Various ultra-high-speed imaging and applications by Streak camera

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Abstract In established theory; two-dimensional imaging using a streak camera is not possible due to restrictions on traditional streak camera design such as entrance slit limitations. Efforts to develop and use streak cameras for two-dimensional high-speed imaging have been ongoing for the past several decades. In 1990, a framing camera using a modified streak tube was developed by Hamamatsu Photonics K.K., Japan, which could capture 3 million frames per second but at only 8 frames per shot. Another early development was Shiraga et al.'s two-dimensional X-ray imager that was capable of 10 ps time resolution and used a multi-pinhole photocathode surface [1]. Since then, the technology for high-speed photography using streak cameras have evolved step-by-step. However, recent advances have resulted in superior performance. In 2014, Gao et al. developed a single-shot compressed ultrafast photography with 100 billion frames/sec [2]. In 2012, Velten et al. successfully developed the one trillion frame per second video camera [3] [4], or so called femto-photography, that uses a sampling method. In this paper, we describe the principles and applications of streak tubes for high-speed, two-dimensional imaging.

Keywords: Streak camera, High Speed imaging, Compressed Ultrafast Photography

1. Introduction

In 2012 Velten et al. used a synchroscan type streak camera to capture two-dimensional images at one trillion frames per second [3] [4] and demonstrated visualization of three-dimensional object hidden around a corner [5]. On the other hand, in 2014 Gao et al., using a single-sweep type streak camera, demonstrated compressed ultrafast photography [CUP] at 100 billion frames/sec [2]. These two epoch-making imaging inventions using conventional streak cameras have been achieved in relatively quick succession. Efforts in imaging technology using streak cameras have been ongoing for several decades, and these two recent reports of innovative technology have opened the possibilities for future applications. Other imaging techniques using streak camera technology have also been reported over the past several years and also are an effective means to apply new applications.

In this paper, we review these various imaging technique that uses basic streak camera technology and streak camera.

2. Spatially Time-Resolved Measurement by Streak Camera

The ultrafast streak camera has become one of the most versatile instruments for the measurement of the dynamic behavior luminous events. The advantages are the ability to determine the optical temporal profile directly, with excellent time resolution up to 200 fs [6], wide time ranges and superior sensitivity and wide wavelength range from X-ray to NIR. When positioning an objective lens in front of the streak camera to relay an object image to the streak slit, it can perform a spatially time-resolved measurement. However, only narrow slit image (20 um to 100 um) can be input to the streak camera for this measurement. It cannot measure temporal profiles precisely with slit widened due to the mixture of temporal and spatial information of the object image.

The data output of streak camera is 2-D image. X axis is space, Y axis is time, and intensity of image is related incident light intensity. Figure1 [a] shows example of framing image for plasma with objective area for streak camera. There is no plasma at t0, then the size of plasma is increasing from t1 to t5 and finally, there is no plasma at t6. Figure1 [b] shows streak image when such plasma measurement by streak camera.

