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# Speckle-suppressed full-field imaging through a scattering medium using a supercontinuum

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**Abstract:** We demonstrate speckle-suppressed full-field imaging through a scattering medium using incoherent supercontinuum (SC) illumination. The patterns in images obtained using SC illumination were found to be more easily identifiable than those in images acquired using coherent direct laser illumination due to the speckle suppression. Even when the optical depth reached 12.3, the patterns remained identifiable. As one of the potential applications, we also demonstrated the imaging for a high-pressure diesel spray using SC illumination.



**OCIS codes:** (030.6140) Speckle; (320.0320) Ultrafast optics; (320.7080) Ultrafast devices; (320.7160) Ultrafast technology.

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## 1. Introduction

The imaging of objects 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 reported recently [1–3]. Because of their prominent photon degeneracy, lasers are the preferred light sources in modern imaging systems and have become indispensable. However, interference among scattered laser photons causes speckles to appear in the resulting images [4]. Although speckles can be used constructively in a variety of ways, they are usually more of a hindrance than a benefit [5]. In shadowgraph techniques, speckles can corrupt the identifiability of some interesting features in objects [6]. If speckle formation could be prevented, the image clarity could be improved. Over the years, some digital image processing algorithms have been developed with the objective of suppressing speckle formation [7]. In addition, preliminary reports have indicated that speckles can be suppressed by adding multiple uncorrelated speckle patterns on an irradiance basis. Uncorrelated speckle patterns can be obtained experimentally based on the time, space, frequency, or polarization diversity from a given object [8]. However, to image rapid transients in scattering environments, it is impossible to generate multiple uncorrelated speckle patterns for its necessary forming time. Consequently, the method of superposition of multiple uncorrelated speckle patterns is unfeasible in such conditions. Experimentally, suppression of speckles in images of rapidly dynamic objects is more challenging than that of speckles in images of static objects.

In the past few years, some efforts have been made to suppress speckles by using incoherent light sources. Cao et al. demonstrated that random lasers, spatial modes of which are inhomogeneous and highly irregular, can be engineered to provide speckle-free full-field imaging in intense optical scattering conditions because of their low spatial coherence [9]. In addition, Yu reduced speckle noise using a broadband green illumination source with low temporal coherence that was generated by loosely focusing a Q-switched Nd:YVO4 laser beam on a tandem-poled $LiNbO_3$ crystal [10]. This method was limited by the very low conversion efficiency of the broadband light source. Some other low-coherence sources such as Xe lamps and light-emitting diodes are also used in many full-field imaging applications. However, these illumination sources which are externally modulated into nanosecond pulses will produce motion blurring effects when they are applied to imaging some rapidly changing objects in scattering environment [11–13], such as diesel spray. While, due to its high time resolution [14, 15] and degeneration of coherence [16], supercontinuum (SC) may be an ideal illumination source for imaging these rapidly changing objects in scattering environment without producing motion blurring effects.

In the study described herein, we employed SC illumination with decreased coherence to achieve speckle-suppressed full-field imaging of resolution test target through a scattering medium. The images obtained using SC illumination were significantly clearer than those generated using coherent direct laser illumination. Even when the optical depth (OD) of the scattering medium was as large as 12.3, the patterns in the images remained easily identifiable. As one of the potential applications, we demonstrated the imaging for a diesel spray in the near field using SC illumination. The images using direct laser illumination were also recorded as a reference. The speckles in the images of spray are significantly suppressed by using SC illumination.

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## 2. Experimental details

To generate images using SC and coherent direct laser illumination, the basic in-line shadowgraphy arrangements depicted in Fig. 1 were used. Ultrafast laser pulses were generated by a Ti:sapphire laser system (Libra-USP-HE, Coherent Inc., USA), which can generate laser pulses with widths of less than 200 fs and energies of about 3.5 mJ per pulse at a repetition rate of 1 kHz, with a pulse spectrum centered at 800 nm. As shown in Fig. 1(a), lens L1 (focal length, $f$ = 150 mm) focused the femtosecond laser pulses inside a 4-cm-thickness quartz cuvette filled with distilled water to generate SC. If the output SC is unstable, its fluctuation from pulse to pulse has negative influence on the analysis of experimental results. The stability of SC is dependent on the power and the spatial distribution of incident light [17]. In order to ensure the stability of SC in our experiment, the power of incident was set at about 0.8 mW, and a circular iris of radius 7.74 mm was placed 100 mm ahead of L1 to generate Fresnel diffraction pattern. The pulse width of SC was measured to be about 10 ps. The generated SC was collected by L2 ($f$ = 100 mm), modulated by a resolution test target (RT-MIL-TP2001, RealLight, China), and passed through a suspension of 3.13-μm-diameter polystyrene spheres. A charge-coupled device (CCD) camera (INFINITY3-1M-NS-TPM, Lumenera Corporation, Canada) was placed in the imaging plane to record the shadowgraph after the beam had traveled through the converging and diverging lenses, L3 ($f$ = 150 mm) and L4 ($f$ = 200 mm), respectively. For comparison, the direct imaging using the 800 nm laser was also done. The setup using the direct laser is shown in Fig. 1(b), which was nearly identical to Fig. 1(a), except that no water-filled cuvette was placed at the focus of L1. And the exposure times of CCD for both imaging using SC and direct laser illumination sources were set at 4 ms.

