SWIFT EI: Event based SWIR sensor for tactical applications

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ABSTRACT

Event-based imagers are an emerging class of sensors with demonstrated advantages relative to traditional imagers. Event-based vision sensors have a limited number of output bits that are only responsive to image variations, thus overcoming the speed and power constraints of the conventional imagers based on image integration.

The *SWIFT EI* the first event-based InGaAs sensor that is sensitive in the Visible to SWIR band (600–1700nm). The main novelty of this sensor is that the event channel outputs in parallel to a conventional fast imaging channel. Moreover, we can reconfigure the event channel to provide a fast laser pulse detection mode (3rd generation ALPD), which also outputs in parallel to the integrated image. In that context we described in detail the architecture, key features, and preliminary simulations of the ROIC.

The *SWIFT EI* is a low SWaP product optimized for tactical wide distribution applications that incorporates the event based FPA. We will present measurement results of the high frame rate (HFR) imaging channel; the event channel that can reach up to 25 kHz of negative, null, or positive signal, and the laser detection channel providing a single bit detection frame up to 50 kHz. This feature is ideal for multi spot tracking and pulse repetition frequency (PRF).

Keywords: Event-based, SWIR, ALPD, InGaAs, ROIC, Laser Pulse Detection, Fast Imaging, PRF

1. INTRODUCTION

High Frame per Second (FPS) imaging in SWIR wavelengths is a highly desirable feature. For instance, autonomous navigation and collision awareness are emerging applications that require fast video imaging in addition to the known SWIR advantages at fog penetration and night vision. In some scenarios, fast integration and fast analog to digital column-parallel conversion are enough to meet the high-frame rate needs. However, these circuits present a bottleneck that practically limits video frame rate to ~ 1 KHz. This bottleneck can be resolved by the introduction of the event based imaging concept [1, 2].

Event-based imaging is an emerging imaging paradigm focused only on variations in the pixel target that breaks the imaging speed bottleneck. Typically, event vision supports movement detection, object recognition and tracking. Moreover, in defense and security applications its fast response allows to detect the presence of fast varying hostile threats.

The detection of laser pulses is a specific case of fast event detection particularly interesting in SWIR. These pulses are very fast, lasting a few hundreds of nanoseconds, and its reflection generates a small charge packet at the pixel level. Finding laser pulses in the image is a difficult task as this laser pulse reflections are slightly above the readout noise. SCD has an established legacy of laser pulse detection [3- 4] but thus far, the detection frame rate was limited to a few hundred hertz preventing useful decoding of pulse repetition frequency (PRF).

Last year SCD presented the first event-based InGaAs sensor that is sensitive in the Visible to SWIR band (600–1700nm) [5]. This sensor follows the line of multi-functional InGaAs/InP SWIR products that was launched in 2013 with the Cardinal 640 VGA 15µm pitch, followed by Cardinal 1280 SXGA 10µm pitch, and by Cardinal 640 Low Noise VGA 15µm pitch [6-8]. The main novelty of this sensor is that the event channel outputs in parallel to a conventional fast imaging channel. Moreover, we can reconfigure the event channel to provide a fast laser pulse detection mode (3rd generation ALPD), which also outputs in parallel to the integrated image. In that context we described in detail the architecture, key features, and preliminary simulations of the ROIC. SCD methods for combining imaging with event and LPD are patented [9-10].

This year we introduce the *SWIFT EI* - a low SWaP sensor optimized for tactical wide distribution applications that incorporates the event based FPA. In the next section, we present the main features of the sensor and we follow with measurement results of the high frame rate (HFR) imaging channel, the event channel, and the laser detection channel providing combined imaging & detection.

