Time-of-flight Optical Ranging Sensor Based on a Current Assisted Photonic Demodulator

D. Van Nieuwenhove, W. Van der Tempel, R. Grootjans and M. Kuijk

Vrije Universiteit Brussel, Electronics and Informatics Department ETRO (LAMI),
Pleinlaan 2, 1050 Brussel, Belgium

The presented optical ranging sensor utilizes a current assisted photonic demodulator (CAPD) in combination with an integrating circuit to measure time-of-flight. The distance information is obtained by correlating received modulated light with the sent-out signal. Simulations and measurements show that the structure is suitable as a pixel in a real-time 3D-camera setup. A CMOS prototype is presented showing 0.25 A/W infrared photo-responsivity, nearly 100% detector demodulation efficiency and good linearity. Different design aspects and possibilities are discussed and evaluated. With averaging, real time sub-cm resolution is achieved at a modulation speed of 20 MHz and using NIR 860 nm light.

Introduction

Distance measurement devices have long been investigated. The recent revival in continuous time-of-flight (TOF) research has opened the way to fulfilling the aim of building a robust and high resolution real-time 3d-camera. Previous attempts using triangulation, interferometry or structured light projection all suffer downsides found in either speed, robustness, cost, accuracy or dynamic range. Research of the last years [1], [3], [4] has shown that time-of-flight might hold the keys to solve above problems emphasizing it as a 3D-camera-of-the-future candidate and an interesting research subject. In this paper a sensor is described that can be used as a pixel for such a camera having the promising capacity of improving above mentioned shortcomings. The basis of the pixel is a very efficient in-substrate demodulator, called current assisted photonic demodulator (CAPD). All displayed measurements in this paper where conducted using NIR light (λ = 860nm), since it is invisible and detectable in normal silicon making it the ideal type of light for the application.

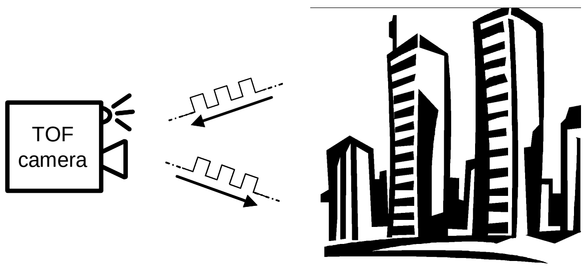

Figure 1 Illustration of the time-of-flight principle

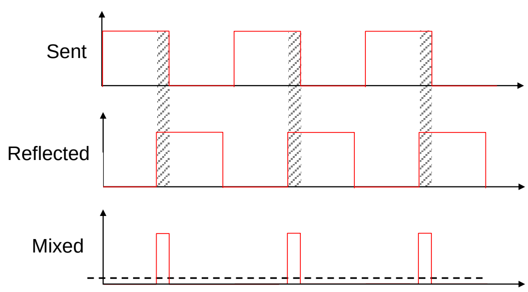

Figure 2 Phase measurements by averaging mixed reflected and sent-out waveforms

Time-of-flight principle

The continuous time-of-flight principle is illustrated in fig. 1: the camera sends out modulated light and measures its reflections on the scene. Within each pixel this reflected signal is mixed with the sent-out signal to obtain the phase shift, as shown in fig. 2. This phase shift can easily be translated in the distance between the pixels and the different points in the scene. This simple technique has many advantages:

- capable of delivering complete images at once, no scanning is needed
- real-time images possible
- robust, without moving components
- high accuracy : the technique is based on the lock-in principle
- scalable accuracy : several parameters influence the signal-to-noise ratio, such as modulated light intensity, integration interval and modulation frequency.
- high dynamic range
- no expensive materials are used

Few drawbacks/constrains exist, most important are the degradation of accuracy proportionate to background light and the limited distance range due to the periodicity of the modulation signal.

Principle of a CAPD

A current assisted photonic demodulator utilizes a guiding current to accelerate electrons towards detecting junctions. Whilst in standard photo detection diffusion is the main transport mechanism, a CAPD uses a current induced guiding drift field. As shown in fig. 3 the photo-generated electron hole pairs are separated: the hole becomes part of the flowing majority current and starts moving towards the p+ region with the lowest voltage, the electron is accelerated in the opposite direction and will, due to the built-in potential barrier of the p^-substrate/p^+ junction, choose to enter the detector node. Mixing is achieved by alternating the current so that correlated amounts of the light-induced carriers arrive at the different detecting junctions [2]. The field amplitude and extension in the substrate are the key factors determining the demodulator qualities. In a CAPD the drift field is spread very well over the substrate resulting in high demodulation contrast and high speed. Further the amplitude of the field is proportionate to the applied substrate voltage and thus scalable.

