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Global Shutter Efficiency Improvement to >100dB in Advanced Global Shutter Imager with Correction Processing

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Abstract— **Complete suppression of the light sensitivity of the storage element is the ultimate requirement for global shutter imager in demanding applications such as high-speed machine vision and advanced driver-assistance systems. A standard metric for the performance evaluation of global shutter pixels is the global shutter efficiency (GSE). The higher the GSE is, the better the performance would be. Here we are reporting on effective solutions to increase the GSE to more than 100dB, implemented by two low-cost methods: spatial domain and temporal domain corrections, without any changes to the pixel array silicon process. The spatial domain approach corrects the parasitic storage node signal by referring the signal from the closest storage node and the temporal domain correction utilizes a second frame signal of the same storage element but with a much shorter integration time as reference. These two approaches significantly improve the GSE performance across a broadband light spectrum from visible to near-infrared and also preserve the GSE improvement over frame rate variations. Additionally, our temporal correction processing selectively corrects the pixels affected by the parasitic light response of the storage element and would not introduce any extra noise to background.**

I. INTRODUCTION

The image quality of high speed objects is restricted by the rolling shutter operation of complementary metal–oxide–semiconductor (CMOS) image sensors, because of the motion artifacts [1-3]. Although global shutter CMOS image sensors have been used for various machine vision and driver-assistance systems, the relative poor performance in suppression of parasitic light still limits its applications in high-speed and strong light environment. Thus the improvement of the global shutter efficiency (GSE) is urgently desired.

Due to the design, fabrication and cost limitations, few CMOS image sensor can implement the per-pixel readout function. Therefore, the global shutter operation has to be realized by an in-pixel storage element, in which the photodiode signal is first globally frozen and then is being rolling readout. Depending on the different implementation of the in-pixel storage, global shutter pixels can be classified into two groups: charge domain [1] and voltage domain [2] pixels. Although the latter has better global shutter performance due to converting the electrons to voltage signal – which is immune to parasitic light, the higher noise floor of the voltage domain pixel restricts its low-light imaging performance which however is desired by automotive driver-assistance applications. Thus the dominant global shutter technique considered in this work focuses on the charge domain pixel design. However, even with a metal shield, the storage diode (SD) still suffers from the parasitic light problems, resulting in low and non-uniform GSE from blue to infrared light, especially for the long wavelength photons penetrating deeply. In this paper, we present two low-cost methods: temporal domain and spatial domain corrections, to increase the GSE to more than 100dB into an existing global shutter pixel (performance parameters included in Table 1), which will benefit future sensor design.

II. THE METHODOLOGY OF GLOBAL SHUTTER EFFICIENCY CALCULATION

The traditional parasitic light sensitivity (PLS) calculation is based on SD signal over PD signal [4] (as equation (1)), or SD quantum efficiency over PD quantum efficiency [2] at one signal point. And GSE is usually the reciprocal of the parasitic light sensitivity:

$$GSE_{single-point} = \frac{1}{PLS} = \frac{Signal_{PD}}{Signal_{SD}} \tag{1}$$

Two problems may reduce the result accuracy of this method. Firstly, the dark signal level (pedestal) should be very accurately subtracted from both PD and SD signals. Otherwise, even 0.1 LSB error residual in the GSE denominator will obviously introduce uncertainty to the final GSE calculation. Secondly, this single point measurement method will be inaccurate if the PD or SD responsivity is not linear with incident photon flux. In this paper, we are proposing a method for evaluating GSE as the ratio between PD responsivity slope over SD responsivity slope, as described in equation (2) and Figure 1. This is an optimized method to effectively circumvent the errors from dark pedestal and signal non-linearity errors.

$$GSE_{slope} = \frac{1}{PLS} = \frac{Slope_{PD}}{Slope_{SD}} \tag{2}$$

The above described method is commonly used for ideal pixel level GSE evaluation. In practical scenes, the idle time differences of SD due to PD integration time and frame rate

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changing, could also reduce the GSE performance. Most image sensors reset SD once until readout has finished, while the parasitic light would be collected during the idle time and next readout time (one period if PD has the identical integration time during continued frames) of the SD, especially at low frame rates, as illustrated in Figure 2. According to ref. [4], the practical effective shutter efficiency (GSE_{eff}) of an image sensor needs to consider the frame period T_f and PD integration time T_{PD} as

$$GSE_{eff} = \frac{1}{PLS*\frac{T_f}{T_{PD}}}. \tag{3}$$

This consideration further worsens the GSE performance in field applications requiring short PD integration time or long frame period.

III. TEMPORAL AND SPATIAL DOMAIN CORRECTION

Considering the parasitic light problem to the SDs of charge domain pixels, some correction methods are strongly desired for improving the GSE performance. In this paper, we introduce the two approaches described below.