2. SWIFT EI MAIN FEATURES

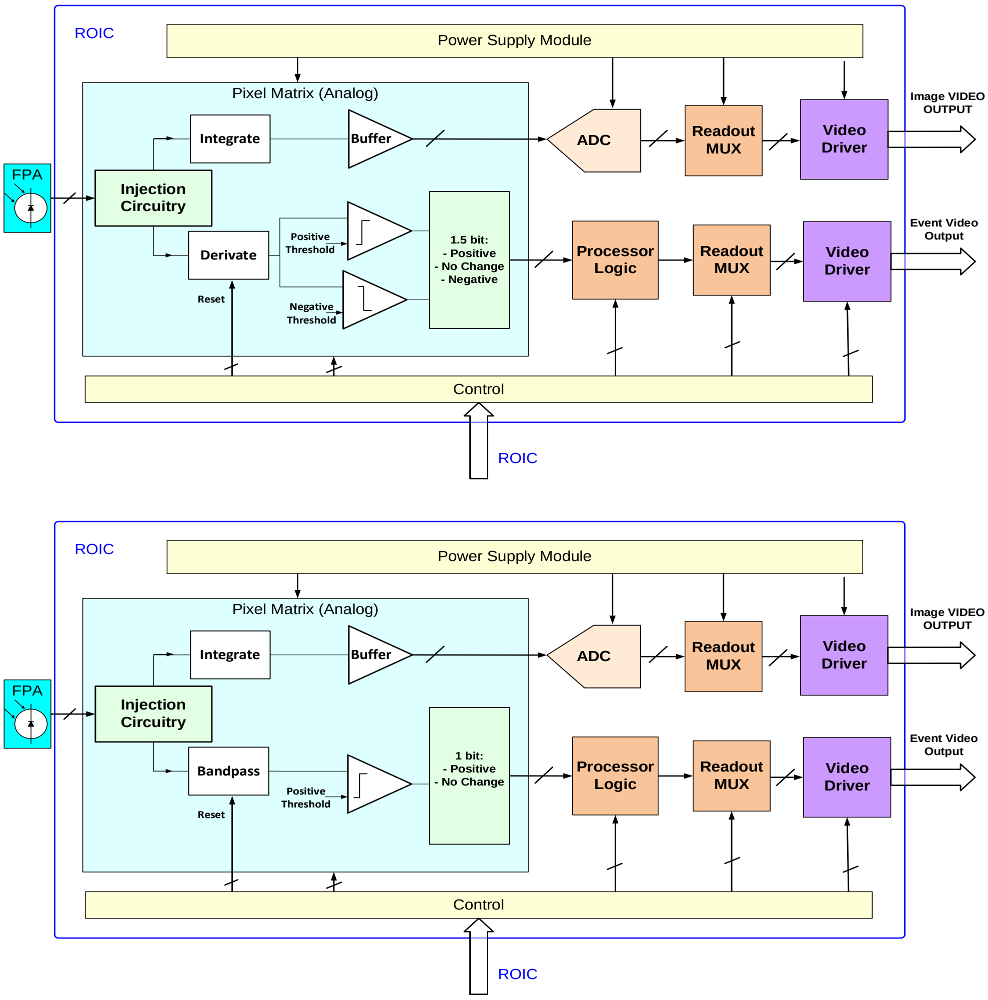

Figure 1: SWIFT EI ROIC Block Diagrams: Top Figure (1a): Imaging & Event Detection, Bottom Figure (1b): Imaging & Laser Pulse Detection

The functional block diagrams of the multi-functional ROIC are shown in Fig. 1, where the top figure presents the simultaneous Imaging & Event detection modes of operation. The bottom figure describes the simultaneous Imaging & ALPD modes.

In the event detection configuration shown in Fig. 1 (a), the signal is injected into the input stage and simultaneously split in the frequency domain by two filters. A low-pass filter enables the signal integration for the imaging, while a high-pass filter provides signal derivation for the event channel. Following, the variations in the derivative channels are compared to a positive and negative channel and an event is recognized as positive or negative if it generates a signal above controlled positive and negative thresholds. From the information point of view, this channel provides three indicative levels (1.5 bits) that indicate the presence of a negative or a positive event, or no change at all. It is possible to disable the imaging channel in this mode in order to further increase the sensitivity of the event mode.

The laser multi-spot detection is implemented by reconfiguring the filters as shown in Fig. 1 (b). The main differences are the replacement of the derivative channel by a band-pass filter, and disabling the negative comparator as the laser signal is only positive. The comparator threshold can be adjusted in order to optimize the sensitivity and false alarm rate (FAR) per a designated laser pulse intensity [4]. The threshold tuning is via direct communication to the ROIC.

