A 2-Tap Indirect ToF CMOS Image Sensor for Multi-Frequency Demodulation

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Abstract. *Indirect time of flight (IToF) allows for accurately retrieving 3D geometry without needing exorbitant time resolution. Nevertheless, the use of continuous-wave (CW) periodic modulation brings the need for multiple frequency measurements to solve depth ambiguities or cope with multi-path interference. Sequential acquisition of multiple frames reduces the frame rate, while harmonic distortion of the modulation waveforms produces wiggling in the depth estimation. This work presents the operation of an IToF CMOS image sensor designed to provide single-shot multi-frequency measurements. A macro-pixel structure allows acquiring multi-frame data in one shot, while resonant demodulation annihilates the harmonic content. The novel architecture consists of* $10\,\mu\mathrm{m} \times 10\,\mu\mathrm{m}$ *2-tap pixels with a 20% fill factor (FF). Post-layout simulations show promising 3D reconstruction for up to 16 different simultaneous frequencies.*

Keywords. CMOS image sensor, time-of-flight, macro-pixel, single-shot, multi-path

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1 Introduction

IToF measures the phase difference between the emitted and the received signal, providing high spatial resolution and straightforward processing compared to the other 3D measurement techniques. IToF works based on modulated continuous or pulsed light in concurrence with the electrooptical demodulation of a photo-mixing device (lock-in pixels). Unlike 2D imaging, in IToF, the integration process is controlled by applying predefined signals to the modulation gates. Therefore, depth calculations are based on samples of the cross-correlation of the received signal and the applied control signal. In this way, the range data of each pixel can be retrieved from a group of measurements [1].

Despite many advantages IToF offers, it has some critical challenges like motion artifacts, background light error, and ambiguous range. One of the other essential issues in IToF systems is Multi-Path-Interface (MPI), meaning that each pixel may receive more than a single bounce, resulting in a superposition of sinusoidal signals reaching the pixel. MPI errors usually increase the measured distance value since the direct path (desired bounce) distance is shorter than the indirect path (undesired bounce).

Typically, the solution for this problem is to increase the number of measurements with different modulating frequencies sequentially, but the resulting increase in the total exposure time decreases the frame rate of depth images. Besides, the required number of frequencies will increase linearly with the number of received bounces. Using the measurements obtained at different frequencies, the distance values for individual bounces can be obtained in a closed form [2]. Here, we demonstrate the successful realization of a single-shot multi-frequency IToF architecture in 180 nm CMOS technology using a resonant demodulation concept.

2 Multi-frequency ToF measuring concept

The use of macro-pixels allows for single-shot multi-frequency demodulation [3], thus enabling multiple-path depth imaging at high frame rates. A macro-pixel can be formed by grouping numbers of pixels modulated with different frequencies, so-called *subpixels*. In this work, we focus on the case of CW sinusoidal modulation, in which a sinusoidal wave of IR light illuminates the scene at the defined frequency, and the reflected light received by the ToF pixels will generate charges that are accumulated according to the demodulation control signals of the taps. The prevalent 2-tap structure is used in our pixel's circuit.

For illustration, Fig. 1 shows a single macro-pixel consisting of an array of 4 by 4 subpixels. Each subpixel has a 2-tap structure, where both taps demodulate with the same frequency with a 180° phase shift. We denote as $f(i)_{0,1}$ the frequency of the demodulating control signal at subpixel i, with $i = 1, ..., 16$ in this case, for both Tap0 and Tap1. For the sake of clarity, the control signals of the 4 subpixels marked with a red square in Fig. 1 are shown on the right. As can be seen, differently from conventional IToF, the demodulating frequencies are different for each pixel. Each of the 16 subpixels can be either connected to the same frequency (conventional IToF) or to 16 separate frequencies. The entire pixel array, including several macro-pixels, can be formed by repeating this pattern.

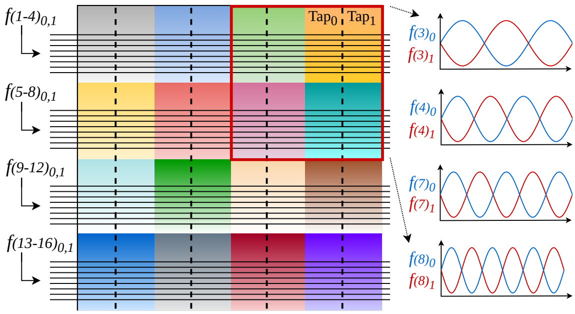

Figure 1. An array of sub-pixels with 16 possible frequencies forming a single macro-pixel.