A. Temporal Domain Correction

The basic principle of temporal domain correction is utilizing the SD signal of the following frames but at much shorter integration time to correct the first normal readout frame which mixes both PD and SD parasitic signal, as described in equation (4):

$$Signal_{corrected} = Signal_{first\ frame} - \frac{\sum_{frame=1}^{n} Signal_{SD_n}}{n} * Gain. \tag{4}$$

Where Gain is the ratio between the first frame integration time and the integration time of the *n* subsequent frames used for correction.

In this experiment, we firstly collect a normal frame which includes both PD and SD parasitic signal. Then we disable PD and collect one or more frames of SD-only signal. And finally these SD-only frames are used to eliminate the SD parasitic signal in the first frame. If frame number n =1 and $Gain$ =1 in equation (4), that means we applied one second SD frame with the same integration time as the period of the first frame, eliminating the PLS with also increasing the photon shot noise by about $\sqrt{2}$ of the SD-only signal. However, this method will reduce the frame rate and is unacceptable for most practical situations. In order to maintain a frame rate like 60 fps, we have to shorten the integration time of following SD-only frame to the range from 1/100 to 1/10 of the first frame period, and then the weaker signal would be amplified by a gain to correct the SD parasitic signal of the first frame with longer frame period. Thanks to the good linearity of SD of the sample sensor, the second frame with shorter integration time can effectively correct the previous frame parasitic light sensitivity, improving the GSE to >100 dB, as the demonstrated in Figure 3.

The shot noise increase would be difficult to be avoided by different frames subtraction. Here, we have two ways to minimize this influence. Firstly, we only correct the obvious ghost artifacts in an image, such as SD-only signal larger than a threshold value, instead of the full frame. This kind of selective correction will not introduce additional shot noise into the area out of the motion artifact region. Secondly, we merge multiple shorter integration time SD-only frames to reproduce a frame with lower temporal noise to improve the image quality. Although this method would be more time consuming, it is still acceptable if each SD frame is fast enough, like 1/100 of the integration time of the main frame.

B. Spatial Domain Correction

Although temporal domain correction is good for some pixel with simple design to correct parasitic light, the reference of the additional frames is still unsuitable for time sensitive applications. If we have two similar SDs, one is used for signal storage and the other is isolated from signal path and used for reference. Then the latter one could correct the parasitic light signal of the functional SD or the main frame mixed with parasitic light, without delaying to the frame rate, as equation (5). Due to the same time slot, the parasitic light could be very similar between the two SDs if designed well, only adding dark shot noise.

$$Signal_{corrected} = Signal_{main\ frame} - Signal_{reference\ SD} \tag{5}$$

However, this method requires new pixel design and cannot be realized in the sample sensor which only has one SD in each pixel. To verify the effectiveness of this idea, we introduce a compromise solution that utilizing the even column SDs as reference to correct odd column SDs. Although the odd and even SDs belong to different pixels and have a 3.0 µm distance (pixel pitch), the correction result is still good enough to achieve > 100 dB GSE, as shown in Figure 3.

C. Corrections for real scenes and variable frame rate.

The above two methods exhibit good GSE performance improvement by parasitic light corrections. In this section, we would like to explore the effectiveness in practical applications.

Firstly we demonstrate the correction effectiveness for different frame rates. As we discussed in the section 2, lower frame rate would suffer more parasitic light due to longer idle time of SDs. Figure 4 shows the GSE_{eff} dropping at low frame rates (at a fixed PD integration time) due to frame period increasing. After either temporal or spatial correction, GSE_{eff} of the sensor appears more immune to the frame period changing, hence benefiting various low frame rate applications. For the spatial correction method, the difference between two SDs will inherently lead to a decrease of GSE correction effectiveness when frame rate is reduced. However, the spatially corrected GSE_{eff} is much better than the original GSE_{eff}. For the temporal correction, the fluctuation comes from the small variations of the corrected SD Signal. As we discussed above, even 0.01 LSB variation in the GSE denominator will obviously introduce uncertainty to the final GSE calculation, within the temporal noise of the sensor.

Further, we demonstrate the GSE correction effectiveness on real scenes where relevant application cases are emulated in lab environment. We capture one frame with strong light source (incandescent bulb). And then capture another SD-only frame with the bulb moved to another position. Due to the parasitic light sensitivity, the second SD-only frame retains the filament image. By combining the two images we emulated a real scene image with motion artifact “ghosts”, as shown in Figure 5(a). To correct this motion artifact, we applied both methods discussed above. For the temporal correction, we captured one more SD-only frame with 1/10 integration time of the initial “ghost” frame. Then corrected the “ghost” frame by the shorter integration time frame with a gain close to 10. However, the simple full frame correction increases the dark shot noise by >40 % in the black patch of the color checker chart in the image, as shown in Figure 5(b). To reduce the background noise, we are proposing a correction processing to only selectively correct the “ghost” image region where the SD-only signal is larger than a certain threshold value. This correction optimization circumvents the extra noise in the background, as shown in Figure 5(c). Finally, we apply the spatial correction method to the original image. The correction algorithm can utilize SD-only signal from either odd or even columns as reference for correcting each other, effectively eliminating the “ghost” image, as demonstrated in Figure 5(d).

