An InGaAs Multi-Functional Fast SWIR Imager with Event-based and Laser Multi-spot Sensing

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***Abstract* - A novel VGA, 10 micron pixel, multi-functional InGaAs imager is presented. This sensor combines standard imaging for daylight use and high-gain mode for low light level use with event-based imaging and laser multi-spot sensing. The fast imaging modes go up to 1.6 kHz for full-frame and are sensitive in the Visible to SWIR band (600–1700nm). The event-based mode and the laser multi-spot mode are able to operate simultaneously to the image with their output provided in a separate video channel. The event mode is responsive to image variations only, enabling to capture landscape events at a rate that is more than x10 faster than the standard imaging. The laser multi-spot mode responds to multiple laser illumination at a fast rate that enables to recognize the presence of laser spot as well as its pulse repetition frequency. This work elaborates on the multi-functional architecture, demonstrate its key features, and shows first measurements of the ROIC and sensor.**

Keywords - SWIR, ROIC, InGaAs, event-based vision, laser detection, laser multi-spot, multi-functional

I. 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 [1-3]. 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 hundreds of Hz [4]. On the other hand, and compared to their visible wavelength counterparts, SWIR pixels have a relatively large pitch that can be used to increase the pixel readout complexity [5]. For fast imaging applications, the pixel can combine multiple functions aimed at sensing fast events that may be present in the target scenario.

Event-based imaging is an emerging imaging paradigm focused only on variations in the pixel target that breaks the imaging speed bottleneck [6]. Typically event vision is intended for machine use, for example, event cameras can be used for 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. Navigation systems such as autonomous vehicles and drones can use event imaging for movement assistance and collision avoidance and at the same time assess motion-based depth information. Other processing options may enable its use to eliminate image artifacts caused by vibrations and turbulence.

On top of this, many lasers operate in the visible and SWIR wavelengths. Hence, laser pulses are a specific case of fast events 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 in standard imaging. Dedicated in-pixel circuitry can be used to enhance the response to fast pulses aiding to the laser detection process [5]. Moreover, there is an increased interest in decoding the laser pulse-repetition rates that are usually modulated up to 10 kHz. Laser decoding enables to identify between different laser sources and provides line-of-sight communication.

This works presents a novel imager, which is the first to introduce event-based imaging and laser-multispot detection in the SWIR wavelengths. This new imager provides a simultaneous conventional high FPS image synchronized to the event-based or to the laser multi-spot output. This imager follows a line of multi-functional InGaAs SWIR products. It is a fast multi-mode VGA imager implemented with a 10µm pitch sensor, while event-based and laser detection are shared between four adjacent pixels outputting a QVGA fast image. The imager is sensitive in the visible to SWIR bands, and provides full format integration of standard video at 1600 Hz with 11 bit output. The multi-spot Asynchronous Laser Pulse Detections (ALPD) works at a fast 50 kHz detection rate that enables the decoding of the laser Pulse Repetition Frequency (PRF) and distinguish between different lasers in the image scenario. Pixel techniques to combine imaging with event and ALPD are patented [7-8].

II. MULTI-FUNCTIONAL MODE OPERATION

Table 1 describes the modes of operation supported and their multi-functional combinations. All the imaging modes support global integration, the Standard Image Integration (SIM) mode integrates the image using a Direct Injection (DI) readout [4,9]; and may operate either as Integration Then Read (ITR) or as Integration While Read (IWR). In addition, a High Gain (HG) imaging mode uses a Charge Trans-Impedance Amplifier (CTIA) readout and Correlated Double Sampling (CDS) [5,9]. The HG imaging is ITR and is binned between four pixels. Moreover, the HG can be synchronized to an active illumination to provide active imaging over a time window of a few µsec.

