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

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

[1]*Media Lab, Massachusetts Institute of Technology, 77 Massachusetts Ave., 02139, Cambridge, MA, USA*
**barmak@mit.edu*

Abstract: We demonstrate single-shot, two-dimensional imaging of ultrafast phenomena using a streak camera and a tilted lenslet array. We derive conditions for parallax-free imaging and experimentally verify the geometry by observing scattering of femtosecond pulses.
OCIS codes: (300.6495) Spectroscopy; (160.5140) Streak imaging; (040.2235) Ultrafast optics.

1. Introduction

Ultrafast imaging allows for observation of picosecond-scale dynamics and has been implemented in fields such as photophysics, photochemistry [1] and macroscopic light transport [2]. Because CCDs cannot achieve such high temporal resolution directly, other methods must be employed to capture two-dimensional (2D) ultrafast phenomena. For example, serial time-encoding acquires 2D images [3] but is limited to ~100 ps shutter speeds. On the other hand, a streak camera resolution is better than 2 ps; however, because of its operating principles, it is limited to a one-dimensional field of view. Recent work has used repetitive sampling via rotating mirrors to acquire the missing vertical dimension, but this multi-shot technique precludes single-shot imaging [2].

We propose here using a tilted lenslet array with a streak camera to record 2D scenes of ultrafast events in a single shot with picosecond resolution. Each lenslet array projects an image at a different height onto the slit aperture of the streak camera, so that both horizontal and vertical information are recorded in a single, multiplexed streak image. Besides providing higher efficiency and resolution than pinhole arrays [4], this technique allows for single-shot recording, which is necessary for observing irreversible ultrafast phenomena, such as laser ablation, sonoluminescence, and laser-induced plasma discharge.

2. Experimental setup: parallax-free condition

As seen in Fig 1. (a), a diffused femtosecond pulse illuminates the object. The image is then captured by a tilted lenslet array (Fig. 1 (b)). A pair of relay lenses image the lenslet array image plane onto the streak camera's slit aperture. For accurate reconstruction, the lenslet images must be parallax-free, i.e., they should differ only in vertical position and only slightly in angle of view.

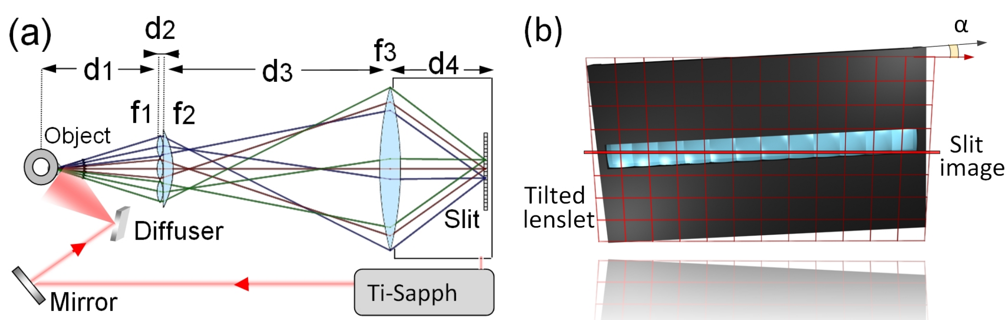

Fig. 1 (a) Schematic of the single-shot setup. The object is illuminated with diffused 50 fs pulses at 795 nm wavelength and 80 MHz rep. rate that are generated with a Ti-Sapphire laser (average power ≈ 800mW). The streak camera and the laser are synchronized. (b) 3D model of lenslet tilted around the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

Unlike vignetteing and aberration, which require compensating optical elements, 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 (IC) and the parallax-free condition (PFC) are found to be:

$$\text{IC: } \frac{1}{f_1}+\frac{1}{f_2}-\frac{1}{d_1}=\frac{1}{\left(1/d_4-1/f_3\right)^{-1}+d_3}, \qquad \text{PFC: } \frac{1}{f_2}=\frac{1}{d_1}+\frac{1}{d_3-f_3}, \tag{1}$$

where the parameters are denoted in Fig. 1 (a). When imaging a point source in the PFC, the cone of light for each lenslet is identical. Therefore, the incident angle of each lenslet chief ray is identical and perpendicular to the slit plane (chief ray angle = 0°, green dots in Fig. 2 (a)). Fig 2 (b) further investigates the PFC and shows variations in adjacent chief ray angles due to alignment geometry.

