

Type II superlattice infrared detectors designed for space at IRnova

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ABSTRACT

In this paper, three types of infrared (IR) Type-II superlattice (T2SL) focal plane arrays (FPAs) with sensitivities in the extended shortwave IR (eSWIR, 1-2.5 μm), medium wavelength IR (MWIR, 3-5 μm) and long wavelength IR (LWIR, 8-12 μm) wavelength regions have been evaluated, all designed and validated for compatibility with space applications. Thanks to high material uniformity and mature fabrication performed on large sized wafers (4''), evaluation on large format FPAs have been performed for all wavelength bands - SXGA format (1280 $\times$ 1024, 10 μm pitch) in MWIR and LWIR and up to 2040 $\times$ 512 pixels, 15 μm pitch for the eSWIR detectors. In common for all these T2SL FPAs are the excellent uniformity (photo response non-uniformity, PRNU < 1-4%), state-of-the-art modulation transfer function (MTF > 60% at Nyquist), very good correctability featuring low residual fixed pattern noise (RFPN < 0.5 $\times$ NETD) and high sensitivity: NETD_{MWIR} < 25 mK (F/4, 16 ms, 130 K), NETD_{LWIR} < 39 mK (F/2, 0.55 ms, 70 K) and NEP_{eSWIR} < 3 fW/Hz^{1/2} (F/2, 1 ms, 190 K). With all of these performances combined, T2SL state-of-the-art imaging quality in both eSWIR and MWIR is presented, as well as a first impressive demonstration of SXGA format LWIR T2SL FPAs paving the way for high-volume production of robust T2SL sensors for space, covering wavebands from eSWIR to VLWIR.

Keywords: Infrared, eSWIR, MWIR, LWIR, T2SL, FPA, IDDCA

1. INTRODUCTION

Type-II superlattice (T2SL) material has proven to be an excellent platform for infrared (IR) focal plane arrays (FPAs), thanks to their design flexibility, high performance, excellent manufacturability and compatibility with both large FPA formats and high operating temperatures. The rapid progress of designs, fabrication processes and formats enabled by the T2SL technology has totally altered the infrared detector market, which today features numerous suppliers worldwide offering T2SL-based FPAs, Integrated Detector Dewar Cooler Assemblies (IDDCAs) and IR cameras for applications across different spectral bands [1].

Robust and reliable midwave infrared (MWIR, 3-5 μm) imaging sensors based on Type-II superlattice (T2SL) have been produced in large volumes at IRnova since 2014. These IR sensors have historically been designed for tactical applications, with state-of-the-art light-weight detectors (T2SL SWaP IDDCA < 250 g) and attractive solutions for security, surveillance and border control thanks to their long lifetimes, (MTTF > 50000 h). In recent years, IRnova has started to adapt its product portfolio towards the space industry, with radiation hard read-out-circuit designs and with T2SL IR sensing material, compatible with humidity and thermal environments typical for space integration and tolerant to proton radiation doses to which detectors are exposed in typical earth observation missions (up to 5E10 protons/cm²).

In this paper, we will give an overview of the wide range of high-performance, high-resolution, game-changing sensors available at IRnova, which can be utilized to improve capability, reliability and affordability for constellations of eSWIR, MWIR, LWIR and VLWIR sensors in space.

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2. eSWIR

In 2023, IRnova started their design of eSWIR T2SL detectors with cut-off wavelengths of 2.5 μm , triggered by the increasing need from the space community for manufacturable, large format sensors covering the extended SWIR region (eSWIR; 1-2.5 μm). High absorption QE, low dark current density and excellent uniformity were demonstrated already in the first fabricated VGA format FPAs [2] and since then the eSWIR T2SL technology has proven to be reproducible both in terms of material quality and FPA performance. The established fabrication processes for 15 μm pitch VGA format eSWIR FPAs, provided a great starting point for customization of eSWIR T2SL detectors for larger formats (2040 $\times$ 512 pixels on 15 μm pitch). Within the European Horizon 2023 project STEP (*Silicon and T2SL European collaboration for a non-dependent supply chain for large eSWIR FPAs*), all the building blocks needed for high yield manufacturing of these large format sensors have been established, including growth and manufacturing of photodiode arrays (PDAs) on 4'' wafers (**Figure 1a**), design and manufacturing of read out integrated circuits (ROICs) compatible with harsh space environments (**Figure 1b**) and fabrication of space prototype FPAs (**Figure 1c**). Validation of the performances of these space prototypes is currently ongoing, using test setups established for this purpose within the EU project STEP and the ESA funded project '*Industrialization of large format eSWIR T2SL FPAs*' (a.k.a. STEP FURHTER). Good uniformity and maintained good performances have been demonstrated also for these large format FPAs, which are also being validated for compatibility with elevated humidity, temperature cycling and radiation (proton radiation, heavy ions, etc), to prepare for future integration in space programs.

