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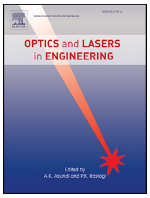

Single-shot spatiotemporal intensity measurement of picosecond laser pulses with compressed ultrafast photography

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ABSTRACT

The spatiotemporal measurement of the ultrashort laser pulses is of great significance in the diagnosis of the instrument performance and the exploration of the laser and matter interaction. In this work, we report an advanced compressed ultrafast photography (CUP) technique to measure the spatiotemporal intensity distribution of the picosecond laser pulses with a single shot. This CUP technique is based on a three-dimensional image reconstruction strategy by employing the random codes to encode the space-time-evolving laser pulse and decode it based on a compressed sensing (CS) algorithm. In our CUP system, the measurable laser wavelength depends on the spectral response of the streak camera, which can cover a wide range from ultraviolet (200 nm) to near infrared (850 nm). Based on the CUP system we develop, we successfully measure the spatiotemporal intensity evolutions of some typical laser pulses, such as the 800 nm picosecond laser pulse, the 800 and 400 nm two-color picosecond laser pulses and the supercontinuum picosecond laser pulse. These experimental results show that the CUP technique can well characterize the spatiotemporal intensity information of the picosecond laser pulses. Moreover, this technique has the remarkable advantages with the single shot measurement and without the reference laser pulse.

1. Introduction

The measurement of the ultrashort laser pulses is a preliminary procedure in many ultrafast optical laboratories, which can characterize the performance of the laser device, and also can explore the interaction between the light and matter. Usually, the characterization of the ultrashort laser pulses includes the determinations of various laser parameters, such as the line width, spectral profile, frequency stability and coherence in the frequency domain; the pulse shape and duration, peak power and repetition rate in the time domain; and the beam diameter, divergence angle, transverse mode and near or far field pattern in the space domain. The auto-correlator is the most commonly used measurement technique of the ultrashort laser pulses, but it can only provide the temporal intensity information in one-dimensional (1D) space. Moreover, some conventional diagnostic devices, such as spectral phase interferometry for direct electric-field reconstruction (SPIDER) [1], or frequency- resolved optical gating (FROG) [2], generally integrate over the transverse coordinate space to obtain the temporal profile. Therefore, these measurement devices only can obtain the temporal information. Actually, in many cases, only the temporal measurement cannot meet the experimental requirements any more. For example, the spatiotemporal distortion of the laser pulses, especially in regenerative amplifier, will greatly restrict the performance of the ultrafast laser system [3]. In fact, the carefully aligned laser pulses are also under distortion more or less, and the most common cases are the spatial chirp and pulses-front tilt [4]. Hence, it is of great significance to develop some new techniques to simultaneously measure the spatial and temporal information of the laser pulses.

The spatiotemporal measurement of the laser pulses has attracted considerable interest in the past twenty years. The researchers usually combined a temporal characterization of a point in the laser spot with a set of spectrally resolved wavefront measurement based on a lateral shearing interferometry [5], test-plus-reference interferometry [6], or Hartman-shack wavefront sensor [7]. However, these techniques bring the complexity of the experimental measurement, and also involve in the coupling of the spatial and temporal information. Fortunately, Gabolbe et al. developed a spatially and temporally resolved intensity and phase evaluation device: full information from a single hologram

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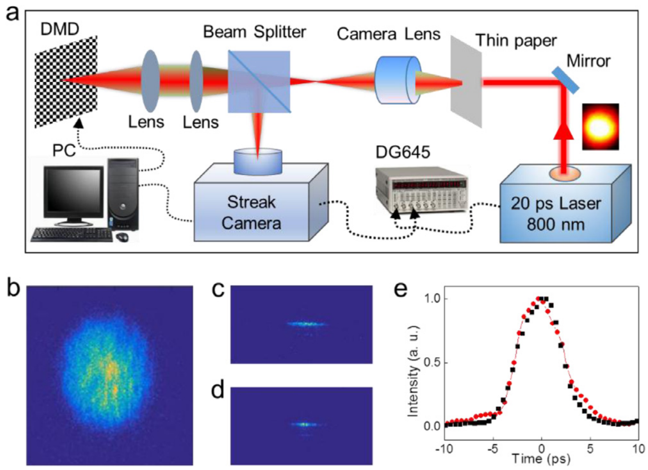

