A 15um CAPD Time-of-Flight pixel with 80% modulation contrast at 100MHz

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ABSTRACT

Results of a 15um Current Assisted Photonic Demodulator (CAPD) pixel showing 80% modulation contrast at a modulation frequency of 100 MHz are presented. This allows to build 3D Time-of-Flight camera systems with either reduced depth noise or reduced modulated light power needs. A performance comparison with the DS325 unchanged, versus one with the modulation frequency and contrast improved, shows an overall 3 times lower sigma depth versus power ratio.

INTRODUCTION

Time-of-Flight (ToF) depth measurement is one of the techniques used in todays growing 3D imaging market. This technique derives distance by measuring the phase delay of reflected light, using in-pixel demodulation [1-3]. This exhibits several advantages versus other techniques, but also involves some key challenges. Improving power consumption in combination with low distance error is the underlying target of the results presented in this work.

CONTEXT

To improve power versus noise behavior of a Time-of-Flight system, the light efficiency properties at the image sensor need to be examined and optimized. In Time-of-Flight systems the distance error is defined by the signal-to-noise ratio (SNR) and the modulation frequency (f_{mod}), cfr. equation 1 [4].

$$\sigma_{depth} \equiv \frac{1}{\sqrt{2} \cdot SNR} \cdot \frac{1}{2\pi} \cdot \frac{c}{2 \cdot f_{\text{mod}}} \quad \text{(equation 1)}$$

The SNR, shown in equation 2, is defined on the signal side by the photo responsivity at IR wavelengths (RE), fill factor (FF), pixel area (A_{pix}), incoming signal flux (Φ_{signal}), integration time (t_{int}) and modulation contrast (C_{MOD}). The noise is split in shot noise generated by ambient or active light and the system noise floor.

$$SNR \equiv \frac{A_{pix} \cdot RE \cdot FF \cdot C_{MOD} \cdot \Phi_{signal} \cdot t_{\text{int}} \cdot \frac{1}{q}}{\sqrt{\left(A_{pix} \cdot RE \cdot FF \cdot \left(\Phi_{signal} + \Phi_{ambient}\right) \cdot t_{\text{int}} \cdot \frac{1}{q}\right) + \left(N_{system}\right)^2}} \quad \text{(equation 2)}$$

Figure 1 shows the PTC of the DS325 camera with and without ambient light equivalent to 2 klux sunlight. Three different operating zones can be identified based on the dominant noise source. At close range this is the active light shot noise, at longer distances it is either the ambient light shot noise which is the dominant noise source (e.g. 177 e^- differential at 2klux sunlight) or in the absence of ambient light the system noise floor, for DS325 being 65 e^- differential. Equation 1 and 2 show that parameters C_{MOD} and f_{mod} are inversely proportionate to sigma depth in all regimes, while other parameters sometimes contribute to both signal and noise. Therefore optimizing C_{MOD} and f_{mod} is the most critical. This is the focus of the pixel optimizations demonstrated in this work.

