

# Focusing polychromatic light through scattering media

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## ABSTRACT

We demonstrate enhanced focusing of polychromatic light through strongly scattering media. The experimental results validate a theoretical relationship among source bandwidth, sample bandwidth, and initial contrast of a far-field speckle. For various combinations of source bandwidth and sample bandwidth, we optimize far-field focal intensity enhancement using a MEMS spatial light modulator to modulate the source beam prior to its propagation through the medium. We achieve focus optimization using a sequential coordinate descent algorithm and Hadamard basis functions to control the spatial phase of the modulator. Enhancement, the ratio of optimized focal intensity to initial speckle mean intensity, is shown to vary monotonically with initial contrast.

**Keywords:** Scattering media, speckle contrast, spatial light modulator, MEMS, adaptive optics, deformable mirror

## 1. INTRODUCTION

Several years ago, Vellekoop et al demonstrated that temporally and spatially coherent light can be focused through static scattering media using a wavefront shaping technique [1]. Subsequently, it was shown that coherent light can be focused through dynamic scattering media. Achievable intensity enhancement was found to depend on the ratio of the speckle decorrelation time to the spatial light modulator control loop cycle time [2, 3]. The ability to focus the light through dynamic scattering media has potential applications in biological microscopy for deep-tissue imaging, where nonlinear optical interactions such as two-photon fluorescence can provide a suitable feedback signal for the focus optimization algorithm [4]. In such applications, the use of short-pulse laser sources motivates an extension of prior research to include the study of optimization in the presence of polychromatic light.

Light propagates in random paths inside a scattering medium, and each path can be considered as a transmission channel. Portions of incident light that are transmitted through different channels interfere with one another and produce speckles in the far field. A spatial light modulator (SLM) of  $N$  segments can be used to create  $N$  independent controlled channels and the phase of each channel can be adjusted through feedback control to produce constructive interference at a point in any focal plane [1, 3]. The number of transmission channels increase with sample thickness. Speckle contrast  $C$ , defined by ratio of standard deviation  $\sigma$  to mean  $\langle I \rangle$  of speckle intensity, remains unity for polarized monochromatic light [5] regardless of sample thickness (assuming this is large enough that the speckle is fully developed). However, when two or more uncorrelated speckle patterns overlap, the contrast is reduced by factor equal to the square root of the number of uncorrelated speckle patterns. Consequently, speckle contrast from a light source with finite bandwidth is less than unity [6]. A polychromatic light source of bandwidth  $\Delta\nu_l$  has finite temporal coherence length  $l_c$ . If the scattering sample is thick enough so that path length fluctuations are greater than the source's temporal coherence length, then the speckles produced by two frequencies separated by  $\Delta\nu_l$  are uncorrelated. When the detected intensity is composed of multiple uncorrelated speckle patterns the SLM can't adjust the phases of all modes simultaneously, so enhancement of optimized focal intensity (normalized by the mean speckle intensity measured before optimization) is lower than it would be for speckles produced by a monochromatic light source [7, 8].

In this paper, we experimentally verify a theoretical model of focus intensity enhancement as a function of speckle contrast, and we confirm a simple relation between contrast and source bandwidth. Speckle contrast and its effect on enhancement of focus was measured for four samples of different thicknesses at varying the source bandwidths.

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## 2. EXPERIMENTAL METHOD

The optical setup of our experiment is shown in Figure 1. The polychromatic light source (Superlum SLD-33-HP) is a 5mW single-mode fiber-coupled superluminescent diode (SLD). The bandwidth of SLD is 29.8nm (14.4THz) with central wavelength 790nm (379THz). Spectrum of light is measured using (Thorlabs CCS175) spectrometer. The inset in Figure 1 shows the measured spectrum of the SLD. Lens L1 ( $f = 25\text{mm}$ ) is used to collimate the light from the SLD fiber. The spectral width of light is controlled using six optical elements. A polarization beam splitter (PBS) transmits vertically polarized light which is then circularly polarized by a quarter wave plate (QWP) and directed onto a diffraction grating (1200 lines/mm) which spreads the source's spectral components spatially. Diffracted light is collimated by a lens (L2,  $f = 200\text{mm}$ ) and directed onto a variable-width slit, which selectively blocks a portion of the source spectrum. A mirror directly behind the slit redirects the remaining portion of the source spectrum back through the same optics, is spectrally recombined by the grating and then horizontally polarized by the quarter wave plate.