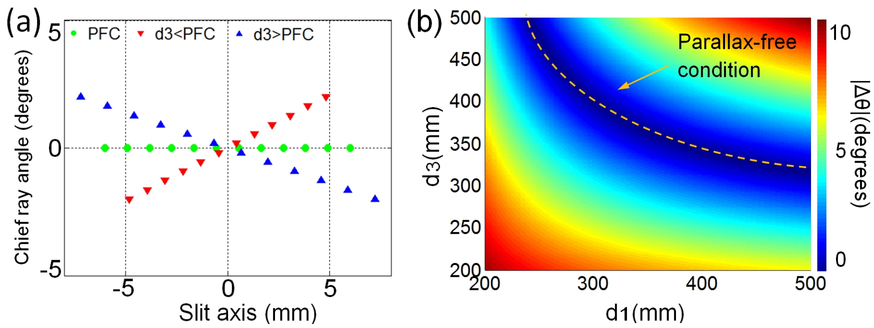

Fig. 2 (a) Chief ray angle variation for each lenslet along the slit. Green dots show PFC; red and blue markers show two cases where the PFC does not hold. The slit length is 15mm. (b) Choosing f_1=20mm, f_2= 150mm, f_3= 100mm, and lenslet diameter D=20mm, d_2=0, the variation between adjacent chief ray angles is shown in degrees (d_4 (not shown) is forced by the imaging condition in Eq. 1).

3. Results and discussion

The results of the setup in PFC alignment are shown in Fig. 3 (a). The image of a ring is captured in a single shot. Each horizontal section of the single streak image contains the complete time profile of a different horizontal slice of the object. Stacking up the sub-images in each instance provides a full 2D movie with a time resolution of 2 ps per frame and 512 frames in total. Example frames of the ring are shown in Fig. 3 (b). We use a similar geometry to image laser-induced plasma discharge in air with time resolution equal to that of the streak camera.

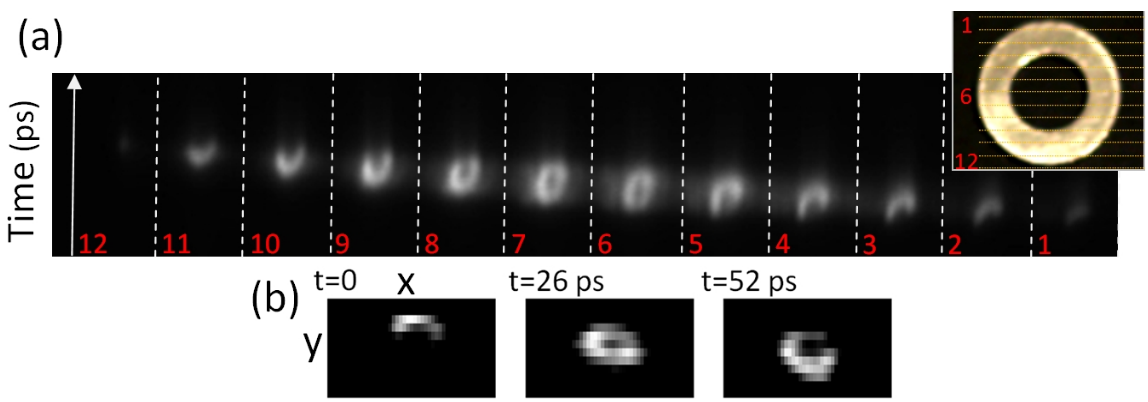

Fig. 3 (a) Measured result for an aluminum ring illuminated with diffused 50 fs IR pulses. The image is a single shot, showing the encoded 2D information along the horizontal axis (each section relates to a different height of the object) as well as the time information along the vertical axis. The inset image shows the ring and each horizontal cross section captured in a single streak image. (b) Individual frames of the ring captured with 2 ps time resolution reconstructed from the single-shot streak image (a). We used a 105mm Nikon camera lens as f_3; the lens was focused at 390 mm, with d_1 = 350 mm, $d_2 \approx 0$ mm, and d_3 = 320mm. The lenslet array tilt angle was 2°.

4. Summary

We have designed and applied an imaging technique that is capable of capturing 2D scene in single shot with 2 ps 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 cavitation bubbles.

5. References

[1] P. R. Poulin, and K. A. Nelson, “Irreversible organic crystalline chemistry monitored in real time,” Science 313, 1756–1759 (2006).

[2] A. Velten, D. Wu, A. Jarabo, B. Masia, C. Barsi, C. Joshi, E. Lawson, M. Bawendi, D. Gutierrez, and R. Raskar, “Femto-photography: capturing and visualizing the propagation of light,” ACM Trans. Graph. 32, 44 (2013).

[3] K. Goda, B. Jalali, “Dispersive fourier transformation for fast continuous single-shot measurements,” Nat. Phot. 7, 102-113 (2013)

[4] H. Shiraga, M. Heya, A. Fujishima, O. Maegawa, K. Shimada, Y. Kato, T. Yamanaka, and S. Nakai, “Laser-imploded core structure observed by using two-dimensional x-ray imaging with 10-ps temporal resolution,” Rev. Sci. Instrum. 66, 772-724 (1995).