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Small Pixel Pitch, High Definition MWIR and Dual Band SWIR/MWIR Imaging Sensors for SWaP-Constrained Applications

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ABSTRACT

Unmanned airborne and dismounted soldier capability requirements continue to push for reduced size, weight, and power (SWaP) and high sensitivity infrared (IR) imaging in applications that were not previously practical. In response to these needs, Attollo Engineering has developed a 1280x1024, 5 µm pixel pitch cooled mid wavelength infrared (MWIR) sensor that pushes the envelope in pixel pitch in addition to a 1280x1024, 10 µm pixel sensor dual band sensor with additional sensitivity in the short wavelength infrared (SWIR) in order to exploit SWIR phenomenology including laser see spot functionality. Both of these sensors offer MWIR sensing capabilities but are also able to leverage aspects of Attollo's detector design to enable SWIR sensing to varying degrees. This class of small pixel cooled, single and dual band IR sensor technology represents advancements in all aspects of the sensor's design and development, and we will discuss the innovations made at Attollo to enable this capability including epitaxial detector design based on III V compound semiconductors, detector array and focal plane array fabrication, design of a low noise, dual band CTIA/DI readout integrated circuit (ROIC), vacuum dewar packaging, and electronics and firmware design. In this paper we will present on the status of high definition small pixel pitch MWIR and dual band SWIR/MWIR imaging technology at Attollo as it relates to these sensors including design and measurement data and imaging

Keywords: SWIR, MWIR, dual band, SLS, see-spot, IDCA, ROIC, ALPD

1. BACKGROUND

Improvements in small pixel infrared sensor technology are reducing the size, weight, and power (SWaP) of sensor systems and enabling the use of cooled infrared sensors in systems where not previously achievable with prior generations of IR detector technology. Advanced detector design, array fabrication, and focal plane array hybridization processes, novel ROIC design, and aggressive sensor packaging allow for packing more capabilities into smaller and smaller sensors. This becomes particularly more so when said FPAs are dual band in nature; for instance, short wavelength infrared (SWIR) / mid wavelength infrared (MWIR).

The primary pressures for reduced SWaP include enhancements of lethality, accuracy, operating conditions, and capabilities of unmanned airborne systems (UAS) and dismounted soldiers. Only recently have cooled infrared sensors been able to be considered in 5" and 6" class gimbals, enhancing their range performance over uncooled solutions. Dismounted soldiers conducting precision targetting applications require the ability to see PRF encoded battlefield lasers for both targetting and pointing applications in the SWIR band while also imaging at night in the MWIR. In all applications, SWIR imaging provides superior haze penetration over visible bands and the ability to see through glass that MWIR imaging does not.

Responding to these needs, Attollo Engineering has developed a family of cooled MWIR and dual band SWIR/MWIR sensors based on III V compound semiconductor strained layer superlattice (SLS) and alloys. The SLS and alloy based detectors that Attollo employs offer a variety of practical advantages over incumbent technologies like HgCdTe and InSb including application specific design optimization, manufacturability and high temperature operation.

In this paper, we will describe the design, optimization, and performance capabilities of small pixel pitch MWIR and dual band SWIR/MWIR sensors that are well suited for the applications described above. This will include details of the device structure and epitaxial design, challenges associated with high operability detector array and focal plane array fabrication, small pixel dual band ROIC design, low SWaP vacuum packaging, and camera integration.

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2. HIGH OPERATING TEMPERATURE MWIR AND SWIR/MWIR DETECTOR DESIGN

Antimonide based, III V compound semiconductors provide a large parameter space for designing and engineering cooled infrared detector for a particular application. During the design of a detector structure among the considerations are cutoff wavelength, dark current, absorption coefficient, absorber thicknesses, band alignment to minimize bias dependence, heterostructure material choices, epitaxial growth limitations, etch depth and street width, etch chemistries and selectivities, etc.; and, like most engineering design problems, these considerations are often interrelated.

Attollo Engineering has developed a wide selection of different Sb-based, III-V alloy and superlattice absorber designs that have been integrated into a variety of single and dual band detector designs. Figure 1 shows a selection of those detector spectra ranging from the MWIR to the VLWIR.