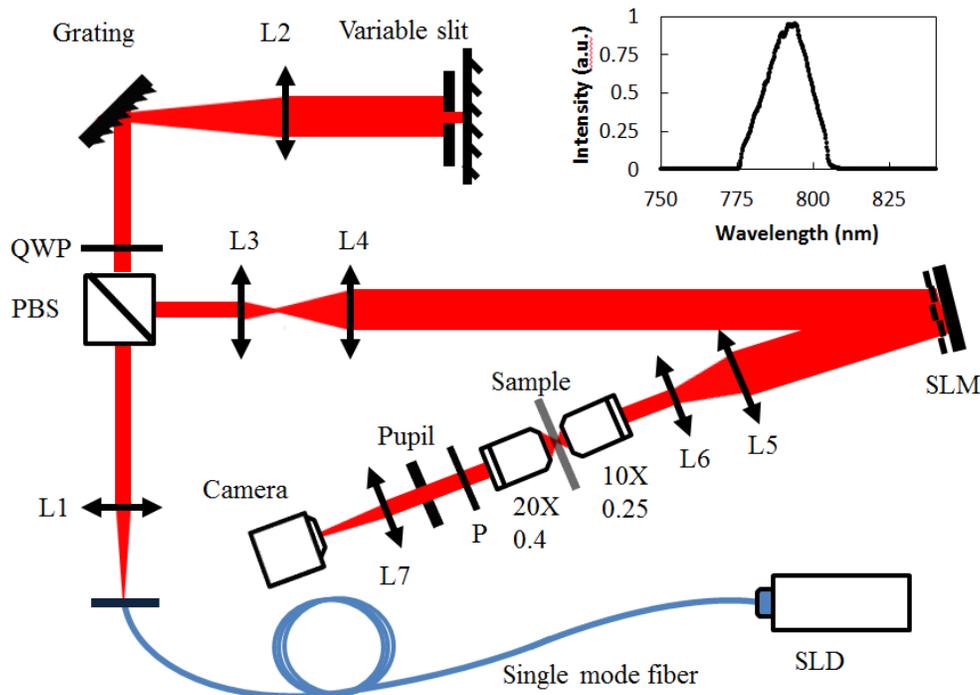


Figure 1. Schematic of the optical setup. The spectrum of a broad-bandwidth illumination source is adjusted as desired using a grating and a variable-width slit before being reflected from a phase-controllable MEMS spatial light modulator. Light reflected from the modulator is transmitted through a strongly scattering medium, and subsequently forms an image comprised of speckle that is detected using a camera. The camera is used to measure initial contrast of the speckle image as a function of the source and sample spectral bandwidths. Then the intensity of one pixel on the camera is maximized using a coordinate descent optimization algorithm to control  $\sim 1024$  Hadamard mode shapes of the modulator sequentially. The maximum optimized enhancement (i.e. the ratio of final peak intensity to mean initial speckle intensity) is compared with initial speckle image contrast, and a direct relationship is observed.

Lenses L3 ( $f = 25\text{mm}$ ) and L4 ( $f = 100\text{mm}$ ) expanded the beam that is reflected from the polarization beam splitter to fill the aperture of a high-speed microelectromechanical spatial light modulator (Boston Micromachines Kilo-SLM). The area of SLM overlapped by the beam includes  $\sim 900$  reflective segments. Each SLM segment measures  $300\mu\text{m}$  square and can be translated in the surface-normal direction over a  $1.5\mu\text{m}$  range electrostatic actuators by an underlying electrostatic actuator. Lenses L5 ( $f = 62\text{mm}$ ) and L6 ( $f = -25\text{mm}$ ) relay the beam to the aperture of a  $10\times 0.3\text{NA}$  microscope objective, which focuses the beam onto the front surface of a strongly scattering sample. A  $20\times 0.4\text{NA}$  microscope objective with tube lens L7 ( $f = 125\text{mm}$ ) relays an image of the speckle pattern at a small distance from the backside of the sample to a CMOS camera ( $\mu\text{Eye USB 2LE}$ ). A linear polarizer (P) behind the collection objective ensures that speckles are produced by a single polarization mode. Speckle size is controlled with an aperture

between the polarizer and the tube lens. Four scattering samples were used for the experiments reported here. The transport mean free path  $l^*$  for these samples were estimated using Mie theory [9], and the sample thicknesses were made to correspond to  $5.2l^*$ ,  $2.1l^*$ ,  $1.1l^*$  and  $0.8l^*$ . The first two samples were made from a suspension of  $1\mu\text{m}$  diameter polystyrene beads in silicone encapsulant (Dow Sylgard 180) and last two samples are made from a suspension of  $6.5\mu\text{m}$  diameter borosilicate beads in the same silicone encapsulant.