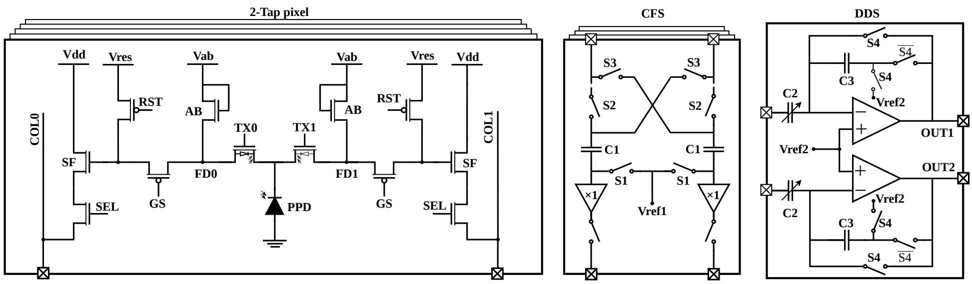

Figure 2. Schematic of the designed pixel and the readout circuitry.

3 Circuit description

Fig. 2 depicts the circuit schematic of the pixel and the following readout circuitry. The design includes a symmetrical structure with a pinned photodiode (PPD) as a photosensitive part, reset, global shutter, source follower (SF), and row select [4] transistors. For the source follower, reset, and row select transistors, proper sizes were selected to optimize signal swing, noise, and image delays. The analog supply voltage (Vdd) is 3.3 V for the pixel for a higher signal dynamic range.

After the exposure time, the following stages are the Column Filter Stage (CFS) and Double-Delta-Sampling (DDS) blocks. The CFS block can process and filter pixel signals. It consists of two decoupling capacitors followed by voltage followers whose outputs can be selected by a column decoder to be sent sequentially through the DDS output stage [5].

4 Chip Architecture

The active pixel sensor, presented in Section 3 operates in reset, integration, and read-out stages to retrieve the 3D data. Fig. 3 shows the layout design of the entire ToF range imaging system, which consists of an array of pixels, the modulation control signal tree, the biasing circuitry, the row, and column decoders, the CFS, and the DDS stage. The system has an array-shared modulation signal generator, row and column control circuits, driver

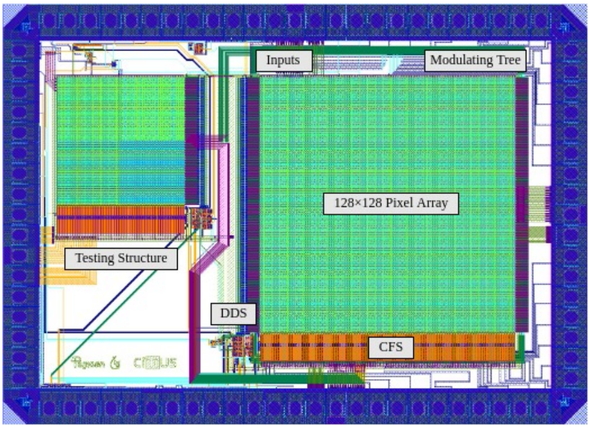

Figure 3. Chip design of the single-shot multi-frequency IToF system with its parts labeled.

circuits, and bias circuits for in-pixel operational amplifiers.

In previous work, we presented a resonant demodulation circuit that uses an off-chip inductance connected across the taps to achieve minimal harmonic distortion [6]. The capability of this system for generating resonant frequencies for modulating the subpixels will be studied experimentally in our future work. However, the simulation results for proving this concept were favorable.

5 Conclusion

This work presents the IToF pixels with readout circuitry. The proposed macro-pixel-based architecture allows for realizing the idea of single-shot multi-frequency demodulation. Furthermore, perfect sinusoidal control signals at the demodulation gates, arising from a resonant construction, enable native harmonic cancellation per pixel or group of pixels. Resonant demodulation can further reduce the average drive current of pixels, resulting in considerable power-saving and paving the way for low-powered 3D imaging systems. The next step is to prepare an experimental setup and test the proposed system.

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