Towards smarter ranging pixels with high dynamic range : sensitivity-tuning of current assisted photonic demodulators

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***Abstract*— The peculiarities of Time-of-Flight ranging with CMOS sensors - with respect to conventional CMOS imaging - allow new ways to enhance dynamic range of these CMOS ranging sensors. This paper discusses how a current-assisted photonic demodulator can be modified to provide enhanced dynamic range. An extra node provides tunable sensitivity to the detector without interfering with the photonic demodulation properties of the device. It can be used to construct smart ranging pixels with extended dynamic range.**

I. Introduction

In CMOS imagers dynamic range is a critical figure of merit. A scene composed of both bright and dark regions is often difficult to capture due to limited dynamic range. A lot of research has already been conducted to improve the dynamic range of today's passive CMOS imagers: sensors with a limited variability of detector capacitance have been proposed [1], multi-sampling imagers taking different frames at distinct exposure times combining them into one image [2], Digital Pixel Sensors [3], combined linear-logarithmic response [4]. While these techniques can also be applied to active CMOS Time-of-Flight (TOF) ranging sensors, due the nature of the measurements obtained in TOF systems, new approaches can be explored, tailored specifically for these TOF sensors.

A typical Modulated Wave Time-of-Flight (MTOF) ranging system is depicted in figure 1. Modulated light is sent to a scene, the reflections are captured by a photonic demodulating sensor which correlates the captured signal with reference signals. These correlations can then be used to extract phase-shift and hence distance information. Since reflection intensities fall with the squared distance, scenes with high dynamic range are inherent to active systems. To be able to measure both close-by and far-away objects the dynamic range of these imaging systems should be very large. Initial solutions, such as multi-sampling, can of course be borrowed from the passive CMOS imager techniques. However, the active MTOF system based on photonic demodulators is actually very different from a passive imager. Sensors in passive imagers measure absolute illumination levels to construct the contrast of the image.

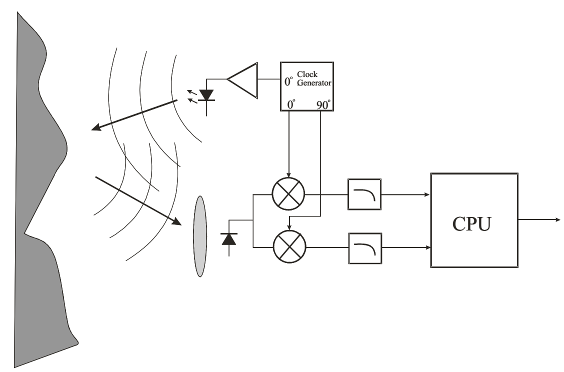

Fig. 1. A typical Modulated Wave Time-of-Flight (MTOF) ranging system.

This means that integration time and conversion gain must be known in order to relate the measurements of the pixels to one-another. MTOF ranging systems measure phase information instead. This implies that each pixel in such a system can be optimized independently, as long as the phase-information is retained. In this paper we will discuss how the current assisted photonic demodulator [5] can be modified to show tunable behavior, making per-pixel optimization possible.

II. the Current-Assisted Photonic Demodulator

The current assisted photonic demodulator (CAPD) was first proposed in [5]. It is a CMOS device based on configurable electric fields. Figure 2 shows the cross-section of a current-assisted photonic demodulator. A majority current is sustained in the substrate by a potential ΔV applied between substrate contacts $Mix2$ and $Mix1$. The electric field determines to which detection junction the electrons, created by captured light, are transferred. With $V_{mix1} > V_{mix2}$ (ΔV>0), the electrons will be transferred to the detecting junction Det1. Likewise, ΔV<0 will send the electrons towards junction Det2. By alternating ΔV we have constructed a photonic demodulator.