Source spectrum bandwidth at different slit widths can be calculated using Equation 1 [10]:

$$\Delta\nu_l = \frac{\left(\int S(\nu)d\nu\right)^2}{\int S^2(\nu)d\nu} \quad (1)$$

where  $S(\nu)$  is the measured spectrum profile and  $\Delta\nu_l$  is the calculated spectrum bandwidth. The calculated bandwidth ranges from 11.8THz at the maximum (7mm) slit width to 2.2THz at the minimum (1mm) slit width, as shown in Figure 2. Experiments were also conducted with a narrow-spectrum source, a 4.5mW laser diode (Thorlabs CSP192) with 0.7nm (0.35THz) bandwidth and 778nm (385.5THz) central wavelength. The source beam was spatially filtered using  $4\mu\text{m}$  pinhole and coupled into single mode fiber using  $5\times 0.1\text{NA}$  microscope objective.

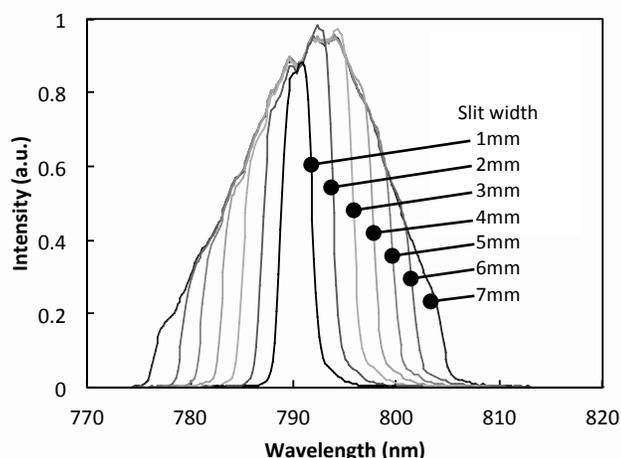


Figure 2. Measured SLD spectrum as a function of variable slit width. The spectrum bandwidth,  $\Delta\nu_l$ , calculated using Equation 1 ranges from 11.8THz for 7mm slit width to 2.2THz for 1mm slit width

Experiments consisted of an initial measurement of speckle contrast at the camera for a particular combination of source bandwidth and scattering sample, followed by execution of an optimization loop aimed at increasing the intensity of a single speckle centered on a selected pixel of the camera. The optimization algorithm sequentially maximizes focal intensity as a function of phase amplitude coefficients for each of 1024 orthogonal Hadamard modes used to control the SLM. This optimization cycle is repeated three times for each experimental initial condition. Detail of this optimization algorithm was reported previously [2].

### 3. RESULTS AND ANALYSIS

The contrast  $C$  of a speckle pattern is defined as [5]:

$$C = \frac{\sigma_I}{\langle I \rangle - I_b}, \quad (3)$$

where  $\sigma_I$  is the standard deviation of speckle intensity and  $I_b$  is the mean background level of camera when source is blocked. The contrast of a speckle image is calculated within the statistically homogeneous region of speckle. The typical size of a single speckle in these experiments spans six camera pixels, and each camera pixel spans  $\sim 6\mu\text{m}$ . Figure 3(a) shows a typical speckle pattern for a scattering sample of thickness  $0.8l^*$  using laser diode source of

wavelength 778 nm. Figures 3(b) and 3(c) show the enhanced speckle intensity after optimization, and the evolution of focal intensity enhancement during optimization.

