



Ballistic imaging through an intense scattering medium using a supercontinuum with a roundabout spatial gate

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Abstract: We propose a new ballistic imaging method that is capable of imaging an object through an intense scattering medium. In this method, a femtosecond supercontinuum and a roundabout spatial gate were used to suppress speckles and filter background noise, respectively. The roundabout spatial gate extracts ballistic light and avoids low-pass spatial filtering to ensure the high resolution of images. The experimental results showed that even when the optical depth of the scattering medium reached 17, the images extracted by the method had improved identifiability and contrast.

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References and links

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1. Introduction

The imaging of objects hiding in scattering media has always been a topic of intense research for industrial, medical, and military applications. Numerous significant studies on imaging through scattering media have been recently reported [1–6]. When a light beam is introduced into a scattering medium, the transmitted light comprises two components characterized by transmission direction, i.e., ballistic and scattering photons. The ballistic component propagates through the scattering medium undeviated in the forward direction. The scattering component undergoes multiple light scatterings or a random walk in the scattering medium. The scattered diffuse light provides a background noise [7]. Because of their prominent photon degeneracy, lasers are the preferred light sources in modern imaging systems and have been indispensable. However, high photon degeneracy leads to coherent imaging artifacts, which originate from the interference that occurs during image formation. The most common manifestation of coherent artifacts is speckle caused by random interference among scattered laser photons at the detector [8]. Although speckles can be used constructively in various ways such as imaging an object through a scattering medium by speckle correlations [9–11], they are usually more of a hindrance than a benefit for transillumination imaging [12]. The "boiling" speckle patterns appear as additional features that are not present in the object and thereby corrupt the identifiability of certain interesting object features. If speckle formation could be prevented, the image clarity would be improved. Over the years, various techniques including digital image processing algorithms have been developed to suppress speckle formation [13, 14].

In the past few years, there has been considerable interest in the application of incoherent laser sources to preclude the formation of speckles. When illuminating with a low-coherence source, interference among scattered photons was prevented leading to a uniform background. Cao et al. demonstrated that random lasers with low spatial coherence can be engineered to provide speckle-free imaging under intense optical scattering conditions [15, 16]. Manna et al. suppressed the issue of speckle by introducing temporal dispersion in the probe beam of He-Ne laser to reduce the temporal coherence [17]. In the last two decades, femtosecond lasers have been reported as a promising tool for laser processing and ultrafast measurements [18–20]. In our previous work, we demonstrated speckle-suppressed full-field imaging through a scattering medium using a femtosecond supercontinuum (SC) illumination [21]. In a weaker scattering medium, the identifiability of the images obtained by this method was notably improved by speckle suppression due to the coherence degradation of the SC [22, 23]. However, when the optical depth (OD) of the scattering medium exceeds 10, the image contrast is severely degraded due to the background noise of scattered photons even though the images have a higher identifiability. A straightforward spatial gate (SSG) is often used to filter the scattered photons, which comprises an aperture at the back focal plane of a lens. However, this kind of spatial gate will decrease the imaging spatial resolution because of low-pass filtering.

In this study, we propose a new ballistic imaging method in which SC illumination and a roundabout spatial gate (RSG) were used. The speckles were suppressed by the SC illumination, leading to a uniform background. Moreover, the RSG was applied to remove background noise and extract ballistic light, which could avoid low-pass spatial filtering to ensure the high resolution of images. This ballistic imaging method is capable of imaging in an intense scattering environment.

2. Experimental details

Figure 1 shows the experimental setup scheme for ballistic imaging using SC illumination with an RSG. Femtosecond laser pulses were generated by a Ti:sapphire laser system (Libra-USP-HE, Coherent Inc., USA), which can generate 800 nm laser pulses with widths less than 50 fs and energies of about 3.5 mJ per pulse at a repetition rate of 1 kHz. As shown in Fig. 1, lens L1 (focal length, $f_1 = 100$ mm) focused the femtosecond laser pulses inside a 5-cm-thick quartz cuvette filled with distilled water to generate the SC. The pulse width of the SC was measured to be about 1.5 ps. The generated SC was collected by lens L2 ($f_2 = 150$ mm), modulated by a resolution test target (RT-MIL-TP2001, RealLight, China) and passed through a suspension of polystyrene spheres with 3.13 μm diameters. The transmission light was collected by lens L3 ($f_3 = 160$ mm), which was placed at f_3 from the object plane. The light pulse was imaged onto a charge-coupled device (CCD) camera (INFINITY3-1M-NS-TPM, Lumenera Corporation, Canada) by a second lens L4 ($f_4 = 200$ mm); the exposure time of the CCD was set at 1 ms.