Another important operation mode of the ROIC is “Imaging Only” mode where the detection channel is disabled and the entire bandwidth is dedicated to imaging. In this case, the sensor can reach 800 FPS at 13-bit image sampling resolution. By reducing the image sampling resolution to 11-bit resolution, the image mode frame rate can reach up to 1600 FPS. The high frame rate mode is of highly desired in both defense and commercial related applications such as hostile fire detection, semiconductor inspection, sorting, multispectral imaging [11].

Parameter	Value
Format & Pitch	640x512, 10µm @ SIM 320x256 with binning @ LNIM, ALPD, Event
Spectral Range	0.6-1.7 (VIS-SWIR)
Quantum Efficiency	>80% at 1550nm
Imaging modes and well capacity	High gain (LNIM CDS) – 50Ke Medium gain IWR (SIM) – 600Ke Low gain ITR (SIM) – 1Me
Operation modes & Maximum FR	SIM only: 800 F/s @ 13 bit resolution 1600 F/s @ 11 bit resolution SIM with Detection: 200 F/s @ 13 bit resolution LNIM: 2000 F/s @ 11 bit resolution ALPD: 50KHz Event: 25KHz
ROIC Floor Noise (typical)	LNIMCDS 50e Medium gain 150e Low gain 260e

Table 1: Main SWIFT EI FPA Features

The main features of the FPA level are summarized in Table 1. The sensing material is based on SCD’s mature 10µm InGaAs technology that covers the VIS-SWIR spectral range and exhibits superior radiometric performance and operability [12]. The Medium & Low gain capacitors are optimized for long-range daylight imaging; while the High Gain LNIMCDS is a separate stand-alone mode that supports situational awareness at low light levels.

The video link consists of up to four channel JESD204B with a maximum combined bandwidth of 16Gbps (4Gbps per lane). When utilizing the maximum bandwidth the sensor can reach maximum frame rate for “SIM only” and up to 25KHz & 50KHz for the Event detection and ALPD channels respectively. With detection channel activated, the imaging channel can support 200 Fps @ 13-bit resolution. The high gain LNIMCDS (as a stand-alone mode) can reach 2000 Fps @ 11-bit resolution.

The SWIFT EI FPA is embedded into a low SWaP ($25x22x6.1\ mm^3$, 9 gr) ceramic package with TEC as exhibited in Fig 2. Although the package was designed for low form tactical systems, it can support relatively harsh environmental conditions such as storage temperature (-55ºc to +85ºc), operational temperature (-40ºc to +85ºc) and cooling capability (ΔT of 40ºc for 30ºc ambient). One additional important feature is the capability to interface high bandwidth video signals without any spurious reflections or losses.

Figure 2: Photograph of the SWIFT EI Ceramic Package (Left) and First SWIR Image (Right)

3. CHARACTERIZATION RESULTS

3.1 Standard Imaging (SIM)

We characterized the standard imaging mode (SIM) for both “Imaging only” mode and simultaneously with the detection channel. In figures 3 and 4, we exhibit results for Mid Gain ITR @ 13-bit utilizing the 0.6Me capacitor.

In Fig. 3 (left hand), we present the noise variance in Digital Level (DL) vs. signal (DL). The signal varies by controlling the illumination level. From the slope of the graph, we can extract the ADC gain (in e/DL) utilizing the formula:

$$(1)\quad N^2 = N_{floor}^2 + \frac{Signal}{Gain}$$

Where the Noise & Signal are both in DL and the Gain is in [e/DL].

The extracted Gain of 92 [e/DL] is close to the design goal. In the right hand side, we exhibit the floor noise histogram. The histogram is narrow and the peak is located just below the expected value of 150 electrons.

In Fig. 4 (left hand), we show the Residual Non Uniformity (RNU) for a 2 point (2P) Gain & Offset correction at 20% and 80% well fill respectively. The RNU is below the temporal noise exhibiting the high quality of the sensing material and uniformity of the ROIC. In the right hand, we present the corrected image at 50% well fill (WF). Note the high level of uniformity where the entire array covers roughly 7 DL. Although we processed until now only prototype level FPAs the operability is above 99.5%.

Finally, when setting the ROIC to “SIM only” mode we managed to achieve a maximum frame rate of 720Hz @ 13-bit resolution. Currently the frame rate is limited by our measurement setup.

