Frequency bandwidth of light focused through turbid media

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We study the effect of frequency detuning on light focused through turbid media. By shaping the wavefront of the incident beam light is focused through an opaque scattering layer. When detuning the laser we observe a gradual decrease of the focus intensity, while the position, size,and shape of the focus remain the same within experimental accuracy. The frequency dependence of the focus intensity follows a measured speckle correlation function. We support our experimental findings with calculations based on transport theory. Our results imply wavefront shaping methods can be generalized to allow focusing of optical pulses in turbid media.

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For decades single and multiple scattering of light have been the subject of intensive research. Correlations in multiple scattered light, due to interference, have been studied intensively using the formalism developed in condensed matter physics [1]. The usefulness of these correlations for optical instrumentation was soon recognized [2]. Recently, frequency-dependent speckle correlations have even been used to study Anderson localization [3]. As an even more striking interference effect, in strongly scattering media acoustic waves and microwaves can be brought to focus with time reversal techniques [4,5]. In the optical regime, time-independent approaches such as phase conjugation [6] and wavefront shaping [7] have been successfully demonstrated allowing, e.g., concentration of scattered light into diffraction-limited foci. In wavefront shaping a spatial light modulator (SLM) is used to control a subset of the incident-free modes on a sample- and force-constructive interference at a specific output location or mode. For pulsed laser applications, as well as local spectroscopy and nonlinear microscopy, these techniques will have to be extended to broadband light. Therefore, it is highly desirable to experimentally study the frequency bandwidth over which these light concentration and focusing methods work.

We present measurements of the frequency bandwidth of the focus that is formed by optimizing the intensity in a target point using wavefront shaping. The result should be valid without modification for phase conjugation [6,8] and transmission matrix methods [9,10]. An illustration of our experiment is shown in Fig. 1. First a focus at a target point behind a scattering layer is created at a frequency ω_0 by optimizing the phase of incident modes. After finding the phase front that maximizes the intensity in a single target mode, we detune the laser frequency to measure the frequency dependence of the focus intensity. We compare our results with the measured speckle correlation function [1] and calculations based on transport theory.

We made a batch of 13 samples of strongly scattering and low-absorption white paint (Hansa Airbrush Pro-color), the thickness ranging from $40 \pm 3\,\mu$m to $155 \pm 19\,\mu$m. The paint consisted of TiO_2 particles and a co-polymer. A droplet of the paint was dried on a standard glass microscope cover slip. From total transmission measurements on each sample of the batch, using a standard integrating sphere setup, we found a transport mean free path ℓ_{tr} of $0.7 \pm 0.2\,\mu$m and an albedo larger than 0.9999. Two samples of this batch, of thickness $155 \pm 19\,\mu$m and $78 \pm 3\,\mu$m, were selected to measure the bandwidth of the focus.

Our experimental setup is shown in Fig. 2. The light source is a coherent MBR-110 CW Ti:sapphire laser with its emission frequency centered at 352 THz (852 nm). The laser can be detuned by up to 40 GHz in a single smooth sweep. To spatially modulate our wavefront, we use a reflective LCD (Holoeye LC-R 2500). We eliminate cross-modulation using a macropixel method combined with spatial filtering, of which details are given in [11]. The area of the SLM is divided into segments, which are groups of macropixels, that have an independently controlled phase. In these experiments the number of segments ($N_s = 208$) is much smaller than the number of incident free modes.

Since the SLM is larger than the sample, the shaped wavefront is demagnified by a microscope objective (NA = 0.90, 63×) and projected onto the sample. The intensity on the back of the sample is imaged onto a CCD camera by a microscope objective (NA = 0.5, 20×). A

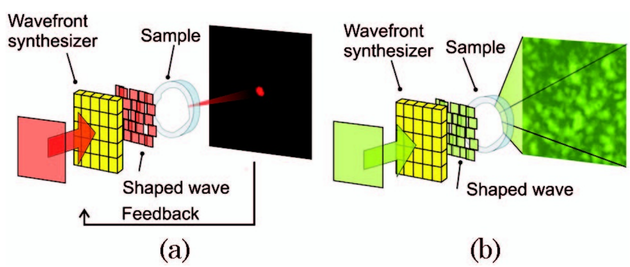

Fig. 1. Illustration of our experiment. (a) Light is focused through an opaque scattering layer using a wavefront synthesizer at a frequency ω_0. (b) The frequency is detuned until at sufficiently large detuning a regular speckle pattern remains.