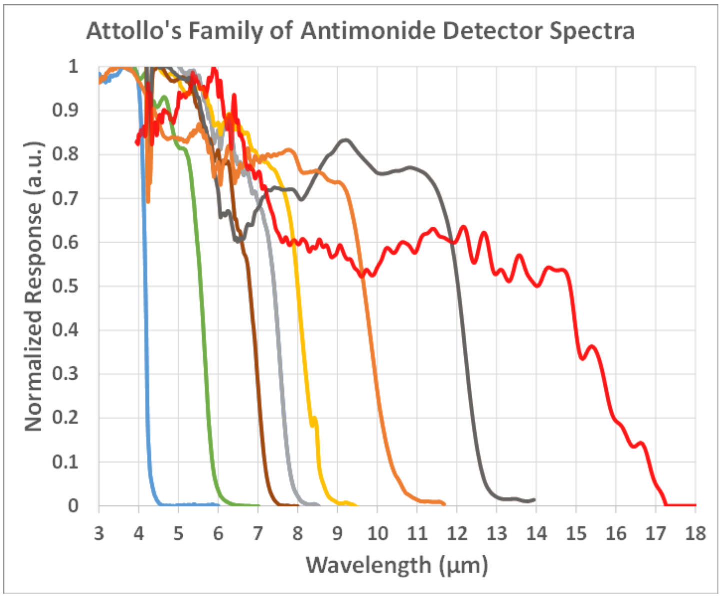


Figure 1 - A selection of Attollo's family of Antimonide detector spectra.

Most Sb-based detector designs at Attollo are based on barrier structures and generic epitaxial structures are shown in Figure 2. All epitaxial growth is done via molecular beam epitaxy (MBE) on both 3” and 4” GaSb wafers. The barrier based design provides a good range of design flexibility and valence band alignment with many of our absorber designs.

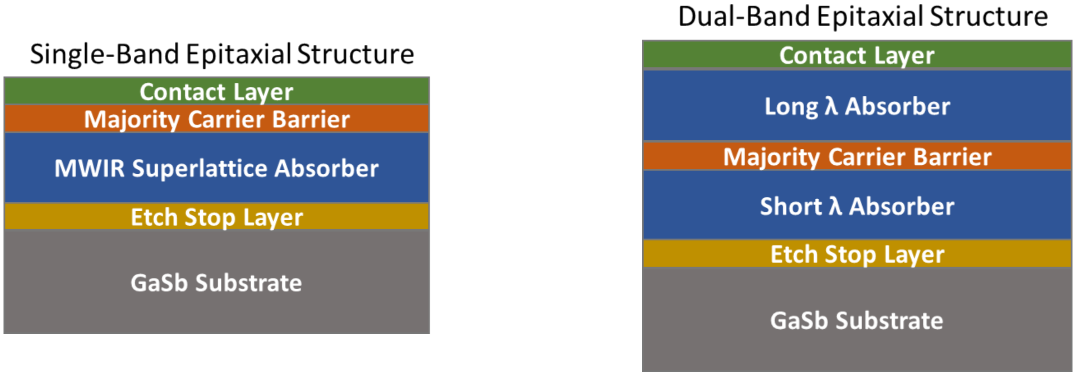


Figure 2 - Schematic cross-sections of single- and dual-band epitaxial barrier detector designs.

One of the unique features of the described epitaxial structures is the inclusion of a backside etch stop layer that allows us to completely remove the GaSb substrate to improve transmission of wavelengths below the 1.8 µm absorption edge of the GaSb substrate as shown in Figure 3.

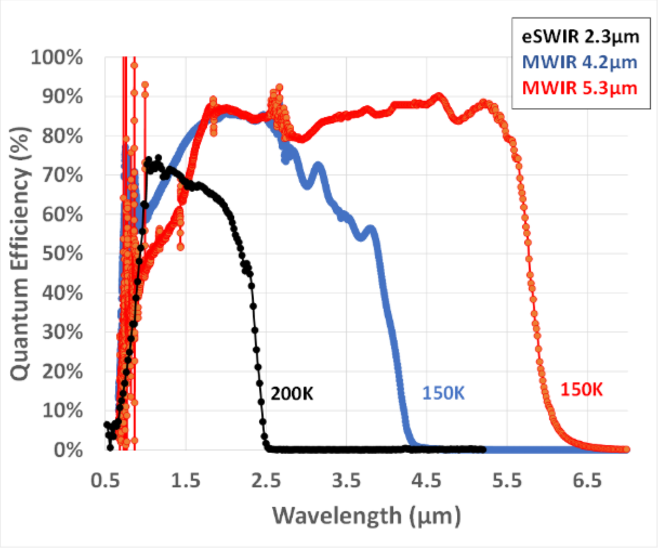


Figure 3 - Spectral quantum efficiency measurements of Attollo's Broadband eSWIR and MWIR sensors shows sensitivity to wavelengths < 1 um.

