Clock management in high range resolution Time-of-Flight range imagers

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Abstract In time-of-flight range imagers, as the range resolution increases, a gating clock skew becomes a serious problem. This paper describes two skew calibration techniques implemented in column-parallel circuits for TOF range imagers. Skew calibration technique with optical response is simple but the long calibration time is required. To reduce the calibration time, self-calibration technique with a bang-bang digital DLL has been developed.

Keywords: Time-of-Flight, 3D imaging, Skew calibration

1. Introduction

With the expansion in the demand for 3D imaging technologies, much attention has been paid to time-of-flight (TOF) range cameras because of its capability to cost effectiveness and real-time acquisition. For this reason, a number of TOF range imagers based on CMOS image sensor technologies have been presented. Particularly in indirect TOF range image sensors, the pixel counts increases to 512x424 pixels [1]. In terms of range resolution, a state-of-the-art TOF range imager [2] has demonstrated high range resolution of 0.25 mm, which corresponds to time resolution of 1.7 ps. Higher time resolution is strongly required for extending the application area of TOF imagers.

To achieve high range resolution, a shorter pulse width or a higher modulation frequency of light source is required in the indirect TOF measurement. As the pulse width decreases or range resolution increases, a skew of gating clock between pixels becomes a difficult problem, because the clock skew causes the reduction of measurable maximum range in particular pixels or unmeasurable pixels. The clock skew also increases with an increase of pixel counts. Therefore, a skew reduction technique becomes more important in TOF range imagers as well as time-resolved imagers. For reduced gating clock skew, a vertical overflow drain (VOD) shutter [3] is effective because of its relatively small load capacitance [4]. However, the high-speed shutter is limited to one-phase gating operation, and the reported skew is 60 ps_{rms}, which is relatively large for the specification of extremely high range resolution [2].

This paper describes two skew calibration techniques with column-parallel circuits in TOF range imagers. One is a skew calibration with optical response [2], and the other is self-calibration with a bang-bang digital DLL [5]. The former is simple, but the calibration time is very long because many measurement points are required to measure the skew. To reduce the calibration time, the latter introduces electronics-only self-calibration scheme.

2. Skew calibration with optical response

Fig. 2 shows a sensor architecture with skew calibration. In addition to a pixel array and readout circuits, this sensor has column-parallel skew calibration to reduce column-wise skew. The gating clock of the modulator, TD, is propagated through an inverter tree, skew calibration circuit, and clock drivers. The propagation of the gating clocks in different paths causes a different delay from pixel to pixel, which corresponds to the skew. In particular, the skew caused by the device mismatch of the pulse drivers and the voltage drop of the power supply line in the modulation clock driver are inevitable, resulting in the large skew between columns.

To reduce the column-wise skew, the skew calibration circuit controls the amount of delay at each column for minimizing the skew. To determine the register value of each delay line in the skew calibration circuit, skew and delay characteristic of the delay lines should be measured. The skew is measured from modulation characteristics as shown in Fig.2. The modulation characteristic means optical responses when the delay of laser trigger is changed. In the modulation characteristics, the skew and delay characteristic are observed as a shift of the peak photocurrent.

The skew calibration is done by turn steps; a coarse calibration and a fine calibration. First, the skew before calibration is measured, when the register value is set to an initial value which is close to the minimum delay condition. For the coarse calibration, the delay characteristics of the first stage of calibration circuits are measured in the same manner as the skew measurement. The modulation characteristics are measured while changing the register value. The delay characteristic is then extracted from them. From the delay characteristic, the register value of the first stage are chosen so that the skew is minimized. Finally, fine calibration is performed in the same manner as that of the coarse calibration.

The prototype TOF range imager [2] demonstrates that the skew is reduced from 173ps_{rms} to 8 ps_{rms}. which are small enough to have measurable range of 30 mm. The prototype is implemented using a 0.11-um CIS technology, and the effective pixel counts are 132(H) x 120(V). The vertical skew, which is associated with a propagation delay in the pixel wiring, is reduced by an in-pixel buffer and decoupling capacitors.

3. Skew reduction with self-calibration scheme

The skew calibration with optical response is simple, but the long calibration time is necessary because the measurement of modulation characteristics. For example, approximately 10^5 to 10^6 measurements or 1 to 9 hours are required for the skew calibration when the frame rate is 30 fps.

To reduce the calibration time, self-calibration circuit is proposed as shown in Fig.3. It consists of a bang-bang phase detector (BPD) and two-stage delay line. Each stage includes a 7-bit up-down counter (CNT), which controls the amount of delay. Besides the main column, it also includes a reference column with almost identical design to the main column. The reference column gives a reference gating clock, REF_CLK for the main column via a clock tree. The BPD detects the phase difference between REF_CLK and a modulation clock of each column, CLK_PIX, and the results, i.e. up and down signals are counted by the CNTs only when enable signals (EN_CALC,

EN_CALF) are asserted. As a result, the two-state delay line of each main column is automatically controlled such that the skews between columns are minimized.