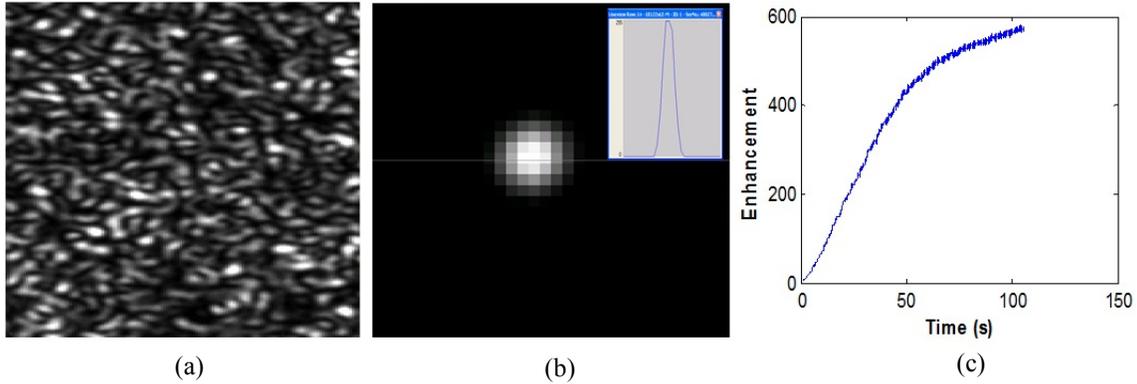


Figure 3. (a) A typical speckle pattern produced by a laser diode source after transmission through a strongly scattering medium; (b) Focused speckle image after optimization. Peak intensity is more than five hundred times brighter than the mean intensity in (a); (c) Peak intensity enhancement as a function of time during optimization.

It has been shown that if  $M$  independent speckle patterns of contrast  $C$  are overlapped, the contrast of resultant speckles will be  $C/\sqrt{M}$  [5]. The number of independent speckle patterns  $M$ , which is also called number of modes, produced by polychromatic light of bandwidth  $\Delta\nu_l$  depends on the transport mean free path  $l^*$  of the scattering sample and the sample thickness. An approximate relation of contrast  $C$  with spectrum bandwidth  $\Delta\nu_l$  and transport mean free path  $l^*$  can be derived using the definition of spectrum bandwidth defined in equation (1).

The coherence length  $l_c$  of the source is defined to be:

$$l_c = \frac{c}{\Delta\nu_l}, \quad (4)$$

where  $c$  is velocity of light. Let  $\langle n \rangle$  be average number of scattering events a photon experiences before exiting the sample in the transmission direction. The sample thickness  $L$  is then given by relation,  $L = \sqrt{\langle n \rangle} l^*$  [11]. The average distance traveled by the transmitted photons inside the sample is  $\langle n \rangle l^*$ . The *extra* distance travelled by scattered photons with respect direct transmission is  $l_s = \langle n \rangle l^* - L$ . Speckles produced by incoherent light source are uncorrelated [12, 13], so that the number modes  $M$  is:

$$\begin{aligned} M &= 1 + \frac{l_s}{l_c} = 1 + \frac{\Delta\nu_l (\langle n \rangle l^* - L)}{c}, \\ &= 1 + \frac{\Delta\nu_l}{c} \left( \frac{L^2}{l^*} - L \right) = 1 + \frac{\Delta\nu_l}{\Delta\nu_s}, \end{aligned} \quad (5)$$

where  $\Delta\nu_s = cl^*/(L^2 - Ll^*)$  is defined as a sample bandwidth. Therefore, contrast  $C$  is given by relation:

$$C = \sqrt{\frac{\Delta\nu_s}{\Delta\nu_s + \Delta\nu_l}}. \quad (6)$$

Contrast was measured for speckle produced using four different samples and eight different source spectral bandwidths. It is expected that the speckle contrast resulting from scattering of a monochromatic source will be unity. However, we measured peak contrast somewhat smaller than unity ( $\sim 0.87$ ), even for experiments conducted with the narrow-bandwidth laser diode source and the thinnest scattering sample. We attribute this discrepancy primarily to experimental limitations associated with the camera: the relatively small ratio between the speckle size and the camera sensor pixel size results in a reduction in measured contrast. We compensated this effect by normalizing measured

contrast by the value we would measure for monochromatic light. Results are plotted in Figure 4. This data fits well with the model proposed in Equation 6.