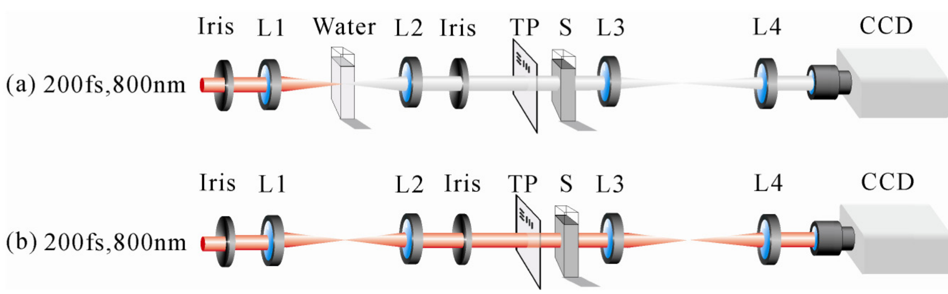


Fig. 1. (a) SC and (b) direct laser illumination setups used for imaging through scattering medium. L1, L2, L3, and L4: lenses; RTT: resolution test target; S: scattering medium.

We also demonstrated imaging for a diesel spray in the near field. In this condition, the resolution test target was replaced by the diesel spray, and the suspension was also taken away. The spray was generated by a single-orifice, common-rail diesel injector (CRIN2-16, BOSCH, Germany) with a nozzle diameter of about 220 μm. The diesel was delivered by a high-pressure diesel fuel pump (CP3.3N, BOSCH, Germany) driven by an electric motor. An integrated electrical controller was used to change the fuel pressure to 400 bar by modifying the load on the electromagnet in the pump. The controller was also used to adjust the time delays and duration of the injector jet. When the injector sprayed, the controller triggered the CCD camera to ensure that it obtained an image simultaneously to catch the moment at which the spray began. In our experiment, the single-shot imaging method was used and the exposure time of CCD was set at 1 ms.

## 3. Results and discussion

In Fig. 2(a), we present the images obtained using coherent direct laser illumination of test patterns located behind a suspension of polystyrene spheres whose OD was varied from 6.37 to 12.32. OD is defined as -ln ($I/I_0$), where $I$ is the intensity of the light exiting the scattering medium and $I_0$ is the intensity of the light entering the scattering medium. The OD of the

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suspension in our experiments was measured using the optical Kerr gate method [18]. Speckles are clearly visible in Fig. 2(a) and corrupt the images significantly, causing intense noise and especially obscuring the smaller lines. The corruption becomes more serious as the OD increases, reaching a disastrous level when the OD exceeds 10. Next, we used SC illumination to obtain speckle-suppressed full-field images of the test patterns after the suspension of polystyrene spheres; the results are shown in Fig. 2(b). These images are dramatically improved compared to those in Fig. 2(a). Even when the OD reaches 12.3, the small bars in the test patterns remain acceptably identifiable.

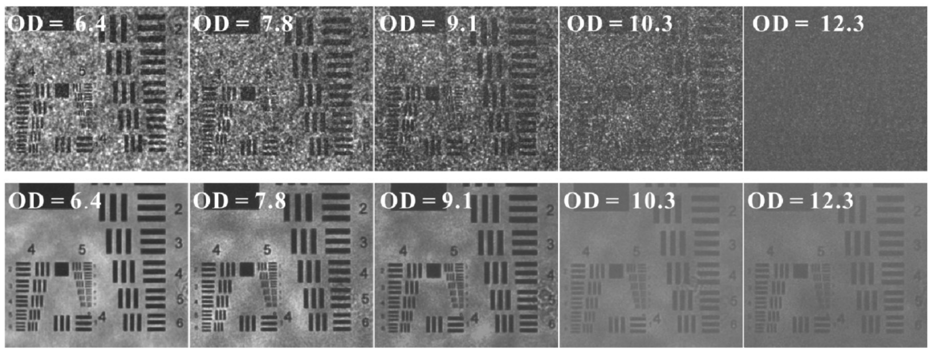


Fig. 2. Images obtained using (a) direct laser and (b) SC illumination of test patterns behind scattering medium under different OD conditions.