IV. CONCLUSION

In this paper, we report on two effective and low-cost GSE improvement methods: temporal domain and spatial domain corrections, applied to a sample sensor with one SD per pixel. In the first method, the parasitic light SD response is corrected by referring following SD-only frames with much shorter integration time. Also we selectively correct the obvious ghost region by thresholding the strong parasitic signal instead of correcting the full frame, without introducing any extra shot noise to background and maintaining image quality.

The second method is proposing a more practical correction based on reference signal from a neighboring SD. We provide the proof of the concept for this spatial correction by utilizing the even column SDs as reference to correct odd column SDs. Although the odd and even SDs are separated by 3.0 µm (pixel pitch), we still obtain a significant improvement in parasitic light suppression.

These two approaches significantly improve the GSE performance across a broadband light spectrum from visible to near-infrared and also preserve the GSE improvement over frame rate variations.

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TABLE I

KEY PERFORMANCE PARAMETERS

Parameter	**Typical Value**
Optical Format	1/4-inch (4.5 mm)
Active Pixels	1280 (H) × 800 (V) = 1.0 Mp
Pixel Size	3.0 µm
Color Filter Array	Monochrome
Chief Ray Angle	28°
Shutter Type	Global Shutter
Input Clock Range	6–48 MHz
Output Pixel Clock (Maximum)	74.25 MHz
Output	
Serial	MIPI, 1−lane or 2−lane
Parallel	12-bit
Frame Rate Full Resolution	60 fps (Parallel, MIPI 2−lane, 12−bit)
Responsivity Monochrome	56 Ke/lux*s
SNRMAX	38 dB
Dynamic Range	71.4 dB
Supply Voltage	
I/O	1.8 or 2.8 V
Digital	1.2 V
Analog	2.8 V
Power Consumption	< 215 mW

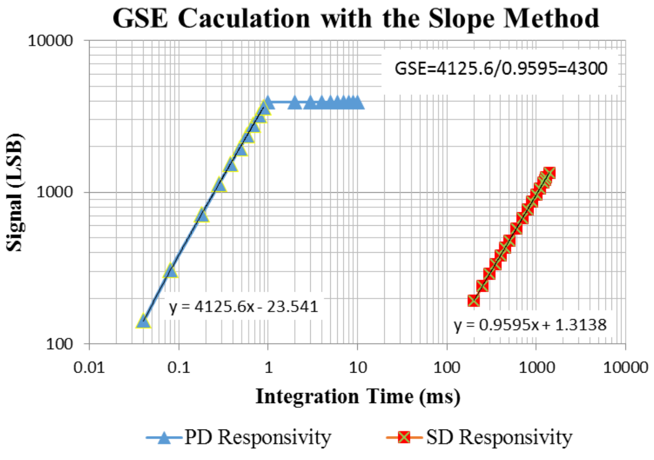

Figure 1. Our GSE evaluation method is based on the PD and SD responsivity slope. Through curve fitting multiple points under the full well, this method could effectively eliminate the dark pedestal and non-linearity errors. Here, this GSE measurement is based on a 550nm light source with F/# 3.

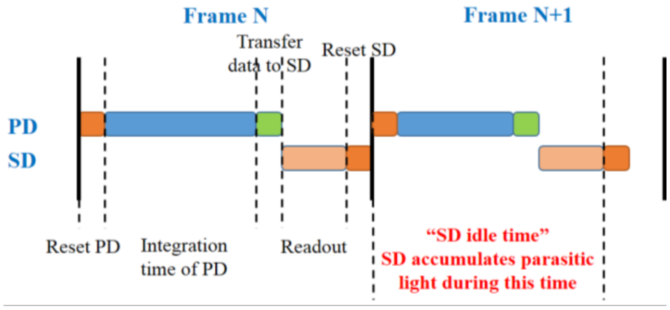

Figure 2. SD would accumulate parasitic light during two resets. If PD has the identical integration time during continued frames, the duration of SD exposure to light is the same as the frame period.