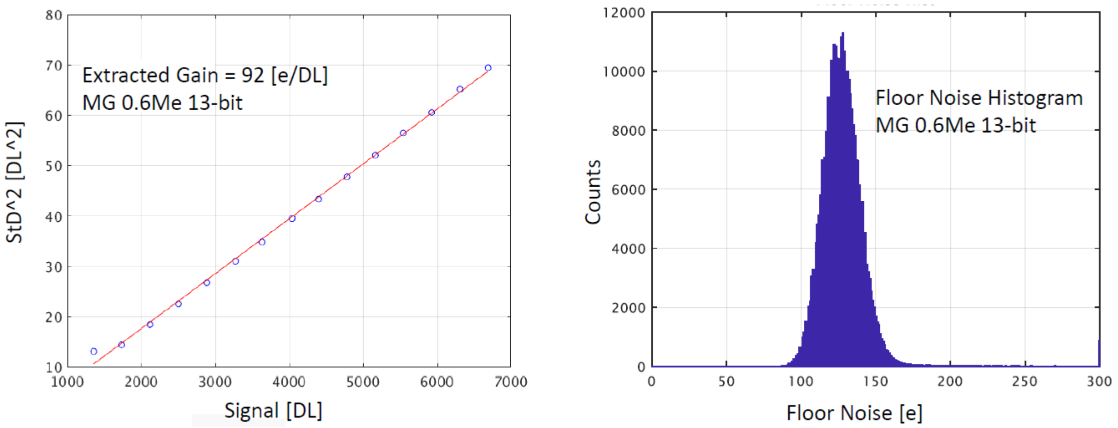

Figure 3: Mid Gain SIM extracted A2D Gain (left hand) and Floor Noise Histogram (right hand)

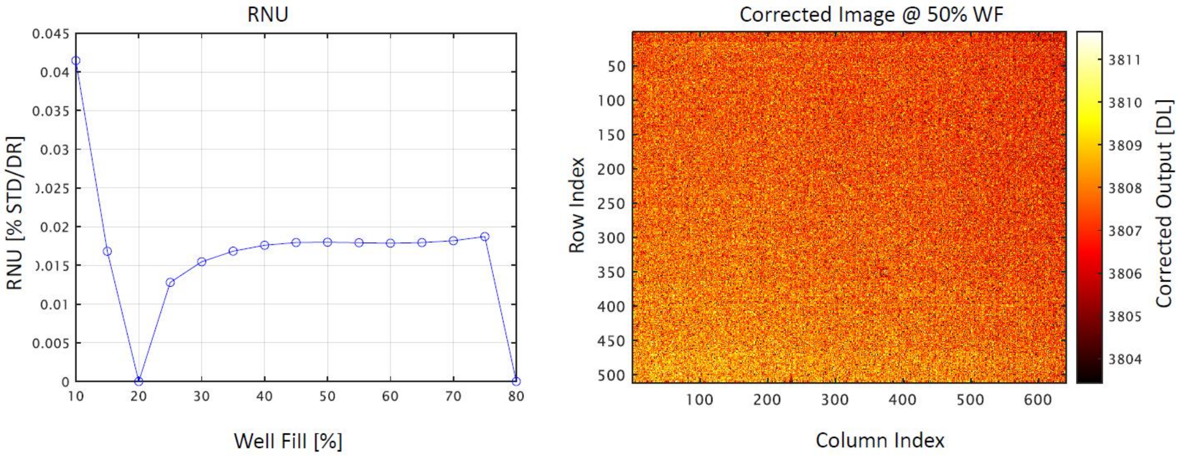

Figure 4: Mid Gain SIM Residual Non-Uniformity (RNU) and Corrected Image at 50% Well Fill (WF)

3.2 Laser Pulse Detection (ALPD)

We characterized the ALPD mode for both “ALPD only” mode (where the imaging channel is disabled) and with simultaneous imaging.

In Fig. 5 we present the first lab demonstration of ALPD + Imaging utilizing 4Gbps lanes. The ALPD frame rate is 14KHz while the Imaging frame rate is 33Hz. The laser pulse power at 1550nm was set to 4000e impinging on an effective 20µm pixel. The laser pulse frequency is 900Hz. The detection sensitivity is better than 95% with False Alarm Rate (FAR) lower than 0.1%. The background flux was very low and hence the SIM signal is close to the floor level. For this particular scenario of low background flux, the SIM channel input stage is too slow to capture the short laser pulses within a reasonable integration period (a few msec).