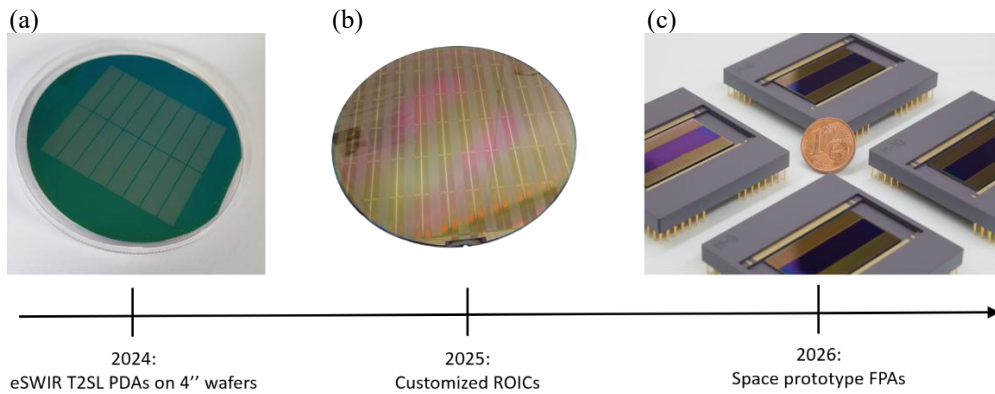


Figure 1. Major milestones achieved in the development of large format eSWIR T2SL FPAs: 1) Validation of eSWIR T2SL detector performances and transfer of PDA fabrication processes from 3'' to 4'' wafers 2) Design and fabrication of large format ROICs, customized for space applications 3) Hybridization and testing of space prototype FPAs.

In addition to space applications, there is also a strong demand for eSWIR T2SL for industrial applications, such as plastic sorting, laser profiling and military applications to see through fog and smoke. To meet these demands, IRnova has established an eSWIR T2SL product in VGA format (640 $\times$ 512 pixels on 15 μm pitch) – Balder, which is available both as FPAs (with T2SL hybridized to space-proven COTS ROICs), and as IDDCA modules with rotary Stirling coolers, which provide the most compact solution, as well as split linear coolers, featuring very low acoustic noise. Balder benefits from all the advantages of T2SL, i.e.:

- High sensitivity (**Figure 2a**)
- High uniformity as illustrated by the response map and the low PRNU and DSNU values extracted (**Figure 2b**)
- Excellent correctability and stability, meaning that with factory settings of the gain and a simple 1-point NUC, very low RFPN are achieved (**Figure 2c**)
- State-of-the-art MTF values of 60% at the Nyquist frequency (**Figure 2d**)
- QE above 70% in the 1.3-2.3 μm wavelength range (**Figure 2e**)
- Low dark current density of 0.3 $\mu\text{A}/\text{cm}^2$ at 190 K ((**Figure 2f**)

With statistics from the first 70+ Balder FPAs produced, very good reproducibility has been demonstrated with PRNU values consistently below 2% and the operability values above 99.8 % for all manufactured FPAs [7].