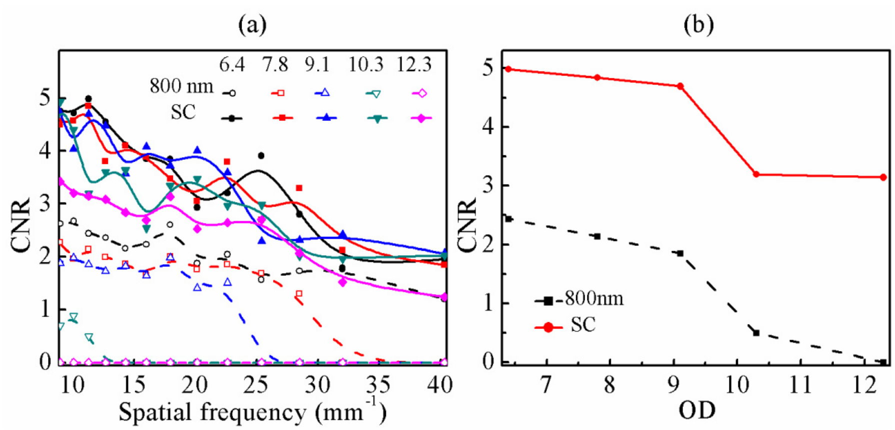


Fig. 3. (a) CNR versus spatial frequency for images obtained using direct laser (dotted) and SC (solid) illumination. (b) CNR versus OD for bars whose spatial frequency is 11.3 mm$^{-1}$.

To quantitatively characterize the qualities of images presented in Fig. 2, we calculate the contrast-to-noise ratio (CNR) which describes the identifiability of a feature of interest against a given background as shown in Fig. 3. Two images acquired in the same condition were used to calculate the CNR in Fig. 3. The CNR is defined as $(<I_A>-<I_B>)/((\sigma_A + \sigma_B)/2)$, where $I_A$ and $I_B$ are the intensities of signal-producing structures A and B in the region of interest (for example, a bar in a test pattern and its surrounding background) and $\sigma$ 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. As shown by the dotted lines in Fig. 3(a), for a given OD, the CNR curves of the images obtained using direct laser illumination decrease as the spatial frequency increases. In addition, the overall CNR curve height decreases with increasing OD. Specifically, the CNRs for an OD of 6.4 are greater than 1 across the entire measured spatial frequency range, while they drop below 1 for ODs of

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7.8 and 9.1 at spatial frequencies of 32 $mm^{-1}$ and 28.5 $mm^{-1}$, respectively, and are below unity across the entire measured spatial frequency range for ODs of 10.3 and 12.3. It is also evident from Fig. 3(a) that the CNRs of the images obtained using SC illumination are greater than those of the images generated using direct laser illumination, for the same OD. Notable, even when the OD reaches 12.3, the CNRs remain above 1 across the entire measured spatial frequency range. Unlike the CNR curves of the images acquired using coherent illumination, those of the images obtained using SC illumination exhibit no significant differences between the different OD conditions. The CNRs of bars whose spatial frequency is 11.5 $mm^{-1}$ are shown for different ODs in Fig. 3(b). The CNRs of the images obtained using direct laser illumination drop quickly from 2.5 to less than 1 as the OD increases from 6.4 to 12.3. In contrast, the CNRs of the images generated using SC illumination remain above 3 for all of the ODs and decline slowly.

Usually, the quality of imaging using SC illumination is affected by speckle issue and multiple scattering times. To understand the mechanism of the improvement of identifiability, these two effects are discussed as follow. First, speckle is usually characterized by the speckle contrast C, which is usually expressed as $C \propto 1/\delta\lambda$, where $\delta\lambda$ is the wavelength bandwidth of the illumination source. As the wavelength bandwidth of SC (~500 nm) is much larger than that of direct laser (~100 nm), the speckles can be suppressed by using SC illumination. In addition, we also experimentally measured the speckle contrast of the images, in which the resolution test target is replaced by a same-thickness uniform transparent target. The result was shown in Fig. 4. As shows in Fig. 4, the speckle contrast is lower for the images taken by using SC illumination than for those taken by using direct laser illumination. On the other hand, according to the Mie scattering theory, multiple scattering times increase with the decrease of wavelength of the incident light [19]. For the same OD, the scattering photons collected by the detector increase with times of multiple scattering. It means the improvement of quality of images was not attributed to multiple scattering times because most of the wavelengths of SC are shorter than that of the direct laser. So, the improvement of identifiability of images obtained by using SC illumination in our experiment was attributed to speckle suppression.