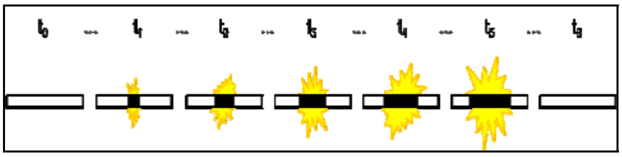

Figure1 (a) example plasma framing image with observed streak slit area

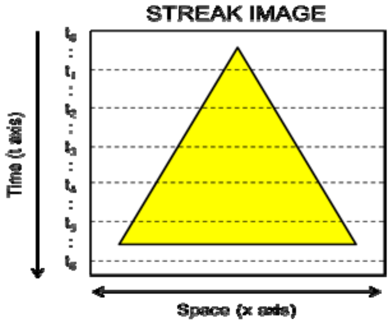

Figure1 (b) Streak image

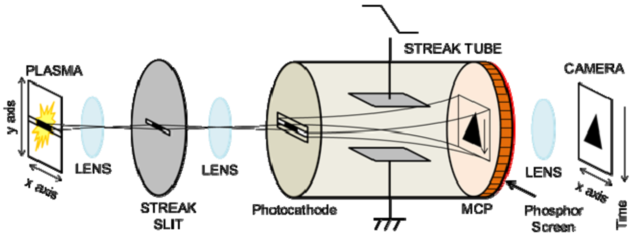

Figure1 (c) The operating principle of the streak camera

3. Two dimensional High speed imaging by streak camera

As described above principle, it seems impossible to realize a two dimensional imaging using streak camera. A brute force method is using several units of streak camera that can be taken several different positions of space-time resolved images. However it's not realistic due to poor vertical space resolution and also the economic rea-son. Still challenge of two-dimensional imaging technology developed by taking advantage of high time resolution with a streak camera is been done for a long time, several approaches have been implemented devised.
Table1 summarized typical techniques and characteristics of the imaging technique using a streak camera.

High speed imaging method	Time resolution (Exposure time)	No. of Frames	Single shot
Multi-imaging x-ray streak camera (MIXS)	11.7 ps	> 15	Yes
Single-shot ultrafast imaging using parallax-free alignment with a tilted lenslet array	2 ps	512	Yes
Two-dimensional sampling image x-ray streak camera (2D-SIXS)	2 ps		Yes
One trillion frame per second video camera (Femto-photography)	1.71 ps	≤ 480	No
A single-shot compressed ultrafast photography (CUP)	35 ps	≤ 350	Yes

Table 1 imaging techniques and characteristics

3-1. Multi-imaging x-ray streak camera (MIXS)

Shiraga et al. have developed Multi-imaging x-ray streak camera [MIXS] with 10 ps time resolution which could take time –resolved 2D X-ray plasma images with 11.7 ps exposure time and 8.7 ps frame interval [8]. The greatest feature of this method is relay the plasma images to the different horizontal position of photocathode of streak tube using pinhole array. Image array is tilted from the photocathode slit. Thus, each slit image can have different positions of the source separated by a constant vertical distance.
Figure 2 shows the principle of the MIXS. And Figure 3 shows an example of the reconstructed MIXS images.

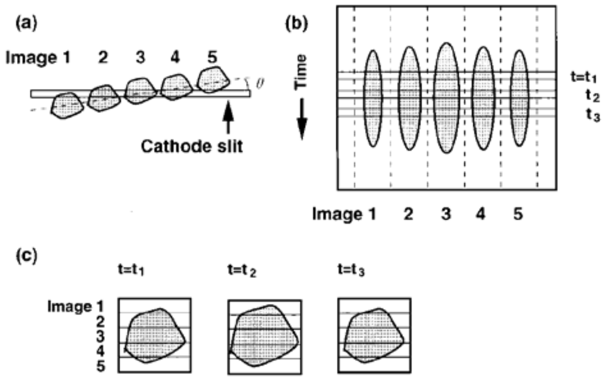

Figure. 2

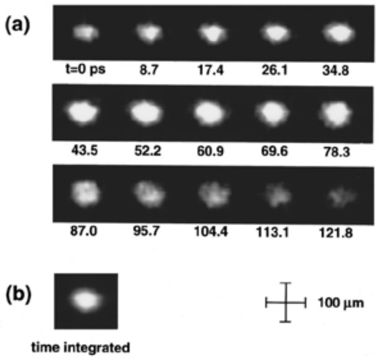

Figure. 3

Figure 2. Principle of MIXS and 2D image reconstruction. (a) Multiple-image array aligned on the photocathode slit with a tilting angle θ. (b) Timeresolved images are obtained by streaking the camera. (c) Time-resolved 2D images are reconstructed by rearranging the images sliced at t=t1 ,t2 ,... .
(Figure 2 is reprinted of Rev. Sci Instrum. : Shiraga, H. et al. 68, 745-749 (1997)])