Fig. 1. Experimental arrangement for single-shot spatiotemporal intensity measurement of the picosecond laser pulses using a compressed ultrafast photography (a). DMD: digital micromirror device; PC: personal computer. The measured 2D laser spot by the steak camera (b). The measured 1D 5 ps laser pulses by the streak camera with (c) and without (d) the thin white paper. The extracted temporal intensity distributions from Fig. 1(c) (black squares) and (d) (red circles) (e). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(STRIPED FISH) to overcome the technical limitations of above measurement methods [8–11]. However, this technique introduced a reference laser pulse, which must be known in advance, and the spectral and spatial resolutions were limited by the bandwidth of the stock interference filter and the pixel number of the digital camera, respectively. Because of these intrinsic technical defects, the STRIPED FISH technique still has a long way to go for widespread applications.

In the study of the laser-matter interaction, various laser pulses were usually involved, such as single-color laser pulse, two-color laser pulses or supercontinuum laser pulse. The existing measurement techniques of the laser pulses have their own merits and demerits, and so it is difficult to find an approximate technique to simultaneously measure these laser pulses. Here, we propose a compressed ultrafast photography (CUP) technique to measure the spatiotemporal intensity information of the picosecond laser pulses. CUP is a single-shot and received-only ultrafast imaging technology [12,13], which can measure the x-y-t transient scenes with the temporal resolution of tens of picoseconds. In our method, by imaging the laser spot that is projected on a thin white paper using the CUP system, the laser spot evolution behavior can be extracted by a compressed sensing (CS) based image reconstruction method [14]. Compared with the STRIPED FISH technique mentioned above, our method does not need the reference laser pulse, which can provide the simpler measurement system. Furthermore, our method can measure the laser wavelength covering with a wide spectral range from ultraviolet (200 nm) to near infrared (850 nm). Based on our CUP system, we successfully measure the spatiotemporal intensity distributions of the near-infrared (800 nm), two-color (800 and 400 nm) and supercontinuum picosecond laser pulses.

2. Experiment

The schematic diagram of the experimental setup for the spatiotemporal intensity measurement of the picosecond laser pulses by using the CUP system is shown in Fig. 1(a). A Ti: Sapphire regenerative amplifier (Spectra-physics, Spitfire Ace-35F) is used to generate the picosecond or femtosecond laser pulses with the central wavelength of 800 nm and repetition rate of 1 kHz. Here, the laser pulse duration can be continuously varied from 50 fs to 20 ps by controlling the pulse compressor in the laser amplifier system. The output laser pulses are vertically illuminated on a thin white paper with the thickness of about 40 μm, and a small fraction of photons can pass through the white paper, thus the space-time-evolving laser spot on the white paper can be imaged using the CUP system. In the CUP system, the dynamic scene $I(x, y, t)$, i.e., the spatiotemporal intensity evolution of the laser pulses, is imaged via a camera lens and a 4f imaging system, and then is encoded in the spatial domain by a digital micromirror device (DMD) (Texas Instruments, DLP LightCrafter). DMD consists of tens of thousands of micromirrors, and each micromirror can be individually turned on or off. The encoded dynamic scene reflected from “on” micromirrors is collected by the same 4f imaging system, and finally is measured by a streak camera (Hamamatsu, C7700). In mathematics, the measured image $E(x, y)$ can be formulated as

