High-resolution time-of-flight range imagers with lateral electric field modulation

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Abstract This paper presents a TOF imager with high range resolution of 0.3mm, which corresponds to 2 ps time resolution. To achieve this high resolution, the imager uses a high-speed lock-in pixel based on a lateral electric filed modulation and a novel ToF measurement technique by using an impulse photocurrent response. To realize a range imager with 2D pixel array, column-wise gating-clock skew calibration is implemented.

Keyword Time-of-Flight range imaging, CMOS image sensor, Lateral electric field modulator, skew calibration

1. Introduction

Recently, ToF 3D scanning systems have attracted rapidly rising attention in combination with 3D printers. One of the common technologies in contactless 3D scanners is light-section method, which has advantages in term of accuracy. The method, however, requires a long base line between a camera and light source to achieve high resolution, and mechanical scanning system. A high range resolution TOF imager provides new possibilities of implementing a miniature head, which allows flexible scanning of an object with a complicated structure.

Although numerous developments ToF range imagers have been reported[1][2][3], the range resolution of CMOS TOF imagers is limited to a few centimeter. For higher resolution, higher modulation frequency is required. However, the modulation frequency used for CMOS TOF imagers is limited to several tens of MHz. The high-speed lock-in

This paper presents a TOF imager with 0.3mm range resolution, which corresponds to 2 ps time resolution. To achieve this high resolution, the imager uses a new TOF measurement technique based on an impulse photocurrent response [4] and high-speed lock-in pixels based on lateral electric field modulator. To realize a range imager with 2D pixel array, column-wise gating-clock skew calibration is implemented to demonstrate simultaneous sub-mm TOF measurements for whole pixel array.

2. Lateral Electric Field Modulators (LEFMs)

High-speed charge modulation is a key technology in ToF range imagers. This is because the modulation speed at a detector should be much higher than the pulse width or modulation frequency of light source, which determine the range resolution. To achieve the high-speed charge modulation, we have proposed a lock-in pixel based on a lateral electric filed modulator (LEFM)[5]. Fig.1(a) shows the concept of the LEFM. The channel potential in the pinned photodiode structure is controlled by the gates, G1 and G2, which are formed along the channel. Since the gates are not used for transferring the charge into or out of them, there is no transfer gates in signal path. As a result, high-speed and loss-less charge transporting can be achieved.

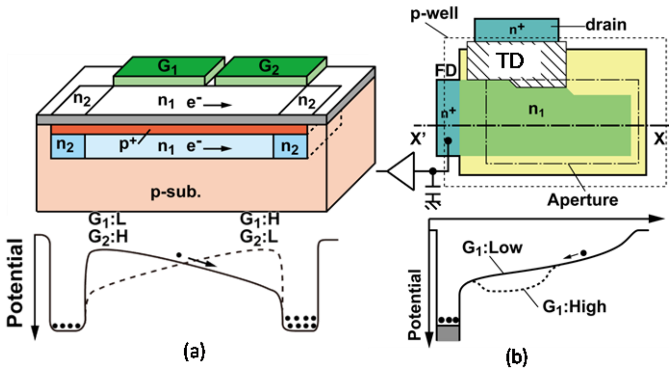

Fig. 1. (a) The concept of LEFM, (b) 1-tap LEFM

Fig.1(b) shows the one-tap LEFM, which is also called as draining-only modulator (DOM). In the DOM detector, when a draining gate (TD) is opened, all of generated electrons in photodiode are drained out. While the TD is closed, generated electrons are transferred into a floating diffusion (FD). The charge transfer and draining are only controlled by lateral electric field from the TD. The DOM requires only the TD, the implementation of the pixel is simple.

3. Sub-millimeter range resolution ToF range imager with column-wise skew calibration

Fig. 2 shows the sensor architecture for sub-millimeter range resolution. The ToF range imager uses an indirect ToF measurement technique with impulse photocurrent response[4],[6]. By using a light source with a very short pulse, the photocurrent response can be regarded as an impulse response. As a result, the range resolution is determined only by the photocurrent response, which facilitates the utilization of the full high-speed capability of the lock-in pixel. The high-speed photocurrent response can be achieved by using DOM lock-in pixels as shown in Fig.1(b).