<table>
<tr><th rowspan="2"></th><th>SIM</th><th colspan="2">High Gain</th><th rowspan="2">No Imaging</th></tr>
<tr><th>ITR & IWR</th><th>ITR</th><th>Active</th></tr>
<tr><td>Event-based detection</td><td>YES</td><td colspan="2" rowspan="2">NO</td><td>YES[a]</td></tr>
<tr><td>Laser Multi-spot detection</td><td>YES</td><td>YES</td></tr>
<tr><td>No detection</td><td>YES</td><td>YES</td><td>YES</td><td></td></tr>
</table>

[a] Can work as image-disabled or event-only sub-modes

Table 1. ROIC multi-functional modes

The event and laser multi-spot modes, referred also together as the "detection" modes, can operate simultaneously with the SIM imaging. The combination of the detection modes with the HG mode is disabled due to pixel hardware limitations.

The transition between the modes at Table 1 is very fast and can be done within one imaging frame by a simple control. As a particular case, the imaging and the detection modes can operate separately. This provides, correspondingly, an imaging-only mode and a detection-only mode.

In most cases the functionality of each mode operating separately improves performance. This is the motivation to support detection-only and imaging–only modes. Particularly, at imaging-only mode, the SIM operation is significantly faster than its corresponding simultaneous imaging-detection operation. On top of this, the event-only mode not only improves event performance, but also allows to reconfigure the block and change its functionality. More details are provided in next section.

III. ROIC DESIGN

Fig. 1 shows the simplified schematic circuit for the imaging modes. At DI mode, the DI-bias transistor together with the V_{DETCOM} voltage determine the bias to the diode, while the diode current is injected to the integration capacitor and subsequently read and drive to the column through a Source Follower (SF). IWR mode is enabled by using multiple integration capacitors, which enable to read from one capacitor while the other is integrating the signal. The imaging output signal is driven from the SF to column-parallel ADCs that provide conversion in the 11-13 bit range. The maximum frame rate is achieved with 11 bit operation and can reach 1.6 kHz.

At HG mode, the CTIA is enabled and the charge is integrated at the feedback integration capacitor. Four diodes are binned to a single feedback capacitor that provides the high gain and proper impedance-matching for CDS operation, thus the pixel effective area for HG operation is 20 µm. The HG mode is ITR only, and provides the best dynamic range and low noise for low illumination scenarios. The CTIA shares the same SF than the DI, but in this case converting to 11bit is enough to meet the dynamic range requirements. The HG mode achieves 2 kHz.

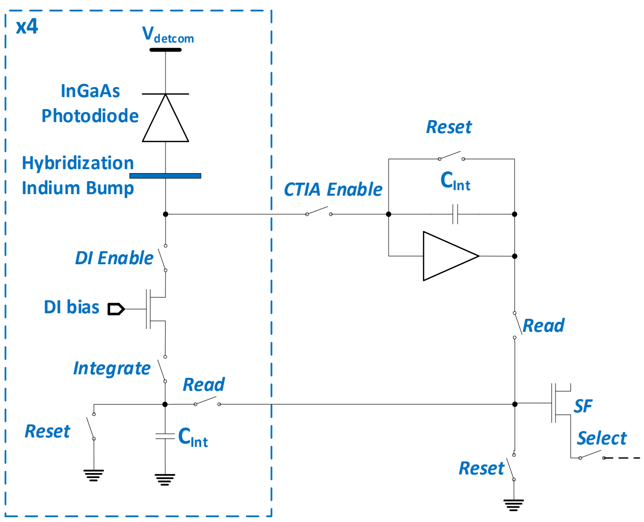


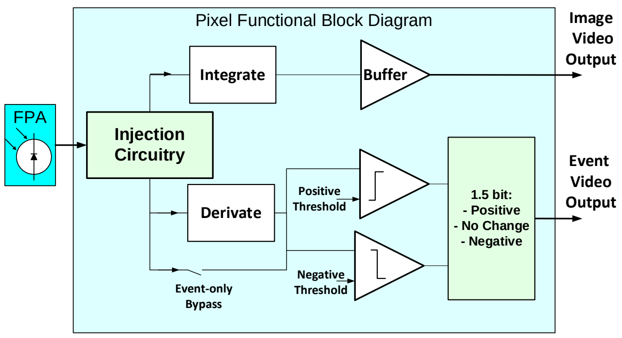
Fig. 1. Simplified imaging schematics

The main parameters for both imaging modes are summarized at Table 2.

