Continuous-wave time-of-flight CMOS detector with commonmode feedback for strong background light applications

Ingelberts, Hans; Deleener, Robin; Boulanger, Sven; Kuijk, Maarten

Published in:
2015 IEEE SENSORS Proceedings

DOI:
10.1109/ICSENS.2015.7370558

Publication date:
2015

License:
Unspecified

Document Version:
Accepted author manuscript

Citation for published version (APA):
Continuous-wave time-of-flight CMOS detector with common-mode feedback for strong background light applications

Hans Ingelberts, Robin Deleener, Sven Boulanger, Maarten Kuijk
Department of Electronics and Informatics (ETRO)
Vrije Universiteit Brussel
Brussels, Belgium
hingelbe@etro.vub.ac.be

Abstract—A novel CMOS demodulation detector for time-of-flight applications is presented. It can handle large amounts of background light by removing the resulting common-mode signal at the detector level. A common-mode feedback circuit is used on top of a current-assisted photonic demodulator (CAPD) to remove the incoming light that is not correlated to the modulation signal. A dynamic element matching (DEM) scheme is implemented to remove mismatches in the compensating current sources that operate at nanoampere currents. The detector is fabricated in a 0.35 μm process and is used to measure the phase of a 1 MHz square-wave modulated laser signal on top of a background light, more than 100 times more powerful, without the use of optical filters. Measurements are performed with and without DEM, demonstrating its need. The detector is a candidate for long range outdoor time-of-flight applications where background light can become multiple orders of magnitude larger than the modulated light.

Keywords—Current-Assisted Photonic Demodulator; Photonic demodulation; Optical detectors; Time-of-flight imaging; CMOS demodulation detector; Strong background light; 3D camera

I. INTRODUCTION

Continuous-wave time-of-flight is one of the preferred techniques currently used in 3D cameras [1]. These cameras measure depth, the distance from an object to the camera. Continuously modulated light is emitted towards an object or a scene and the phase difference between the reflected modulated light and a reference demodulation signal of the same frequency is measured. The phase difference depends on the time the light has travelled to the scene and back and is, through the speed of light, proportional to the distance the light has travelled. The phase is measured by looking at the amount of overlap of reflected modulation light (S) and the reference demodulation signal, which we call the in phase signal (S_0°). In an effort to make the measurement insensitive to any extra background light that is uncorrelated to the modulation, differential demodulation detectors also measure the overlap with the inverse of the demodulation signal (S_180°). Uncorrelated light will, on average, show up equally in S_0° and S_180° and its contribution is removed by taking the difference S_0° - S_180°. These signals can also be decomposed in a differential (S_d) and common-mode (S_cm) part.

\[ S = S_0° + S_180° \]  

It can easily be seen that the difference of the in- and out-of-phase signals only depends on the differential part.

\[ S_0° - S_180° = 2S_d \]  

All demodulating CMOS detectors contain a medium to convert the signal of photons (S) of the incoming light into electrons, and a mechanism to direct the resulting photocurrent that is in phase with the demodulation signal (I_0°) to one diffusion node and the current that is out of phase (I_180°) to another diffusion node (Fig. 1). The capacitance (C) of the diffusion nodes is used to convert the accumulated charge into a voltage. Before a measurement, the voltages on these capacitors are reset to a certain voltage (V_reset) and during the measurement the capacitors are discharged by their respective photocurrents (Fig. 2). After an integration period (ΔT) a voltage difference (V_out), proportional to the difference in photocurrents, can be read out.

\[ V_{out} = V_2 - V_1 = \left( V_{reset} - \frac{I_{180°}}{C} \Delta T \right) - \left( V_{reset} - \frac{I_{0°}}{C} \Delta T \right) = \left( I_{0°} - I_{180°} \right) \Delta T / C = I_{diff} \Delta T / C \]  

This work was supported in part by the HERCULES project VeRONICa.

Fig. 1. Typical differential demodulation detector equivalent circuit.

Fig. 2. Operating signals of a differential CMOS demodulation detector.
The capacitors are discharged by both the common-mode current \(I_{cm}\) and differential current \(I_d\). However, we are only interested in the differential part. Any background light that is not correlated to the modulation signal will show up as common-mode photocurrent and will discharge both capacitors equally. In Fig. 3.a and from (5) it can be seen that this is no problem for moderate background intensities as \(V_{out}\) is independent of the common-mode. For strong background intensities however, both capacitors discharge quickly to their saturation voltage and the time available to develop a voltage difference becomes very short, putting a limit on the attainable SNR.