This CAPD detector can be integrated in an Active Pixel architecture [6]. Using a 3T architecture a reset, an output

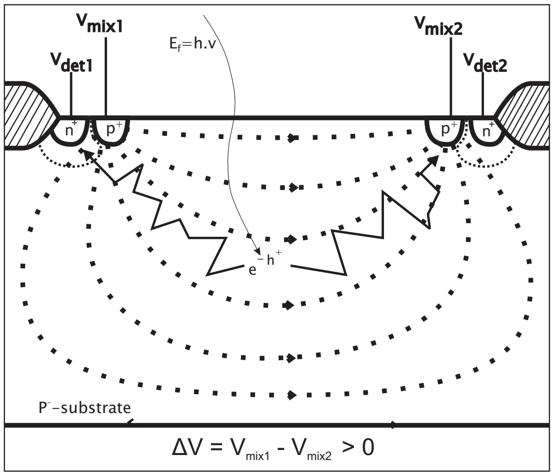

Fig. 2. Cross-section of a CAPD detector. A potential ΔV>0 = $V_{mix1} - > V_{mix2}$is applied, creating an electric field in the substrate. The electrons are transferred by drift to the selected detection junction. For ΔV>0 the electrons will be detected at Det1, ΔV<0 at Det 2.

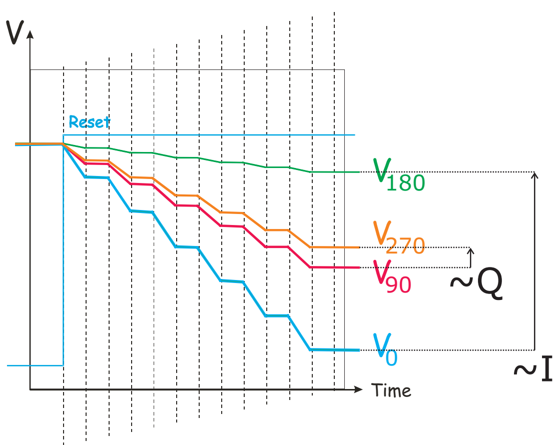

Fig. 3. Cycles.

and a select transistor are added for each detection node. The device is operated much like a conventional active pixel sensor (APS). The detection node is reset and integration is started. Note that here the detector is not a simple n-well, but must be operated by applying the right signals to the Mix substrate contacts. Hence, the charge collected after integration at the detection junction Det1 represents a correlation of the received photonic signal and the signal applied to $Mix1$. To obtain the phase-shift information of the photonic signal, multiple correlations must be performed and compared. As described in [6] several correlations are needed to remove back-ground illumination, reflection intensity and other imperfections from the equations. These values can be obtained time-sequentially (in the case of 1-tap and 2-tap CAPD's) or simultaneously (4-tap CAPD). Typically the received optical signal is correlated with the original modulation signal, its inverse, its quadrature and its inverse quadrature signal, yielding V_0, V_{180}, V_{90} and V_{270} respectively, as shown in figure 3. For sine-wave modulated TOF the phase is calculated using the equation 1 with $I = V_{180} - V_0$ and $I = V_{270} - V_{90}$.

$$\phi_{sine} = \arctan \frac{Q}{I} \tag{1}$$

It is clear that the *difference* between correlations holds the wanted phase information - in other words the photonic demodulator measures *relative* instead of absolute levels to obtain phase-shift and hence depth information. This fundamental difference implies that every pixel can autonomously optimize its sensitivity, conversion gain or integration time. The setting of each pixel does not need to be known to calculate the phase-information from the measured correlations, as long as these correlations are obtained with the same setting.