Figure. 3. Reconstructed MIXS images. (a) Time-resolved images. Relative time is indicated. Framing interval is 8.7 ps and exposure time of each framing is 11.7 ps. (b) Time-integrated image of MIXS obtained by accumulating the MIXS data. (Figure 3 is reprinted of Rev. Sci Instrum. : Shiraga, H. et al. 68, 745-749 (1997)])

3-2. Single-shot ultrafast imaging using parallax-free alignment with a tilted lenslet array

S Heshmat, B., et al. developed single shot, two –dimensional imaging of ultrafast measurement, 2 ps frame inter-val and 512 frames in total [9]. The main difference to MIXS by Shiraga's method is visible light instead of X-ray and using Tilted lenslet array instead of pinhole lens array.

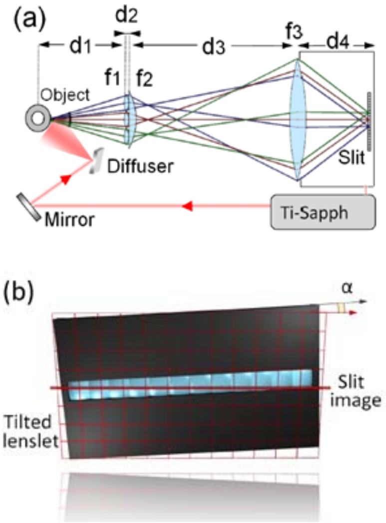

Figure. 4 (a) Schematic of the single-shot setup. The object is illuminated with diffused 50 fs pulses at 795 nm wavelength and 80 MHz rep. rate that are generated with a Ti-Sapphire laser [average power ≈ 800mW]. The streak camera and the laser are synchronized. (b) 3D model of lenslet tilted around the optical axis. Each lenslet has the diameter of D = 3.4mm. (Figure 4 is reprinted of CLEO Sci. Innov. : Heshmat, B., et al., (2014).)

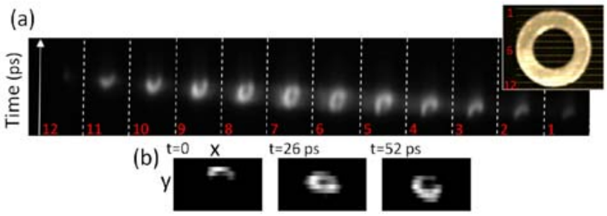

Figure. 5 (a) Measured result for an aluminum ring illuminated with diffused 50 fs IR pulses. The image is a single shot, showing the encoded 2D information along the horizontal axis [each section relates to a different height of the object] as well as the time information along the vertical axis. The 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 f3; the lens was focused at 390 mm, with d1 = 350 mm, d2 ≈ 0 mm, and d3 = 320mm. The lenslet array tilt angle was 2°. (Figure 5 is reprinted by CLEO Sci. Innov. : Heshmat, B., et al., (2014).)

3-3. Two-dimensional sampling image x-ray streak camera (2D-SIXS)

Shiraga et al. proposed two-dimensional sampling image x-ray streak camera (2D-SIXS) which has large photo-cathode with 30 X 30 sampling points [1]. One of the key technique of this method is select the proper time range for observed plasma time profile in order to avoid the overlapping the streak images at other sampling point.

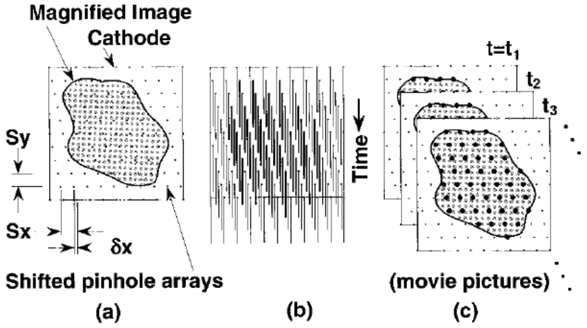

Figure 6. Principle of 2D-SIXS.
(a) Distributed sampling points on the photocathode.
(b) Streaked image of the sampling points.
(c) Reconstructed 2D images at selected times.
(Figure 6 is reprinted of Rev. Sci Instrum. : Shiraga, H. et al. 68, 745-749 (1997))