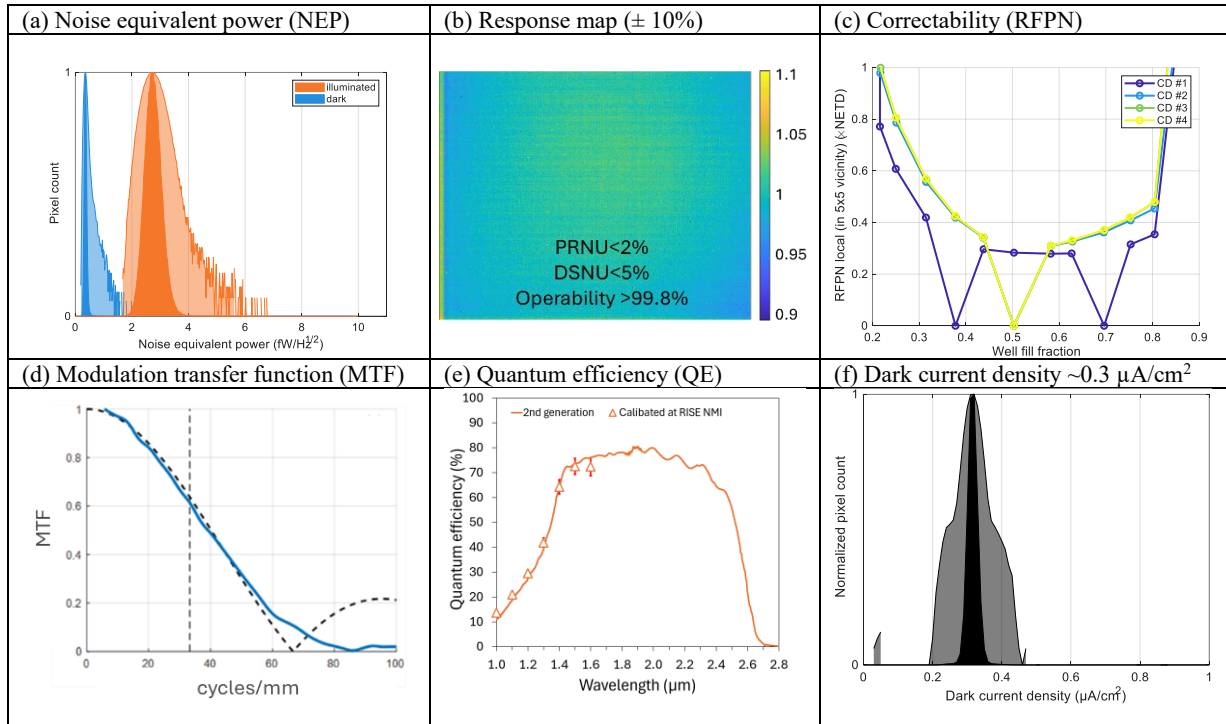


Figure 2. Measured performances of the Balder eSWIR T2SL FPA operated at 190 K, 1 ms integration time, showing: (a) NEP histograms plotted in linear scale (dark orange/blue) and log scale (light orange/blue), (b) Map of the optical response ($\pm 10\%$ contrast) including extracted values of PRNU, DSNU and operability (c) Residual fixed pattern noise, (d) Measured modulation transfer function (MTF) (solid line) compared to the ideal MTF (dashed line) for $15\mu\text{m}$ pitch FPAs, (e) Quantum efficiency $> 70\%$ (f) Dark current density histogram of an FPA.

The combination of high sensitivity, excellent uniformity and cutting-edge MTF of these sensors translate into excellent imaging properties as demonstrated in **Figure 3** with the 1st generation eSWIR T2SL FPAs integrated in Photon-etc's thermo-electrically (TE) cooled camera, Zephir-2.5e [3]. Images are taken for different scenarios, showing sharp outdoor imaging, demonstration of see-through-smoke capability as well as sensitivity in the near IR wavelength range ($< 1 \mu\text{m}$), using the light-source from an iPhone's face-id (**Figure 3**).