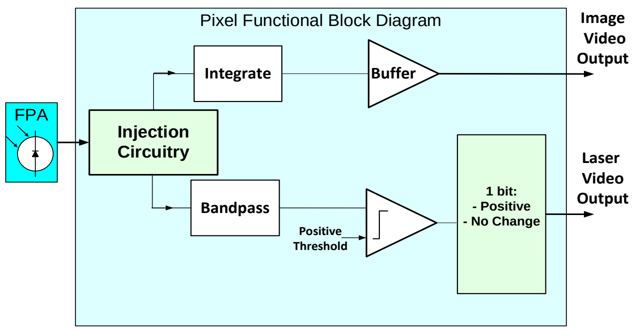
Mode	Parameter		Units	Value
SIM	***Format***		N.A.	VGA
	Full well capacity	***IWR***	ke-	500
		ITR		900
	Readout Noise	***IWR***	e-	150
		ITR		260
	Max. Frame Rate (13/11 bit)	***No Detection***	FPS	800/1600
		With Detection		200/250
HG	***Format***		N.A.	QVGA
	Full well capacity	***ITR***	ke-	50
	Readout Noise		e-	50
	Max. Frame Rate (11 bit)		FPS	2000

Table 2. ROIC main imaging parameters

The detection modes are combined within the schematics shown at Fig. 1. The signal reconfiguration that enables the detection modes reuse the CTIA amplifier. Due to this constraint the detection modes can operate only simultaneously to the SIM mode.



(a)



(b)

Fig. 2. Pixel functional block diagram: (a) event detection (b) laser multi-spot detection

Fig. 2 describes the detection modes by functional block diagrams. The upper figure (a) shows the block diagram for the event mode. The signal is injected into the DI circuit and simultaneously split in the frequency domain by two filters [8]. 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 3 levels (1.5 bits) that indicate the presence of a negative or positive event, or no change, as usually done in dynamic vision systems [6].

The image can be disabled to provide an event-only mode. At first, this can be done to improve event sensitivity and eliminate possible parasitic coupling between the event sensing and the image read. However, disabling the image integration performed by the low pass filter also enables to bypass the high-pass filter as this last one is no further required for signal splitting. To this end a bypass filter switch has been implemented as shown in Fig. 2. (a). While usually the event mode is targeted high frequency fast variations, this variant of the event-only mode enables to extend it to respond to low frequency variations.

The laser multi-spot detection is done by reconfiguring the filters as shown in Fig. 2 (b). The main differences are in replacing the derivative channel by a band-pass filter [7], and in disabling the negative comparator as the laser signal is only positive. The end of this reconfiguration is to provide the best filter noise matching in order to detect low energy laser signals.

Table 2 summarizes the main parameters for the detection modes

Mode	Parameter	Units	Value
Event	***Format***		QVGA
	Event rate	kHz	0.5-25
	Sensitivity	e^-	1500
Laser multi-spot	***ALPD/SLPD Sensitivity***	e^-	2000
	ALPD Rate	kHz	0.5-50
	ALPD duty cycle	%	100

Table II. ROIC main detection parameters

Fig. 3 shows the ROIC floor plan, the VGA pixel channel is connected to column-parallel detection channels and column-parallel detection channels. The matrix read is done by rolling and after conversion it is driven by four video channel outputs.