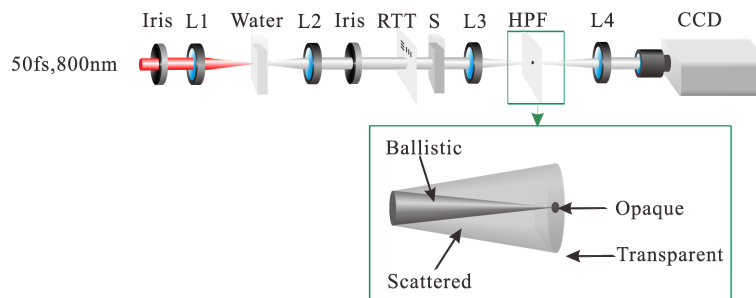


Fig. 1. Schematic diagram of the ballistic imaging using SC illumination with an RSG. L1, L2, L3, and L4: lenses; RTT: resolution test target; S: scattering medium; HPF: high-pass filter.

In the experiment, we first captured a speckle-suppressed image using SC illumination through an intense scattering medium as the raw image. Then, we obtained a background image by placing a high-pass filter with an opaque disk at the back focal plane of L3 as shown in the green rectangle of Fig. 1. Because the ballistic light passed through the scattering medium without deviation and was focused on the back focal plane of L3, the opaque disk blocked the ballistic photons. In order to effectively block ballistic photons and allow most of the scattering photons to pass through, the opaque disk of 1 mm in diameter was chosen in our experiments. On the other hand, the lower spatial frequency components of the object were located at the center portion at the back focal plane of L3 and the higher spatial frequency components spread away according to Fourier optics theory. Thus the background image would contain the high spatial frequency information of the object. We finally subtracted the background image from the raw one to extract the ballistic image. We call this process RSG for convenience.

3. Results and discussion

Figure 2 shows images obtained by different methods through the scattering medium at an OD of 11. As a reference, the image of the object behind water is shown in Fig. 2(a). In Fig. 2(b), we present the image obtained using 800 nm laser illumination behind a scattering medium with an OD of 11. OD is defined as $-\ln(I/I_0)$, where I is the intensity of the ballistic light and I_0 is the

intensity of the incident light. When the OD of the scattering medium was below 12, an ultrafast optical Kerr gating method was used to directly determine the OD value [24]. Meanwhile, a linear relation between the OD and the volume concentration of the scattering medium was also measured [24, 25], in terms of which, the more intense scattering medium with a bigger OD was prepared. Speckles are clearly visible in Fig. 2(b), and they cause intense noise, corrupting the images significantly. Then, we used SC illumination to capture speckle-suppressed images of the object in the scattering medium, and the result of which is shown in Fig. 2(c). The laser speckle effects are significantly mitigated, and the image is dramatically improved compared to those in Fig. 2(b). We extracted the speckle contrast ($C = \sigma/\langle I \rangle$, where σ is the standard deviation of intensity and $\langle I \rangle$ is the average intensity) from Fig. 2(c) as 0.07 and found that it is much lower than 0.24 as in Fig. 2(b). However, the contrast of the image is clearly decreased by the scattering medium. For comparison, we employed an SSG of 1 mm in diameter at the back focal plane of L3 to filter the scattering noise of the images captured by SC illumination; the imaging result is present in Fig. 2(d). Although the contrast is significantly improved, edge contours of the bar images in the test patterns significantly blur because the high spatial frequency information of the object is filtered by the SSG. The maximum resolvable spatial frequency is 7.13 lp/mm for imaging by SC illumination with an SSG, which corresponds to a spatial resolution of 70 μm . Next, as shown in Fig. 2(e), we employed SC illumination with an RSG as described in the experimental details to improve the speckle-suppressed image contrast captured by SC illumination. Both the identifiability and contrast of the images captured by SC illumination with the RSG are significantly improved. The maximum resolvable spatial frequency is 40.3 lp/mm, which corresponds to a spatial resolution of approximately 12 μm .

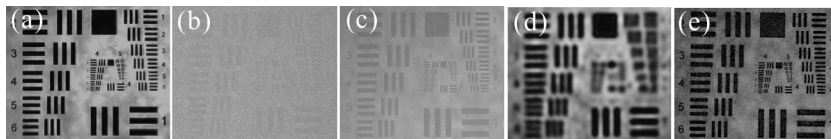


Fig. 2. Images obtained in a scattering medium with OD of 11 using (a) 800 nm laser without the scattering medium, (b) 800 nm laser, (c) SC illumination, (d) SC illumination with an SSG, (e) SC illumination with an RSG.