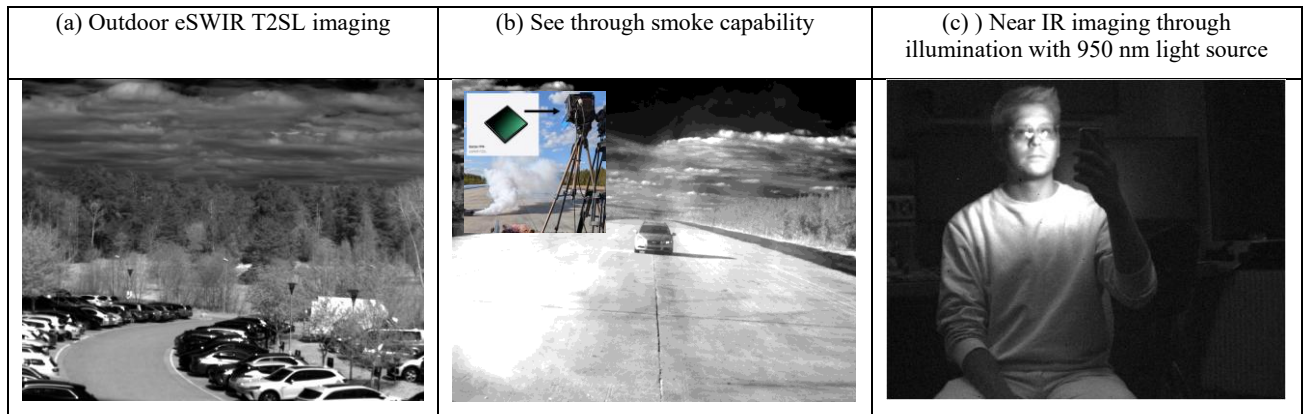


Figure 3. Infrared imaging with Balder eSWIR T2SL FPA fabricated by IRnova, when integrated in the TE-cooled Zephir-2.5e camera by Photon-etc, -80°C operating temperature, demonstrating (a) outdoor imaging, (b) see-through-smoke capability of eSWIR T2SL, showing the eSWIR scene and the corresponding visible scene in the inset (c) NIR imaging with the eSWIR sensor, demonstrated by illumination with an iPhone's FaceID ($\sim 950 \text{ nm}$).

3. MWIR T2SL – NJORD MW

IRnova's state-of-the-art detector for MWIR, Njord, is a high operating temperature (HOT, 130 K), SXGA format (1280×1024 pixels, 10 μm pitch) detector. This detector was developed in the ESA GSTP project 'High performance Type-II superlattice detectors' (a.k.a EuroSWAP) and is targeting both tactical and space applications. With respect to space compatibility, IRnova's MWIR T2SL material used for both Oden (HOT MWIR T2SL in VGA format) and Njord has proven to be tolerant to proton radiation up to fluences of 5×10^{10} protons/cm² in recent CNES R&T studies [4], demonstrating:

- 1) Maintained high operability (> 99.9 %)
- 2) Only minor degradation of dark current density and quantum efficiency (QE)
- 3) Full recovery of all performances after 7 days of annealing at ambient temperature.

Furthermore, for the design of the SXGA ROIC, specific design rules and manufacturing node were applied for radiation hard ROICs design.

Njord provides high sensitivity (Figure 4a), excellent spatial uniformity (Figure 4b) and state-of-the-art modulation transfer function (MTF = 60% @ Nyquist, thanks to the lack of crosstalk between the pixels (Figure 4c). All of these features combined, result in unprecedented imaging quality with true high-resolution imaging (Figure 4d). As illustrated in Figure 4e, this imaging quality and performances are maintained for long time periods without the need of recalibration, thanks to the detectors' good temporal stability. Even with several cool downs over a time period of 71 days, the RFPN values are maintained well below $1 \times \text{NETD}$, when only a simple offset correction is applied. This clearly demonstrates the robustness of this technology, which simplifies any on-board calibration procedure. When operating the detector at 130 K and 60 Hz, with an F/4 aperture, and a 3.6–5.1 μm bandpass filter, temporal and spatial NETD values stay below 25 mK and 6 mK, respectively.

Since the release of the Njord detector in 2025 [5], their operabilities have continuously increased thanks to the maturation of manufacturing of these large format, small pitch detectors and they are now consistently reaching operabilities above 99.9 % [6]. The non-operability criteria used to calculate this operability are: 1) Response deviations > ± 10 % from the local median, 2) Temporal NETD > 60 mK, 3) Spatial NETD > 40 mK, which are truly stringent conditions. Furthermore, thanks to high operating temperatures of these MWIR T2SL sensors, they can either be combined with compact rotary or split-linear coolers for low Size, Weight and Power (SWaP) applications (**Figure 4f**), or with very long lifetime (LLT) solutions when 24/7 operation is required (Njord LLT).