$$\boldsymbol{E}(\boldsymbol{x},\ \boldsymbol{y}) = \boldsymbol{TSCI}(\boldsymbol{x},\ \boldsymbol{y},\ \boldsymbol{t}) \tag{1}$$

where $\boldsymbol{C}$ is the spatially encoding operator, $\boldsymbol{S}$ is the temporally shearing operator, and $\boldsymbol{T}$ is the spatiotemporally integrating operator. To recover the original dynamic scene, it needs to inversely solve Eq. (1). Here, a two-step iterative shrinkage/thresholding (TwIST) algorithm is employed [15], and is given by

$$\arg\min_{I}\left\{\frac{1}{2}||E-\boldsymbol{TSCI}||^2+\gamma\Phi(I)\right\}, \tag{2}$$

where $\Phi(I)$ is the regularization function in the form of total variation, and γ is the regularization parameter.

Considering that the temporal resolution of our CUP system is about 4 ps, which depends on the streak camera, we measure the spatiotemporal intensity evolution of the 20 ps laser pulse in order to better show the dynamic process. The measured dynamic laser spot by the CUP system is shown in Fig. 1(b). Because of the shearing operation in the streak camera, the measured laser spot becomes an ellipse from a circle. Based on the measured image $E(x, y)$ (see Fig. 1(b)) in the streak camera and the random codes on DMD, the spatial and temporal information of the laser pulses can be reconstructed. The streak camera is an ultrafast photodetection device, which can transform the temporal profile of a light signal into a spatial profile by shearing the photoelectrons to the vertical direction with a time-varying voltage. Therefore, it can be used to record the laser intensity evolution within the pulse duration when the incident slit is opened with a very small width [16]. This conventional function enables us to directly measure the laser pulse duration, which can serve as a reference in our subsequent 2D image reconstruction. It is worth noting that the incident slit of the streak camera is fully open in our CUP experiment, which is different from the use of traditional measurement method.

In our experiment, we place a thin white paper to project the spatial distribution of the laser pulses for imaging. To show that the thin white paper does not affect the measurement of the laser pulse duration, we measure the laser pulses in the cases of with and without the thin white paper. Here, we minimize the incident slit width of the streak camera for 1D measurement, and measure a 5 ps laser pulse, which is almost the measurable limit of our CUP system for 2D measurement. Fig. 1(c) and (d) show the measured 1D images of the 5 ps laser pulse by the streak camera with and without the thin white paper, respectively. To facilitate the comparison, we extract the temporal intensity distributions from Fig. 1(c) and (d), and the calculated results are shown in Fig. 1(e). It can be seen that the measured laser pulse durations keep unchanged with and without the thin white paper. Obviously, the thin white paper does not affect the 5 ps laser pulse, let alone the 20 ps laser pulse in our CUP experiment.

3. Results and discussion

3.1. Single-color laser pulse measurement

With the rapid development and gradual maturity of the laser technology, the ultrashort laser pulses have been widely applied to various related fields, such as ultrafast phenomena [17], material processing

