Dual Waveband: Exploiting a Broader IR Spectrum in Dynamic Imaging Environments

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ABSTRACT

Dual Waveband devices have been in the marketplace for many decades; Leonardo UK for example, launched the Condor II MCT MW/LW DWB camera in the mid 2000's. Most imaging systems will pick a single IR waveband (SWIR/MWIR/LWIR/VLWIR) and there are sound justifications for doing so. However, in some applications – particularly where the scene can vary dynamically, there is a strong argument in incorporating multiple IR wavebands in a single detector, without requiring two separate detectors in a system to achieve this.

In this paper, potential scenarios are reviewed where having a DWB sensor capability is advantageous. A summary of DWB products manufactured by Leonardo UK are presented, including the latest 12µm MWIR-LWIR Dual Waveband Infra-Red (DWB-IR) high-performance detectors, along with the performance benefits and challenges of moving to finer pitch DWB structures. Leonardo UK DWB devices use a "back-to-back" diode arrangement, whereby the waveband is selected by changing the bias polarity across the diode stack; thus ensuring spatial coherence between the two wavebands.

In addition to MW/LW DWB systems - other MCT DWB structures are reviewed, all of which can, or have been grown using Metal Organic Vapour Phase Epitaxy (MOVPE) on low cost GaAs substrates at Leonardo UK. New technologies within the IR industry that can help manage some of the challenges in operating DWB systems are assessed.

1.0 THE INFRA-RED SPECTRUM

This paper will discuss IR (Infra-Red) imaging in three key zones. In general, devices that operate within the regions below fall under the following definitions.

- Short-Wave IR (SWIR) 0.9µm – 2.5µm
- Mid-Wave IR (MWIR) 3µm – 5µm
- Long-Wave IR (LWIR) 7µm – 14µm

As shown in Figure 1, even in clear conditions – the absorption of certain wavelengths by the atmosphere (H_2O, CO_2, O_3 etc.) largely dictates the ranges above. What makes selecting the right zone for a given application so difficult is that, whilst in ideal conditions – most systems based on SWIR/MWIR/LWIR will perform suitably well for most applications, changes in the atmosphere away from ideal conditions can significantly tip the balance in favour of one imaging zone over another.

In the next section, the key physical characteristics of imaging in each IR waveband are presented, and the key advantages and disadvantages of each system. The evaluation will remain in the context of human-vision systems, although many of the advantages/disadvantages are applicable to machine-vision systems too.

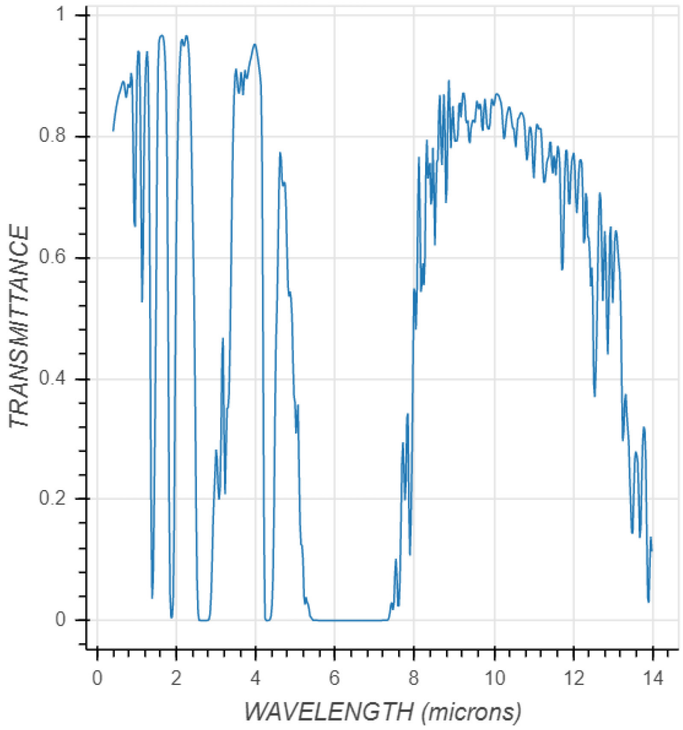

Figure 1: Transmittance from 0.4µm to 14µm in clear mid-latitude conditions (Via MODTRAN).