This results in sensitivity to wavelengths below 1 µm which includes the range of many common lasers lines (1064 nm, 15xx nm) and the full SWIR band. Through the use of external filters, a variety of additional capabilities can be added to a traditional MWIR sensor.

3. SMALL PIXEL, HIGH-DEFINITION DETECTOR WAFER PROCESSING

Attollo has developed detector array fabrication processes for high-definition arrays at 5 µm, 8 µm, and 10 µm pixel pitches with dual-band detector arrays being fabricated at the two larger pixel pitches. As detector pixel pitches decrease to less than 10 µm, careful control of critical dimensions (CD), layer-to-layer registration (Figure 4), and process uniformity across the full wafer become increasingly important to maintain high yield. Tolerances for error are reduced and high aspect ratio, low-damage dry etch processes are required especially for dual-band devices, in order to maintain high fill-factor for optimal quantum efficiency.

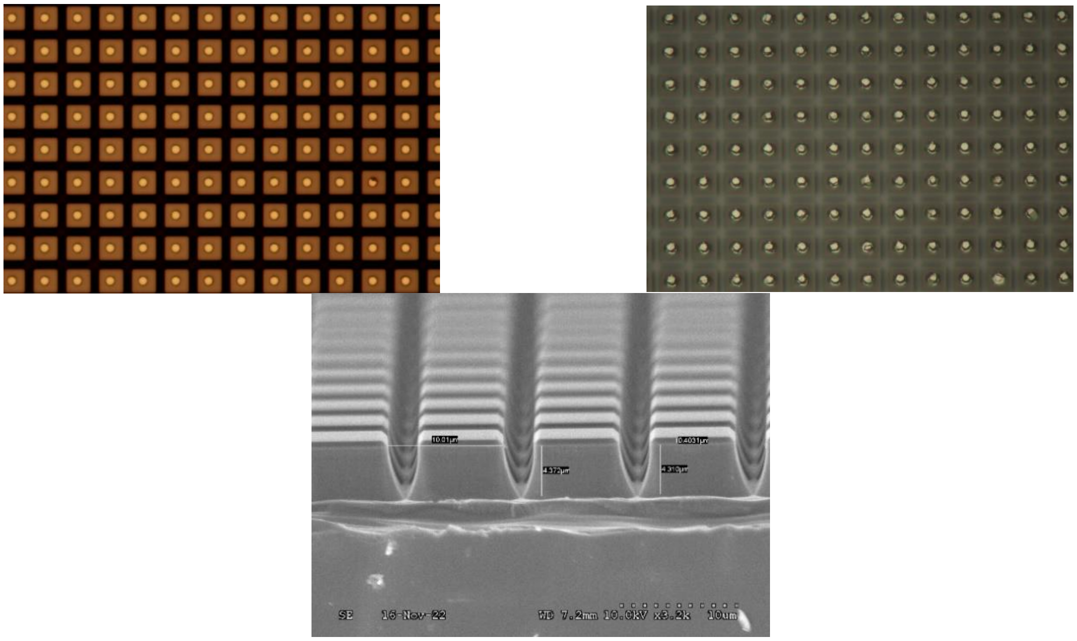


Figure 4 – Layer to layer registration and critical dimension control on a 10 µm pixel pitch for (left, top) contact metal and (right, top) indium layers to underlying process steps are critical to high yielding detector arrays. (right) High aspect-ratio etching of a dual-band detector on a 10 µm pixel pitch.

We have developed full-wafer processes for high volume manufacturing on 3" and 4" GaSb wafers. Examples of SXGA and HD arrays fabricated on both 3" and 4" wafers are shown in Figure 5.

