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Two-phase SLIPI for instantaneous LIF and Mie imaging of transient fuel sprays

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We report in this Letter a two-phase structured laser illumination planar imaging [two-pulse SLIPI (2p-SLIPI)] optical setup where the “lines structure” is spatially shifted by exploiting the birefringence property of a calcite crystal. By using this optical component and two cross-polarized laser pulses, the shift of the modulated pattern is not “time-limited” anymore. Consequently, two sub-images with spatially mismatched phases can be recorded within a few hundred of nanoseconds only, freezing the motion of the illuminated transient flow. In comparison with previous setups for instantaneous imaging based on structured illumination, the current optical design presents the advantage of having a single optical path, greatly simplifying its complexity. Due to its virtue of suppressing the effects from multiple light scattering, the 2p-SLIPI technique is applied here in an optically dense multi-jet direct-injection spark-ignition (DISI) ethanol spray. The fast formation of polydispersed droplets and appearance of voids after fuel injection are investigated by simultaneous detection of Mie scattering and liquid laser-induced fluorescence. The results allow for significantly improved analysis of the spray structure. © 2016 Optical Society of America

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Over the past 30 years, laser sheet imaging has been extensively used for spray characterization, including the visualization of liquid breakups, ligament formation, flow velocity, spray evaporation, and wide-field droplet sizing [1,2]. However, the very first investigations already reported the challenges imposed by multiple light scattering for the application of two-dimensional (2D) scattering techniques in optically dense sprays [3]. These include the appearance of blur on the recorded image, the reduction of resolution and, therefore, the introduction of both image artifacts and large errors in quantitative imaging. These issues were addressed by combining, for the first time in 2008,

laser sheet imaging with structured illumination, a technique known as structured laser illumination planar imaging (SLIPI) [4,5].

In SLIPI, a sinusoidal pattern is spatially imprinted on the light sheet, usually by means of a grating (e.g., Ronchi or sinusoidal grating). The resulting “lines structure” is then imaged a number of times after inducing a spatial phase shift. This is usually done by displacing the grating along the modulation direction. As a result, several images, often called modulated “sub-images,” are recorded at different spatial phases. The common number of employed sub-images for a SLIPI image reconstruction is three, but it has been shown that two [6], or even one, image could be used in some situations [7].

For spray imaging, the three-phase SLIPI (3p-SLIPI) approach has been employed mostly for averaged imaging. In this case, the setup often consists of one grating and a continuous or a pulsed laser illumination for steady or transient sprays, respectively. However, the three sub-images must be correctly averaged to be assumed statistically identical. Based on this assumption, 2D mapping of droplet size [8] and temperature [9], as well as three-dimensional spray reconstruction of the extinction coefficient [10], has been achieved during the past five years. For instantaneous imaging, 3p-SLIPI demands the recombination of three laser pulses, each passing through a separate grating and arriving at the sample with a time separation of only a few hundreds of nanoseconds in order to freeze the spray motion [11]. This recombination of three independent optical channels results in large losses in laser power. It also requires the use of both three intensified cameras and three pulsed laser sources, thus largely increasing the cost of the system and the complexity of the optical arrangement.

To circumvent these challenges, a two-pulse SLIPI (2p-SLIPI) approach, where two sub-images are used instead of three, has recently been demonstrated [6]. In this configuration, two modulated light sheets of high spatial frequency and with mismatched phases are used. The 2p-SLIPI image is then generated from the absolute value of the intensity difference between the two sub-images and by filtering out the resulting residual lines in the Fourier domain such as

$$I_{2p\text{-SLIPI}} = F_{2\nu} \left(\sqrt{(I_0 - I_{180})^2} \right), \quad (1)$$

where $F_{2\nu}$ denotes the Fourier filtering, while $I_{2p\text{-SLIPI}}$, I_0 and I_{180} are light intensities corresponding to the resulting SLIPI image and the two modulated sub-images, respectively. Note that the subtraction $(I_0 - I_{180})$ is responsible for the appearance of residuals which are located at the crossing point between the two modulated patterns. At this location, the light intensities between the two sub-images are equal and cancel out, providing a gap of information appearing periodically at twice the frequency of the modulated sub-images. This lack of information can be filled by using three or more phases, explaining why the structured illumination is primarily based on the recording of three modulated sub-images. Therefore, if one wants to use a two-phase approach, a Fourier-transform post-processing is needed to remove those undesired frequency components. It should be noted that some desired image information contained at these specific frequencies will also be lost in the post-processing. Thus, to remove as little information from the spray image as possible, one should use a modulated light sheet with a spatial frequency as high as possible, while still correctly resolving the lines structure. However, by extracting the average of the two sub-images, a conventional image corresponding to a homogeneous illumination can directly be reconstructed.