1.1 SWIR in IR-Imaging Applications

Despite being in the 'infra-red' SWIR has much in common with visible imaging, whereby imaged objects are detected by reflected light from another source (usually sunlight or moonlight), as the thermal emission alone from objects in typical terrestrial scenes in SWIR is usually too low to be useful for imaging – unlike MWIR & LWIR. This key differentiator largely forms the basis of the advantages and disadvantages of SWIR systems over the rest of the IR spectrum.

Due to the radiation behaving very similar to visible light with reflections, the images are typically more intuitive to assess by an operator – thus making identification of targets easier in some cases. The reflective nature of SWIR highlights a key disadvantage – due to the need for a light source, a passive SWIR system will not operate in pitch-black conditions; this can be mitigated by making use of a SWIR in 'active' modes such as Burst Illumination LIDAR (BIL), which is made practical due to the commonality of high-powered solid-state lasers in the SWIR wavelength range. Leonardo UK has demonstrated this technology within high gain avalanche photodiode SWIR devices [1].

The reliance on an external source also means that a very high dynamic range is required for a SWIR system due to the large variances in the source radiation (daylight and moonlight for example).

For a fixed aperture size, a SWIR system enables the highest resolution within the IR waveband. This is due to the fact that the diffraction limit of an optical system scales with wavelength, as shown in Figure 2. More detail on the Sparrow Undulation Condition is discussed in [2].

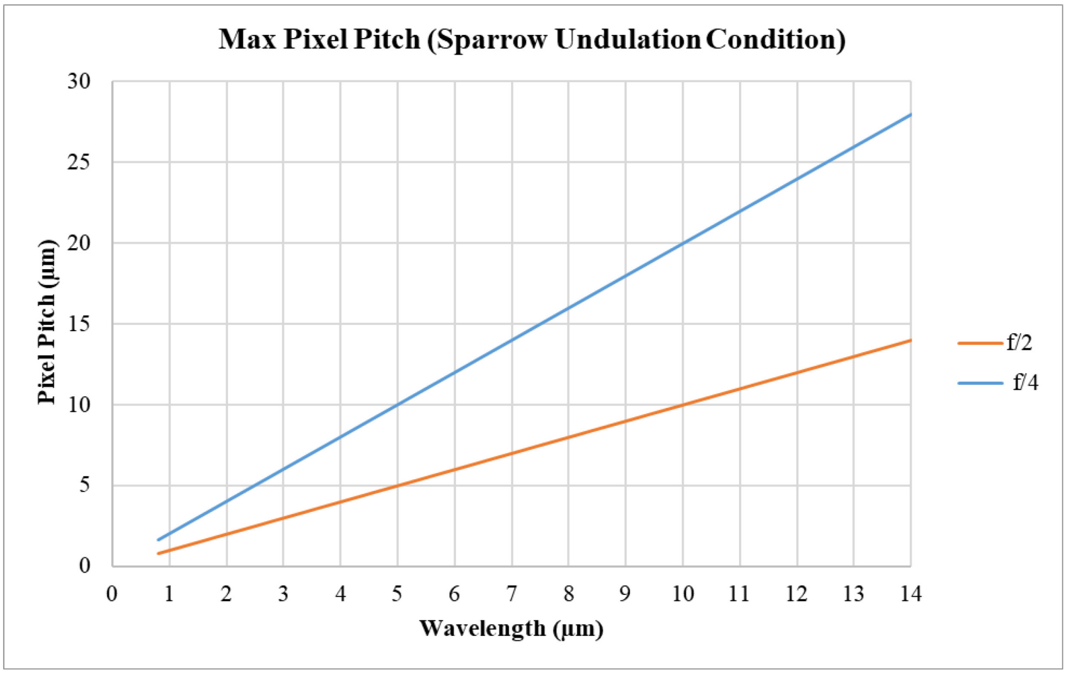

Figure 2: The maximum pixel pitch that defines the diffraction limit as a function of wavelength (for two common aperture sizes).

1.2 MWIR in IR-Imaging Applications

MWIR imaging, in clear and warm (i.e. ~290K+) conditions offers the best outright target detection range in either day or night. MWIR has a very high peak transmission at around 4µm (as shown in Figure 1)– which, over long distances provides much higher transmission thought the atmosphere, as shown in Figure 3. The high peak transmission can be a disadvantageous when there is either direct sunlight in or near the FOV (solar dazzle), or being reflected off nearby surfaces (glare/clutter), as this can 'dazzle' MWIR systems if the detection waveband around 4µm is used.