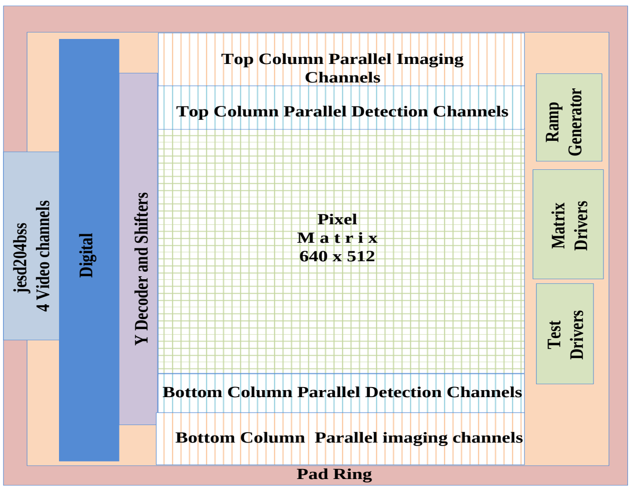


Fig. 3. ROIC Floor plan

Fig. 4 shows the packaged prototype used for first measurements and characterizations described in the next section.

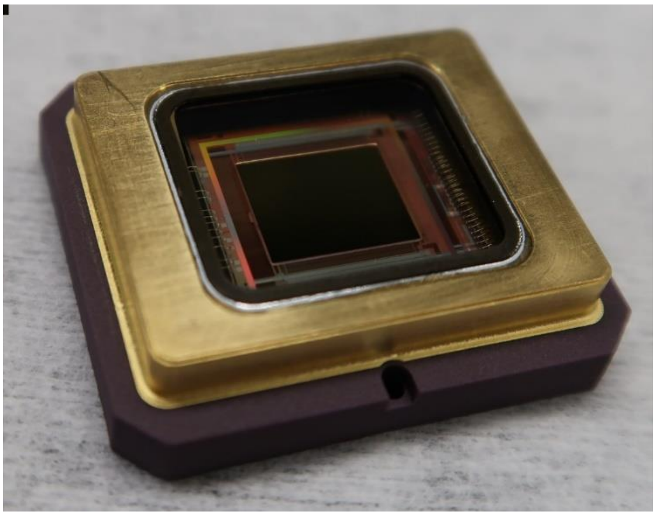


Fig. 4. Packaged prototype photo

IV. Measurements

Fig. 5. shows an image captured by the new imager at SIM mode. Fig. 6. Shows the SIM noise floor histogram.