As the range resolution increases, skew of the gating clock becomes a serious problem. The TD of DOM pixels is provided through an inverter tree, skew calibration circuit, and clock drivers, causing a different delay from pixel to pixel. In particular, the skew due to device mismatch and voltage drop of power supply line in the modulation clock driver are inevitable. In the proposed sensor, the available range is a few tens of millimeter, which corresponds to a few hundreds of picosecond. If the skew is comparable or larger than the measurable range, each pixel has different measureable range, thereby simultaneous capturing for all pixels cannot be achieved. To calibrate the skew column by column, two-stage voltage controlled delay lines (VCDLs) with 7-bit current-steering DACs is implemented in every column. The 1st and 2nd stages of VCDL are used as a coarse and fine calibration, respectively.

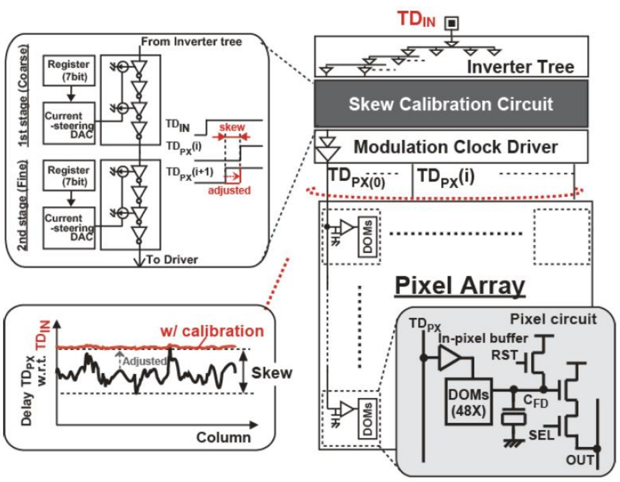

Fig.1 Proposed ToF range imager.

The ToF imager is fabricated in 0.11um CIS technology. The pixel array is 310(H) x 120(V), in which main pixel count is 132(H)x120(V). Fig. 3 shows a measured skew distribution with and without the skew calibration. As expected, a large skew of 850 ps_{p-p} or 173 ps_{rms} is observed before calibration. The skew includes both random and systematic components, which are supposed due to device mismatches and a voltage drop of power supply, respectively. After the calibration, the skews are reduced to 81 ps_{p-p} or 8 ps_{rms}, which are within the measurable range. Fig.5 shows a measured distance and resolution as a function of the distance to a mirror target. In this measurement, data of all main pixels were taken into account. The integration time is set to 33 ms. From the measurement results, the non-linearity is below 3 %FS at 32 mm range. The resolution within the measurable range is measured to be 0.3 mm on average.

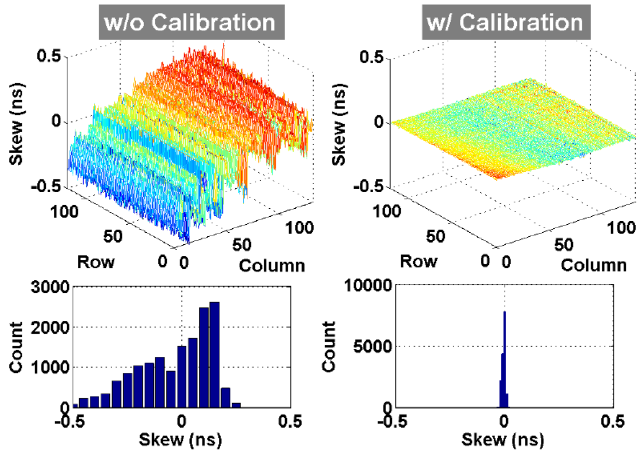

Fig. 2. Measured skew w/o and w/ skew calibration.

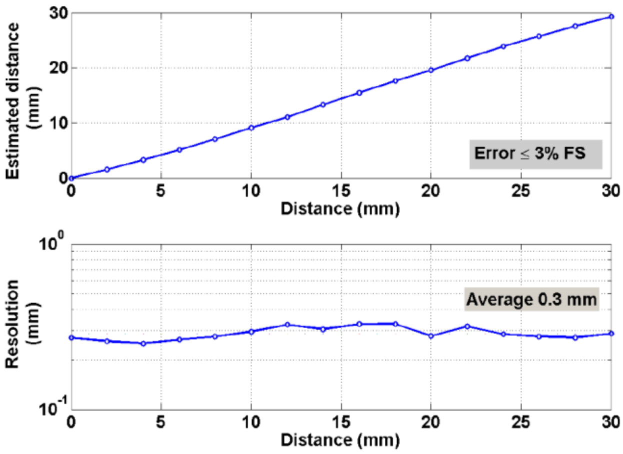

Fig. 3. Measured distance and resolution

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