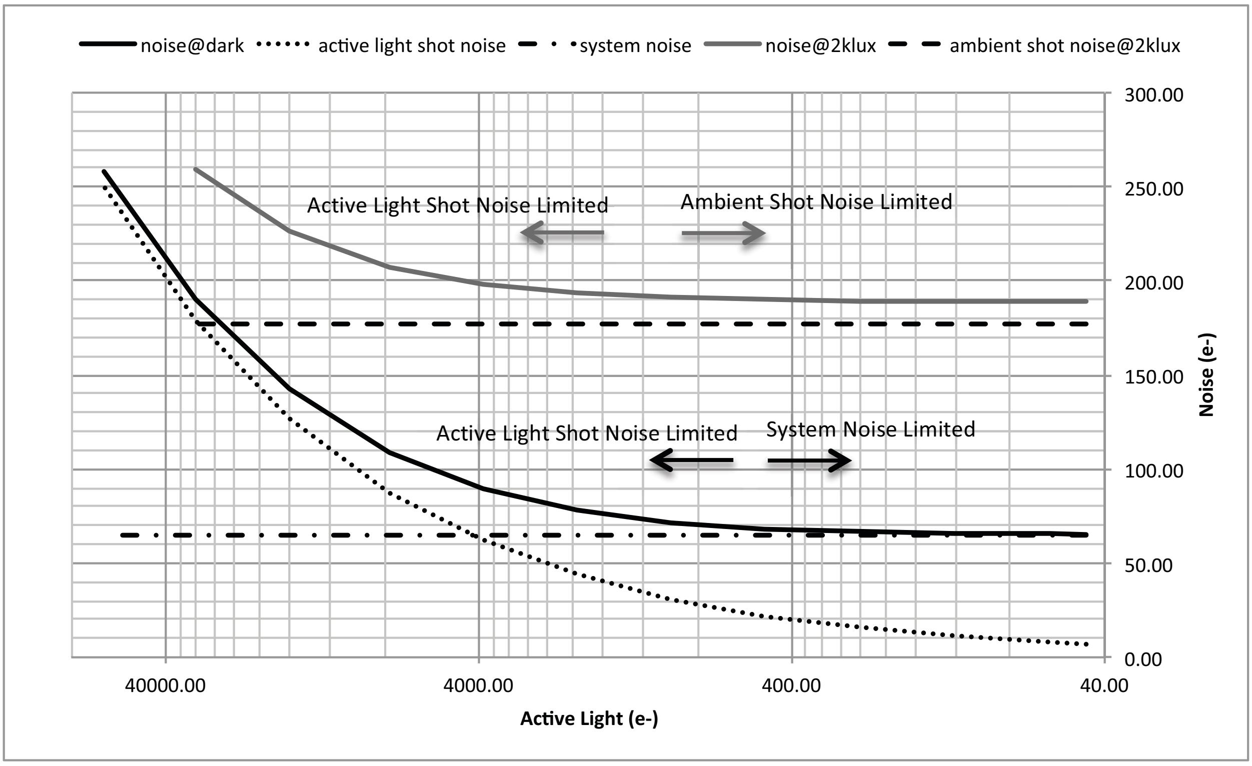

Figure 1 DS325 Noise vs Active Light showing regions dominated by active light shot noise, ambient light shot noise and system noise floor

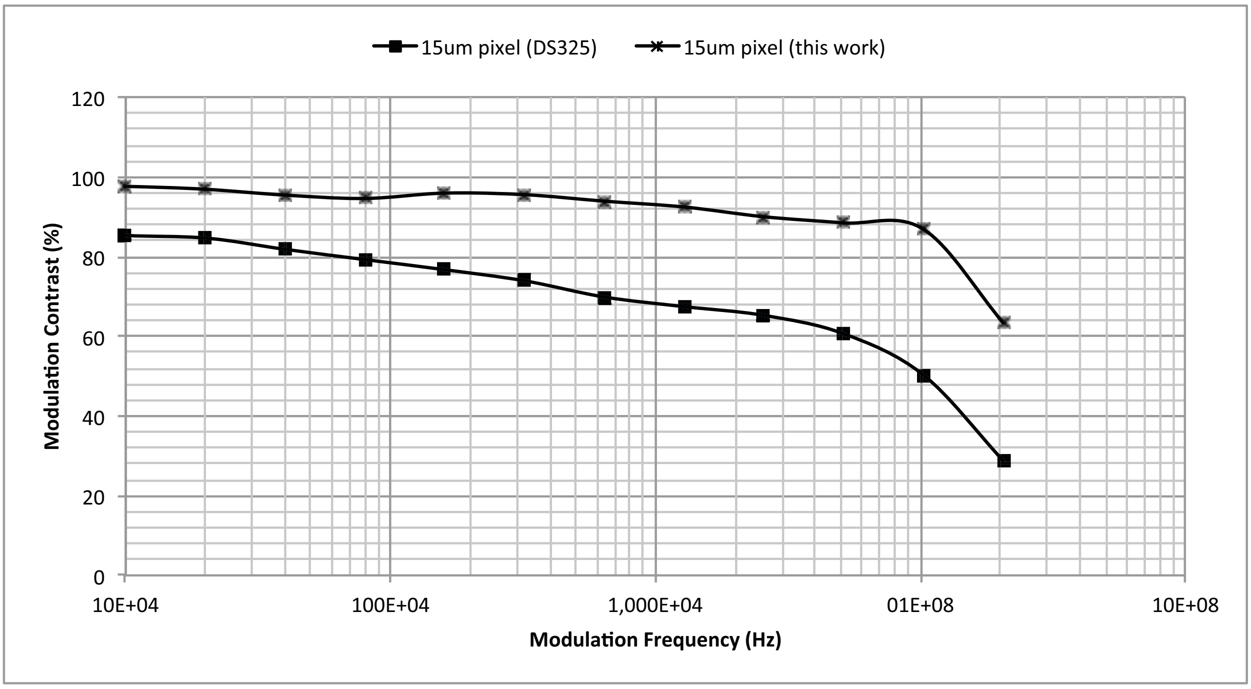

Figure 2 Modulation contrast versus modulation frequency for current and new 15um pixel