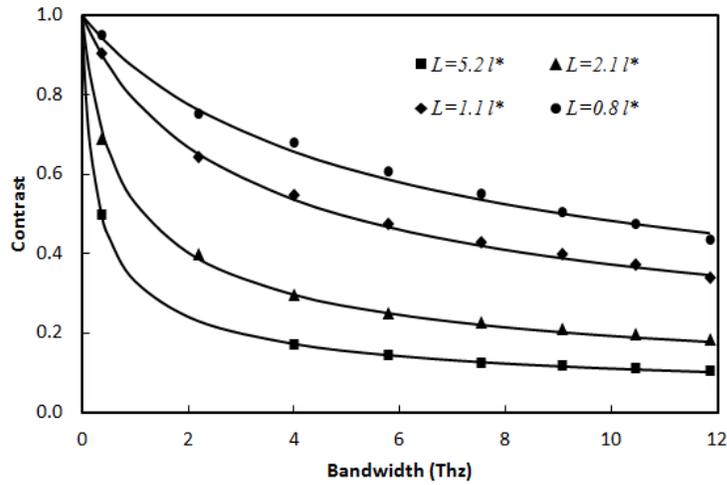


Figure 4. Contrasts  $C$  versus spectrum bandwidths  $\Delta\nu_l$  of four samples thicknesses  $5.2l^*$ ,  $2.1l^*$ ,  $1.1l^*$  and  $0.8l^*$ , where  $l^*$  is the transport mean free path. Dots represent the experimentally measured data while lines represent the model fits using equation (6).

The maximum intensity enhancement that can be obtained by wavefront shaping is related to the number controlled channels  $N$  and the number incident modes  $M$ . A SLM having  $N$  segments can produce  $N$  independent controlled channels. In the case of a monochromatic source ( $M=1$ ), then the SLM corrects the phases of  $N$  independent channels of the single mode.. The expected intensity enhancement  $E$  with a monochromatic source is given by [1]

$$E = \frac{\pi}{4}(N - 1) + 1 \quad (7)$$

Enhancements and contrasts for a variety of samples measured at varying spectrum bandwidths are plotted in Figure 5. Note that there is a nearly monotonic dependence between optimized focus enhancement and initial speckle contrast, and that maximum enhancement approaches the value predicted by Equation 7 for experimental conditions producing the highest initial contrast.

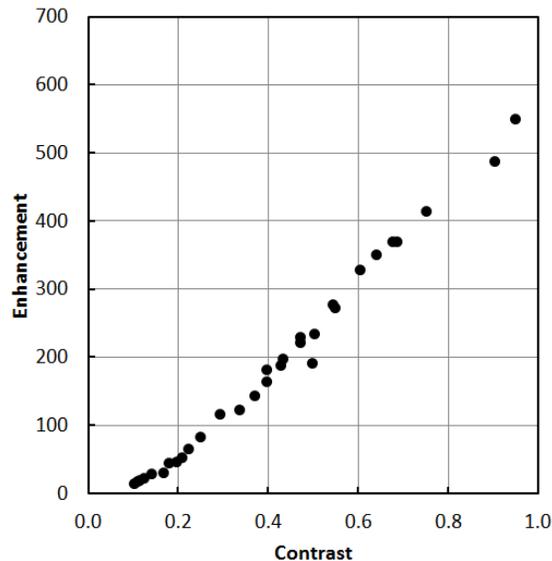


Figure 5. Measured values of optimized enhancement  $E$  versus initial speckle contrast  $C$ . Enhancement appears to be a function of initial contrast for all combinations of sample bandwidth and source bandwidth.

#### 4. CONCLUSIONS

The speckle contrast of a polychromatic light source from strongly scattering medium has been shown to have a simple relation with sample bandwidth (which is in turn related to thickness and transport mean free path of sample) and source bandwidth, as confirmed by experiments using four samples of different thickness and a polychromatic light source of  $\sim 30\text{nm}$  bandwidth. Optimization of intensity of a single speckle was achieved using coordinate descent control with 900 segments in a spatial light modulator. Enhanced focal intensity was achieved for initial speckle contrast as low as 20%. Peak enhancement achieved was found to vary monotonically with initial speckle contrast.

#### 5. ACKNOWLEDGEMENTS

The authors thank Roman Barankov and David Giese for sample preparation and for helpful discussions. This work was supported by the National Academies Keck Futures Initiative (NAKFI) grant number NAKFI-IS10 from the W.M. Keck Foundation. The authors thank Boston Micromachines Corporation (BMC) for providing the SLM used in this work. Professor Bifano acknowledges a financial interest in BMC.

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