doi:10.3788/gzxb20154409.0930002

基于面阵 CCD 的高时间分辨瞬态光谱探测技术

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摘 要:为了提高 CCD 的扫描速率并将其应用于百纳秒级瞬态超快现象的探测,提出一种基于面阵 CCD 的高时间分辨的瞬态光谱测量方法,并对其进行了实验验证.该方法采用帧存储的工作思路,对面阵 CCD 的工作时序进行改进,以实现高时间分辨率的探测.LED 脉冲光实验结果表明,探测帧频可达 10 Mfps,时间分辨率达到 100 ns,并且能够连续成像 2 048 次.该方法对扩展 CCD 在瞬态光谱检测领域的应用具有借鉴意义.

关键词:瞬态光谱检;电荷耦合器件;超快扫描;驱动时序;爆发式存储

中图分类号:TN29 **文献标识码**:A **文章编号**:1004-4213(2015)09-0930002-5

High Time Resolved Transient Spectrum Detection Technique Based on Area CCD

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Abstract: To raise the scan rate of CCD and apply to the hundred nanosecond scale transient phenomena detection, a transient spectrum detection method with high time resolution was proposed and demonstrated by experiment, based on area CCD. By reforming time sequence of CCD and utilizing principle of frame restore, detection with high time resolution was achieved. LED impulse light experiment was performed to demonstrate feasibility of the method. Experiment results show that this transient phenomena acquisition method based on area CCD is efficacious. Detection frame rate can be as high as 10 Mfps. Time resolution is less than 100 ns, and can be able to image 2 048 frames continuously. The experiment is of importance to expand application of CCD in the transient spectrum detection area.

Key words: Transient spectrum detection; Charge Couple Device; High speed scan; Drive sequence; Burst restore

OCIS Codes: 300.6530; 320.7100; 040.1520; 040.1880; 040.6070

0 Introduction

Image sensing technique with high space and time resolution has been a hot spot in scientific research. More and more scientific researches need an even higher spatial or time resolution.

In many scientific researches, high speed detection is performed on some transient physical processes such as explosion, shock wave and high voltage discharge. Spectrum acquisition is the main method to analyze and study these transient processes[1]. So, it's obvious that improving high speed solid state image sensing technique is of importance.

Currently, scan rate of linear CCD can only reach 70 kHz, and has been used in some transient spectrum acquisition system[2]. However, time resolution of these CCD is still too low to satisfy the necessity of high speed transient imaging (with time resolution less than 10 μs).

To raise frame rate of CCD, some efforts have

Foundation item: The National Natural Science Foundation of China(Nos. 11305259, 11205238)
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Received: Apr. 3, 2015; **Accepted**: Jul. 2, 2015

been done. A special area CCD was produced using framing imaging technique by Lincoln laboratory, and frame rate of the CCD can be as high as 1 MHz[3-4]. Another method to achieve high speed imaging is to configure several CCD transfer gates around photodiode as frame memory. This can lead to a very high frame rate, but only several limited frames can be taken continuously, which is also called burst image sensor[5]. Burst image sensor utilizing ISIS technique (in situ storage image sensor) has been manufactured, with the frame rate reaching as high as 16 Mfps[6]. A most recent literature shows that a frame rate of 1 Gfps can be reached theoretically by technique similar to ISIS[7].

Although these CCDs can reach a relatively higher frame rate, structure of these devices is very complicate and requires an even higher technology level. This makes these methods difficult to be widely used. Therefore, we propose a kind of ultrafast spectrum acquisition method based on ordinary area CCD. By reforming time sequence of area CCD, this method can take more consecutive frames and realize a frame rate as high as burst image sensor. No complicate or special techniques are required. A similar consideration has been performed on linear CCD by building an ultrafast spot detection system, and feasibility of the idea is demonstrated[8]. However, realization of ultrafast linear detection based on area CCD is still a challenging work and means a lot to the ultrafast solid state image sensing technique.

This article will mainly describe realization and demonstration of ultrafast linear detection based on area CCD, which is meaningful to the application of CCD in the transient spectrum detection area.

1 Principle of ultrafast linear detection based on area CCD

There are mainly four charge transfer methods for traditional area CCD: frame transfer, interline transfer, frame-interline transfer, and full frame transfer. All these four transfer method have a bottleneck of low signal (charge) output rate. Many area CCDs intend to raise signal output rate by using multiple output ports, but this will make the related driving circuit extremely complicate and huge. Therefore, we expect that charges generated during light integral period can be stored inside CCD and don't hurry to output. Multiple frames will be taken and stored inside CCD before the storage area gets full. In this way, high frame rate can be obtained.