III. Dynamic Range in MTOF CMOS Ranging Sensors

A reason why increased dynamic range in TOF systems is highly desirable was mentioned in the introduction. Active imaging is inherently confronted with big differences in reflection intensities. If the CAPD pixel saturates when measuring the correlations, the calculated phase will be distorted and lost. However, a very short integration time to prevent saturation of these pixels yields bad SNR for correlations obtained in pixels focused on far-away regions. Saturation can be caused by the active signal itself, for example when the pixel is focused on a close-by object, or by background light illumination. Saturation caused by background light is worse because it does not contribute to the relative information and introduces extra noise. The background light illumination in MTOF has the same effect as the dark current in conventional imaging: decreased of the dynamic range. Figure 4 shows a plot of the different situations in active TOF imaging. The vertical axis represents the active reflected signal while on the horizontal axis the sum of the background light signal and the dark current is plotted. Our hypothetical sensor has a saturation level of about 30000 electrons, which is shown by the saturation boundary, and a total sensor noise (reset and read-out noise) of about 40 electrons. A region can be identified where the measurements are limited by the active signal shot noise. Below this curve the limit is due to the total sensor noise and the shot noise of the dark and background current. At low background light levels (neglecting the dark current) the sensor has a large dynamic range DR1. With increasing background light levels the dynamic range drops steeply as less signal swing is available for the active signal and the shot noise of the background light increases (dynamic range DR2). A possible situation is depicted in figure 5 with the dashed lines representing a saturated signal. The integration time is too long and all relative information between the two dashed lines is lost at the end of the integration. A straightforward solution is to control the sensitivity of the pixels capturing high intensities on a per-pixel basis. A first possibility, depicted by the solid lines, is to let the pixel autonomously decide when to stop integrating by abruptly cutting the sensitivity of the detector when saturation is near. In this way, the relative information is held until the end of the global integration time.

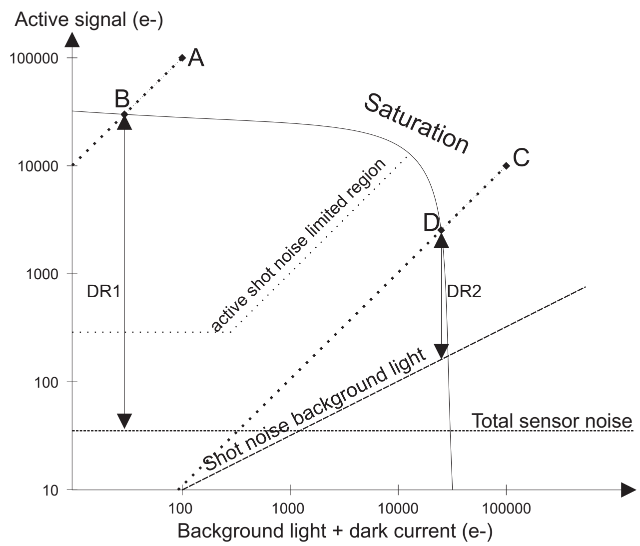

Fig. 4. Different situations in active imaging given a fixed integration time. The total sensor noise includes the reset and read-out noise. For convenience the dark current and background light current are considered one. The information in A and C is lost after saturation. Smart pixels can clip them to B and D respectively and hold the information.

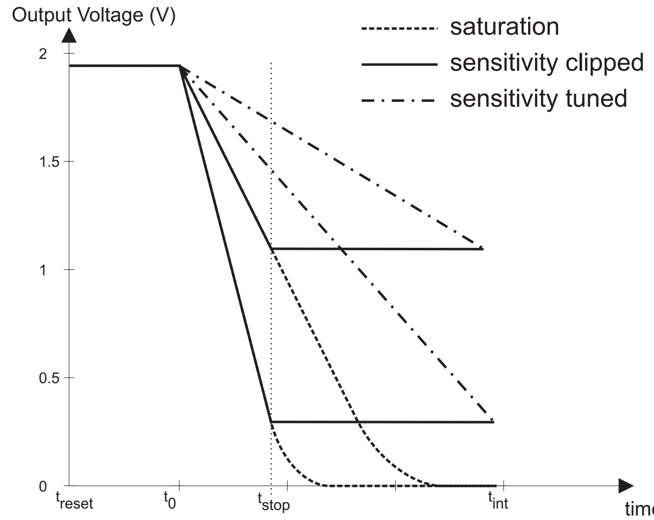

Fig. 5. The dashed lines represent the saturated signals without smart integration. A CAPD sensor with sensitivity tuning operated as an in-pixel electronic shutter can hold the information until read-out (solid lines). Continuous control of the sensitivity can create the signals depicted with the dash-dotted lines.