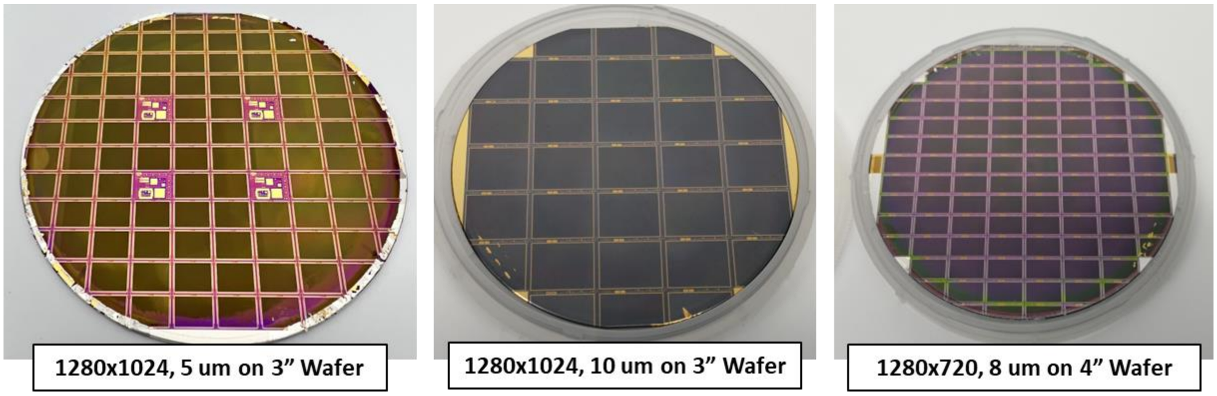


Figure 5 - 3" and 4" wafer fabrication of SXGA and HD detector arrays on 5 µm, 8 µm, and 10 µm pixel pitches.

4. SMALL PIXEL, HIGH-DEFINITION READOUT INTEGRATED CIRCUITS

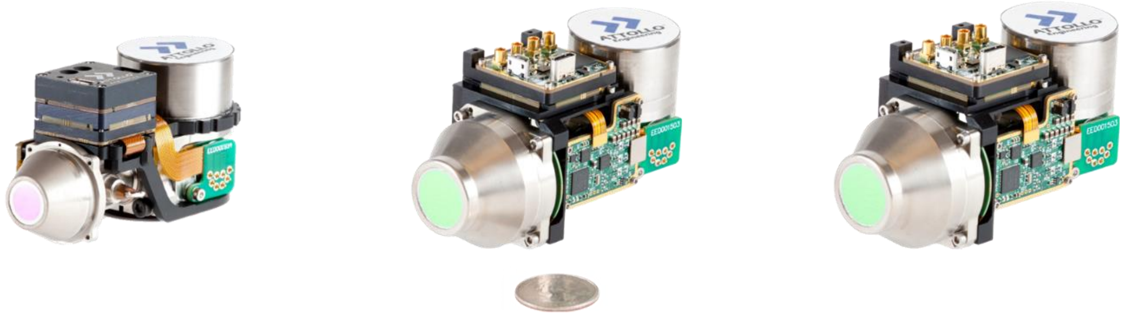
Attollo has developed a suite of small pixel pitch, high-definition readout integrated circuits (ROICs) for use in MWIR and dual-band SWIR/MWIR applications with a wide variety of features. All of our ROICs utilize column-parallel analog to digital converters and an all-digital chip interface which greatly simplifies integration with camera and test electronics and reduces susceptibility to electromagnetic interference (EMI). Table 1 provides a summary of Attollo's small pixel pitch, high-definition ROICs and their relevant characteristics.

Table 1 - Small pixel pitch, high-definition ROICs for single-band MWIR and dual-band SWIR/MWIR sensors.

Parameter	AE1906	AE2001	AE2002
Format	1280 x 1024	1280 x 720	1280 x 1024
Pixel Pitch	5 µm	8 µm	10µm
Operating Mode	Global Shutter ITR	Global Shutter ITR, IWR	Global Shutter ITR, IWR
Frame Rate	60Hz	60 Hz	> 120Hz
Full Well Capacity	0.56Me-	3.3Me-	SWIR – 36ke- MWIR – 4.4Me-
Read Noise	<50 e-	<900 e-	SWIR < 30e-
Pixel Amplifier	Direct Injection	Direct Injection	CTIA for SWIR DI for MWIR
Anti-blooming	Yes	Yes	Yes
Windowing			1kHz frame rate
Output	Digital	Digital	Digital
Integration Time Control	External trigger Free-running	External trigger Free-running	External trigger Free-running

5. GRIFFIN HD5 MWIR CAMERA CORE

The detector array and ROIC development described above has lead to the development of Attollo's Griffin family of single-band MWIR cameras and Hydra family of dual-band SWIR/MWIR cameras which feature the exceptionally low size, weight, and power summarized in Figure 6



