Compact Ambient Light Cancellation Design and Optimization for 3D Time-of-Flight Image Sensors

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A highly compact ambient-light-cancellation (ALC) circuit for 3D time-of-flight (ToF) image sensor pixels is presented. It is implemented in a 320x240 pixel (QVGA) sensor with 14um pixel pitch in a 90 nm backside illumination (BSI) image sensor process. The ALC circuit has less than 3% fill factor impact and is very suitable for scaling to smaller pixels. An algorithm to optimize ALC performance is also presented. The QVGA sensor has been demonstrated at up to 40k lux of ambient light (moderate sunlight) and the reported ALC circuit and system is expected to be applicable to much higher lighting conditions, such as over 100k lux (intense sunlight).

Conventional ToF and newer RGBZ image sensors [1] are candidates for capturing 3-D image media in consumer devices, as well as for enabling gesture control of smart televisions, mobile devices and other equipment. Widespread application of ToF sensors to mobile devices is dependent on both pixel miniaturization and ALC. Compact ALC is also necessary for widespread adoption of RGBZ image sensors. ToF sensors commonly use high-frequency modulated near-infrared (NIR) light sources to determine object range from the phase shift of the reflected signal. Immunity from ambient room light is achieved using modulation "lock-in" and narrow-band optical filters. However, in stronger lighting, such as daylight or direct sunlight, the residual ambient light can cause premature pixel saturation and total loss of range information. Several techniques for ambient light cancellation (ALC) [2-5] have been previously reported. However, these techniques need large complicated circuits which have made pixel size reduction difficult.

A typical ToF pixel has a demodulator with two output ports controlled by complementary clock signals, which have 0^o and 180^o phase shifts relative to the light source in one field, and 90^o and 270^o phase shifts in the next field. The in-phase and out-of-phase signals are integrated on two floating diffusions (FD), respectively, and two fields are required to generate the four phase amplitude signals, designated as A_0, A_2, A_1, and A_3. The range information can be calculated from the four samples using the following equations,

$$d = \arctan\left(\frac{A_3 - A_1}{A_2 - A_0}\right) \cdot \frac{1}{2\pi} \cdot \frac{c}{2 f_{MOD}} \quad (1)$$

where d is the extracted distance between the sensor and the object being measured. If any one of the four signals is saturated, the range data calculated becomes invalid. To solve this problem, two discrete-time charge-domain sources are implemented inside each pixel in our sensor. When activated, the circuit injects the same number of holes into each FD. The electrons stored in the floating diffusion recombine with the injected holes and keep the FD from saturation. (We note a similar circuit has been used for a 1b DAC in pixel-level ADC circuits [6]). The pixel architecture is shown in Fig. 1.

Each hole source consists of three PMOS transistors, which are controlled by signals ALC1, Valc, and ALC2. The transistor in the middle acts like a MOS capacitor. When biased in strong inversion region, for a given process, its capacitance is only determined by its geometry, and the number of holes it can store is determined by the bias voltage Vb_alc, as shown in (2).

$$Q_{mid} = C_{ox} \cdot W_{mid} \cdot L_{mid} \cdot \left(VAAPIX - V_{b\_alc} - \left|V_{thp}\right|\right) \tag{2}$$

The charge transfer process during ALC operation is shown in Fig. 2. At the beginning of the operation, the MOSCAP in the middle is filled with holes, which quantity is calculated by (2). At the end, all holes are transferred to the FD, and three transistors are empty. The ALC transistors can also be used to reset the pixel using different timing.

As indicated by (1), only differential signals $(A_3 - A_1)$ and $(A_2 - A_0)$ are used for phase and range calculation. Within one pixel, as long as the two outputs, Pixouta (A_0, A_1) and Pixoutb (A_2, A_3), perform the same number of ALCs, ideally, the range calculation stays the same. However, transistor mismatch will introduce some non-linear range error to each. Temporal kTC noise of the ALC circuit is less than the photon shot noise of the optical input signal.

To deal with high intrascene dynamic range of ambient light illumination, a multiplexor is also included in each pixel to control the gate voltage of the MOSCAP. The multiplexor either allows the Vb_alc pulse train to be passed to the MOSCAP or block it by sending a constant VAAPIX. The decision is made by comparing the two pixel outputs with a reference voltage. Only when both outputs are below the reference level, Vb_alc is selected by the multiplexor, and the ALC will be performed. Two comparators and an AND gate for decision making are implemented inside the column readout. The timing diagram and a sample pixel output are shown in Fig. 3. The pixel size is further reduced by sharing the MOSCAP and the top transistor for pixels in adjacent rows. The inclusion of the ALC circuit in the pixel reduces pixel fill factor by 3%, which effect is also mitigated by the use of backside illumination.

To optimize the performance of the ALC, an algorithm has been developed to find the optimal values of ALC parameters. Input parameters to the calculation include sensor linear range V_{MAX}, frame integration time T_{INT}, expected maximum differential signal $V_{DMAX} = |Pixouta - Pixoutb|$ and common-offset signal $V_{CMAX} = \min\,(Pixouta, Pixoutb)$ accumulated during the frame exposure. The goal is to determine the ALC cycle parameters including the minimum number of pulses per frame, *N*, ALC reference voltage *Vref*, signal reduction from one ALC operation, V_{ALCA}, and the time when ALC pulses should be applied, $t_1..t_N$. The solution reported below fulfills all these requirements.

$$V_{ref} = V_{ALCA} \tag{3}$$

$$t_i = T_{INT} - V_{ref} \times T_{INT}/V_{CMAX} \times (N - i) - d \tag{4}$$

where $N = \lfloor t_N/\Delta t \rfloor$, i∈$\boldsymbol{N}$, i=1..N. The first pulse at t_1 may be omitted and solution exists when $t_N \geq 2\ \Delta$t. In practice, input parameters must be relaxed to avoid saturation and clipping due to noise, pixel-to-pixel sensitivity, pixel full well capacity, comparator threshold and other variations.