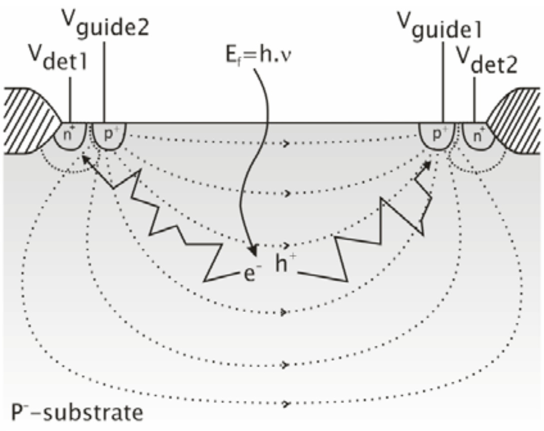

Figure 3 Current Assisted Photonic Demodulator (CAPD), the configurable current determines towards which detecting junction the minority carriers are driven

CMOS Implementation

In fig. 4 layouts are shown of possible 0.35µm CMOS CAPD implementations. Two possible configurations are shown: a centralized and a linear. The centralized setup has a minimal detecting junction size, and thus a

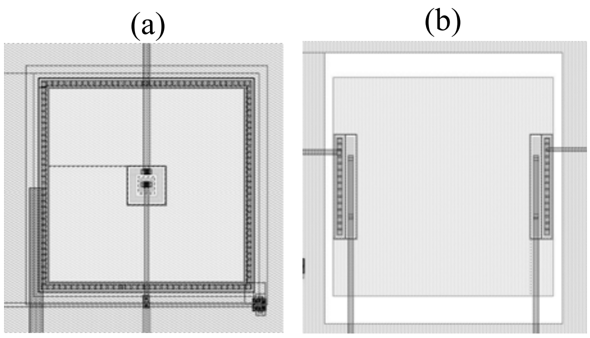

Figure 4 Layout of a centralized (a) and linear (b) shaped CAPD

minimal capacitance. Drawback is the high current density in the center, resulting in a higher resistance and, due to this non-uniform conductivity, the applied drift field will not be spread equally over the sensitive area, lowering the speed of the device. The linear implementation is an alternative for this problem: no current concentration occurs, so that the applied field is evenly distributed, but at the cost of a larger detector node. Choosing between both structures has to be done having this speed to detector capacitance trade-off in mind.

Measurements

Figure 5 shows measurements performed on a centralized 30x50 μm^2 and a linear 50x50 μm^2 prototype. It can be seen that both perform very well in DC having nearly 100% demodulation contrast from very low guiding field voltages on. The centralized CAPD slightly outperforms the sensitivity of the linear. This is probably due to the presence of surrounding nwells, placed there to isolate the pixel and prevent it to be distorted by

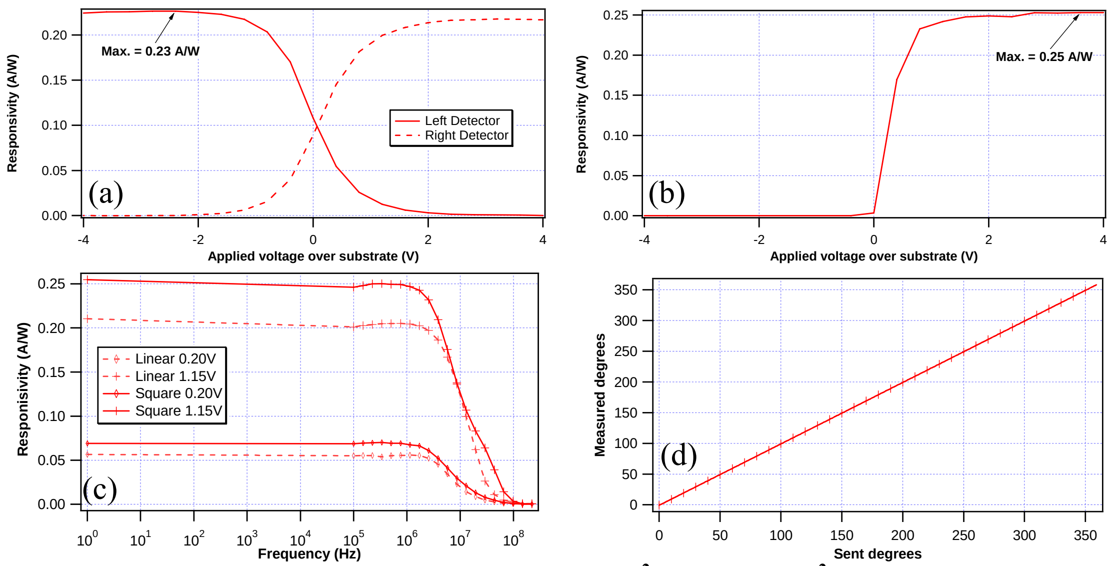

Figure 5 Comparison between rectangular 30x50 μm^2 and 50x50 μm^2 linear CAPD: (a) static measurements of linear CAPD (b) static measurements of rectangular CAPD (c) dynamic measurements (d) linearity measurements performed at a modulation frequency of 1MHz