We report a novel 2p-SLIPI optical arrangement which takes advantage of the birefringence (double refraction) property of a calcite crystal. The working principle is depicted in the zoomed area shown in Fig. 1. When two linearly cross-polarized laser pulses pass through the crystal with a direction perpendicular to the crystal surface, the horizontally polarized pulse maintains the same path (ordinary ray), while the vertically polarized pulse is displaced (extraordinary ray) due to experiencing a different index of refraction [12]. At the exit of the calcite, this displacement introduces a phase shift in the modulated pattern between the two recorded sub-images. This way, the generation of modulated sub-images with mismatched phases is purely optical and, thus, not “time-limited.” The degree of displacement is defined by the wavelength of the incident light, as well as the thickness and the orientation of the optical axes of the crystal, currently 0.125 mm.

The approach is tested for the first time in a transient multi-jet direct-injection spark-ignition (DISI) spray, where ethanol is injected into an optically accessible constant volume chamber. To understand the formation and evolution over time of such spray systems, the recording of instantaneous images showing the spatial distribution of the liquid fuel is necessary. Such information is important to better assess the role of liquid fuel injection in the internal combustion engine efficiency and emissions formation chain. Here, only one spray plume from a five-hole DISI injector (BOSCH) is visualized, and the results between instantaneous 2p-SLIPI and the conventional approach are compared.

The optical arrangement of the 2p-SLIPI setup for simultaneous recording of liquid LIF and Mie signals is shown in Fig. 1. The signals are recorded using two scientific CMOS cameras (LaVision GmbH). Two pulsed 532 nm Nd:YAG lasers (laser 1, Quanta Ray; and laser 2, Quatel Brilliant) with equal laser fluence and top hat beam profile are used. The time duration of each pulse is in the order of 6 ns, while the repetition rate is 10 Hz. The beam profile of these pulses is spatially encoded by a “lines structure” after crossing a transmission

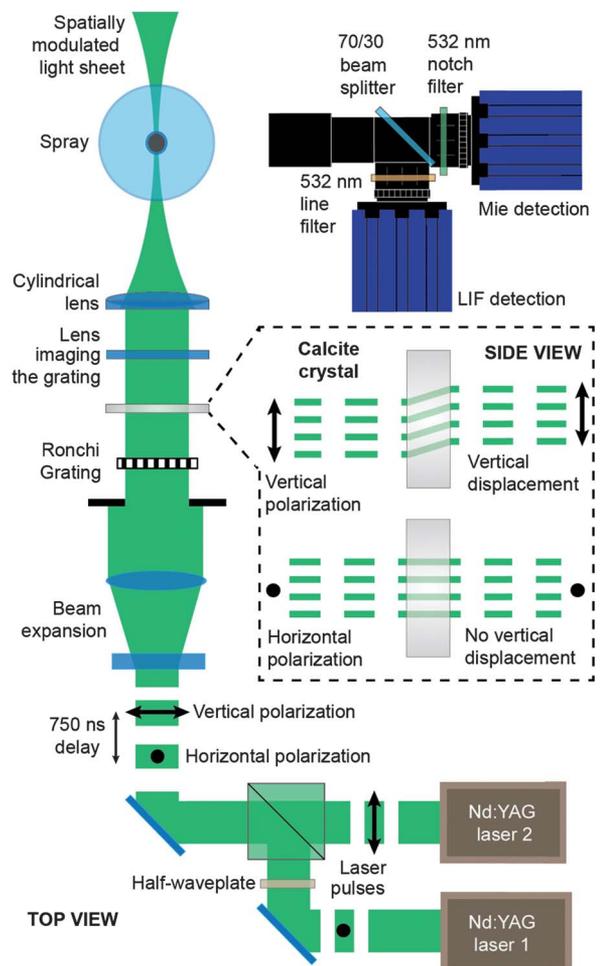


Fig. 1. Top view of the optical arrangement of 2p-SLIPI setup for simultaneous LIF and Mie detection. A spatially modulated light sheet is created by means of a Ronchi grating, while the displacement of the line pattern is operated by employing the birefringence of a calcite crystal, as illustrated in the zoomed area.

