A Real time 3D video CMOS sensor with time gated photon counting

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Abstract— The real time acquisition of a 3D scene has been recently democratized by video game consoles. The most popular approaches such as the structure-light and the stereo vision are appropriate for short distances but they are not well suited for long time measurements in the range of a hundred meters up to a few kilometers or a scattering environment. In this case, the time of flight method is more convenient but is limited by the heavy and expensive hardware requirement for military applications. Indeed, a strong laser illumination and a time gated intensified camera is generally used to carry out this kind of measurement. The signal reflected at a long distance is so weak that very few photons reach the camera, thus using an image intensifier is mandatory. Moreover, the acquisition time and processing is quite long as several laser pulse are required for distance measurement and several frame of distance measurement are required to build a 3D scene. As a consequence, real time measurement cannot be achieved at this time. The paper describes a novel CMOS imager based on time gated single photon avalanche diode in order to detect the reflected light and accomplish distance memorization. The processing is fully parallelized and embedded within the pixel. The pixel includes 46 transistors, operates independently and has a size of $36 \times 43 \mu\text{m}^2$. As a result, the readout of the sensor generates the 3D images immediately in real time.

Keywords—Real time 3D video, SPAD, Photon counting, Time gating

I. INTRODUCTION

Over the past few years, more and more active imaging systems have been used and tested [1][2]. The potential of such systems in the fields of long-range observation [3] and in the vision through scattering environments [4] has shown clear advantages. Following a patent filed concerning a process of 3D imaging [5], this paper described a CMOS sensor based on this new process. This matrix active imaging system named MAITODIC (Matrix Active Imaging system of direct conversion TOMographic Data Into a Color image 3D) directly converts the tomographic data of a scene into a 3D image where every depth slice of the scene is represented by a color (according to a predefined color or depth code). Contrary to systems measuring the time of flight, this system assumes that the time of flight is known and only the information arriving at this precise moment is taken into account. This eliminates the backscattering effects

during the propagation of the light through scattering environments, like rain, snow, fog, mist or smoke, which distort the distance information.

II. THE MAITODIC SENSOR

A. Concept of the 3D imaging

Active imaging is a visualization technique using an image sensor array and its own illumination source to display directly a two-dimensional image of the scene. According to the synchronization between the illumination and the recording, it is possible to improve the visibility through the scattering environments. The use of light pulse sources like lasers and triggered intensified cameras with low exposure times enables range gating. More exactly, it allows us to visualize a space slice of the scene at a certain distance according to the laser pulse and to the acquisition time. In full field active imaging, three methods exist to determine the 3D of a scene. The first is based on the acquisition of a tomographic images sequence [6]. The second uses the analysis of intensity profile according to the visualized scene depth [7]. In both cases, the information is processed to have the 3D scene. The third method independently measures the time of flight of a round trip of the laser pulse between the object in the scene and the imager for each pixel [8]. Its reading mode, reducing the images frequency, especially when the pixels number is significant, limits certain applications when the speed is a very important factor. Furthermore, if particles (rain, fog) are in front of the imager, the measured distance does not correspond to the object distance in the scene but to that of particles. Conversely, MAITODIC assumes that the time of flight is known and only the information arriving at this precise moment is taken into account. Each time measurement value corresponds to a distance but also to a depth code (color) that will appear in the 3D image as the location of objects situated at this range. The scene will so be scanned in depth by slice, by modulating the known time of flight.

The architecture of the sensor is depicted in Fig 1. Every active pixel of the MAITODIC matrix operates independently and is driven by a common sequencer. They are equipped with a single optoelectronic sensor, an integrator, a comparator and a memory. So at the desired time of flight, if the retro-

Fig. 1. Synoptic of the MAITODIC sensor with its pixel architecture

reflected light is intense enough compared with a threshold value, meaning that there is actually a reflection on an object, the pre-selected distance is memorized and the pixel is locked. Otherwise, the next time of flight is expected. A blocked buffer stays in this state until the next 3D recording of the scene. When the entire scene is scanned, all the buffers can be transferred at once towards the image memory, which can be read during the next 3D recording of the scene. The image frequency is not penalized by the number of pixels during the acquisition process. In case the intensity of a single pulse by slice cannot be enough to obtain an integrated signal level above the threshold value, it is possible to accumulate several laser pulses and, contrary to the usual time of flight measurements, to increase the number of pulses for the same slice within the limits of the image frequency. On the other hand, it is not necessary to have the same number of pulses by visualized slice. So furthest slices can receive more pulses than the closer one.