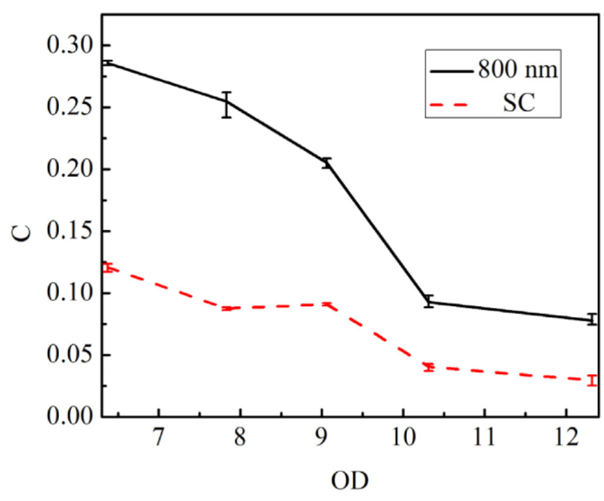


Fig. 4. C versus OD for images obtained using direct laser (solid) and SC (dotted) illumination.

As one of the potential applications, we further demonstrated imaging for a high-speed diesel spray using SC illumination. The images using direct laser illumination in same condition were also recorded as a reference. The results obtained were removed inhomogeneous background artifacts resulting from the illumination source after applying a flat-field correction to each image [20]. At first, the images of diesel spray at the tip of the injector obtained by using direct laser and SC illumination are shown in Figs. 5(a) and 5(b), respectively. The diesel jet can be seen issuing from the tip of the injector, and the diameter of the injector orifice (220 μm) indicates the spatial scale. Magnified views of sections of Figs. 5(a) and 5(b) are also shown. Clearly, the speckles around the liquid core are suppressed significantly and the surface micro-structures are more easily recognizable in Fig. 5(b) than in Fig. 5(a). In addition, images of the spray 2-cm below the nozzle were also obtained by using direct laser and SC illumination; these are shown in Figs. 5(c) and 5(d), respectively. The speckles are greatly reduced in Fig. 5(d), comparing with those in Fig. 5(c). For a rough quantitative comparison, the speckle contrasts of the region in rectangle marked in Figs. 5(c) and 5(d) were calculated, which are 0.54 and 0.35 respectively. The results showed that the speckles of imaging for atomized diesel sprays can be suppressed by using SC illumination.

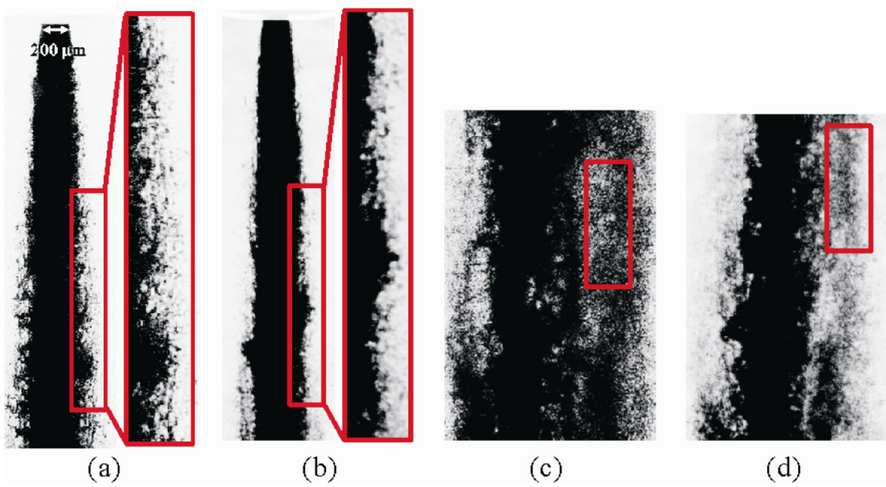


Fig. 5. Near-field images of diesel spray at the tip of the injector obtained using (a) direct laser and (b) SC illumination. Images of diesel spray 2 cm below nozzle acquired using (c) direct laser and (d) SC illumination.

## 4. Conclusions

We achieved speckle-suppressed full-field imaging through a scattering medium with different ODs using SC illumination. The images obtained using SC illumination were clearer than those generated using coherent direct laser illumination due to the speckle suppression. Even when the OD exceeded 10, the patterns in the images remained reasonably identifiable. Thus, SC illumination is ideally suited for imaging in intense scattering environments. Furthermore, we imaged a high-pressure diesel spray using both types of illumination and found that the surface micro-structures were more easily recognizable in the images acquired using SC illumination than in those obtained using direct laser illumination.

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