We have also tested the “ALPD only” mode with the advantage of minimum “dead time”. We increased the laser pulse frequency to 3KHz. The left hand image in Fig. 6 demonstrates laser pulse detection at in interval of ~ 12 ALPD frames that corresponds to the ration between the ALPD frequency of just above 36 KHz and that of the laser source. Since the ratio is slightly higher than 12 the interval can increase to 13. The detection probability is above 95% with FAR < 0.1%. Again, the frame rate is currently limited by our measurement setup.

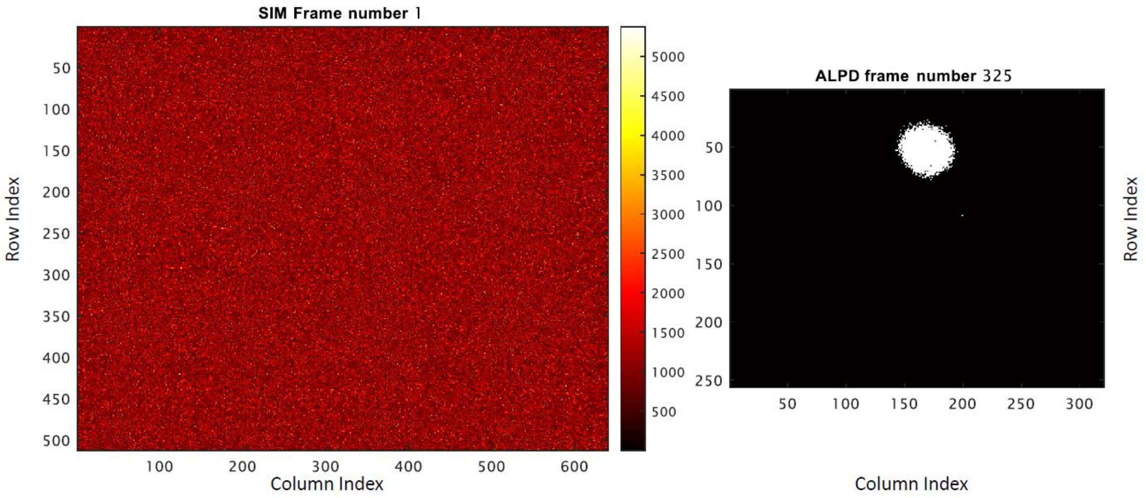

Figure 5: First lab demonstration of Simultaneous Imaging and ALPD. On the left the SIM image floor noise (no background illumination) and on the right laser spot detection with 4000e intensity.

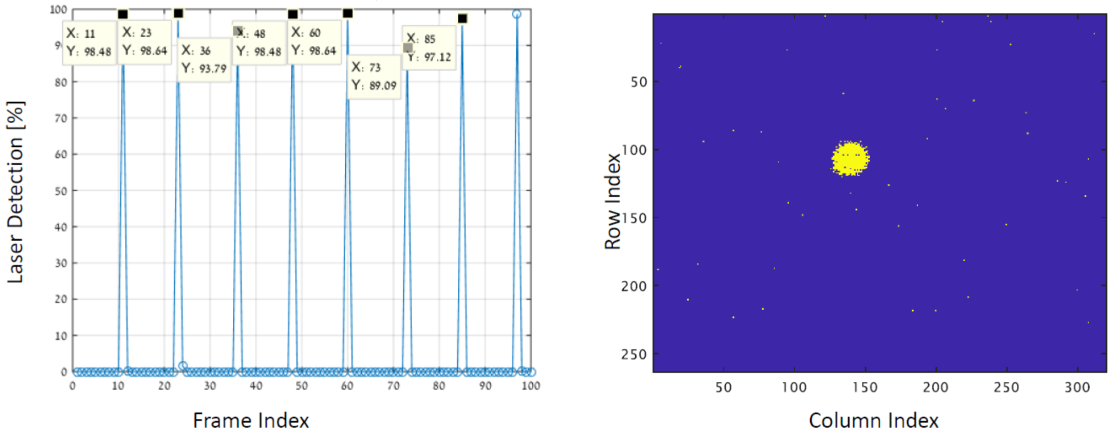

Figure 6: High Frame Rate (~ 36KHz) ALPD Only Performance. On the right hand side, we see the ALPD response with very few single pixel FARs. On the left hand side the laser detection every 12 ALPD frames. In between there is no detection with very low FAR background.