Fig. 1 shows the principle of ultrafast linear scan based on area CCD. The basic idea is exposing the top line of area CCD, and shielding all the others to be used as charge cache. Frames taken by the exposed area is rapidly stored in the cache area. This can lead to a very high frame rate.

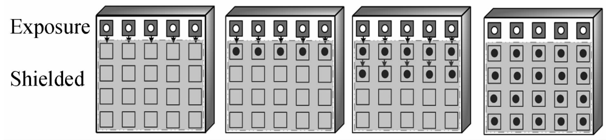

Fig. 1 Principle diagram of ultrafast linear scan based on area CCD

At the beginning of spectrum acquisition, the first line is exposed and collects photoelectrons. After the collection, photoelectrons are transferred to the adjacent shielded storage line. In the process of transfer, the exposed line is acquiring the next frame of light information. After the completion of first frame transfer, the second frame transfer begins. Constantly repeat the process, until all the storage area is crammed. Then, stop acquiring light, and transfer the signal charge in the storage area out of CCD under the control of vertical and horizontal transfer sequence.

The idea of using shielded lines of CCD as storage may be similar to burst image sensor to some extent. Compared to the burst image sensor, this method doesn't need to restructure CCD and no complicate technology is used. For one thing, this can reduce complexity of the device, for another, driving circuit of the system will be much more simplified. Furthermore, an equivalent or much higher frame rate can be achieved and more frames can be taken consecutively, compared to burst image sensor technique.

2 Detection system

Different from ultrafast spot detection system based on linear CCD structured by ZHU, et al[8], system design of linear scan system based on area CCD is a more complicate and challenging work. To achieve a high frame rate, CCD device should have a relatively higher vertical transfer rate. Driving sequence and circuit around should also be carefully dealt with to make the design fulfill our expectation.

2.1 Linear scan system based on area CCD

We choose FT50 frame transfer CCD made by DALSA company as our design target. FT50 CCD has a vertical transfer rate as high as 10 MHz. The expected time resolution can be 100 ns.

The structure of our system is shown in Fig. 2. Time sequence of CCD is generated by FPGA, so as the control signal of analog to digit converter[9]. Signal generated by CCD is led to A/D converter. After the conversion of analog signal, the induced digital signal is led to FPGA. Finally, the digital data is uploaded from

FPGA to PC through USB interface[10-11].

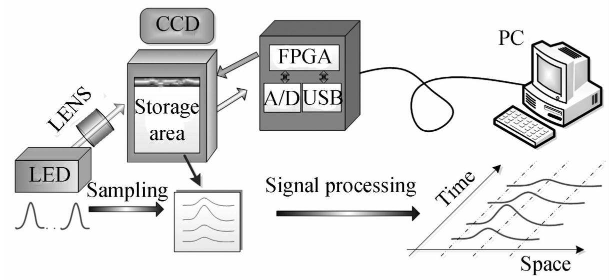

Fig. 2 Structure of the ultrafast linear scan system based on area CCD

2.2 Timing sequence

Fig. 3 shows the equivalent structure and time sequence of the detection method. For the exposed line of CCD, charge collection and transfer are alternately operated under the control of vertical transfer sequence. Each electrode of exposed line collects photoelectrons in its high voltage period, while transfers photoelectrons to adjacent deep potential well (high voltage area) in its low voltage period. Alternate change of high and low voltage makes photoelectrons accumulate and transfer from exposed area to storage area. It's evident that the final linear detection rate or frame rate equals vertical charge transfer rate. To avoid photoelectrons in storage area from being covered by next frame, time sequence of the storage area should be synchronous to the exposed area.

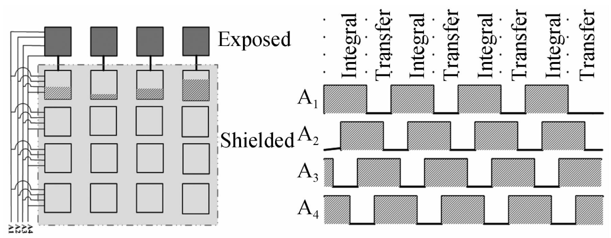

Fig. 3 Equivalent structure and drive sequence of linear scan system based on area CCD

3 Experimental results and discussion

A demonstration of the idea is performed by introducing a LED impulse light experiment. The structure of the experiment shows in Fig. 1. Impulse light generated by LED is led to the first line of CCD after being focused by lenses (the first line of CCD is exposed while the others are shielded). Intensity of the LED changes periodically. By detecting the change of impulse light intensity, a photograph showing the changing process of light intensity is expected. The installation of the system is shown as Fig. 4. Focal length and amount of image pixel is well designed to make sensitivity of the system relatively high[12].