Ronchi grating of four line-pairs/mm spatial frequency. The pattern is imaged and focused as a sheet of light inside the spray chamber by two respective cylindrical lenses. The incident laser sheets have a height of 90 mm and a thickness of $\sim 500 \mu\text{m}$. A time delay of 750 ns is set between the two laser pulses, while the two cameras are running on double exposure mode. This allows the recording of the pair of modulated sub-images, required to generate the 2p-SLIPI image, while freezing the spray motion. The liquid LIF and the Mie scattering are recorded on the respective cameras forming two images each of 2560×2160 pixels. To collect the two signals using only one objective, an in-house camera stage is designed. The system is housing a cube beam splitter (70% reflection for the LIF signal and 30% transmission for the Mie signal), which is placed just behind the objective to divide the optical signal into two. This simplifies the alignment for obtaining the same field-of-view on both cameras. For the fluorescence, an organic luminescence dye, Eosin (Kingscote Chemicals, USA) is added at 0.5 vol.-% of the liquid fuel, which here is 100% ethanol. When the liquid solution is excited at 532 nm, the LIF broadband emission occurs between 540 and 680 nm. The LIF emission is detected by using a 532 nm (17 nm FWHM)

notch filter in order to exclude the excitation light, and the Mie scattering signal is detected by using a 532 nm (1 nm FWHM) laser line pass filter.

The spray chamber is operated at 0.2 MPa and 298 K which represents a high load engine operation. The fuel temperature is fixed to 298 K, and the injection pressure is set to 16 MPa. The injection duration is kept constant 1800 μs .

The post-processing of the sub-images recorded using the setup described in Fig. 1 is shown in Fig. 2. In (a), a sub-image of the incident illumination with its fast Fourier-transform (FFT) can be seen. The vertically imprinted lines structure, appearing at a spatial frequency of ν on the light sheet, can be better viewed in the respective zoomed area. In (b), an image before Fourier filtering [using Eq. (1)] is shown along with its FFT. As mentioned, the 2p-SLIPI approach generates residual lines, appearing at twice the incident modulation frequency (2ν). By increasing the incident illumination frequency, these residual lines can be “pushed” farther from the zeroth-order frequency, thus becoming nearly unnoticeable [6]. Finally, to obtain a residuals-free image, a band-rejection Gaussian filter ($F_{2\nu}$) is locally applied at the location of the residual frequencies, as shown in (c). By doing so, the 2p-SLIPI image is obtained with minimal losses in image resolution, as seen in the zoomed image areas. The results of the instantaneous LIF and Mie images from both conventional and 2p-SLIPI detections are shown in Figs. 3(a) and 3(b), respectively. The acquisition time is set to 2500 μs after the visible start of the injection. The conventional images, which suffer from multiple

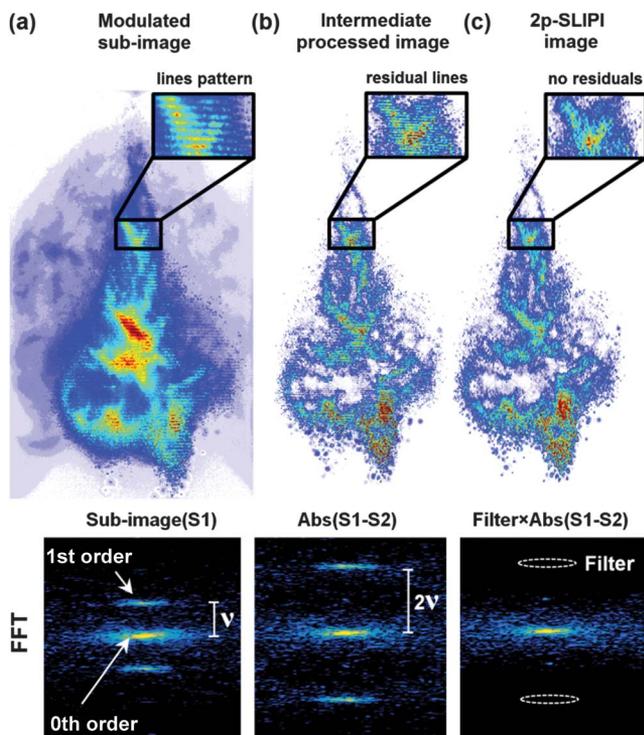


Fig. 2. Illustration of post-processing to extract a 2p-SLIPI image. (a) Sub-image for LIF detection is shown along with its FFT. (b) Intermediate image showing the absolute value of the subtraction ($I_0 - I_{180}$) and its FFT image are shown. (c) 2p-SLIPI image, along with its FFT, can be seen. A local band-rejection Gaussian filter is used for the removal of the residual lines. Note that any spray information residing within the filter range is also removed.

light scattering effects, show a background signal emerging from the other four spray plumes located at the back of the imaged spray.