3.3 Event Detection

In order to verify the event mode, we built a dedicated setup in our lab. The setup consists of a rotating chopper for event generation that works as a mechanical shutter, blocking a background light source. The rotating chopper has openings of different sizes to verify event response with different frequencies. This is shown in Fig. 7a where the inner frequency is 3500Hz and the outer frequency 70Hz.

Fig. 7b exhibits a captured event image for both opening sets. The green color represents a positive variation while the red color indicated a negative variation. The gap in between represents a null variation below threshold. Fig. 7c shows the simultaneous SIM image captured by the imager - at a frame rate of 150Hz - which, as expected, is blurred due to the fast rotation of the chopper.

In order to interpret the “coupling” between the positive and negative response we compared the results with the event channel simulation shown previously [5]. In the top left hand side of Fig. 8 we present the actual input signal induced by the chopper outer opening in pA while rotating counter clockwise. In the bottom left hand, we present the simulated output and indeed, we find a consecutive “Positive – Null – Negative” response. This response evolves from the implementation of the detection channel: The high-pass filter that provides signal derivation followed by short integration and Sample & Hold (S&H). This particular measurement provides us the chopper frequency and the distance between the slits.

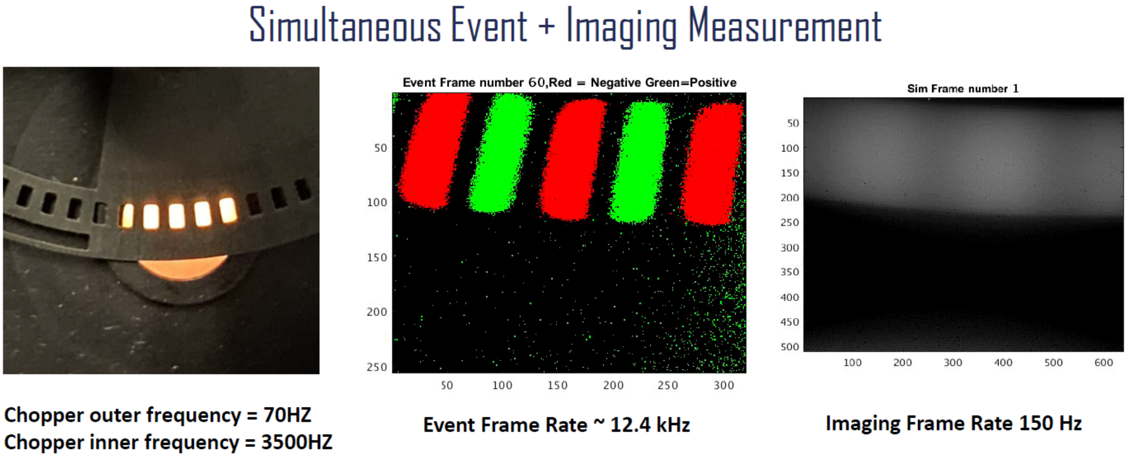

Figure 7: Simultaneous Event + Imaging Measurement. (a) Chopper setup (b) Captured event image (c) Captured SIM image