3-4. Femto-Photography

Two-dimensional imaging technique of one trillion frames per second, which is reported by the MIT been featured in various media, also paper that has been announced as the application [2] it became a big topic. This technique is called A trillion per frame per second video camera or Femto Photography [3,4,5]. The main component of this method is femtosecond laser, scanning mirrors, synchroscan streak camera. It is a measurement by the integration, rather than a single shot, is a method for obtaining an image by shifting the observation location little by little by also scanning mirror. It can be performed ultrahigh sensitivity and good SN imaging is characterized.

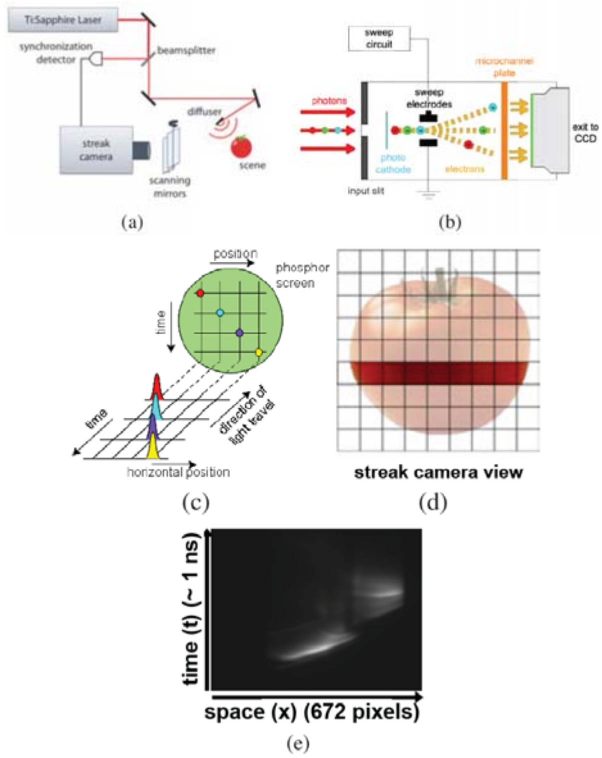

Figure 7 Setup for capturing a single 1D space-time photo. (a) A laser beam strikes a diffuser, which converts the beam into a spherical energy front that illuminates the scene; a beamsplitter and a synchronization detector enable synchronization between the laser and the streak sensor. (b) After interacting with the scene, photons enter a horizontal slit in the camera and strike a photocathode, which generates electrons. These are deflected at different angles as they pass through a microchannel plate, by means of rapidly changing the voltage between the electrodes. (c) The CCD records the horizontal position of each pulse and maps its arrival time to the vertical axis, depending on how much the electrons have been deflected. (d) We focus the streak sensor on a single narrow scan line of the scene. (e) Sample image taken by the streak sensor. The horizontal axis (672 pixels) records the photons' spatial locations in the acquired scanline, while the vertical axis (1 nanosecond window in our implementation) codes their arrival time. Rotating the adjustable mirrors shown in (a) allows for scanning of the scene in the y-axis and generation of ultrafast 2D movies such as the one visualized.
(Figure 7 is reprinted of Velten, A. et al. Femto-Photography: Capturing and Visualizing the Propagation of Light, http://giga.cps.unizar.es/~diegog/ficheros/pdf_papers/femto.pdf. Figure 7 (a)-(d), credit: (Gbur 2012 [10]))

3-5. Single-shot compressed ultrafast photography at one hundred billion frames per second

Gao et al. developed a single-shot compressed ultrafast photography with 100 billion frames/sec [2]. The result-ant system can capture a single, non-repetitive event at up to 100 billion frames per second with appreciable sequence depths [up to 350 frames per acquisition].