Fig. 5. SWIR image in SIM mode

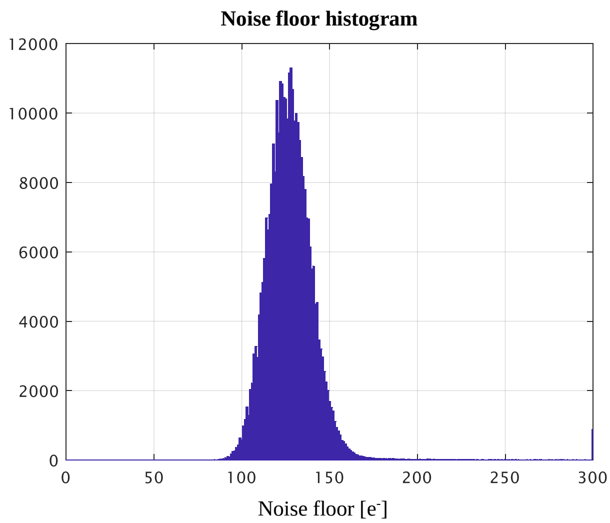


Fig. 6. Dark noise floor histogram for the SIM image

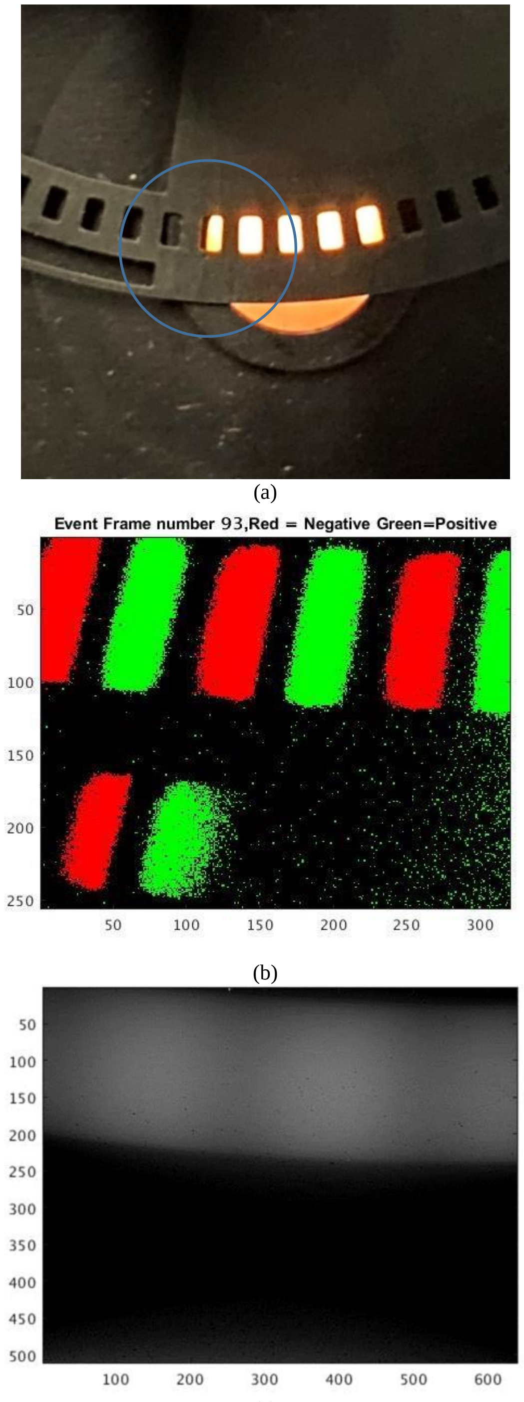


Fig. 7. Event imaging: (a) measurement setup, (b) event channel output, (c) simultaneous SIM image

Fig. 7 (a) shows the event setup used to test the prototype and a single frame capture the event video. The setup consists of a rotating chopper for event generation that blocks a background light source. The rotating chopper has openings of different sizes to verify event response with different frequencies. Fig. 7 (b) shows the captured events, where green indicates a positive variation and red indicates a negative variation. The area captured by the event image is denoted by the blue circle in Fig. 7 (a). The inner shutter (the upper in the figure) generate events at a rate of 3500 events per second, and the outer shutter (the lower in the figure) does it at 70 events per second. Both event edges are well recognized. Fig. 7 (c) shows the simultaneous SIM image captured by the imager, which, as expected, is blurred due to the fast rotation of the chopper.

Fig. 8. Shows a laser spot captured at 10kHz. The laser energy generates 4 ke^- for the four shared pixels (1 ke^- per diode). Despite the low laser energy, the signal is detected with a very low number of false alarms.

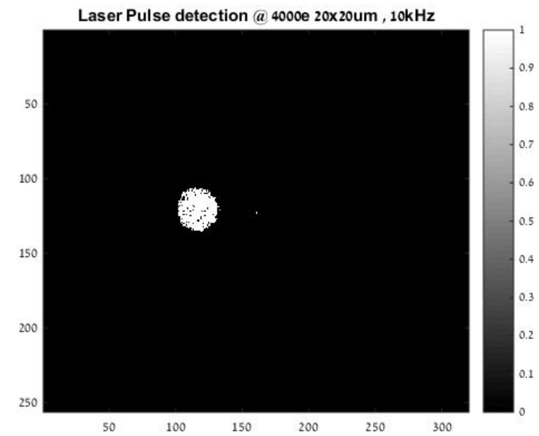


Fig. 8. Laser spot captured at 10 kHz, the FAR observed is <0.1%

V. SUMMARY

A novel VGA, 10 micron pixel, multi-functional InGaAs imager has been presented. The multi-functional modes enable simultaneous combination of SIM mode with detection modes. In addition, an HG mode can be used at low light level conditions. The imager prototype and first measurements have been presented, showing simultaneous SIM and detection, event-based imaging and fast laser detection.

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