Geiger-mode Three-dimensional Image Sensor for Flash LIDAR

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ABSTRACT

JAXA has been developing Flash LIDAR as a sensor for obstacle detection by lunar and planetary landers and for on-orbit rendezvous and docking. This paper describes a 3D image sensor with Geiger-mode avalanche photodiodes and its pixel circuit for Flash LIDAR.

1 Introduction

Landing sites of planetary landers for scientific observation or resource exploration are generally unexplored sites, which may not always be ideal for landing. Therefore, planetary landers require three-dimensional (3D) images for terrain measurements, obstacle avoidance, and detection of attitude with respect to the ground immediately before landing. As a typical example, OSIRIS-REx [1], launched in 2016, uses flash LIDAR for guidance, navigation and control.

LIDAR systems that obtain a 3D image can be roughly divided into two types: scanning and flash. A scanning LIDAR scans a narrow laser beam across the target, while Flash LIDAR irradiates a diffuse laser beam. Currently, scanning LIDARs are widely used for imaging on the ground. Since a narrow beam is used, long range operation is possible but the mechanical scanning mechanism is too complicated to increase the frame rate. In recent years, a high-speed scanning LIDAR using an optical phased array has been proposed.

Flash LIDAR is a LIDAR system that uses diffuse laser irradiation to acquire 3D digital images of the field of view of a 2D array of sensors (3D image sensor) [2]. Flash LIDAR is characterized by excellent time synchronization of image acquisition due to its high frame rate and by high system reliability due to its simple structure. Flash LIDAR, along with millimeter-wave radar, is a promising candidate for sensors in autonomous cars, automatic construction machines, and drones, which need to find the locations of roads and obstacles.

JAXA is developing a 3D image sensor for Flash LIDAR, which is required for obstacle detection by lunar and planetary landers and for on-orbit rendezvous and docking [3 – 5].

2 3D Image Sensor

The 3D image sensor consists of two layers: a sensor layer with Geiger-mode avalanche photodiodes (Gm-APDs) placed in an array of 128 × 128 pixels, and a CMOS ROIC (readout IC) layer with a TDC (time-to-digital converter) circuit for each pixel. The Gm-APD in the sensor layer is connected to the pixel circuit in the ROIC layer by flip-chip bonding. Figure 1 shows a photo of a prototype 3D image sensor, with the sensor chip mounted directly on the substrate. The Gm-APD of the prototype sensor has a spectral response range of 900-1690 nm, a sensitivity-effective diameter of 9 μm, and a pixel spacing of 55 μm. To suppress the dark current of the APDs, this chip needs to be cooled to -20°C or lower.

The ROIC, fabricated by a 0.18-μm CMOS process, consists of a high-speed clock generation and distribution circuit, a pixel circuit with TDC function and a SPI (Serial Peripheral Interface) to read its value. The overall configuration of the ROIC and the pixel circuit are shown in Figure 1.

The counter clock that drives the TDC circuit is 500 MHz. The TDC achieves a resolution of 1/4 of the clock cycle by using two clocks with different phases of 90°. The TDC is a 15-bit counter, and the 2 bits on the least-significant bit side are the phase combination of the clock. The next 4 bits are a toggle counter, and the 9 bits on the most-significant bit side are an M-sequence code generator. The TDC circuit counts up when the ranging gate signal (ARMING) is high, and stops counter operation when the ARMING goes low or the comparator detects a photo event signal from the Gm-APD.

The entire 3D image is divided into 16 blocks of 16 x 64 pixels. These pixel data are read out through the SPI (Serial Peripheral Interface) of each block. The readout clock is up to 40 MHz and can support a frame rate of 1 kHz or higher.