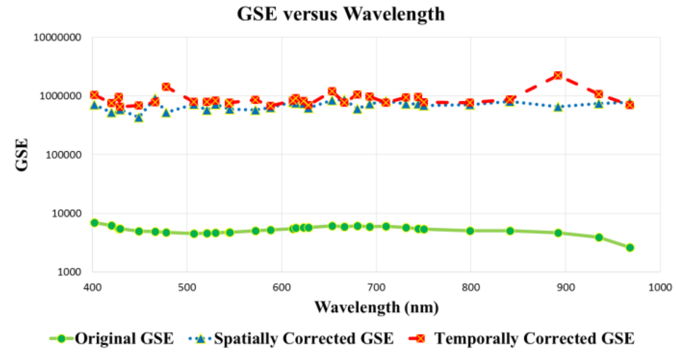

Figure 3. The GSE performance in the center region of interest (ROI) of the sample sensor versus wavelength, showing the corrected GSE $>10^5$ (i.e. > 100dB) by the spatial (blue curve) and temporal (red curve) processing algorithms versus the original GSE (green curve). F/# 3 is used here.

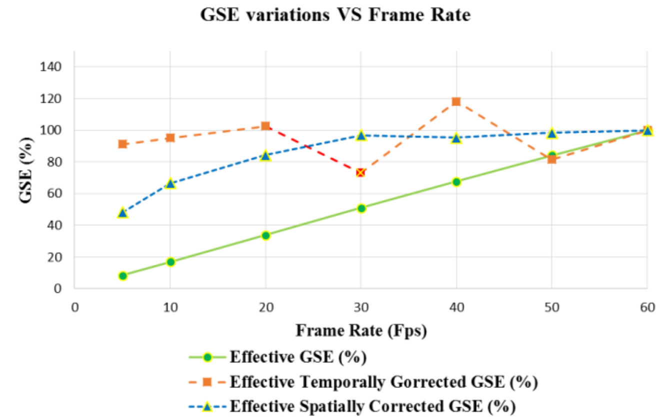

Figure 4. The original GSE_{eff} (green line) is proportional to the frame rate if the PD integration time was fixed. The GSE with 5 fps frame rate is only 8.5% of the value with 60 fps. The corrected GSE_{eff} are more immune to the frame rate. A 530nm light source with F/# 3 is used here.

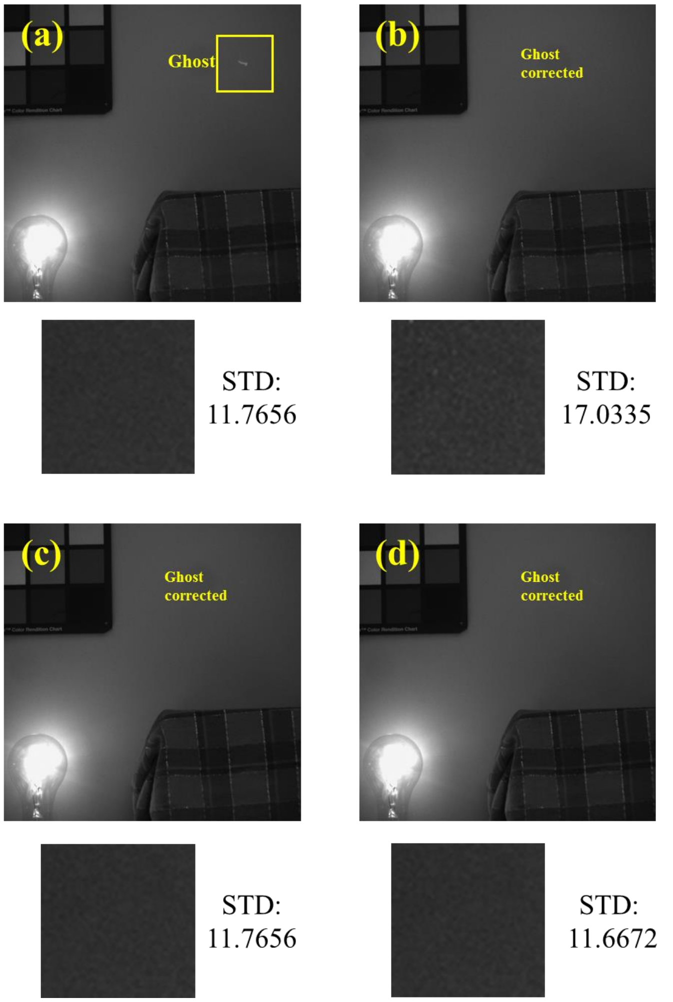

Figure 5. Emulated motion artifact "ghost" from a moving light source. (a) Original frame with the ghost image of filament (highlighted by the yellow square). (b) Full frame of (a) is corrected by the temporal method with background noise increasing. (c) Selected temporal correction method applied only to the ghost region without worsening the background noise. (d) Full frame of (a) is corrected by the spatial method showing less noise compared to full frame temporal method.