An array of these pixels can be operated synchronously at a low frame-rate needed for low-intensity reflections of far-away objects, without saturation of the pixels corresponding to near-by objects, extending the dynamic range of the sensor. Applying this method to figure 4, the signals corresponding to point A can be clipped to B, the signals in point C clipped to D. Note that the dynamic range at the output has not increased, but due to the non-linear behavior (clipping) a bigger range of illumination levels can be processed without saturation and without loss of relative information. A similar result can be obtained by reducing the sensitivity during the integration. Instead of clipping the integration time, the sensitivity is tuned. While these approaches require different control circuits, the results are similar. Both approaches rely on controlling the sensitivity in-pixel in a digital or analogue way.

IV. A TUNABLE CURRENT-ASSISTED PHOTONIC DEMODULATOR

To implement tunable sensitivity of the current assisted photonic demodulator an extra drain region was added in the photosensitive area [7], as shown in Figure 6. This region consists of a substrate contact and a detection junction, connected both at the same potential V_{drain}. When a positive potential V_{drain} is applied to this node, a fraction of the photo-generated electrons available in the substrate is attracted to the drain tap and collected using the detection junction. This influences the amount of electrons involved in the demodulation, reducing the overall sensitivity of the detector, while the photonic demodulation continues unhindered.

V. MEASUREMENTS

Figure 7 shows a measurement of the sensitivity of the device when different drain tap voltages are applied. The voltage over the channel was incremented from 0.4V - Mix contacts switched between -0.2V and 0.2V - to 2V - Mix contacts switched between -1V and 1V. Since the Mix potentials are balanced around 0V and the drain tap is located in the center of the device, applying V_{drain} = 0V does not change anything to the performance of the device and relative sensitivity is 100%. Increasing the voltage of the drain tap decreases the overall sensitivity as shown in figure 7. With low channel voltage increasing the drain tap voltage creates a steep drop of the sensitivity. This can be used as an electronic shutter, enabling the first option to enhance dynamic range mentioned in §3. As

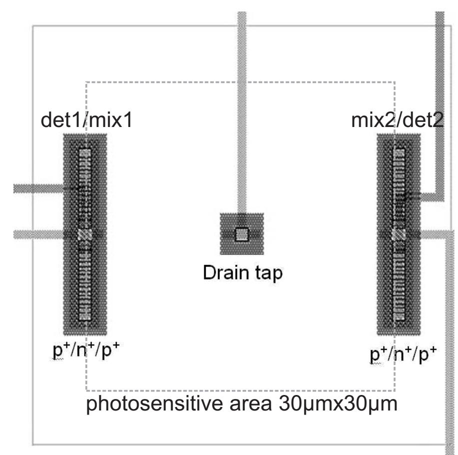

Fig. 6. Top view of a prototype CAPD detector with drain tap for sensitivity tuning. A potential V_{drain} is applied to the drain tap sensitivity tuning contact. If V_{drain} rises, a fraction of the photogenerated electrons is drawn to the drain contact, tuning the overall sensitivity of det1 and det2.

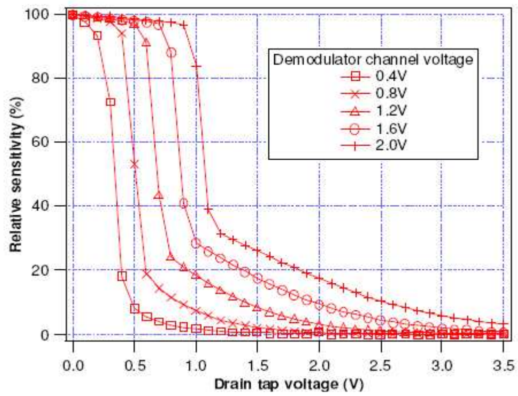

Fig. 7. Measurement of relative sensitivity versus drain voltage at different demodulator channel voltage ΔV.

the demodulator channel voltage is increased, the drain voltage necessary for the initial sensitivity drop increases. Also, the drain tap gradually loses the power to fully quench the sensitivity, showing a more gradual control of the sensitivity. This allows the continuous in-pixel sensitivity tuning. Work on ranging pixels based on the CAPD with tunable sensitivity is on-going.

VI. Conclusion

We presented a current-assisted photonic demodulator with tunable sensitivity. We discussed how this device can be used to construct smart MTOF ranging pixels. While the dynamic range at the output remains unchanged, the non-linear behavior allows an increased dynamic range of the input light intensities.

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