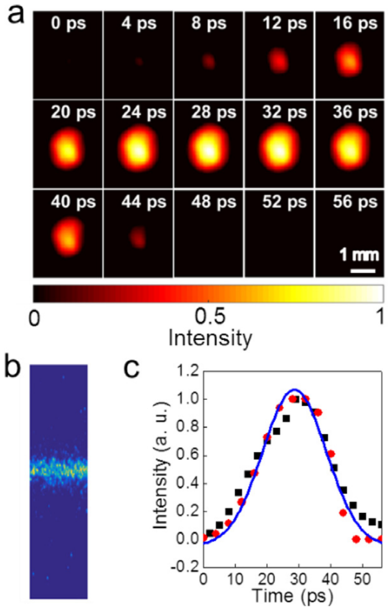

Fig. 2. Experimental results of the spatiotemporal intensity measurement of the 800 nm picosecond laser pulse. The 2D image reconstruction results by the TwIST algorithm (a). The direct 1D measurement result by the streak camera (b). The extracted temporal intensity distributions from Fig. 2(a) (red circles) and (b) (black squares), together with the Gaussian fitting (blue line) (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[18], precision surgery [19], optical communication [20], and so on. As well known, the ultrashort laser pulses have promoted the development of physics, biology, chemistry, materials and many other subjects. In turn, the advance of these subjects calls for some superior techniques to characterize the ultrashort laser pulses that we utilized. As mentioned above, many measurement techniques in the past decades gave us a new observation of the ultrashort laser pulses. However, due to the restriction of the spectral response, it is difficult for a fixed measurement device to capture a very wide wavelength laser pulses, such as the measurements of the ultraviolet and infrared laser pulses. In our CUP system, the measurable laser wavelength depends on the spectral response of the streak camera, which can cover from ultraviolet (200 nm) to near infrared (850 nm).

We measure the 20 ps laser pulse with the central wavelength of 800 nm by using our CUP system and reconstruct the spatiotemporal intensity evolution by the TwIST algorithm, and the reconstructed images at each moment are shown in Fig. 2(a). It can be seen that the whole evolution process from the appearance of the laser spot to disappearance can be clearly observed. More importantly, the spatial distribution of the laser spot at each moment can be well demonstrated. Obviously, the CUP technique can provide a powerful tool to obtain the spatiotemporal intensity evolution information of the picosecond laser pulses. In order to determine the laser pulse duration, we can extract the laser intensity evolution from Fig. 2(a), and the calculated result is shown in Fig. 2(c). It is evident that the measured laser pulse shape can well obey the Gaussian distribution in the time domain, which is fully consistent with the output characteristics of the laser pulses. For further validating the accuracy of our CUP system, we also measure the laser pulse duration with the streak camera, here the incident slit of the streak camera is limited to a small scale of a few microns, and therefore the traditional measurement method of the laser pulse duration is performed. The measured image is shown in Fig. 2(b). Similarly, the laser intensity evolution can also be extracted from Fig. 2(b), and the calculated result is also given in Fig. 2(c). Both the two measurement methods can obtain the temporal information of the picosecond laser pulses, but our CUP technique can simultaneously get the spatial information, which helps to promote the applications of the related fields.

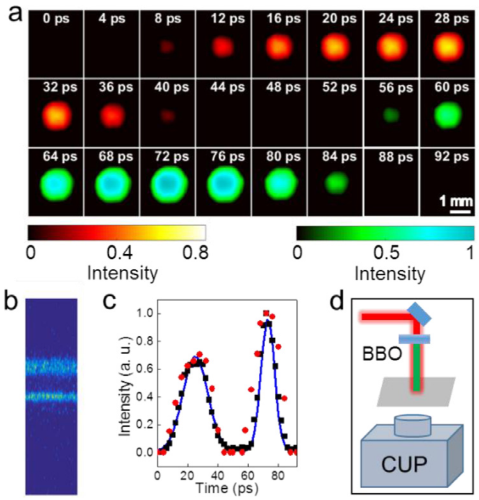

Fig. 3. The same as Fig. 2, but the spatiotemporal intensity measurement of the 800 and 400 nm two-color picosecond laser pulses. Here, the two-color laser pulses are obtained by the 800 nm picosecond laser pulse exciting the BBO crystal (d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Two-color laser pulse measurement

The two-color laser pulses have shown to be a well-established tool in controlling the nonlinear interaction processes of the laser and matter, such as terahertz radiation [21], or molecular orientation [22]. Here, the two-color laser pulses are the combination of the fundamental frequency laser and its second harmonic generation. The previous STRIPED FISH technique is sensitive to the laser central wavelength [8–11], and so it is difficult to cover the wide wavelength range of the two-color laser pulses. As shown in Fig. 2(a), the CUP technique has been proven to be able to measure the spatiotemporal intensity distribution of the single-color laser pulse. Since our CUP system can measure the laser wavelength covering a wide range from ultraviolet (200 nm) to near infrared (850 nm), the spatiotemporal intensity information of the two-color laser pulses can be obtained if the two laser wavelengths are both within this spectral range.