III. CMOS SENSOR DESIGN

This new architecture of real time 3D video sensor has been integrated within a CMOS sensor realized in a standard 180 nm technology. The different blocks are described below.

A. Sequencer

The sequencer generates the signals to drive the pixels of the sensors. It adjusts the delay between the light trigger and the gating signal of the pixel in order to choose the spatial slice depth according to the time of flight of the photon for the round trip in the considered medium (generally the air). In the same way, the width of the gating signal is related to the thickness of this spatial slice. At the beginning of a 3D frame, the sequencer resets all the pixels by activating the $\text{Frame}_{\text{Reset}}$ signal. To measure a signal at a given spatial slice, a depth code, which is in reality a specific voltage, corresponding to this spatial slice is set on V_{DEPTH} . Then the sequencer order a predefined number of light pulse shots and temporal gates with a fixed delay. This one can be adjusted in regards of the expected returned signal strength and can be, for instance, increased for the very long distances where a photon is not necessarily detected at each laser pulse. If a pixel detects a sufficient number a photon, meaning that there is an object at this distance that reflect the light, the pixel locks automatically and samples the preset V_{DEPTH} . Subsequently, the sequencer chooses another spatial slice and operates a new burst of laser pulse, etc.

All the measurement parameters such as the number of temporal slices, their thickness, their absolute position are completely defined by the sequencer and the number of V_{DEPTH} code that can be resolved by the pixel. This approach makes the system very versatile and usable for short and long ranges as well as fine and coarse 3D measurements.

At a light pulse repetition rate of 20 MHz and a target of 256 numbers of spatial slices, the average numbers of photon events that can be counted for each slice is 78125 per second. Thus the Dark Count Rate (DCR) of the SPAD which is in the order of 1 kHz, is relatively insignificant. Moreover, the effective DCR is strongly reduced by the time gate operation of the system. If a video rate of 25 images per second is aimed, the average number of photon events per 3D image and per slice is thus 3125, ensuring a very good signal to noise ratio mainly limited by the photon shot noise.

The light pulse repetition rate for long range measurements is generally limited to about 100 kHz for a distance of 1.5 km for instance. In this case, the number of possible photon events per second is reduced to 390 events per slice, i.e. only 15 photon events per slice and per image at a video rate of 25 image per second. Thus, the pixel sensitivity and especially the integrator sensitivity must be sufficient to detect 15 events.

B. Time gated optoelectronic sensor

The number of photon that hit the sensor for long range measurements can be as weak as one photon per pixel and per laser pulse. Thus, a very sensitive sensor has to be able to detect the optical signal. A Single Photon Avalanche Diode (SPAD) based optoelectronic front end has been chosen to provide the high sensitivity. Moreover, a SPAD can operate in gating mode by biasing the junction above or under the breakdown voltage. The detail of the optical front end is depicted in Fig. 2.

The SPAD is based on a P+/N_{well} junction with a double Pwell/STI guardring [9]. The transistors $\text{Mp}_{\text{Quench}}$ and $\text{Mn}_{\text{Quench}}$ act as a passive quenching resistor and active quenching switch respectively. Transistors Mp_{Lock} and Mn_{Lock} allows to lock the pixel when Pixel_lock signal is high by forcing the quenching of the SPAD and blocking the SPAD Reset. Indeed, when a pixel has detected a reflection and memorized the depth code, its front-end is disabled to lock this pixel and reduce power consumption by the way.