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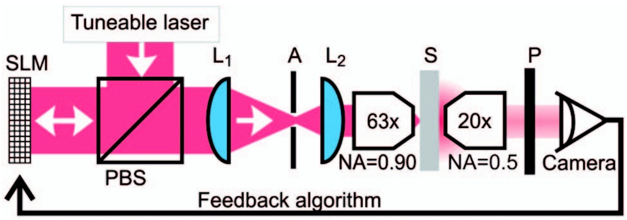

Fig. 2. Experimental setup. PBS, polarizing beam splitter; A, aperture; L_1 and L_2, lenses; 63×, microscope objective; 20×, microscope objective; S, sample; P, polarizer.

sequential optimization algorithm [12] finds the wavefront that maximizes the intensity in a single outgoing mode, defined as a diffraction-limited spot on the camera. In each step of the feedback algorithm the optimum phase of a segment is determined by scanning the phase of that segment. The phase that results in the highest output intensity in the output mode is set on the SLM. The intensity in the optimized mode is roughly 2 orders of magnitude larger than the average intensity in the other modes. The optimization does not alter the average intensity in the other outgoing modes significantly. After the optimization we detune the laser. The optimization and detuning procedure was repeated at 20 different positions on the same sample by displacing the sample $10\,\mu$m after each measurement to change the observed sample realization.

In Fig. 3 we show images of the focus at the frequency (352 THz) where the optimization has been performed (a) and at a frequency detuning of 1.1 GHz (b) and 2.3 GHz (c). The measurement is performed on a $155 \pm 19\,\mu$m thick sample. The intensity gradually decreases, and the position, size, and shape do not change considerably.

By correlating speckle patterns resulting from a nonoptimized incident wavefront, we obtain a correlation function $C(\Delta\omega)$ [13]. Speckles within the field of vision of our camera (which is smaller than the sample thickness) have the same ensemble-averaged frequency correlation function [14]; hence we may replace an ensemble average by an average over positions. The speckle correlation function C is known to have a width of approximately D/L^2, where D is the diffusion constant of light in the materials and L is the thickness of the sample.

We plot the normalized intensity of the focus and the correlation $C(\Delta\omega)$ in Fig. 4(a) and find they are very similar in shape and width. In Fig. 4(b) we plot the FWHM of the correlation function and the focus intensity versus the enhancement η to study the influence of imperfect modulation. The enhancement is defined as the focus peak intensity divided by the ensemble-averaged nonoptimized speckle intensity at the position of the focus. In

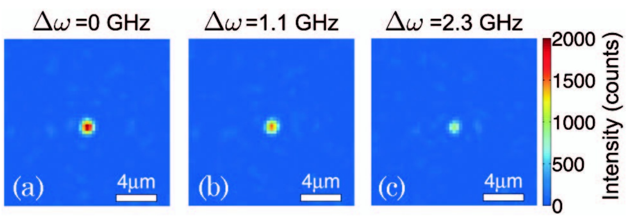

Fig. 3. (a)–(c) Focus intensity while the frequency detuning is increased from 0 to 2.3 GHz. The intensity decreases, while its position, shape, and size remain roughly the same.

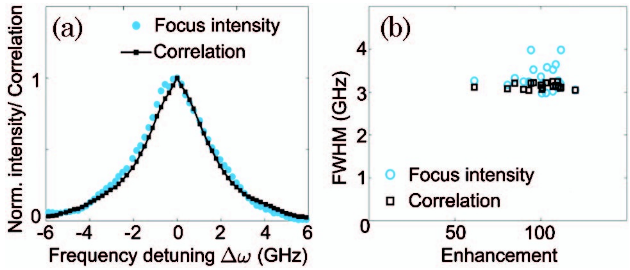

Fig. 4. (a) Normalized intensity of the focus versus the frequency detuning $\Delta\omega$. Black squares, correlation $C(\Delta\omega)$ of the background speckle. The intensity and correlation show identical behavior. (b) Frequency width of the focus and correlation versus enhancement. The symbols represent a single measurement, and the error is smaller than the symbol size.

most of our measurements the FWHM frequency of the correlation and that of the intensity are equal within experimental reproducibility. For these 20 measurements intensity enhancements between 61 and 120 were obtained. For our 208 segments the theoretically expected average enhancement is 163, with an expected spread of 13 [7]. The fact that the theoretical enhancement is not reached indicates imperfect modulation due to noise or ambient effects such as temperature drifts. Since these ambient effects vary with time, we have measurements with a varying degree of imperfect modulation.