To verify the ability of our CUP system to measure the two-color laser pulses, we construct a two-color (800 and 400 nm) laser pulses by putting a BBO crystal in the optical path before the thin white paper, and the simple experimental arrangement is shown in Fig. 3(d). Due to the group velocity dispersion, the 800 nm laser pulse is faster than the 400 nm laser pulse. Fig. 3(a) shows the reconstructed results by the TwIST algorithm based on our experimental data. Two laser pulses are obviously observed, and the former pulse comes from the 800 nm laser, while the latter one comes from the 400 nm laser. Moreover, the pulse duration of the 400 nm laser is slightly smaller than that of the 800 nm laser, which should be due to the laser intensity threshold limit in the second harmonic generation. Similarly, we also measure the temporal distribution of the two-color laser pulses by the streak camera to validate the accuracy of our image reconstruction, and the measured result is shown in Fig. 3(b). As expected, the two laser pulses are clearly observed. In order to make a better comparison, we extract the laser intensity distributions from Fig. 3(a) and (b), and the calculated results are shown in Fig. 3(c). The calculated results by the two measurement methods are in good agreement, which further proves the feasibility of the CUP technique.

The spectral response of our CUP system can cover a wide range from ultraviolet (200 nm) to near infrared (850 nm), thus our CUP system can be applied to the spatiotemporal intensity measurement of the multi-color laser pulses as long as all the laser wavelengths are within this spectral range, such as the conventional four-color laser pulses with the wavelengths of 800, 400, 266 and 200 nm, which can be obtained by the harmonic generation of the 800 nm laser pulse from Ti: Sapphire regenerative amplifier [23]. Furthermore, our CUP system occupies a two-dimensional measurement, and therefore can measure the arbitrary space and time shapes of the picosecond laser pulses within the temporal resolution of the streak camera (4 ps).

3.3. Supercontinuum laser pulse measurement

The supercontinuum generation is a significant nonlinear optical process, in which a narrowband laser pulse can efficiently evolve into a relatively broadband laser pulse. The supercontinuum laser pulse has a large range of applications, such as stimulated emission depletion microscopy [24], optical coherence tomography [25], and optical rogue waves [26], and so on. However, the supercontinuum laser pulse is extraordinarily complex and unstable in the time domain [27]. Usually, the measurement of the supercontinuum laser pulse needs to average over many times, and obtains an estimation of a typical result [28–31]. The multiple shot measurement will bring a lot of artifacts and cover the complexity of the laser pulses itself. It has never come true to measure the temporal intensity of the supercontinuum laser pulse with a single shot until a cross-correlation frequency-resolved optical gating (FROG) technique was proposed [32], which can achieve a wide spectral range by using a polarization-gating geometry and a large temporal range by significantly tilting the reference pulse. However, this technique can only measure the temporal information of the supercontinuum laser pulse, but cannot get the spatial information. Here, our CUP technique can solve the spatiotemporal distribution measurement of the supercontinuum laser pulse.

We conduct the experiment of the supercontinuum laser pulse generation by focusing an intense 800 nm picosecond laser into a cuvette containing water via a lens with the focal length of 300 mm. In the same way, the supercontinuum laser pulse is vertically illuminated on the thin white paper, and the CUP system measures the spatiotemporal distribution, as shown in Fig. 4(d). In this experiment, the supercontinuum spectrum is about within the range of 460 to 860 nm, which almost can be covered by the spectral response of our CUP system. Fig. 4(a) shows the image reconstruction results with the spatiotemporal intensity evolution of the supercontinuum laser pulse by the TwIST algorithm. Compared with the original 800 nm picosecond laser pulse in Fig. 2(a), the supercontinuum laser pulse is stretched due to the self-phase modulation under the strong laser field. Obviously, the CUP technique can well reconstruct the spatiotemporal intensity information of the supercontinuum laser pulse. Similarly, we also give the 1D measurement result by the streak camera for comparison, as shown in Fig. 4(b). Fig. 4(c) presents the extracted temporal intensity distributions from Fig. 4(a) and (b). It is easy to see that these two measurement results can fit well with each other. In addition, this experiment also reveals that the CUP technique has the ability to measure the supercontinuum laser pulse in both the time and space domains with a single shot.