The background intensities encountered in indoor applications are usually moderate and when used with an optical filter in front of the imager, to select the wavelength of the modulated light, today’s commercial depth cameras perform very well. This changes dramatically for outdoor applications. The intensity of the sunlight on a bright day can be several orders of magnitude stronger than the modulated light, even using filters. One can calculate that, imaging an object, located 16 m from a camera, using laser light at 850 nm and emitting 20 mW average power, one can expect, on a sunny day and using a 25 nm wide optical band pass filter, a background signal more than 1000 times stronger than the modulation signal. A typical CMOS imager has an output swing of 2.5 V. With a differential signal 1000 times weaker than the common-mode, a maximum \(V_{out}\) of only 2.5 mV would be reached before saturation. A solution is required.

II. SOLUTION CONCEPT: COMMON-MODE FEEDBACK

The proposed solution to avoid saturation is to cancel out the common-mode photocurrent by continuously recharging the detector capacitors with a current exactly equal to the common-mode photocurrent. A way to achieve this is by keeping the common-mode voltage on the capacitors constant. The total current flowing into \(C_1\) and \(C_2\) is

\[
I_{C1} = I_a - I_0° = I_a - I_{cm} - I_d \quad (6a)
\]
\[
I_{C2} = I_b - I_{180°} = I_b - I_{cm} + I_d \quad (6b)
\]

If the common-mode voltage \(V_{cm}\) is constant its derivative is zero.

\[
V_{cm} = (V_1 + V_2) / 2 \quad (7)
\]
\[
dV_{cm} = \frac{dV_1 + dV_2}{2} = \frac{(I_{C1} + I_{C2})}{2C} dT = 0 \quad (8)
\]

From (6a), (6b) and (8) it follows that
\[
I_a + I_b = 2I_{cm}
\]

And, when \(I_a\) can be made equal to \(I_b\), then
\[
I_a = I_b = I_{cm}
\]

The common-mode voltage is sensed with a resistive divider and kept to a constant level \(V_{ref}\) with a feedback amplifier that controls transistors M1a and M1b, operating as current sources. A reset transistor M2 can initialize the capacitor voltages to \(V_{ref}\) at the beginning of a measurement. Because the common-mode photocurrent is cancelled out at the integration capacitors, any change in the output voltage after releasing the reset is only proportional to the differential photocurrent and is therefore independent of the background light.

III. PRACTICAL SOLUTION: DYNAMIC ELEMENT MATCHING

The common-mode feedback solution requires that the currents supplied by current sources M1a and M1b are perfectly matched \((I_a = I_b)\). However, these currents are in the order of a nanoampere. This means the transistors operate in weak inversion mode where the expected current mismatch can be in excess of 20% (200 pA) for small sized transistors. The differential photocurrent however, can be very small and in the order of picoamperes and would be completely masked by the mismatch current.

The proposed solution is to use a dynamic element matching (DEM) scheme (Fig. 5). In this scheme the current sources are continuously switched by DEM1. The DEM switch is controlled by a 50% duty cycle square wave such that on average the current supplied to each capacitor is equal to \((I_a + I_b) / 2 = I_{cm}\).

During a measurement the voltage on a capacitor will go up when that capacitor is connected to the current source that supplies the larger current and down when connected to the other source (Fig. 6). Sampling of the output should be performed at the end of one period of the switch control signal.
Gradients of process parameters along a CMOS wafer also cause mismatches in the detectors. To eliminate these, a second DEM element, DEM2, is used to switch the photocurrents. To perform correct measurements, the photocurrent that is in phase with the demodulation signal should always flow to C1 and the out of phase current to C2. With dynamic element matching of the detector this is not true anymore. Comparing Fig. 2 and Fig. 7.a, it is clear that a wrong amount of charge is directed towards the integration capacitors after a DEM switch. This can be corrected by inverting the phase of the demodulation signal each time the DEM element is switched as in Fig. 7.b.

To avoid charge leaking from one capacitor to the other, it is also necessary to buffer the capacitor voltages before the resistive common-mode sensor with buffers B1 and B2.