Applying Wien's law, high temperature exhaust emissions from rocket or jet plumes typically have peak emissions in MWIR, making them much easier to detect in the MWIR compared to other IR wavebands.

In warm terrestrial scenes, the MWIR band offers the greatest contrast relative to the amount of incoming flux, which means, in situations where a detector is limited by the CHC (charge handling capacity), then a better NETD (Noise-Equivalent Temperature Difference) can be obtained in the MWIR compared to the LWIR (as shown in Table 1). Being CHC-limited is common in small-pitch analogue ROIC detectors, due to physical space limitations for integration capacitors in the pixel circuit. The high contrast also can also make target identification easier against backgrounds of a similar temperature, such as mountains or hills.

1.3 LWIR in IR-Imaging Applications

LWIR offers much more photon radiance than MWIR and SWIR for a standard 300K scene, and subsequently offers the best NETD in stare-time limited applications due to the diminished shot-noise contribution, relative to MWIR. At colder temperatures (arctic environments), LWIR will often be advantageous over MWIR and SWIR systems as their relative fluxes flux diminishes rapidly below 300K.

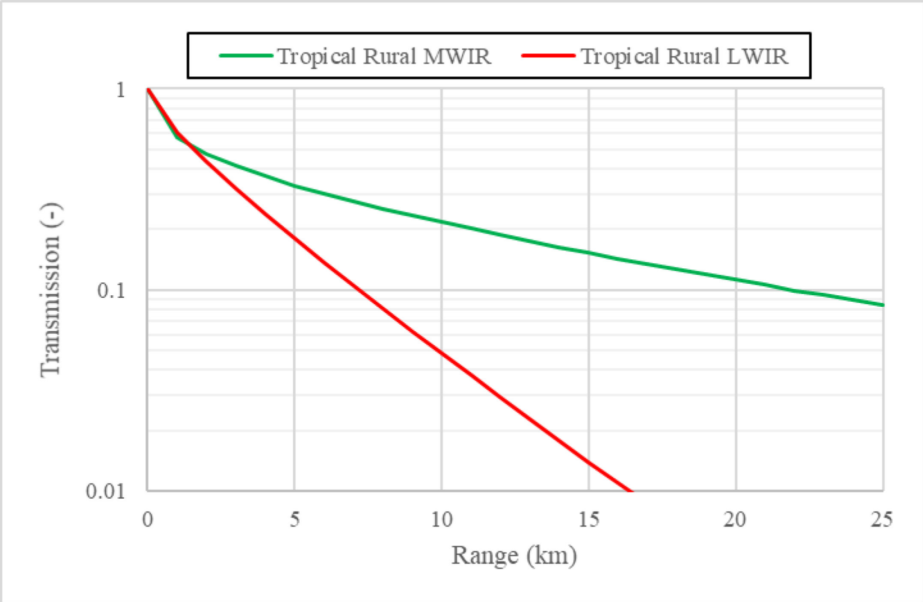

Figure 3: Atmospheric Transmission vs range in MWIR and LWIR in clear. tropical rural conditions (Via MODTRAN).

Table 1: Photon radiance and differential photon radiance (contrast) across SWIR, MWIR and LWIR bands for a temperature of 298K.

	SWIR 0.9-2.5µm	MWIR 3-5µm	LWIR 8-14µm
Photon Radiance (Phot/sec/m2/Ster)	9.13 x 1015	3.89 x 1019	2.92 x 1021
Differential Photon Radiance (Phot/sec/m2/Ster/K)	6.25 x 1014	1.42 x 1018	4.40 x 1019

LWIR radiation is also much more effective transmitting through smoke, fog and dust when compared to MWIR and passive SWIR. A review by Richardson and Driggers [3] showed that when high turbulence is present, the ID range of MWIR degrades more rapidly than LWIR, and in some cases, LWIR can surpass the performance of MWIR when high atmospheric turbulence is present.