To quantitatively characterize the image quality presented in Fig. 2, we calculated the contrast-to-noise ratio (CNR) that describes the identifiability of a feature of interest against a given background as shown in Fig. 3(a). The CNR is defined as $(\langle I_A \rangle - \langle I_B \rangle) / ((\sigma_A + \sigma_B) / 2)$, where I_A and I_B are the intensities of the signal-producing structures A and B in the region of interest (e.g., a bar in a test pattern and its surrounding background) and σ is the standard deviation of the pixel intensity. When the CNR approaches unity, the image noise is comparable to the feature contrast. Thus, structures are unidentifiable if the CNR is less than 1. We define the CNR to be 0 if the structures of the object are entirely invisible. Moreover, we measured the modulation transfer function (MTF) for the analysis of image contrasts. The MTF is defined as $(I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$, where I_{\max} is the maximum intensity and I_{\min} is the minimum intensity in the square-wave grating. The MTF is normalized by the maximum contrast of all experimental data. As shown in Fig. 3, the CNR and MTF of the images obtained using 800 nm laser illumination are less than 1 and 0.05, respectively. The CNR for SC illumination is greater than 1 across the entire measured spatial frequency range because of speckle suppression. However the MTF of the images obtained using SC illumination is less than 0.1 over the entire measured range because of the scattering background noise. The CNR and the MTF of the images obtained using SC illumination with the SSG are notably increased; however, they sharply drop to 0 at spatial frequencies of 7.13 lp/mm because of low-pass filtering. When SC illumination with the RSG is used, the CNR and MTF of the images are close to those of the reference (without the scattering medium), showing improved identifiability and contrast. The above results illustrate that when the ballistic imaging method

using SC illumination with an RSG is used, the image speckles and scattering noises are effectively suppressed.

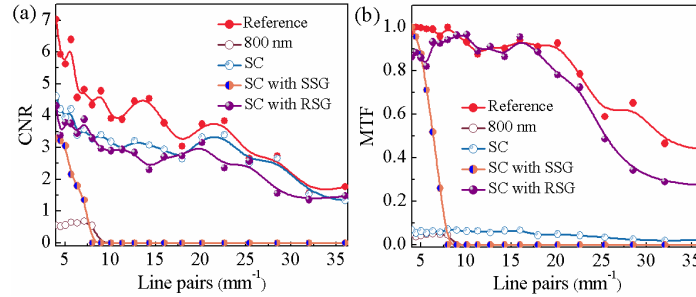


Fig. 3. (a) CNR and (b) MTF versus spatial frequency for images shown in Fig. 2.

Both of the ballistic imaging methods, in which SC illumination with an SSG or RSG is used, can improve the identifiability and contrast of images in an intense scattering environment. However, compared to SC illumination with the SSG, the spatial resolution of the images captured by SC illumination with an RSG is significantly higher. For the ballistic imaging of SC illumination with the RSG, the light intensity of raw images can be described by $I_0(x, y) + I_b$, where I_0 is the ballistic light intensity and I_b is the background noise caused by scattered photons with low coherence. I_0 can also be expressed as $|\mathbf{E}_{\text{high}}(x, y) + \mathbf{E}_{\text{low}}(x, y)|^2$, where $\mathbf{E}_{\text{high}}(x, y)$ and $\mathbf{E}_{\text{low}}(x, y)$ are the electric field intensity of the high and low spatial frequency components of ballistic light, respectively. Here, we consider the background noise as uniform because the speckles are significantly suppressed. Thus, the light intensity of the image obtained with the high-pass filter is described by $|\mathbf{E}_{\text{high}}(x, y)|^2 + I_b$. Thus, the result I_{result} extracted by SC illumination with an RSG is explained in the following form:

$$I_{\text{result}}(x, y) \propto |\mathbf{E}_{\text{low}}(x, y)|^2 + 2\mathbf{E}_{\text{low}}(x, y) \cdot \mathbf{E}_{\text{high}}(x, y). \quad (1)$$

Here, the inner product of Eq. (1) indicates that both the high and low spatial frequency components of the ballistic light were extracted by SC illumination with an RSG. Therefore, for the images captured by SC illumination with the RSG, the spatial resolution is protected against degradation. In addition, the scattering noise background I_b is eliminated, and the contrast of the images is enhanced. It should be noticed that this method is mainly suitable for a static experiment. When this method is required for a dynamic experiment, the raw image and background noise image should be captured simultaneously by splitting the imaging beam into two beams.