**IV. IMPLEMENTATION**

A continuous-wave time-of-flight detector with common-mode feedback is implemented in a 0.35 μm CMOS process of X-Fab. The detector is based on a Current-Assisted Photonic Demodulator (CAPD) [2]. This CMOS demodulation detector uses an internally applied and modulated electric field to select between in- and out of-phase photocurrents, reaching an excellent demodulation contrast.

**TABLE I. DETECTOR SPECIFICATION**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPD size</td>
<td>30 μm x 30 μm</td>
</tr>
<tr>
<td>Total size without bondpads and bias circuits</td>
<td>100 μm x 100 μm</td>
</tr>
<tr>
<td>Supply voltage (Vdd)</td>
<td>3.5 V</td>
</tr>
<tr>
<td>Power consumption (excluding bias and CAPD)</td>
<td>20.5 μA</td>
</tr>
<tr>
<td>Integration capacitance</td>
<td>33.5 fF</td>
</tr>
<tr>
<td>Maximum common-mode current</td>
<td>3 nA</td>
</tr>
<tr>
<td>Output swing</td>
<td>+/- 1V</td>
</tr>
<tr>
<td>Modulation frequency</td>
<td>1 MHz</td>
</tr>
<tr>
<td>DEM switch frequency</td>
<td>10 kHz – 100 KHz</td>
</tr>
</tbody>
</table>

**V. TESTING AND RESULTS**

The detector is bonded to a ceramic package without top seal and soldered onto a printed circuit board with all the necessary power supplies, DACs and ADC. The detector board is connected to an FPGA development board. Measurement control and signal generation is implemented on the FPGA. The FPGA board is connected to a PC and the measurements are controlled over a serial terminal. Modulated light is provided by a square-wave modulated 680 nm laser diode and background light by a 50 W halogen lamp. No optical filters are being used. To simulate light travelling towards an object and back, the laser modulating signal is phase shifted using a PLL in the FPGA.

The differential output voltage is measured for different phase shifts of the modulated laser light. This output shows the expected linear relation to the phase with a maximum when the demodulation signal completely overlaps the modulation signal and a minimum when the inverse of the demodulation overlaps with the modulation signal (Fig. 8). To unambiguously measure the phase, a second measurement with a 90° shift of the modulation is needed. A clear improvement of the sensitivity of the output can be seen when enabling DEM (Fig. 9). The effect of the mismatch of the current sources can be clearly seen in Fig. 10.

![Fig. 6 DEM signals.](image1)

![Fig. 7 Detector mismatch switching (a) without and (b) with demodulation phase inversion.](image2)

![Fig. 8 Differential output voltage relation to the modulated signal phase for a background to modulation ratio of 130.](image3)
VI. PRACTICAL USE

The overhead of the additional circuitry will limit the achievable pixel density for integration into 2D-arrays. In this first implementation, the area for the required circuitry per pixel is about an order of magnitude larger than the photosensitive area. However, it can be envisaged that in future implementations, the circuit area can become reduced significantly by using a more advanced CMOS process node. Furthermore, for long haul range-finding it can also be more efficient to make the detector area much larger (e.g. 100 μm x 100 μm), for receiving a larger part of the incident modulated light. In both cases, a more reasonable fill-factor can be achieved for the two-dimensional arrays implementations of the proposed principle.

The proposed principle can further be combined with other measures to cope with high background light, i.e. by band pass filtering the incident light, and/or using a short measurement duty cycle. The band pass filtering gives an easy factor 20 reduction of the common mode incident light. The short measurement duty-cycle principle, based on emitting e.g. ten times more modulated light in a ten times shorter period, results in another factor ten times reduced background light perception. The three principles can probably be combined without hindering each other.

Another advantage of the regulation of the detector common mode output, is the fact that now a continuous detector output becomes available that can be used in a DLL-feedback implementation, such that distances can be measured much faster, e.g. at a frame rate of 1000 fps or more [3]. In the latter case it may be sufficient to implement only the common-mode feedback, without the dynamic element matching.

VII. CONCLUSION

A new method to remove the common-mode photocurrent in an optical CMOS demodulation detector has been presented. A solution, in the form of dynamic element matching, for the mismatch in both the necessary nanoampere current sources and in the detector is provided. The result is capable of performing phase measurements of a modulated light signal on top of a background light that is more than 100 times stronger. Because the detector continuously provides a measure of the integrated phase difference between the modulated light and a reference signal, it can be used as part of a delay locked loop.

REFERENCES