3 Characteristics of ROIC

The ROIC has a function called test pulse that can be used to check the electrical characteristics of the pixel counter. The test pulse signal is input to the comparator of the pixel circuit shown in Figure 1. This function delivers a counter stop signal to all pixels in the Y direction of a column of each block. In other words, when X = k (k = 0 – 15) is selected, the stop signal is delivered to all the pixels with Y = 0 - 127 for X = 0 + k, 16 + k, 32

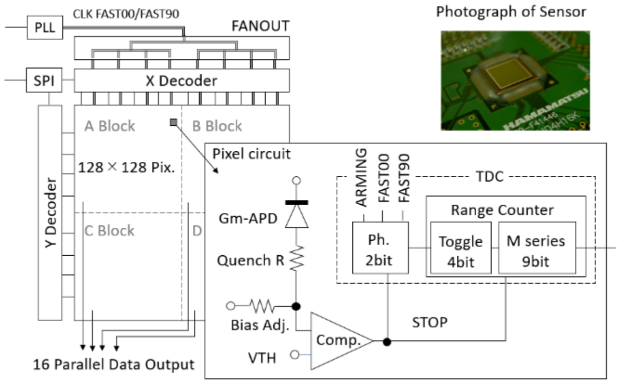

Fig. 1 Outline of 3D image sensor

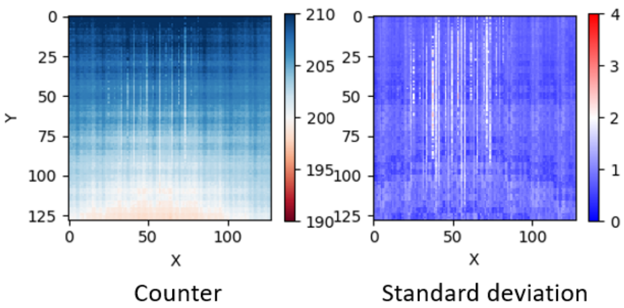

Fig. 2 Delay offset distribution at each pixel

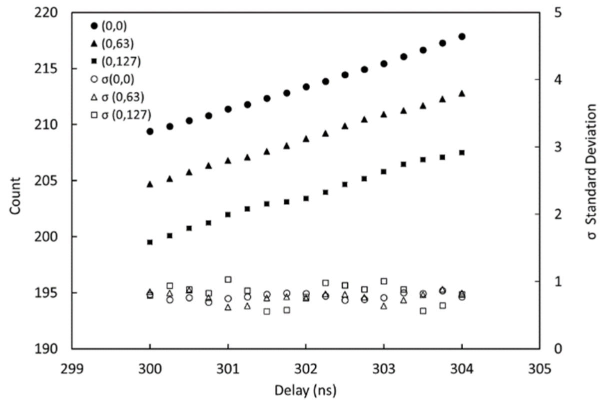

Fig. 3 Pixel TDC response

+ k, 48 + k, 64 + k, 80+k, 96+k, and 112+k. Therefore, the counter operation of all pixels can be tested by sequentially selecting k = 0 to 15 by external commands. Using the test pulse function, we measured the delay offset of all the pixels and the results are shown in Fig. 2. In this device, the Gm-APD needs to be cooled down to -20℃. For this reason, the temperature of the device is maintained at -20° C by a Peltier controller. The timing between the ranging gate ARMING and the test pulse is controlled by the delay pulse generator.

Figure 2(a) shows the distribution of the pixel counter values and Fig. 2(b) shows their standard deviation. The vertical and horizontal axes show the Y and X coordinates of the pixel. The colors are the TDC counts in Fig. 2(a) and the standard deviation in Fig. 2(b). The results show that the propagation delay in the chip from upstream (top) to downstream (bottom) of the counter clock is approximately 10 ns (20 counts). The standard deviation of the pixel counters is less than 2 least significant bits, indicating that all pixel counters functioned well.

The characteristics of the pixel counters were measured for (0,0), (0,63), and (0,127) by varying the input timing of the test pulse, and the results are shown in Fig. 3. The reason for selecting these three coordinates is that the clock delivered from the PLL propagates from y=0 to y=127, and thus the operation of the pixel counters located upstream, center, and downstream of the clock delivery can be measured in detail. The horizontal axis shows the delay time of the electrical pulse, the left vertical axis shows the pixel counter value, and the right vertical axis shows the standard deviation of the pixel counter. The counter clock was delivered in the direction from (0,0) to (0,127). We can see that the counter values of the three pixels are monotonically increasing and the standard deviation is about 1 LSB. The result shows that the system functioned well until (0,127), which is the farthest pixel from the PLL.

4 Conclusions

This report gave an overview of the purpose and development of a 3D image sensor for Flash LIDAR at JAXA. We are planning to conduct indoor and outdoor pulsed laser measurement experiments with this device in the near future.

Acknowledgments

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