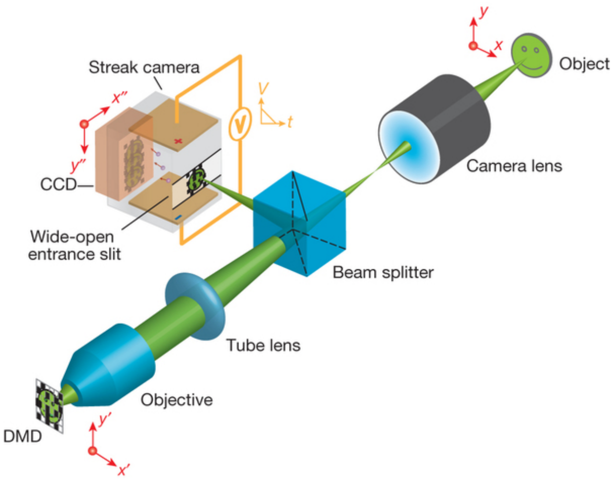

Figure 8 CUP system configuration.

CCD, charge-coupled device; DMD, digital micromirror device; V, sweeping voltage; t, time. Since each micromirror (7.2 mm X 7.2 mm) of the DMD is much larger than the light wavelength, the diffraction angle is small (~4°). With a collecting objective of numerical aperture NA50.16, the throughput loss caused by the DMD's diffraction is negligible. See text for details of operation. Equipment details: camera lens, Fujinon CF75HA-1; DMD, Texas Instruments DLP LightCrafter; microscope objective, Olympus UPLSAPO 43; tube lens, Thorlabs AC254-150-A; streak camera, Hamamatsu C7700; CCD, Hamamatsu ORCA-R2. (Figure 8 is reprinted of Gao, L. et al. Single-shot compressed ultrafast photography at one hundred billion frames per second, Nature 516, 74-77 (2014])

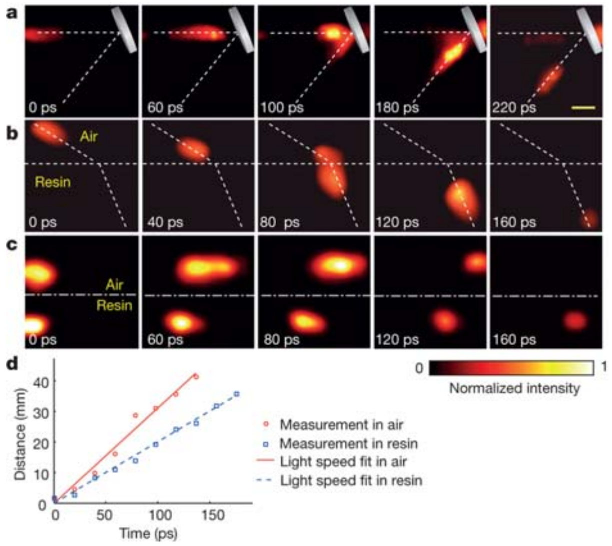

Figure 9. CUP of laser pulse reflection, refraction, and racing in different media.

a, Representative temporal frames showing a laser pulse being reflected from a mirror in air. The bright spot behind the mirror is attributed to imperfect resolution. b, As a but showing a laser pulse being refracted at an air–resin interface. c, As a but showing two racing laser pulses; one propagates in air and the other in resin. d, Recovered light speeds in air and in resin. The corresponding movies of these three events (a, b, c) are shown in Supplementary Videos 2, 3 and 4. Scale bar (in top right subpanel), 10mm. (Figure 9 is reprinted of Gao, L. et al. Single-shot compressed ultrafast photography at one hundred billion frames per second, Nature 516, 74-77 (2014))

3-6. Other methods

In high speed imaging using streak tube, there are other methods. Using bundle fiber (2D for object and 1D for streak input) method is reported by Kodama R. et al. [11], The step voltage is applied to V and H plates with MCP shuttering method that is Framing streak camera is reported by Takeshita T. et al. [12], and Femtosecond laser flashed frame imaging was also developed by Takiguchi et al. [13]. Refer each paper for details..

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