Single-shot ultrafast imaging using parallax-free alignment with a tilted lenslet array

Barmak Heshmat[1,*], Guy Satat[1], Christopher Barsi[1], Ramesh Raskar[1]

[1]*Media Lab, Massachusetts Institute of Technology, 02139, Cambridge, MA, USA*
**barmak@mit.edu*

Abstract: We have used tilted lenslet arrays in a parallax-free configuration along with a streak camera to record streak images of a scene that contain spatial 2D and time information of the illuminated scene. We cover the optical design of such system in paraxial approximation and use the proposed geometry to experimentally verify the concept. The alignment geometry for a parallax-free condition is revealed, the results show the significant potential of this technique for recording irreversible ultrafast phenomena in different applications such as study of plasma discharge, ultrafast photochemistry and cavitation bubbles.

OCIS codes: (3006495) spectroscopy, (1605140) streak imaging, (0402235) ultrafast optics

1. Introductions

Ultrafast imaging is an emerging technique for recording a scene with ultrafast dynamics. Such technique has been used extensively in photochemistry [1]. Since limited electronics can be used to detect such high temporal resolutions, streak cameras are still one of the only devices capable of recording with 2ps time resolution. Unfortunately streak tubes provide only single horizontal line due to principles of electron deflection used in the CRT tubes of the streak camera. This problem has triggered researchers to use other types of techniques to capture the missing vertical dimension of the scene. Among the previous methods rotating mirrors [2], dispersive Fourier transform [3], and pinhole arrays have been proposed for visible and X-ray streak imaging [4]. Here we propose using tilted lenslet array along with a streak camera. Lenslet arrays have higher efficiency than pinholes and can potentially provide better spatial resolution. Unlike the rotating mirrors, with this technique the images can be recorded in single shot that is necessary for irreversible ultrafast phenomena.

As seen in Fig. 1 (a) the setup uses a simple diffused femto-second pulse illumination for the object. The image is then captured by a tilted lenslet array as shown in Fig. 1 (b). Due to the lenslet tilt, each lenslet image is projected at a different height on the input slit of the streak camera and thus both horizontal and vertical information are recorded in this multiplexed streak image.

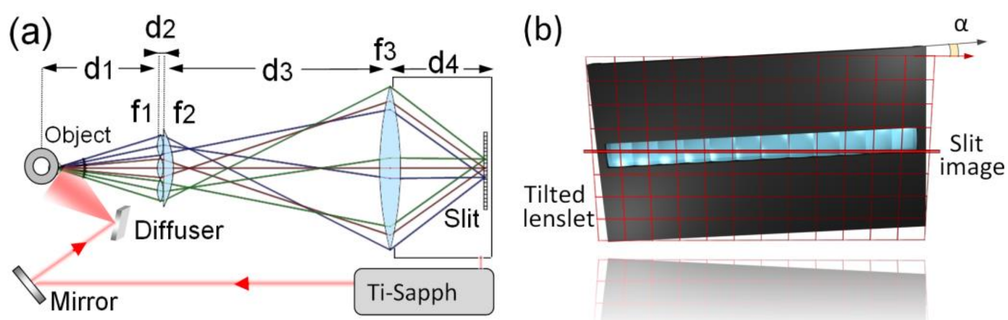

Figure 1. (a) Schematic of the single shot setup. The object is illuminated with diffused 50 fs pulses at 795 nm wavelength and 80MHz rep. rate that are generated with a Ti-Sapphire laser (Ave. power ≈ 800mW). The streak camera and the laser are synchronized. (b) 3D model of lenslet tilted around the optical axis. Each lenslet has the diameter of D=3.4mm.

2. Parallax-free condition

The images formed by the lenslets should differ only in vertical position and very slightly in angle of view, thus they must be parallax free with the object exactly at the same location in each image. Unlike the vignetteing and aberration that require additional optical elements to be compensated, the relative parallax of the images captured by each lenslet can be removed by initial alignments. Using an extension of ray transfer matrix analysis for the case with a lenslet array the imaging condition and the parallax free alignment are found to be:

$$\text{imaging condition}: \frac{1}{f_1}+\frac{1}{f_2}-\frac{1}{d_1}=\frac{1}{1/(1/d_4-1/f_3)+d_3},\quad \text{parallax}-\text{free condition}: \frac{1}{f_2}=\frac{1}{d_1}+\frac{1}{d_3-f_3}.$$

Where the parameters are as in Fig. 1 (a). When imaging a point source in parallax-free alignment the cone of light should be identical for each lenslet and therefore the incident angle of each lenslet chief ray is identical and perpendicular to the slit plane (chief ray angle = 0) as shown with green dots in Fig. 2 (a). Fig 2 (b) further investigates the parallax-free condition (PFC) and shows variations in adjacent chief ray angles with regard to alignment geometry.