Griffin HD5
1280x1024, 5 um
3-5 um or 1-5 um
<221 grams

Griffin HD8
1280x720, 8 um
3-5 um or 1-5 um
<250 grams

Hydra HD10
1280x1024, 10 um
1-2.5 um & 3-5 um
<250 grams

Figure 6 - Attollo's single-band Griffin 5 um and 8 um pixel pitch and dual-band Hydra 10 um pixel pitch cooled IR cameras

All of Attollo's cameras are based on a modular electronics platform, centered around either a 4- or 16-input processor board. The camera electronics stack supports all the bias and supply generation needed for the FPA, the clocking and communication with the FPA's digital interface, and the receipt and processing of pixel data coming from the FPA. The processor board conducts standard image processing steps like pixel re-ordering, non-uniformity correction, bad pixel replacement, automatic gain control, automatic exposure control, etc.

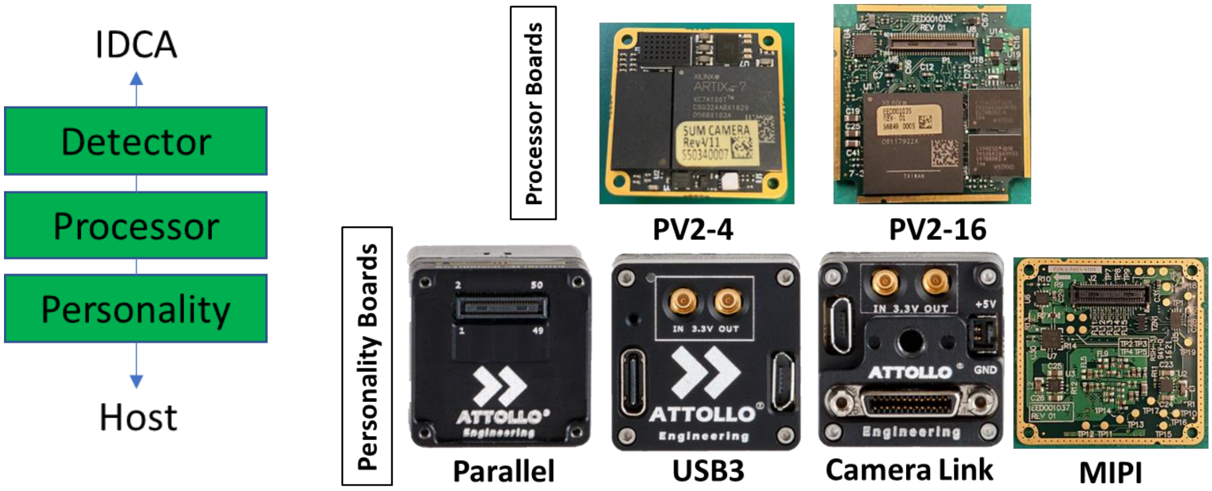


Figure 7 - (left) A high level block diagram of the Attollo camera electronics based (right) one of two different processor boards and one of many different output interfaces depending on host requirements.

Many different output interfaces are supported including 16-bit parallel CMOS, USB3 video, Camera Link, and MIPI CSI-2. Command and control of the camera is done over UART, SPI, or I2C and all cameras support external triggering for synchronization with lasers in support of see-spot applications.

The Griffin HD5 MWIR camera utilizes an FPA based on the AE1906 ROIC and a SLS-based MWIR detector packaged into an extremely small vacuum package and integrated with a high efficiency rotary Stirling cooler. The Griffin HD5 is the same package and electronics as the Griffin VGA5 but features 4 times more field of view. A typical noise equivalent delta temperature (NEDT) map and histogram are shown in Figure 8, where the median NEDT is < 32 mK with an operability of 99.8% at F/1.4 against a 20°C background.