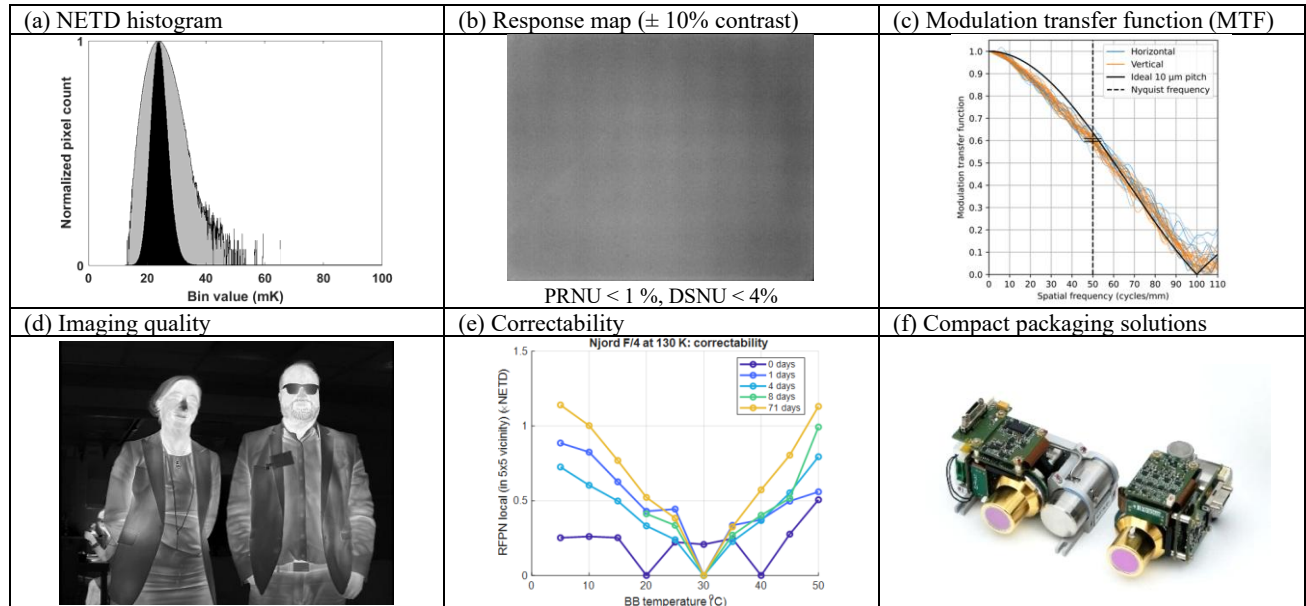


Figure 4. Overview of performances of IRnova's SXGA format HOT MWIR T2SL detectors - Njord at F/4, 130 K, including (a) NETD histogram plotted in linear (white) and log (grey) scale. (b) Response map, shown with $\pm 10\%$ contrast, (c) Modulation transfer function, with 60% MTF at Nyquist, (d) High resolution infrared image (e) Correctability with RFPN < $0.5 \times \text{NETD}$ in the 10-50 C range, with measurements repeated at 5 different cool downs over a time period of 71 days, with simple offset correction applied at the start up (f) SWaP T2SL IDDCAs with split-linear and rotary Stirling coolers.

4. LWIR AND VLWIR T2SL

Following the success of the Njord MW detectors, the family of SXGA T2SL detectors for space is now being expanded with development of SXGA format long wavelength IR (LWIR, 9.5 μm cut-off) T2SL and very long wavelength IR (VLWIR, 11.5 μm cut-off) T2SL FPAs. Thanks to the versatility of the ROIC designed for Njord with two gains (1.5 Me- and 5 Me- capacitors) and the compatibility with both p/n and n/p polarities, it is compatible also with LWIR and VLWIR T2SL material. IRnova's first 10 μm pitch SXGA format LWIR T2SL FPA was demonstrated in early 2026, showing very promising results, with high absorption (35 % absorption QE in single pass), low dark current density and with first sharp images collected in a lab setup [7]. Since then, additional evaluation has been performed to estimate the performances of these FPAs. From spectral measurements performed on PDAs hybridized to fanout boards, the spectral QE has been extracted (read and black solid lines in **Figure 5: Measured spectral QE for LWIR T2SL SXGA FPA with and without ARC, compared to absorption QE.** **Figure 5**). Without ARC, strong Fabry-Perot oscillations are observed, with QE values ranging from 50 to 20% peak-to-valley. With ARC tailored for broadband transmission deposited on the FPAs, the oscillations are dampened as expected and the QE values at long wavelengths ($\sim 9.5 \mu\text{m}$) slightly increased. The external QE measured is, however, not as high as expected from the high absorption QE in the material (dotted line in **Figure 5: Measured spectral QE for LWIR T2SL SXGA FPA with and without ARC, compared to absorption QE.** **Figure 5**), which indicates that a too short diffusion length of charge carriers in the detector limits the collection efficiency. Design and growth optimization is currently ongoing to enhance the collection efficiency in the detector, to fully benefit from the high absorption in the T2SL material.

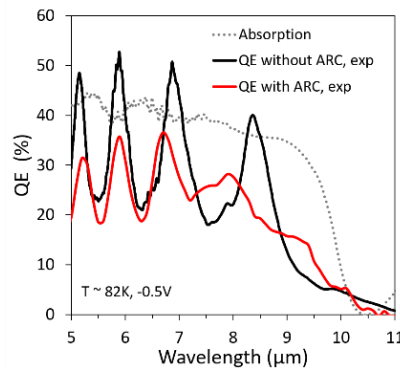


Figure 5: Measured spectral QE for LWIR T2SL SXGA FPA with and without ARC, compared to absorption QE.

