dark counts of the CCD. The standard deviation of shot noise is equal to the square root of the ensemble averaged intensity on the target position measured in photoelectrons. The laser excess noise is found by measuring the laser intensity on the target position in time.

In Fig. 5 we show the measured final enhancement as well as the result of Eq. (8) versus the

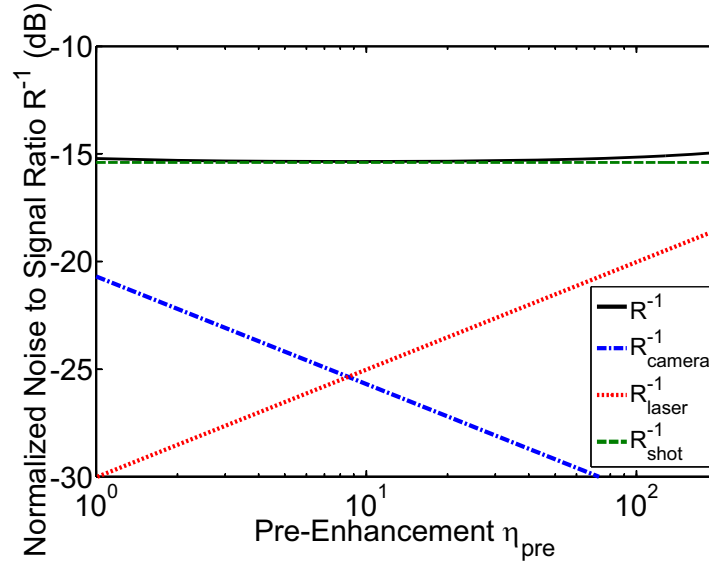


Fig. 4. Three contributions to the normalized noise to signal ratio versus the pre-enhancement factor at a fixed photon budget. The black curve shows the total noise to signal ratio. The dashed green curve represents the noise to signal ratio when there is only shot noise, the dashed blue curve the noise to signal ratio when there is only camera read-out noise, and the dashed red curve the noise to signal ratio when there is only laser excess noise.

pre-enhancement. Both the experiments and the model are based on two-step sequential algorithm. Each data point represents a single measurement. Different values of η_{pre} are obtained by varying N_{pre} between 1 and 850 in each measurement. We choose $N = 850$ in all measurements. We used a fixed integration time as 83 ms and fixed laser power for a fixed photon budget per optimized segment. At low η_{pre} , we observe that the final enhancement rises slightly with η_{pre} , until it reaches a plateau at $\eta_{pre} \approx 10$. This rise is due to suppression of the camera read-out noise as more signal impinges on the camera. In the plateau the final enhancement is limited only by the shot noise. A further rise in η_{pre} decreases the final enhancement due to increase of the laser excess noise. When the pre-enhancement is very high ($\eta_{pre} > 100$) the final enhancement is below the pre-enhancement ($\eta_{pre} > \eta$). In this case, the enhancement is limited by laser excess noise. The measured enhancements vary with an RMS variation of 60 which is caused by the long term laser power drift. The average laser power during the optimization varies by 6%. This leads to a change of the shot noise which results in a variation of the enhancement factor. It is seen in Fig. 5 that the measured enhancement agrees very well with the model predictions with no adjustable parameters.

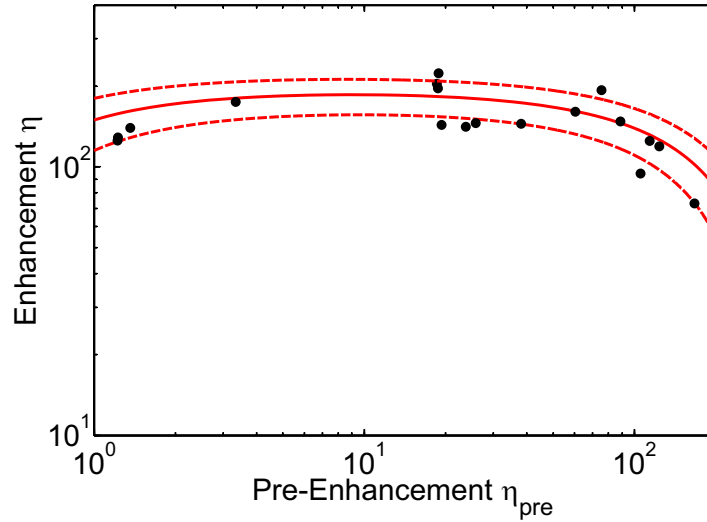


Fig. 5. The final enhancement versus the pre-enhancement. The black dots show the experimental data. The red curve shows the enhancement according to Eq. (8) without adjustable parameters. The area between dashed red lines expresses the uncertainty region of the enhancement factor due to intensity drift at the target position during optimization.

5. The maximal enhancement in the shot noise limit

The pre-optimization step with $\eta_{\text{pre}} \approx 10$ suppresses the camera read-out noise which brings the experiment into the shot noise limited regime. In the shot noise limited regime $\sigma = (\eta_{\text{pre}} \langle I_A \rangle)^{1/2}$, therefore using Eq. (7) the normalized signal to noise ratio is $R = 2(\langle I_A \rangle)^{1/2}$. Ensemble averaged target intensity $\langle I_A \rangle$ can be obtained by averaging the target intensity on the CCD over several random incident wavefronts. In Eq. (9) we obtain maximal enhancement in shot noise limit shown as

$$\eta_{\text{max}} = \frac{\pi \langle I_A \rangle}{4}. \quad (12)$$

This equation shows η_{max} is only proportional to the number of ensemble averaged photoelectrons detected per optimized segment in a given photon budget.

In case an optimization is performed with limited laser power and within a limited time, as is relevant in dynamic environments, there is a fixed photon budget for the whole optimization and increasing N will lead to a smaller number of photons per measurement. In the case of a fixed photon budget for the whole optimization we can use the same derivation and find a slightly different result, namely $\eta_{\text{max}} = (\pi/6)(I_T/3)^{1/2}$, where I_T is the total number of detected photons. Remarkably for a fixed photon budget per optimization the maximal enhancement is proportional to the square root of the photon budget.

6. Conclusion

Wavefront shaping experiments using phase only modulation and linear algorithms reported in literature show a range of enhancements between 50 and 1000. In most of those experiments the limiting factor is likely to be noise. Therefore we have investigated wavefront shaping by feedback in the presence of experimental noise. We distinguish the effect of three types of noise namely the camera read-out noise, the shot noise, and the laser excess noise. The camera read-

out noise can be reduced using a two-step optimization procedure. Two-step optimization is remarkably robust; even with a low-end camera and a very noisy laser, we show this procedure obtains shot noise limited performance. We obtain a maximal enhancement that is only proportional to the number of photoelectrons detected per optimized segment.

A wavefront shaping experiment requires the measurement of one row of the transmission matrix of the multiple-scattering medium. A focusing experiment with high enhancement factor is a signature of a precise transmission matrix measurement. Our measurements show that a wavefront shaping experiment using phase only modulation and linear algorithms is limited by basic physical principles, namely quantized detection of light. Therefore we conclude that our two-step optimization method can be used to realize shot noise limited transmission matrix measurements. In addition, our method can be used to achieve shot noise limited signal for applications such as imaging through opaque biological tissue.

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