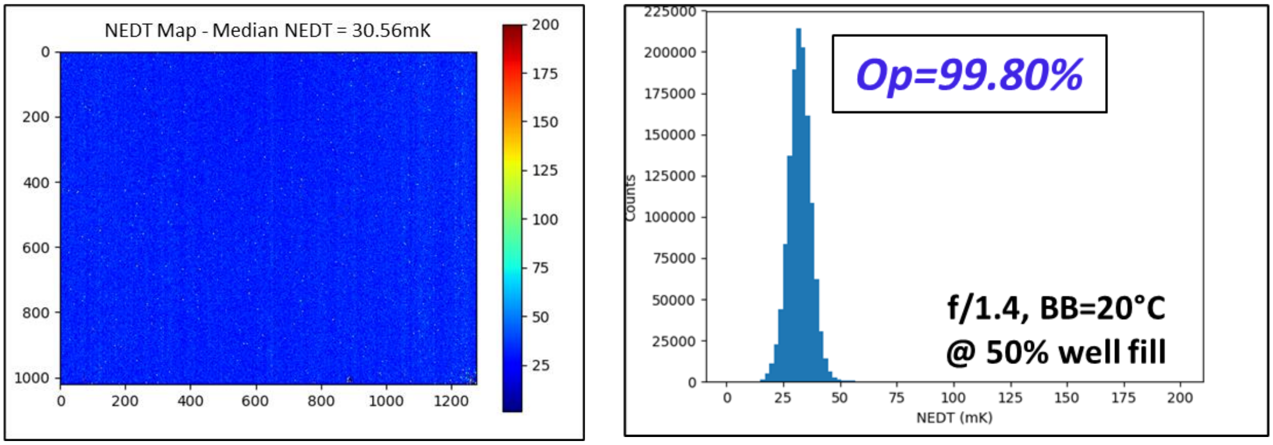


Figure 8 - NEDT (left) map and (right) histogram of an HD5 MWIR FPA with a median NEDT of < 32 mK and an operability of 99.8%.

Still frames captured from Griffin HD5 video imagery are shown in Figure 9 and show the high resolution and wide field of view offered by the sensor.

Figure 9 - SXGA, 5 um pixel pitch MWIR imagery captured with the Griffin HD5 camera core.

The Griffin HD8 camera core features a larger pixel pitch and well-size at 8 µm and 3.3Me-, respectively, and with the same strained layer superlattice-based MWIR detector as the Griffin HD5. The HD8's format and pixel pitch may be advantageous for use in systems where very fast optical designs are not practical. Representative nighttime imagery is shown in Figure 10.

Figure 10 - Nighttime MWIR imagery taken with the Griffin HD8 camera core.

6. DUAL-BAND SWIR/MWIR SENSOR TECHNOLOGY

Attollo has been developing dual-band SWIR/MWIR detector technology since 2020 with initial approaches utilizing MWIR1/MWIR2 dual-band detector designs that incorporated a cold filter to create a SWIR/MWIR sensor; a representative spectral response of the underlying MWIR1/MWIR2 detector design is shown in Figure 11 (left). This was later followed up by a true SWIR/MWIR detector design that allowed for a simpler cold filter design and had significantly improved SWIR in MWIR spectral crosstalk. Additionally, by reducing the MWIR cutoff wavelength to 4.2 µm, higher operating temperatures can be achieved; although the cutoff can still be tuned to cover the full MWIR band. The spectral response of the SWIR/MWIR dual-band detector design is shown in Figure 11 (right).