If the OD increases further, the percentage of ballistic photons collected in the detector unfortunately reduces sharply compared to that of scattering photons. Then, insufficient ballistic photons can be extracted by SC illumination with an RSG. In this case, we applied SC illumination with a combination of the SSG and RSG to extract the ballistic photons. In detail, we captured the image by SC illumination with an SSG as a raw image to increase the percentage of ballistic photons collected in the detector. In addition, we captured the noise background after locating a 1 mm high-pass filter in the center of the SSG. Then, we subtracted the background noise from the raw image to extract the ballistic image just as in the RSG method. Here, an iris of 5 mm in diameter was chosen for improving the signal-to-noise ratio of the raw image. As for the size selection of the iris, we also took into account a sufficient spatial resolution of the imaging process.

As shown in Fig. 4, we present the obtained images using these different methods at a scattering medium OD of 17. Without the spatial gate, the images obtained by 800 nm laser illumination and SC illumination are shown in Figs. 4(a) and 4(b), respectively. The structures inside the object were invisible in the images captured by these two methods. In Figs. 4(c) and 4(d), we respectively present the images obtained by 800 nm laser and SC illumination with the

5 mm SSG. Although a portion of scattering noise is filtered by the SSG, the “boiling” speckles produced by the residual scattering photons ruin the structural information of the object. The effects of laser speckles in the image, as shown in Fig. 4(d), are significantly mitigated, and the identifiability of the image is dramatically improved when compared to Fig. 4(c). However, the image contrast is still not ideal because of the uniform background noise caused by residual scattering photons. Next, we present the image captured by SC illumination with a combination of the SSG and RSG in Fig. 4(e). The contrast is significantly improved when compared to the raw image captured using SC illumination with the SSG.

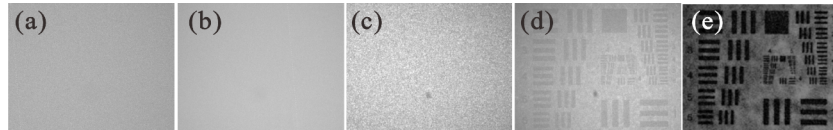


Fig. 4. Images obtained in a scattering medium with OD of 17 using (a) 800 nm laser, (b) SC illumination, (c) 800 nm laser with an SSG, (d) SC illumination with an SSG, (e) SC illumination with a combination of an RSG and SSG.

As a quantitative measure of the images presented in Figs. 4 (c)-4(e), we extracted the CNR and MTF versus the spatial frequency of the features on the test chart. The CNR and MTF of the image obtained by 800 nm laser illumination with the SSG are zero across the entire measured spatial frequency range. By contrast, for the raw image captured by SC illumination with an SSG, the CNR is notably enhanced and the MTF is improved but slightly. Moreover, using SC illumination with the combination of an SSG and RSG, the MTF is significantly increased after the removal of the homogeneous background noise of the raw image captured by SC illumination with the SSG (Fig. 5).

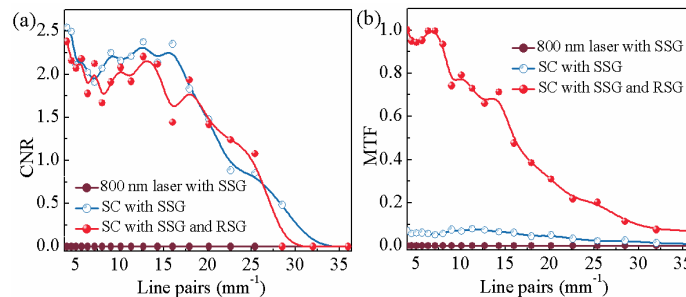


Fig. 5. (a) CNR and (b) MTF versus spatial frequency for images shown in Figs. 4(c)-4(e).

4. Conclusions

In conclusion, we propose a new ballistic imaging method in which SC illumination and an RSG were used. The SC illumination suppressed the speckles, leading to a uniform background. Moreover, the RSG removed background noise and extracted ballistic light. In addition, this method avoided low-pass spatial filtering to ensure the high resolution of images. This ballistic imaging method is capable of imaging in an intense scattering environment. The experimental results showed that even when the OD of the scattering medium reached 17, the images extracted by this method had an improved identifiability and contrast.

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