illumination coming from outside of the pixel. In the linear setup electrons are guided closer to these nwells causing some of the carriers to be lost. In the centralized setup all used carriers are guided to the center. In fig. 5c dynamic results of both CAPD's are shown for two different substrate voltages. It can be seen that the increase in guiding field strength has a double effect: a sensitivity and a bandwidth improving effect. Again there is a difference in sensitivity between both CAPD's as a consequence of the surrounding nwells. At 0.2V substrate voltage bandwidths are respectively 4.5 MHz for the centralized and 4.9 MHz for the linear CAPD, at 1.15V bandwidth is 5.6 MHz and 7.6 MHz. Figure 5d shows the measured to the sent-out phase for a shift of one period at 1 MHz,

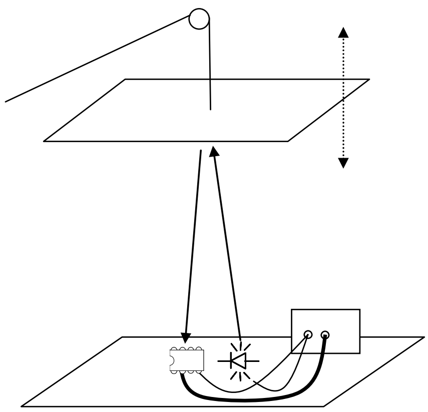

Figure 6 Measurement setup

illustrating the linearity properties of the device.
In fig. 6 our lab setup to perform a first set of distance measurements is shown. A plate, adjustable in height, was mounted above a CAPD pixel, consisting of a CAPD and a simple integrating circuit, and a modulated light source, built using 16 LED's and generating a total light output of 0.5 W. We used 20 MHz as modulation frequency. The pixel was calibrated at 70 cm. A total integration interval of 8 ms was used in combination with an averaging step over 25 samples, resulting in a refresh rate of 5 Hz. Figure 7 shows measurement results of a distance sweep from 40 to 100 cm. At the shortest distance sub-cm accuracy is achieved. The rather large systematic error is due to the limited effort done in these proof-of-principle measurements to reduce the non-linear effects beyond the -3dB frequency of the demodulator. Further changes, like replacing the used square with sinusoidal modulation and improving the optical side of the setup, should be completed to enhance these results.

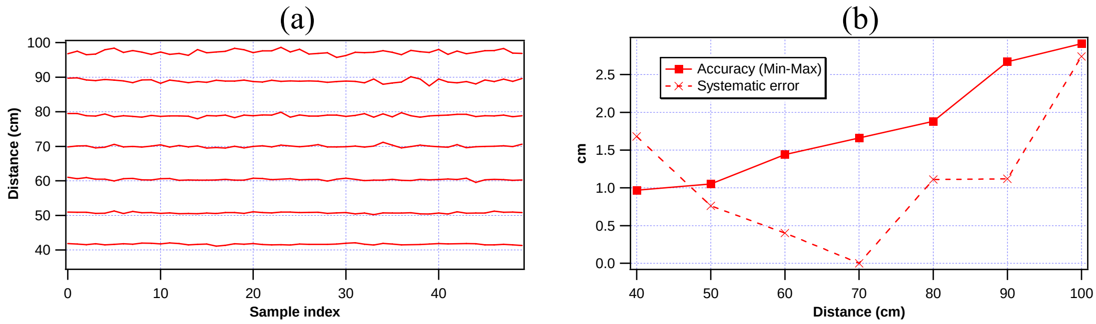

Figure 7 Distance measurements showing values (a) and accuracy/error information (b)

Conclusion

We have illustrated the efficacy of an optical ranging sensor based on the time-of-flight principle. Measurements show that the used current assisted photonic demodulator has good properties and forms an efficient pixel opening perspectives for sub-cm resolution real time 3D-cameras. Expansion of this proof-of-principle to more accurate results and eventually matrices is needed to further develop this technology.

Acknowledgment

The research activities described in this paper were funded by the Fund for Scientific Research-Flanders (FWO-Flanders).

References

[1] P. Gulden, D. Becker, M. Vossiek, "Novel optical distance sensor based on MSM technology," IEEE Sensors Journal, vol. 4, pp. 612-618, October 2004

[2] D. Van Nieuwenhove, W. van der Tempel, and M. Kuijk "Novel standard CMOS detector using majority current for guiding photo-generated electrons towards detecting junctions", in proc. 10th Annu. Symp. of the IEEE/LEOS Benelux Chapter, Mons, 2005, pp. 229-232

[3] R. Schwarte, " Dynamic 3D Vision", in Proceedings of the Conf. IEEE EDMO, 2001, pp. 241-248

[4] R. Lange and P. Seitz, "Solid-State Time-Of-Flight Range Camera", IEEE Journal of Quantum Electronics, vol. 37, NO. 3, March 2001.