The $\text{Mp}_{\text{SPAD_reset}}$ allows to reset the SPAD to a biasing above the breakdown voltage. Two delayed control signal are used in

Fig. 2. Schematic of the time gated optoelectronic sensor

order to generated subnanosecond reset time as described in [10]. V_{anode} voltage is tuned to set the SPAD excess voltage above the breakdown limit and the separate power supply V_{DDSPAD} and V_{DD} allows us to adjust the effective threshold of the M_{pcomp} and M_{ncomp} inverter based comparator.

If the SPAD is triggered, the cathode voltage decreases and is detected by the comparator setting its output to high. The $\text{Gate}_{\text{Elec}}$ gating signal generated according the technique described in [10] is then used to gate the comparator signal. At first order, the gate width is given by the time between the effective reset of the SPAD to the end of the $\text{Gate}_{\text{Elec}}$ signal. Temporal width as short as 200 ps has been reporter in [10]

C. Integrator and comparator

The integrator follows the time gated front-end and is based on a charge transfer process [11] and depicted in Fig. 3. The nodes N_2 and N_1 are reset to V_{DD} at each new depth measurement and each laser pulse respectively. After each generated time gate, the G_{TX} signal, typically in the range of 1 volt to 1.4 volts potentially allows us to transfer a part of the N_1 charge into node N_2 regarding the voltage of node N_1 . The first model of the circuit can be explained by assuming the parasitic capacitances C_1 of node N_1 and C_2 of N_2 . The M_{NGTX} allows to transfer charges from node N_1 and node N_2 until its V_{GS} voltage is above the threshold voltage V_{TH} . As the charges transfer is operating, the N_1 voltage increase and turn off M_{NGTX} when the V_{GTX} to N_1 voltage reach V_{TH} . The charges Q_1 transferred to node N_2 during this process is then given by:

$$Q_1 = C_1 \cdot \left[(V_{G_{\text{TX}}} - V_{N_1}) - V_{\text{TH}} \right] \quad (1)$$

Following the injection of the Q_1 charges, the voltage of node N_2 decreases. If the voltage of node N_1 is initially biased above $V_{\text{GTX}} - V_{\text{TH}}$, no charge transfer occurs. Thus resetting node N_1 to V_{DD} ensure that the N_2 is not affected until the transistor M_{NSPADOUT} changes N_1 voltage to V_{Gain} voltage when a SPAD_{out} signal arise from the optoelectronic front-end meaning that a photon has been detected in the temporal gate. In this case, the N_2 voltage decreased by a quantum ΔV_Q given by:

$$\Delta V_Q = \frac{C_1}{C_2} \cdot \left[(V_{G_{\text{TX}}} - V_{\text{Gain}}) - V_{\text{TH}} \right] \quad (2)$$

A second order approach shows that the longer the width of the G_{TX} signal, the higher the absolute value of V_Q . Indeed, the transistor still transfer charges when operating in the subthreshold mode. Therefore, V_Q can be adjusted thanks to V_{GAIN} and the G_{TX} duration to a few tens of mV down to a few μV allowing to reach the threshold of the output inverter with

Fig. 3. Schematic of the integrator and the comparator

a number of detected photon in the range from 10 up to 10000 detection events.

D. Memory and readout

The memory unit is depicted in Fig. 4. It includes a RS memory, a digital demultiplexer with an unselected output set to '1' and a selected output following the input, two PMOS based sampling cell that sample the V_{DEPTH} signal into the $\text{Depth}_{\text{Odd}}$ or the $\text{Depth}_{\text{Even}}$ node capacitances. Each node can be readout as a classic 3T video imager on the column bus by NMOS based source followers that can be selected by the Sel_{Odd} or Sel_{Even} signals and a current source at the column bottom.