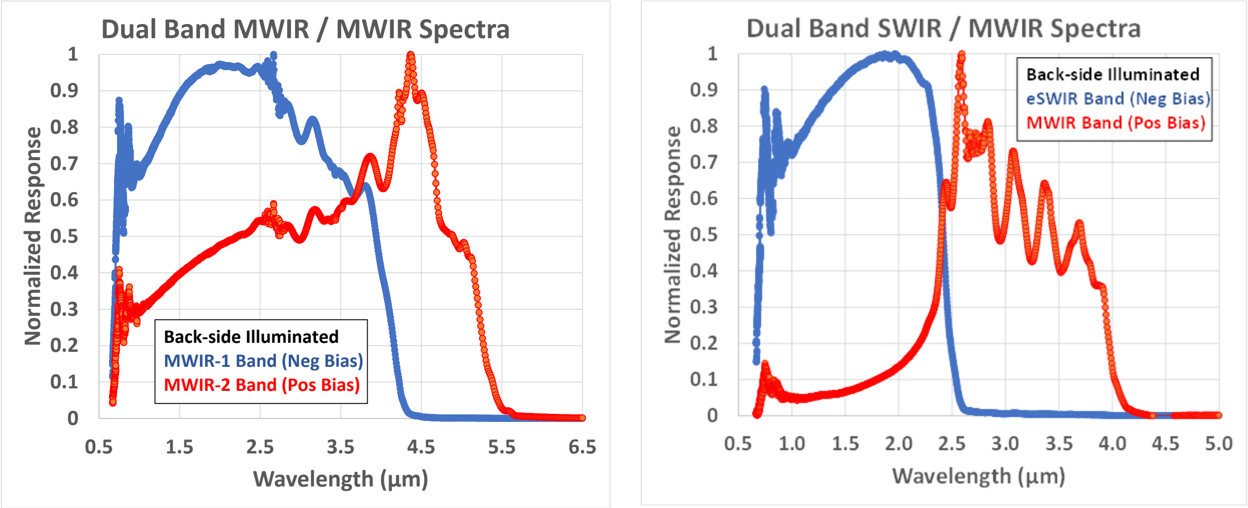


Figure 11 - Relative spectral response for (left) MWIR/MWIR dual-band detector and (right) SWIR/MWIR dual-band detector.

Imagery from the MWIR/MWIR frame-sequential, dual-band device with cold filter to segregate the SWIR and the MWIR channels is shown in Figure 12 in a 1280x720, 8µm pixel pitch format. The use of the cold filter to block the emissive signal in the SWIR (MWIR1) band was fairly effective but due to the overwhelming difference in SWIR irradiance from solar reflected light in the day to emissive signal in the ~4.4 – 5.2 µm band, SWIR in MWIR crosstalk was still noticeable depending on lighting conditions when operating in the MWIR (MWIR2) band. This crosstalk could be partially mitigated by increasing the MWIR1 absorber thickness but at the expense of other device performance characteristics.

Figure 12 - (left) SWIR and (right) MWIR daytime imagery from a frame-sequential, 1280x720, 8 um dual-band imager with direct injection (DI) inputs for both channels.

However, by moving to a true SWIR / MWIR dual-band detector architecture we were able to substantially reduce spectral crosstalk to the level of < 5% across the SWIR band of interest. Additionally, this detector was mated with the AE2002 ROIC, described previously, that features a capacitive transimpedance amplifier (CTIA) unit cell for the SWIR polarity and a direct injection (DI) input for the MWIR polarity of the frame-sequential ROIC. The CTIA channel allows the sensor to achieve very low read noise of < 30 e- which improves the low-light performance over the DI unit cell.

Figure 13 - (left) SWIR and (right) MWIR late dusk imagery from a frame-sequential 1280x1024, 10 µm dual-band SWIR/MWIR with a CTIA and a DI input for the SWIR and MWIR channels, respectively.

Further FPA development and IDCA packaging is underway with this SWIR/MWIR sensor technology and will be integrated into the same vacuum packaging as the HD8 sensor, marking a substantial reduction in SWaP by offering state-of-the-art SWIR and MWIR imaging in a single system aperture and with a single set of processing electronics.

7. SWIR/MWIR LASER SEE-SPOT

The dual-band SWIR/MWIR sensor described previously is sensitive to common battlefield lasers at wavelengths including 850 nm, 1064 nm, and 15xx nm. By pairing the aforementioned SWIR/MWIR sensor with a laser event detector, like Attollo's Mantis which is capable of detecting, decoding, and generating a trigger signal, a very compact and capable laser see-spot solution is realized.

Attollo has taken steps to ensure that their ROICs support low-latency exposure triggering and short integration times to support laser see-spot. By using short integration times, we are able to isolate the laser spot from the solar-illuminated background and create what we call a "laser frame." This is immediately followed up with a normal exposure time frame, or "context frame", and is then combined with the "laser frame" with false coloring of the isolated laser spot as shown in Figure 14. The advantage of laser see-spot image is that one can visually verify the location and dimensions of the actual laser spot including any overspill and underspill of the target.

PRF detection, decode, trigger, and PreCognitive^{TM} laser imaging, and passive imaging

Figure 14 - The Mantis event detector, when paired with a SWIR/MWIR dual-band sensor, enables the detection, decode, triggering, laser imaging, and passive imaging in either SWIR or MWUR in a very compact system solution.

8. SUMMARY AND CONCLUSIONS

Attollo Engineering has continued to mature their 5 µm and 8 µm small pixel pitch MWIR sensor technology by developing the Griffin HD5 and HD8 high-definition format sensors for single-band MWIR imaging in very low SWaP packages designed especially for airborne and handheld applications. This technology has been extended to the development of the dual-band SWIR/MWIR Hydra HD10 high-definition sensor at a 10 µm pixel pitch, offering the capabilities of two infrared sensors in a single system aperture. When paired with a laser event detector, like the Mantis, these sensors are capable of laser see-spot applications in addition to passive SWIR and MWIR sensing.