This surrounding light conceals the real structure, as well as the presence of voids within the spray. On the contrary, the 2p-SLIPI images reject this unwanted signal, depicting a faithful

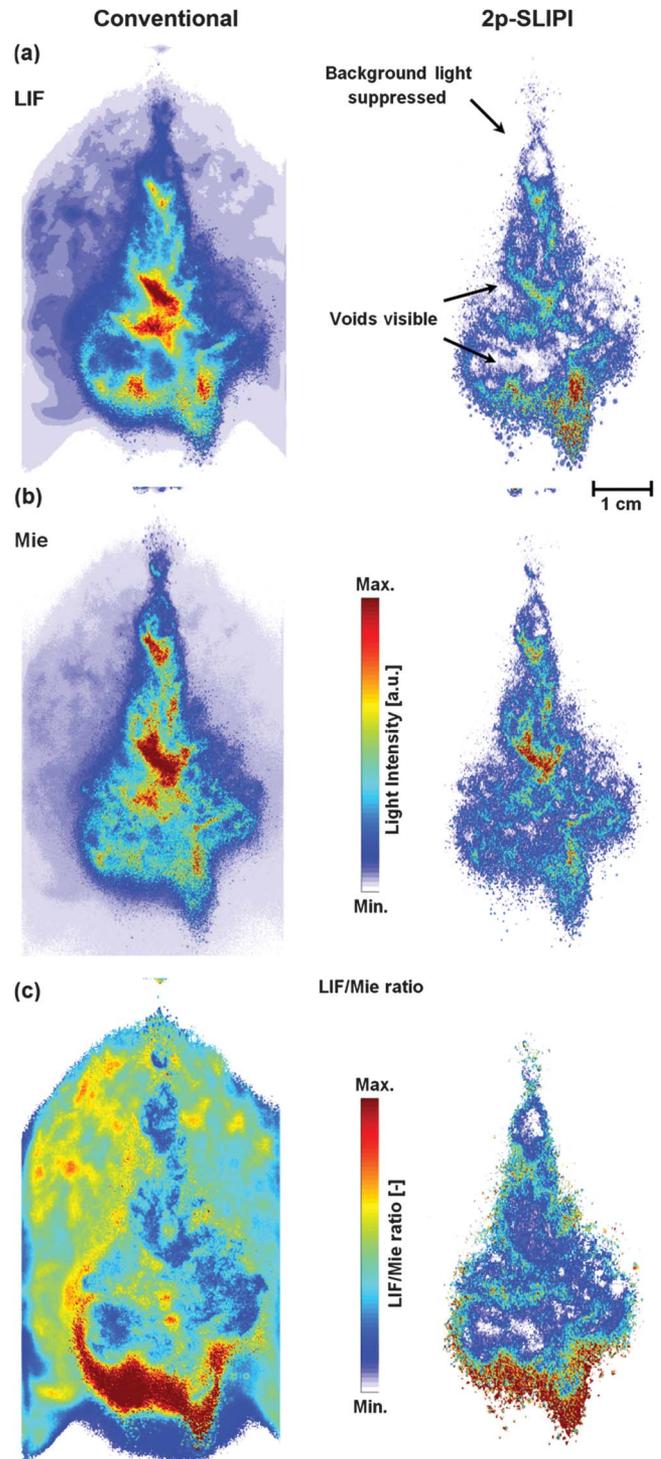


Fig. 3. Comparison between conventional light sheet imaging and 2p-SLIPI for instantaneous (a) LIF, (b) Mie scattering, and (c) LIF/Mie ratio. The transient ethanol spray is imaged at 2500 μs after the visible start of the injection. The 2p-SLIPI approach generates images cleaned up from multiple scattering artifacts.

representation of the spray within the plane of the light sheet. As a result, the inhomogeneous spread of droplet clouds can now be clearly seen. It is also observed that the appearance of voids is more pronounced on the LIF than the Mie images. This can be explained as follows: the fluorescence signal is volume dependent, while the Mie scattering signal is related to the surface area of the droplets. As a result, it can be deduced that the areas where no fluorescence is perceived, but where a Mie scattering signal is detected, are characterized by the presence of small droplets. In this context, it should be noted that for the present conditions (90° scattering, the range of expected droplet sizes), the Mie signal of the differently polarized components is almost identical.