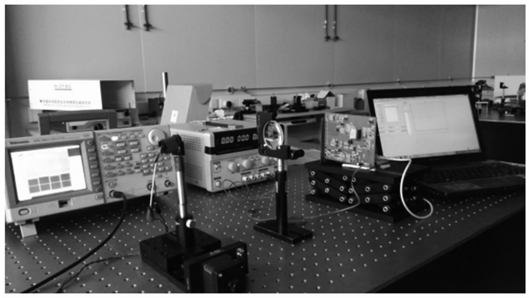

Fig. 4 Installation of the scan system

Scan rate or the detection rate of CCD is set to be 10 MHz. Period of the light impulse is set to be 6.67 μs, with duty cycle of 1/3.

After the detection, we restructured the photograph by gathering the entire derived linear image to form a two dimensional photograph, showing as Fig. 5.

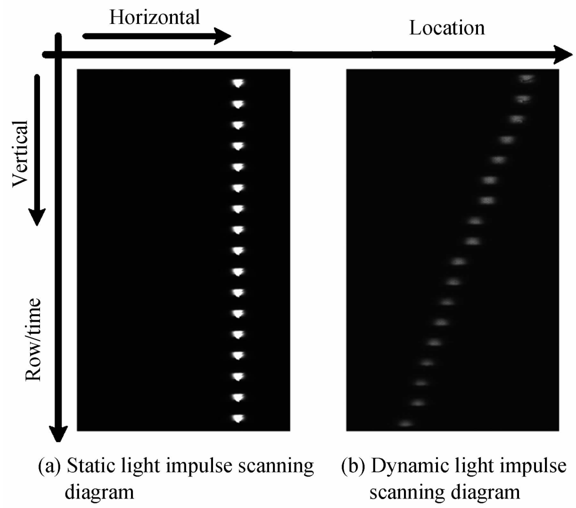

Fig. 5 LED light impulse scanning images

An obvious conclusion can be made from Fig. 5: this method of linear detection based on area CCD expands the changing process of light intensity on time scale. The photograph records the change of LED light intensity explicitly. In a moment, LED source comes bright. Before the intensity of the source turns to 0, the consecutive scanned image forms a bright spot. When the light source turns dark, dark area appears in the relevant position of the photograph. As the light source alternatively turns bright and dark, bright spots appear periodically in Fig. 5. The horizontal direction actually provides the position information of light source, while the vertical direction is a time axis which provides the intensity changing process of the light source. The two dimensional photograph provides a time expansion of one dimensional time varying image.

Fig. 6 shows intensity distribution of static light impulse scanning image in three dimensions. This could be an intuitionistic explanation of how intensity changes

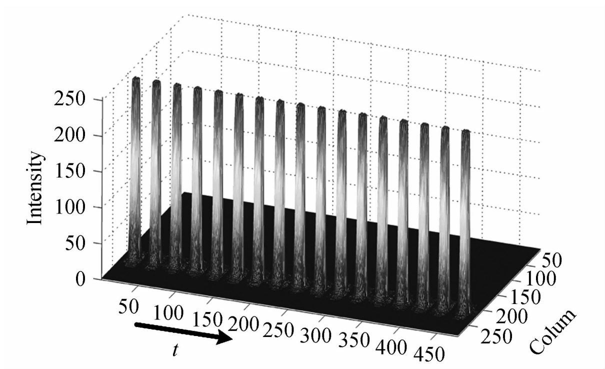

Fig. 6　Intensity distribution of static light impulse scanning image

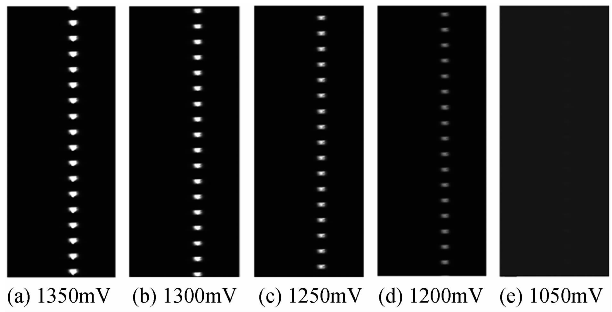

Fig. 7　Scanning images of different light intensity

with time. The axis "column" in horizontal plane shows position of the static light source, while the axis "row" (or "t") represents direction of time.