2.0 DUAL BAND DETECTOR TECHNOLOGY AT LEONARDO UK

If only one thing can be summarised from the previous section, it is that the environment an imaging system is operating in has a significant bearing on the optimal waveband of choice. It is common for a system to incorporate multiple, independent IR detectors to be able to adapt to dynamic environments – to ensure the best possible performance without compromise DWB detectors are an attractive option, as single detector solutions will typically offer size, weight, power and cost benefits on comparison.

DWB detectors grown by Leonardo UK use a back-to-back diode structure, allowing for perfect spatial coherence between wavebands. Figure 4 give detail of such a diode arrangement, by using a dual-polarity ROIC – either waveband can be utilised by changing the bias direction across the diodes.

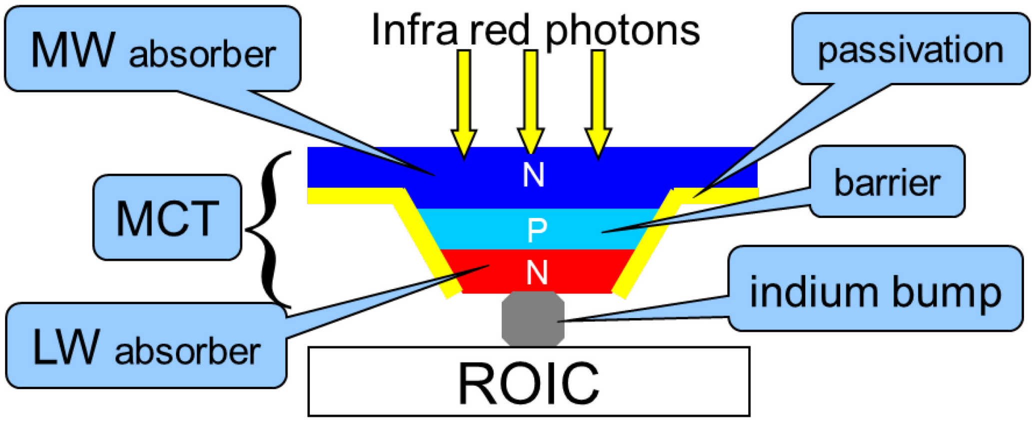

Figure 4: A MW/LW DWB pixel arrangement with back-to-back diodes.

Leonardo has published several papers on DWB technology, most commonly with MW/LW configurations [3] which allow for the longer detection ranges offered by MWIR along with the atmospheric robustness of LWIR.

Passive/active SW/MW [4], [5] are another configuration that enables thermal and 3D BIL capability in a single system

MW/MW [6] overcomes the issues highlighted in section 1.2 with solar clutter, whereby the 'red' and 'blue' portions of the MWIR range (essentially either side of the 4.3µm CO_2 absorption band) can be assessed independently to assess the source of MWIR radiation. This is advantageous in machine-vision missile-warner systems, whereby solar sources of MWIR radiation can cause false alarms.

The flexibility of the MCT MOVPE process means that the same growth reactor can be re-configured to make all the structures mentioned above, and others, whilst allowing for tight control of respective wavebands. Leonardo UK can be grow all these structures on low-cost GaAs substrates.

2.1 Developments of 12µm MWIR/LWIR DWB Arrays

The development and rationale of moving to smaller pitch MWIR/LWIR devices is summarised in extensive detail in [7]. Further updates made throughout 2022/2023 have been made on the 12µm pitch, 1280 x 1024 pixel MWIR/LWIR DWB arrays – and the top-level results are presented in Table 2.

Table 2: Comparison of 2022 results on 12µm MWIR/LWIR DWB Arrays versus 2023 results, the 2023 results are underlined in bold text.

Waveband (µm)	Integration Time (ms)	$NETD/NETD_{BLIP}$	Defects (%)	Signal Efficiency (%)
MWIR (3.7-5)	16.5 / **12.3**	1.20 / **1.20**	1.78 / **0.22**	47.0 / **52.0**
LWIR (8-9.4)	0.70 / **1.00**	1.10 / **1.10**	0.33 / **0.82**	56.0 / **38.0**

The results indicate a significant improvement in the MW performance, with a near order of magnitude reduction in MW defects, and improved signal efficiencies in the MWIR region.

The LWIR performance has degraded slightly compared to the previous wafer iteration, but this is largely dominated by a shorter than anticipated spectral band, which naturally degrades the QE, and it is clearly evidenced in the measurements above. Despite this, the overall defects are still below 1% - and the changes to recover the spectral bandwidth are understood to further improve performance.