In Fig. 3(c), the ratio of the respective LIF and Mie images is provided. Based on a number of assumptions such as the LIF signal is related to the volume of the droplets and the Mie signal is related to the droplets surface area, the Sauter mean diameter (SMD) can be quantitatively extracted. However, the non-sphericity of the droplets, their evaporation, as well as the level of dye concentration, make accurate quantitative droplet SMD measurements very challenging, even when single light scattering only is detected [13,14]. Despite those issues, the LIF/Mie image division allows the technique to cancel light extinction effects and provides qualitative information related to droplet

SMD. For an accurate quantitative SMD mapping, a reliable calibration procedure would be required using, for example, a phase Doppler interferometer, as shown in [8].

In Fig. 4(a), a series of four LIF/Mie ratio 2p-SLIPI images are shown. It is observed that the large droplets are located at the leading edge of the spray, while the central regions are characterized by the presence of small droplets. The drag forces at the spray front support collision of the fuel droplets accompanied with droplet coalescence. This leads to larger droplets at the spray front which is typical for DISI sprays [15,16]. The droplets with lower kinetic energy are pushed away from the spray axis and from the outer region [16]. From the standard deviation image of the LIF/Mie ratio calculated from 150 instantaneous images [Fig. 4(b)], it is seen that the spray front is not symmetric, and it is characterized by large spatial variations of the droplet size distribution from one injection to another. This is explained by the strong turbulent droplet dispersion occurring there due to the presence of large vortices.

In conclusion, the 2p-SLIPI approach offers great advantages in the analysis of transient sprays, thanks to its capability of suppressing the effects from the multiple light scattering, along with providing instantaneous imaging. The highly turbulent spray motion with large eddies, the presence of large droplets at the spray front, as well as the appearance of voids and small droplets in the spray center can now be clearly visualized. All those observed features provide valuable insights for a better understanding of transient spray systems. Finally, by using a similar optical arrangement, the technique opens new possibilities for further instantaneous spray characterization using two-color LIF thermometry and particle tracking velocimetry.

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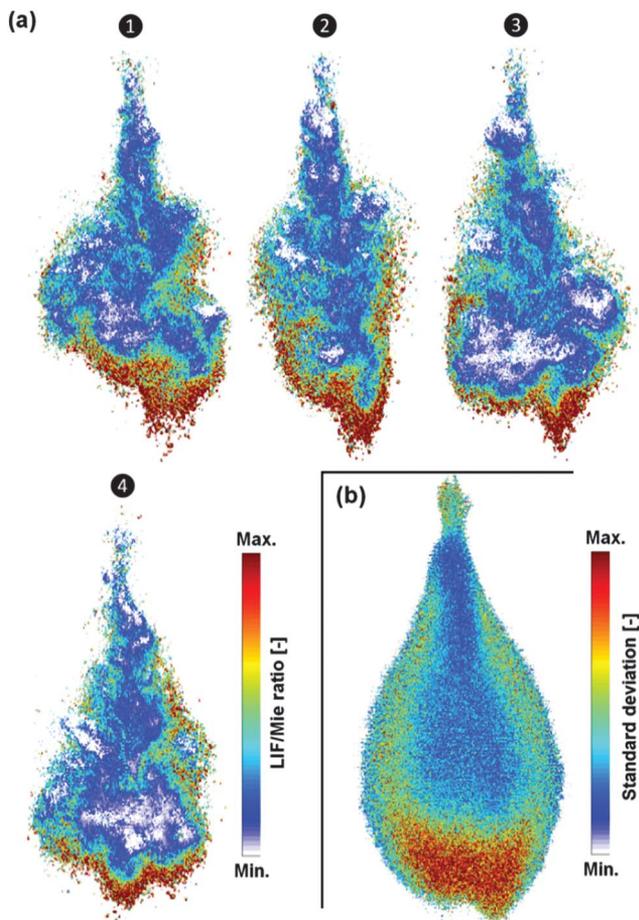


Fig. 4. (a) Four examples of instantaneous 2p-SLIPI images of the LIF/Mie ratio. (b) Standard deviation LIF/Mie ratio determined from 150 2p-SLIPI images. The results highlight the importance of shot-to-shot variation of the droplet relative SMD.

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