Intensity change shown in Fig. 5 is well consistent to the actual LED light source variation. Period of LED intensity change can be back restored from scan rate and distance of two adjacent peaks. For 10 MHz scan rate in our experiment, the adjacent two scan (or frame) have an interval of 0.1 μs. The average interval of two adjacent peaks is about 67.1 lines (calculated by average of ten impulse peak) in Fig. 5. So, period of LED intensity change can be calculated as 0.1 μs×67.1=6.71 μs. That is well consistent to the actual 6.67μs period. Therefore, feasibility of the idea of linear detection based on area CCD is demonstrated to be available, and a detection rate or frame rate of 10 MHz is actually realized, with a time resolution of 100 ns.

Certification is also performed on position changed light source, as Fig. 5 (b) shows. Moving direction of light source was parallel with CCD row. When position of light source changed, the system recorded its changing process. Fig. 5 (b) also shows intensity change while light source is moving. The lower left incline of the light spot indicates that light source is moving to the left (depends on the lens system, for an inverse image system, lower left incline indicates a right side motion). Since time axis in Fig. 5 is uniform, it's easy to evaluate velocity of the light source at any point of time. Light spot track is not a straight line incline to the left. This is mainly caused by an inhomogeneous of the light source moving velocity. However, this can also be an evidence to prove that this sort of high speed linear scan method is effective, since it can record the variation of light source condition truthfully.

Experiment is also performed on LED of different intensity and different impulse frequency.

Fig. 7 shows the results when this new scan method is performed on LED of different intensity.

LED light intensity is controlled by its drive signal. When the voltage of drive signal goes high, intensity is enhanced. When the drive voltage reaches 1 050 mV, LED is lighted, and slight light spot can be seen from Fig. 7 (e). With increase of drive voltage, light spot taken by the imaging system gets brighter and brighter. When the drive voltage reaches 1 350 mV, light saturation happened.

Fig. 8 shows the results when the LED flash frequency changes.

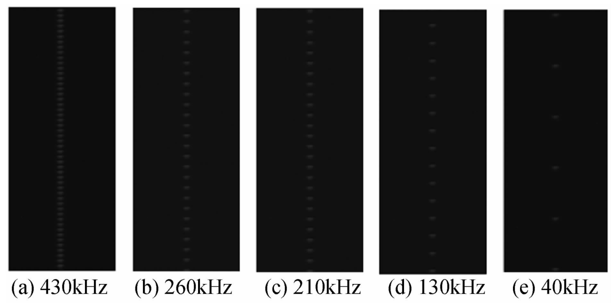

Fig. 8　Scan image of different LED flash frequency

Although brightness of spots in Fig. 8 is a little dim, it's still obvious to see that flash of different frequency can be imaged by the system precisely. Impulse width of LED drive signal in Fig. 8 is constant, so as other conditions except frequency. When the frequency gets higher, flash spot turns to be closer. Frequency relationship can also be seen from Fig. 8 obviously. As an example, frequency of Fig. 8(a) is about 10 times larger than Fig. 8 (e). This is supported by the scanning image that space of every 2 spot in Fig. 8(e) is consistent with the space of every 10 spot in Fig. 8(e).

Both the two experiment of imaging under different conditions indicate that the imaging system is efficient and available.

4　Conclusion

On the basis of research on the operating method of area CCD, we restructured working sequence of area CCD and proposed a kind of ultrafast linear scan method based on area CCD. Demonstration of the idea was done. The results show that this linear scan method based on area CCD can reach a detection rate or frame rate of 10 MHz (decided by the CCD device). Time resolution can be 100ns. Effectiveness is also demonstrated by experiment on LED under different intensity and frequency. This detection rate and time resolution is far higher than the detection rate of current ordinary linear CCD. Compared to the burst image sensor, this method owns an equivalent high frame rate and is able to take more frames consecutively (theoretically 2 048 frames can be taken consecutively). The experiment will greatly promote the application of CCD in the transient spectrum detection area. A further demonstration using some more complicate spectrum would be more significant.

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