Fig. 4 shows two captured range images. In the top image, the mannequin and part of the chair behind it have wrong range data due to ambient light saturation on at least one tap. In the bottom image, the correct range data is obtained. Fig. 5 shows the range error at 1m with increasing ambient light. It is about 1% at 100lux, and about 5.5% at 40,000lux at f/2.4 and 120 fields per second.

In conclusion, we have demonstrated a compact ALC circuit that can cancel ambient light signals effectively. An easy to implement algorithm to optimize the control parameters is also developed. The compact pixel design enables smaller pixel size for high resolution and/or small form-factor applications.

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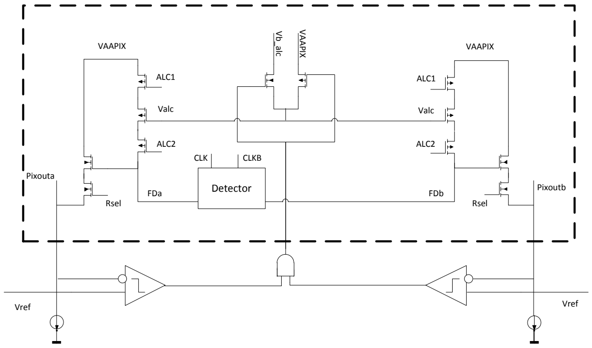

Fig. 1. TOF pixel with three-transistor discrete-time charge sources for ALC. Comparators, AND gate and source follower bias are inside the column readout circuit.

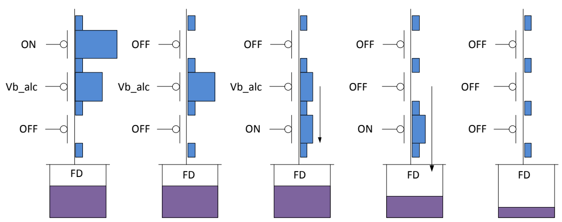

Fig. 2. Schematic illustration of charge transfer process during ALC operation. ALC circuit generates hole packet which recombines with electrons in demodulator FD output.

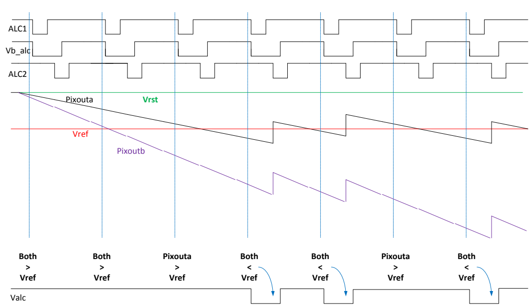

Fig. 3. ALC timing diagram and sample pixel outputs.

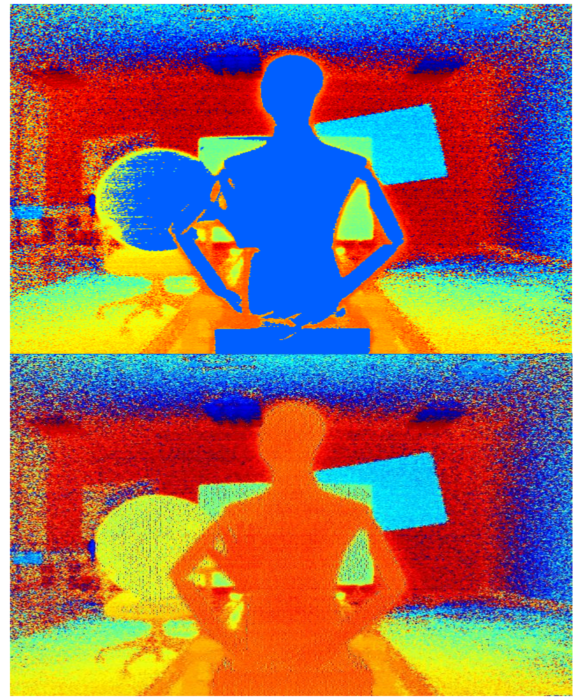

Fig. 4. Captured range images under 40k lux ambient light without (top) and with (bottom) ALC control.

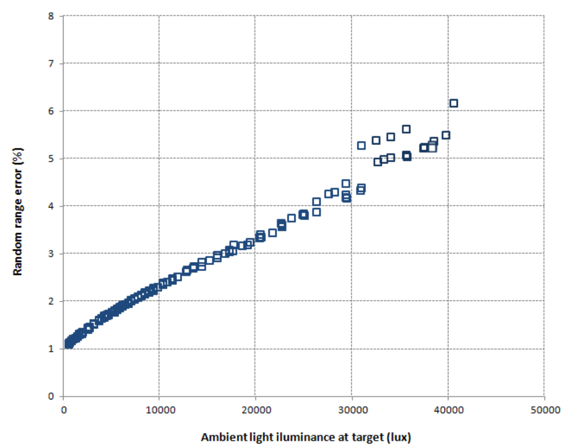

Fig. 5. Range error as a function of ambient light at 1m with ALC at f/2.4 and 120 fields per second.