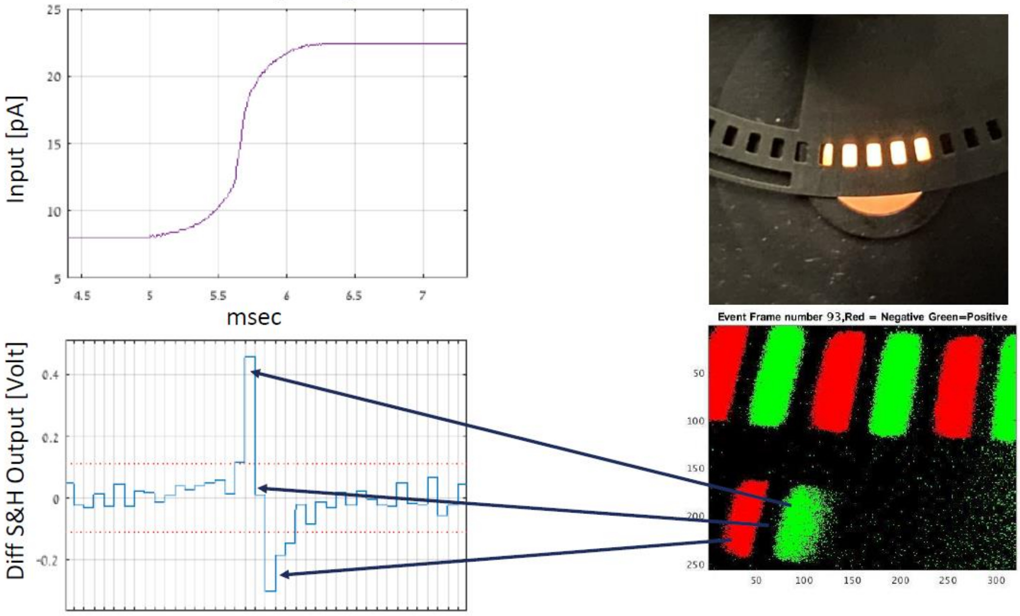

Figure 8: Blade rising edge response (Right Hand) verified by simulation (Left Hand). The chopper is rotating counter clockwise. Note that for the inner part the response is falling edge with a “Negative-Null-Positive” response

4. SUMMARY

In this paper, we have presented the ***SWIFT EI*** – a low SWaP sensor based on the event SWIR FPA.
The main features of the sensor were tested and verified. Specifically we exhibited high quality SWIR imaging, high frame rate (HFR) standard imaging, simultaneous event detection & imaging and simultaneous 3rd Generation ALPD & imaging. Hence demonstrating a state-of-the-art new type multi-function sensor. In the coming months ahead, a full proof of design tests will be completed, including full qualification at various ambient temperatures. In addition, in parallel, we are developing specific proximity electronics for the sensor supporting easy evaluation of the sensor by potential users.

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REFERENCES

[1] M. Mahowald and C. Mead, "The silicon retina," Scientific American, vol. 264, pp. 76–83, 1991
[2] G. Gallego et al., "Event-based Vision: A Survey", IEEE Trans. On Pattern Analysis and Machine Intelligence, 2020
[3] Shkedy L. et al. "Multi-function InGaAs detector for SWIR imaging," OPTRO 2930312, 2014
[4] C.G.Jakobson et al. "A 10 µm pitch, SXGA Multifunctional IRFPA ROIC with In-Pixel Laser Event Detection and High Dynamic Range Imaging", IISW 2021, Hiroshima, 2017
[5] C.G.Jakobson et al. "Event based SWIR sensor" SPIE-DCS, Infrared Technology and Applications XLVIII, 2022
[6] R. Fraenkel et al., "Development of low-SWaP and low-noise InGaAs detectors", SPIE-DSS, Proceedings Vol. 10177 Infrared Technology and Applications XLIII, Anaheim, 2017
[7] I.Hirsh et al.," Low SWaP SWIR video engine for image intensifier replacement". SPIE-DSS, Proceedings Vol. 10624 Infrared Technology and Applications XLIV, Orlando, 2018
[8] O.Ofer et al.," Performance of low noise InGaAs detector", SPIE-Defense Commercial Sensing, Proceedings Vol. 11741 Infrared Technology and Applications XLVII, online only, 2021
[9] S.Elkind, E.Ilan, R.Dobronislin, " Detector pixel signal readout circuit using an AC signal component in implementing an event detection mode per pixel", US Patent US9215386B2
[10] C.G.Jakobson, N.Ben-Ari, I.Nevo, N.Shiloah,"A pixel Readout Circuit and a Method for Imaging", IL262372, US patent US11533448 B2, 2019
[11] e.g. Y. Karni et al., "Spatial and spectral filtering on focal plane arrays" Proc. SPIE. 10624, Infrared Technology and Applications XLIV
[12] R. Fraenkel et al., "High Definition 10µm pitch InGaAs detector with Asynchronous Laser Pulse Detection mode" Proc. SPIE. 9819, Infrared Technology and Applications XLII