Tennant's rule 07 [8] is a popular method for estimating the dark current density limit for high performance MCT material, as a function of the material wavelength cut-off and array temperature; we can see that both wavebands have dark current densities comparable with rule 07 in Figure 5.

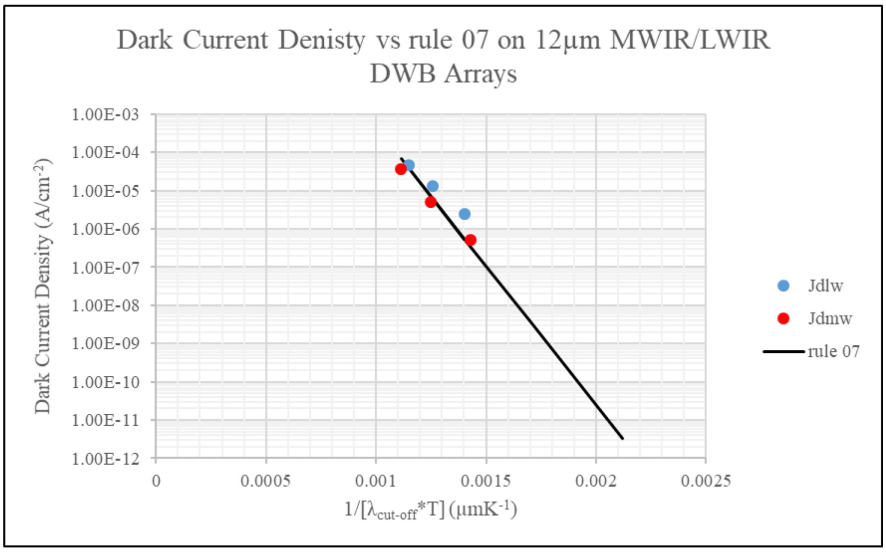

Figure 5: Dark Current Density measured relative to rule 07.

Leonardo UK are now manufacturing 12µm MWIR/LWIR DWB Arrays with sub-1% defects in both wavebands, which is considered to be one of the key performance benchmarks in-line with industry expectations. The latest growth iterations retain the ~3% MW into LW spectral crosstalk (for a 300K black body) that was measured on previous wafers. Figure 6 provides sample imagery from a demonstration camera unit; the subject is holding an acetate sheet that is transparent in the MWIR but opaque in the LWIR.

Figure 6: Sample imagery taken from a 12µm pitch, 1280 x 1024 pixel MWIR/LWIR DWB Demo Camera.

3.0 CHALLENGES & EMERGING TECHNOLOGIES FOR DWB SYSTEMS

The areas that pose the most challenges in creating performance-optimised DWB detector systems can be inferred from Figure 2 and Table 1.

Figure 2 shows that the smallest pixel pitch size for a diffraction-limited system will require a different aperture f/# or pixel pitch that is directly proportional to the desired wavelength. A 5µm wavelength in the MWIR at f/4 will be diffraction limited to 10µm; but if the system also contained a 10µm wavelength LWIR component, then to approach the same diffraction limit the system needs to either have 20µm pixels, or require an f/2 aperture. There are a number of methods to solve this issue in a DWB system which have been adopted in various systems such as microscan, VAM (variable aperture mechanism) and fixed, spectrally selective filters [9], [10], [11]

Table 1 highlights the significant variance with respect to the number of incoming photons between wavebands. This poses challenges for the ROIC with DWB capability, as the optimal CHC for each operating mode can be very different. Digital Pixel ROICs (DPROICs) are one solution for this, they allow a significantly broader range of CHC's and thus can be 'tuned' to a particular IR waveband far easier than analogue ROICS, which require a large range of selectable capacitances to be programmed into a pixel circuit, which is challenging for small pitch pixel processes.

4.0 SUMMARY

The relative merits of imaging in SWIR, MWIR and LWIR were discussed – and the difficulty in relying on one IR waveband for optical performance. Back to back DWB structures, manufactured at Leonardo UK are also presented, giving spatially coherent pixels and two bandwidths within a single detector solution.

The latest developments on 12µm pitch DWB MW/LW arrays are also discussed, showcasing sub-1% defects in both wavebands.

5.0 REFERENCES

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