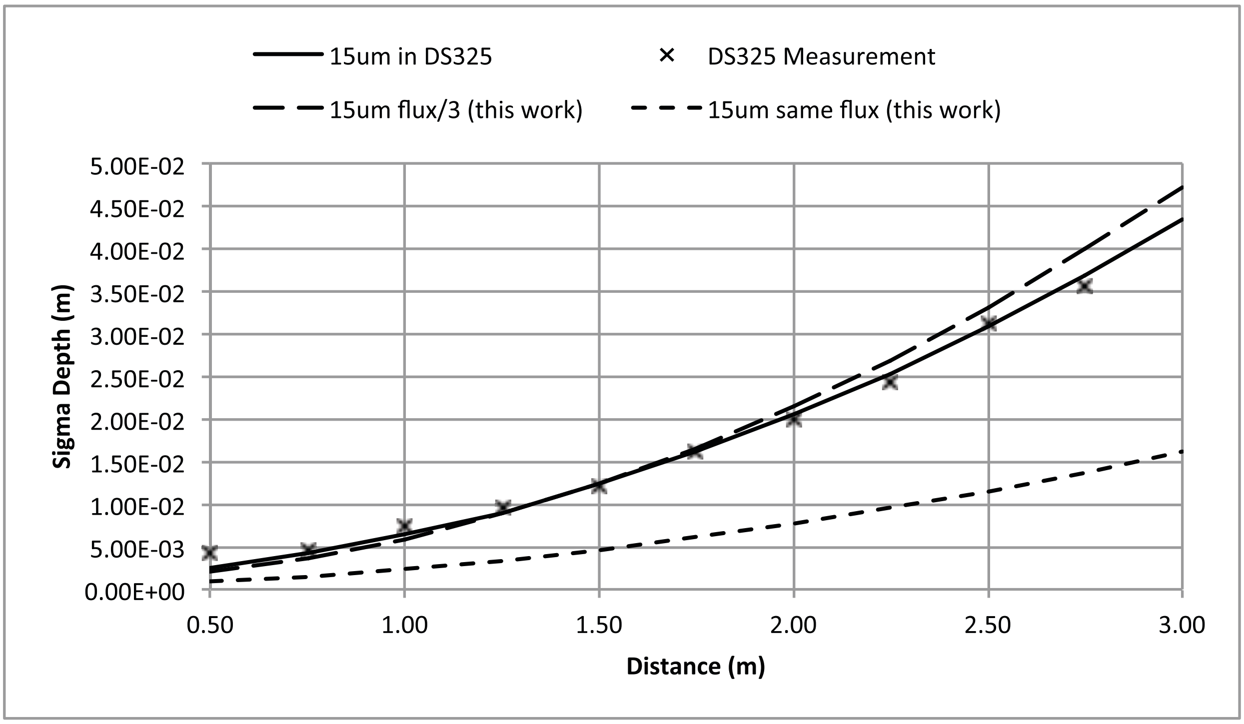

Figure 3 Sigma depth versus noise for DS325 with current and new 15um pixel

Resolution	320x240
Lens F#	1.11
Field-of-View	74(h) x 58(v) x 87(d)
Illumination Power (optical)	70 mW (avg)
Illumination Type	Laser / 850nm
Frame Rate	Up to 60 fps
RGB	720p
Connection	USB 2.0
Total Power (electrical)	< 2.5W

Table 1 System Specifications DS325 Camera

RESULTS

Measurement results are presented based on the system configuration of the DS325 camera, having a field-of-view of 74(h) x 58(v) x 87(d) with an average illumination power of 70mW optical. General system specs are given in Table 1. The pixel used in this work is based on the CAPD principle, using direct drift field generation in the silicon to achieve high ToF demodulation contrast [3,4]. Figure 2 shows the pixel modulation contrast over frequency for the pixel used in the product, and the newly developed. As can be seen the reference pixel achieves about 60% contrast at 50MHz, where the new pixel achieves 80% at 100MHz. The resulting sigma depth versus distance performance is shown in Figure 3. The measurements are obtained with the current pixel in the DS325 versus a moving white wall from 0.5 – 3m, simulations are shown for a system based on the current pixel (DS325) and presented pixel, as well as for the presented pixel whereby the active light flux is reduced by a factor of 3. As can be seen, in this way, an approximate improvement of a factor 3 w.r.t. noise versus power efficiency is achieved. To position these parameters versus the state of the art some parameters are put next to each other in Table 2, for the current, new and Kinect 2 sensor, shipping with the Microsoft Xbox One game console. Power consumption numbers show that also on this level the pixel is competitive.

	DS325	Kinect 2	This Work
Technology Node	0.35um	0.13um	0.35um
Resolution	320x240	512x424	10x10
Pixel Pitch	15um	10um	15um
Modulation Contrast	60%@50MHz	68%@50MHz	80%@100MHz
Operating Frequency	50MHz	80 MHz (avg)	100 MHz
Responsivity@860nm	0.32A/W	0.144A/W	0.32A/W
Pixel Fill Factor	45% (native)	60% (w/ uLenses)	45% (native)
Pixel Power (avg)	5.5uW/pixel	5.5uW/pixel (1.2W/#pixels)	4uW/pixel (excl. optical core driver)

Table 2 Overview of pixel parameters for DS325, Kinect 2 and this work [5]

CONCLUSION

A 15um Current Assisted Photonic Demodulator (CAPD) pixel showing 80% modulation contrast at a modulation frequency of 100 MHz was presented. Plugging these results into a DS325 configuration, we can achieve a 3 times lower sigma depth or 3 times lower illumination power. Bringing the topology to smaller technology nodes is expected to further drive power, efficiency and frequency improvements.

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