A new 3D frame starts with the reset of the RS memory by setting the $\text{Frame}_{\text{Reset}}$ signal. As a consequence, the output $\bar{Q}$ is set to '0'. Depending on the selected frame with the $\text{Frame}_{\text{Sel}}$, the corresponding sampling cell is then on, i.e. the sampling capacitance voltage is following V_{DEPTH} . Meanwhile, the unselected sampling cell is off, i.e. it memorizes the previous sampled value. This feature allows the readout of the previous frame (Odd numbers for instance) while the acquisition of the current is being operated (Even numbers for instance).

During the measurement of a given spatial slice, its corresponding depth code is set with the V_{DEPTH} voltage. If a reflection is measured at this slice, the $\text{Reflexion}_{\text{Detect}}$ signal is kept inactive and thus has no effect on the sampling cell behavior. In other cases, as soon as the $\text{Reflexion}_{\text{Detect}}$ signal arises, the RS memory is set on and the selected frame sampling cell samples and hold the current V_{DEPTH} . At the same moment, the lock signal is set to '1', then the optoelectronic front-end is locked, i.e. the SPAD is always quenched and as a result can't detect any new photon.

Fig. 4. Schematic of the memory unit and the readout

IV. LAYOUT

The layout of a single pixel is depicted in Fig. 5. The pixel pitch is $36 \times 43 \mu\text{m}^2$. Some additional decoupling capacitances have been added within the pixel to ensure good operation while switching the SPAD on/off. The diameter of the SPAD active area is $15 \mu\text{m}$ which leads to a fill factor of more than 11%. The routing of the high speed signal has been treated with particular attention to ensure a good propagation. The technique described in [10] allows us to compensate the skew to guarantee a sub nanosecond synchronicity.

Fig. 5. Layout of a single pixel

V. SIMULATION RESULTS

To illustrate the functionality of the sensor, the simulation of a depth measurement with a systematical photon detection is shown in Fig. 6. The simulation begin with an active $\text{Frame}_{\text{Reset}}$ and a $\text{Depth}_{\text{Reset}}$.

Fig. 6. Simulation results of a pixel detection, integration and locking

An arbitrary sinusoidal signal is applied to V_{Depth} to demonstrate that the pixel locked when a sufficient number of reflection has been detected. Indeed at the 15th trigger, at 0.9 μs , the integration node V_{N2} reach the 0.9 Volts comparator threshold thus inducing the pixel Lock. Before the lock, the sampling voltage node $\text{Depth}_{\text{odd}}$ follows the V_{DEPTH} voltage and after the lock, its last value is sampled and held. At 1.7 μs , a $\text{Depth}_{\text{Reset}}$ reset the integration node to VDD. At 1.8 μs , the $\text{Frame}_{\text{Reset}}$ signal unlocks the pixel. In normal operation mode, the $\text{Frame}_{\text{Reset}}$ is applied once per frame and the $\text{Depth}_{\text{Reset}}$ signal is applied at each new spatial slice.

VI. CONCLUSION

A Real time 3D video sensor with a time gated optical front-end and an active pulse light source is presented. The main characteristics of the sensor are summarize in table I. It offers several advantages with regard to the vacuum tube based image intensifier like the compactness. The photon counting

capability of the sensor makes it possible to operate at a very long range of up to few kilometers through scattering environments. All pixels operate independently and in a fully parallelized process that makes it possible to handle more than 1000 Giga photon event assuming a 256×256 pixels array at a light pulse repetition rate of 20 Mhz. The sensor directly generates a 3D video image at a frame rate of 25 images per second or more without the need of a heavy post processing [12]. Concerning the long range 3D single photon imaging performed by a time gating approach with a SPAD [13], to the author's knowledge, it is the first time a SPAD based smart pixel that directly generates the 3D image is presented.

TABLE I. SENSOR CHARACTERISTICS

Parameters	Value
Temporal gate, Depth resolution	Down to 200 ps, 3 cm in the air
Pixel size	$36 \times 43 \mu\text{m}^2$
Acquisition range	From a few cm up to several km
Light pulse repetition rate	Up to 20 MHz
Pixel transistor count	46
SPAD Diameter - Fill factor	$15 \mu\text{m}$ - 11%

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