3.4. Technical limitation and strategy

As shown in Figs. 2–4, the CUP technique provides a well-established tool to measure the spatiotemporal intensity information of the picosecond laser pulses. However, a disadvantage is that it cannot obtain the related phase information. In our experiment, the temporal resolution of the CUP system is 4 ps, which is limited by the streak camera, and therefore only the laser pulses with tens of picoseconds can be measured. Recently, Liang et al. used an updated streak camera (Hamamatsu, C6138) to achieve the temporal resolution of 100 fs [33]. Moreover, we proposed a multiple encoding imaging method to break the temporal resolution [34]. The spatial resolution of the CUP system can be adjusted by varying the focal length of the camera lens, but the size of the field of view will be correspondingly changed. In this work, we can improve the spatial resolution by varying the laser beam size to match the field of view. Our CUP system can measure the laser pulses with a very wide spectral range from 200 to 850 nm, which depends on the spectral response of the streak camera, but it has no spectral resolution. Combining with a spectrometer, CUP can realize the laser pulse measurement with the spectral resolution. In the future study, we look forward to making more improvement and exploiting more applications of the CUP technique.

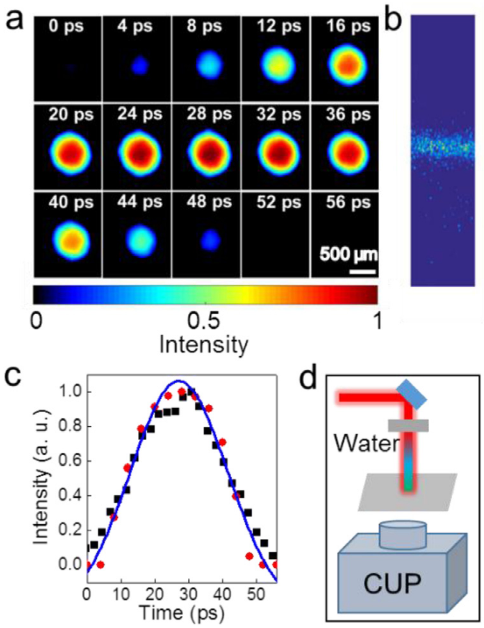

Fig. 4. The same as Fig. 2, but the spatiotemporal intensity measurement of the supercontinuum picosecond laser pulse. Here, the supercontinuum laser pulse is generated by the intense 800 nm picosecond laser pulse propagating in the water (d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

In summary, we have demonstrated a very simple and practical CUP technique to measure the arbitrary spatiotemporal intensity distribution of the picosecond laser pulses with a single shot. Our CUP system can measure the complex laser pulses with a wide spectral range from ultraviolet (200 nm) to near infrared (850 nm). We have successfully obtained the spatiotemporal intensity information of the 800 nm picosecond laser pulse, the 800 and 400 nm two-color picosecond laser pulses and the supercontinuum picosecond laser pulse by using our CUP system. The temporal and spectral responses of our CUP system depend on the performance of the streak camera. By replacing another type of streak camera, our CUP system can be further applied to measuring the extreme ultraviolet or infrared picosecond and even femtosecond laser pulses. We hope this CUP technique can open up some new applications in the spatiotemporal intensity measurement of the laser pulses involving the laser fusion laser or free electron laser in the near future.

Acknowledgments

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.optlaseng.2019.01.002.

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