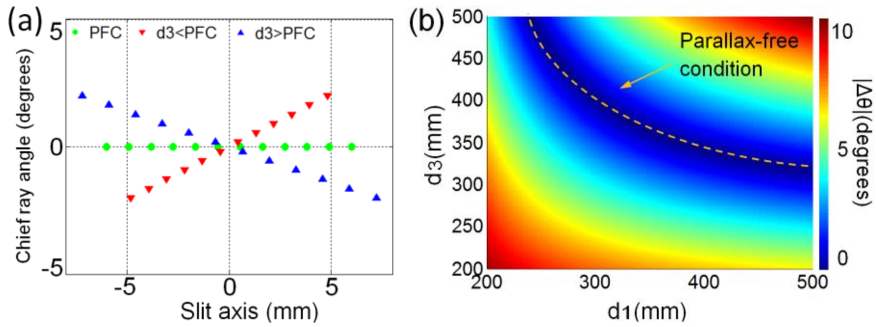

Figure 2. (a). Chief ray angle variations for each lenslet along the slit. Green dots shows PFC, red and blue markers shows two cases where the PFC does not hold. The slit length is 15mm. (b) Choosing f1=20mm, f2= 150mm, f3= 100mm, and lenslet diameter D=20mm, d2=0, the variation between adjacent chief ray angles is shown in degrees (d4 is forced by the imaging condition-not shown).

3. Results and discussion

Using the setup in PFC alignment the results are obtained as seen in Fig. 3 (a). The image of a ring is captured in a single shot. By stitching back the lines related to each height, the image is reconstructed at each time instance. This provides a real-time imaging that can be recorded live as a video with 0.5×10^{12} frames per second. Fig 3 (b) shows the results for the ring in three different time instances. By similar geometry we also imaged laser induced plasma discharge in air with time resolution equal to that of the streak camera (results not included in this summary).

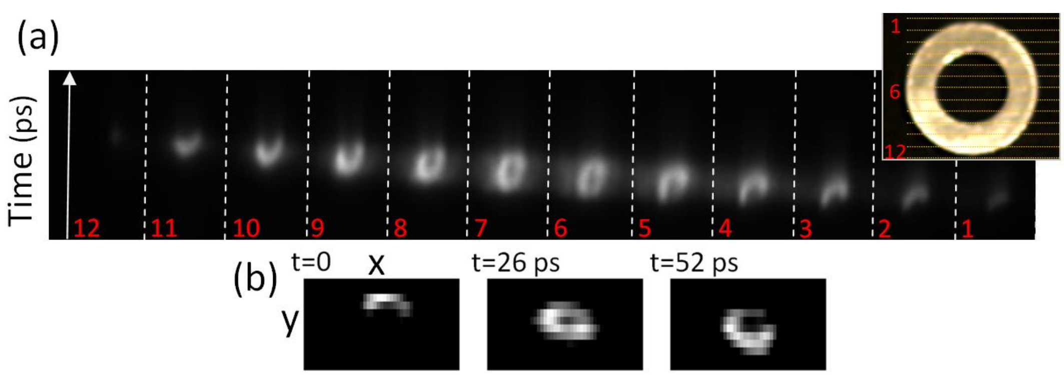

Figure 3 (a) Measured results for an aluminum ring illuminated with diffused 50 fs IR pulses. The image is a single shot showing the encoded 2D information along the horizontal axis (each section relates to a different height of the object) as well as the time information along the vertical axis. The inset image shows the ring and how each horizontal cross section is captured in a single streak image. (b) Image of the ring captured with 2ps time resolution with a single shot streak image. We used 105mm Nikon camera lens as f3, the lens was focused at 390mm, d1 was 350mm, d2 was 0, and d3 was 320mm. Lenslet array tilt angle was 2 degrees.

4. Summary of results

We have designed and applied an imaging technique that is capable of capturing 2D scene in single shot with 2ps time resolution. The results are experimentally demonstrated for a metallic ring illuminated with fs pulses and are extendable to irreversible ultrafast phenomena in photochemistery, plasma filamentation and cavitations bubbles.

5. References

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