In this clock-skew calibration circuit, two clock trees are used; one is for the gating clock drivers supplied to pixels and other is for the reference clocks. The clock tree for distributing the reference clocks into all the columns is a key point of the design. Since the load capacitance of inverters in the clock tree is much smaller than that of the modulation clock drivers connected to pixels in each column, the clock skew due to the clock tree is also much smaller than that of the clock drivers.

A prototype TOF range imager with 256 (H) x 8 (V) pixel counts is implemented using 0.11um CIS technology. The column pitch is 22.4 μm. With calibration, the skew is reduced from 247 ps_{rms} to 25 ps_{rms}. The calibration time is only 12 μs, which is much shorter than that of the skew calibration with optical response.

4. Conclusion

This paper describes skew calibration techniques in TOF range imagers. By combination with the column-parallel skew calibration and the in-pixel buffer, the resulting skew is less than 10 ps_{rms}. Self-calibration is possible to implement the BPD-based digital DLL in each column, which has an advantage of short calibration time.

5. Acknowledgements

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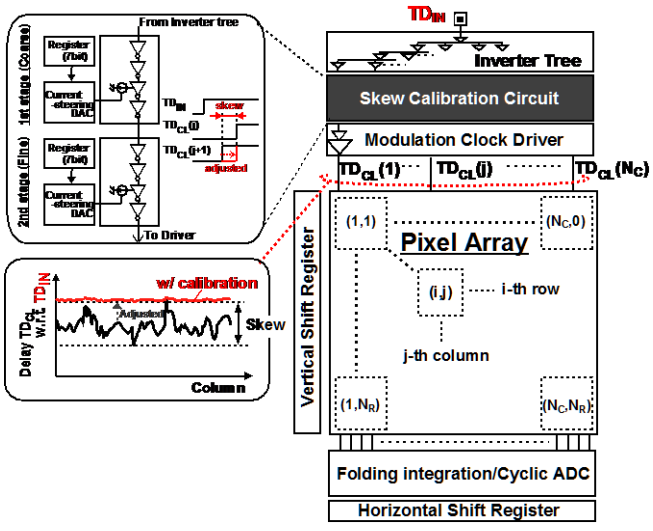

Fig. 1. Sensor architecture with skew calibration circuits by using optical response

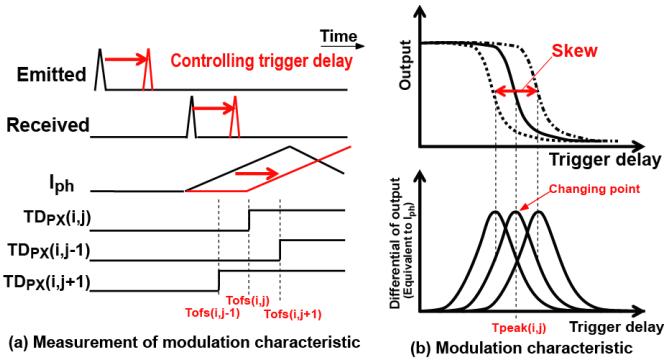

Fig. 2. Measurement of modulation characteristic to measure the skew and delay charactristics of the delay lines

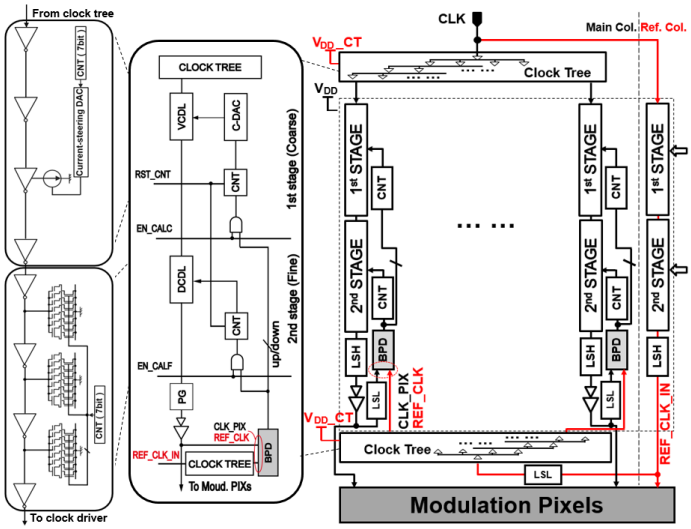

Fig. 3. Skew self-calibration circuits with BPD and dual clock-tree

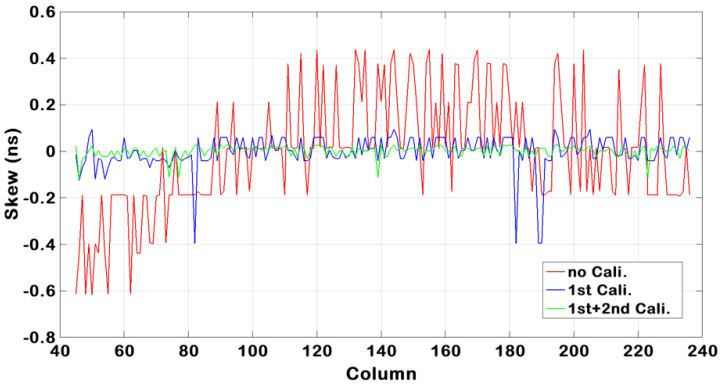

Fig. 4. Skew measurement results

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