We now compare the average over 20 measurements of the FWHM frequency of the focus intensity ($\Delta\omega_I$) and FWHM frequency of the measured speckle correlation ($\Delta\omega_C$). In Table 1 we show the measured $\Delta\omega_I$, $\Delta\omega_C$, and their standard deviation σ for two samples. The values of $\Delta\omega_I$ and $\Delta\omega_C$ coincide within σ. Hence we conclude from our measurements that the FWHM frequency of the focus intensity and of the correlation are equal within experimental error.

To interpret our observation, we calculate the frequency dependence of the intensity using transport theory. The electric field in a single outgoing mode E_b, as a function of ω, is determined by the fields E_a in incident modes $\{a\}$ and the transmission coefficients $t_{ba}(\omega)$:

$$E_b(\omega) = \sum_{\{a\}}^{N_s} t_{ba}(\omega) E_a. \tag{1}$$

To maximize the field in target mode β at frequency ω_0, we need to cancel the phase induced by the sample. Recent work has shown that if both amplitude and phase can be modulated, the ideal optimum E_a is proportional to the complex conjugate of $t^*_{\beta a}$:

$$E_a^{\mathrm{opt},\beta}(\omega_0) = T_\beta^{-1/2} t^*_{\beta a}(\omega_0), \tag{2}$$

Table 1. Average Over 20 Sample Realizations and the Standard Deviation (σ) of the FWHM Frequency of the Focus ($\Delta\omega_I$) and the Speckle Correlation Function ($\Delta\omega_C$) for Two Samples of Different Thickness

Thickness	$\Delta\omega_I \pm \sigma$	$\Delta\omega_C \pm \sigma$
$155 \pm 19\,\mu$m	3.32 ± 0.30 GHz	3.14 ± 0.07 GHz
$78 \pm 3\,\mu$m	26.1 ± 2.5 GHz	25.3 ± 0.5 GHz

where $T_\beta = \sum_{\{a\}}^{N_s} |t_{\beta a}|^2$ to normalize the total input power in mode β.

By combining Eqs. (1) and (2) we find an expression for the frequency dependence of the focus intensity $I_\beta^{\text{opt}}(\omega_0 + \Delta\omega)$. Normalizing to the intensity at $\Delta\omega = 0$ we find

$$\frac{I_\beta^{\text{opt}}(\omega_0 + \Delta\omega)}{\langle I_\beta(\omega_0)\rangle} \approx \eta C(\Delta\omega), \tag{3}$$

where $C(\Delta\omega)$ is the speckle correlation function and η is the enhancement for perfect phase and amplitude modulation. The approximation involves replacing the average over all modes of $t_{\beta a}(\omega_0 + \Delta\omega)t_{\beta a}^*(\omega_0)$ with the ensemble average of this term. Moreover, we use that for weak disorder this term is independent of the incident and outgoing modes. The intensity of the focus is thus proportional to $C(\Delta\omega)$, which is also seen in our experimental results in Fig. 4.

The obtained enhancement in experiments is always below the ideal enhancement. To model the effect of imperfect field modulation, the field is described as a superposition of the optimal field and an orthogonal error term [12]. We find that the optimized intensity is described by Eq. (3) plus a fluctuating correction term. This term is zero for $\Delta\omega = 0$ and has an average value of 1 for large frequency detuning. For $\eta \gg 1$ the correction can be neglected, showing that the frequency width of the intensity is independent of the enhancement, i.e. independent of the degree of control [12].

The fact that the frequency width of the focus is independent of the enhancement shows that the single-frequency optimization process does not alter the path length distribution. This is understood by closer examination of the fields that are aligned to the target mode β. These fields are described by $t_{a\beta}E_a$ that represents an infinite sum over all possible paths through the sample entering in mode a and leaving it in mode β. Hence the focus is always built up by infinitely many random phases with the same path length distribution. This exemplifies the difference between our wavefront shaping method in turbid media and adaptive optics which corrects aberrations in the geometrical optics limit by making all optical paths of the exact same length [15].

In conclusion, we have shown measurements of the frequency dependence of the light focused through an opaque scattering medium. We found that the frequency dependence of the intensity is similar to the $C(\Delta\omega)$ correlation function, i.e., the average frequency dependence of speckle. This behavior is independent of the obtained enhancement of the focus. Our results have implications for the focusing of broadband light in turbid media, such as biological tissue. A single-frequency optimization may be used to focus light only within a bandwidth given by the speckle correlation function.

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