From initial evaluation of the FPAs at 70 K, the following performances have been extracted:

- **Sensitivity:** 39 mK temporal and 16 mK spatial NETD values, with F/2, 0.55 ms integration time.
- **Uniformity:** PRNU values of 4 % and DSNU values of 15 % (Figure 6a). Although these values are slightly higher than what is typically observed in corresponding eSWIR and MWIR T2SL detectors (Figure 2 and Figure 4), these are still good values considering that this is the first trial with 10 μm pitch SXGA format LWIR T2SL.
- **Correctability:** Low RFPN values are extracted ($< 0.6 \times \text{NETD}$), in line with the correctability properties observed for T2SL in MWIR and eSWIR (Figure 6b).
- **MTF:** Simulations predict MTF values close to 60% at Nyquist frequency, similar to measured performances for eSWIR and MWIR FPAs, showing the consistency of the T2SL technology (Figure 6c).

First imaging with these FPAs (Figure 6d) shows the great potential of LWIR T2SL technology, showing sharp imaging at an operating temperature of 85 K (F/2, 300 μs integration time), despite the non-optimized test setup used to collect the picture. Further improvement of both design and fabrication processes of these LWIR detectors is currently ongoing, including also an extension of the cut-off wavelength to 11.5 μm , to enter the very longwave infrared (VLWIR, 10.5-14.5 μm) region, meeting the needs of future space programs.

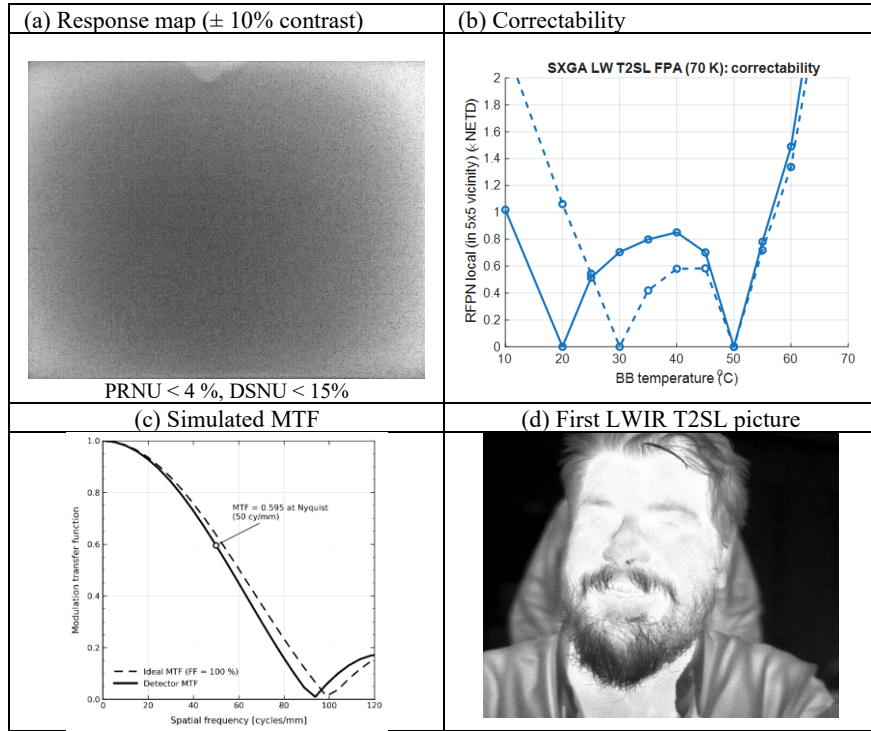


Figure 6: (a) Optical response maps with $\pm 10\%$ contrast, Operability $\sim 99\%$ (b) Correctability with $RFPN < 0.6-0.8 \times NETD$ demonstrated, for two different 2-point NUC conditions (c) Simulation of MTF for SXGA LWIR T2SL FPA with ARC deduced at $8.5 \mu\text{m}$, showing MTF of $\sim 60\%$ at Nyquist (d) First LWIR T2SL picture taken in a lab test setup at 85 K, 300 μs , F/2.

5. CONCLUSION

In this paper, the performances of T2SL FPAs covering three different wavebands, i.e. **eSWIR**, **MWIR** and **LWIR** have been summarized.

For eSWIR, space compatible T2SL FPAs (i.e. FPAs robust to protons, heavy ions, temperature cycling, moisture and long-term storage), sensitive in the $0.8-2.5 \mu\text{m}$ wavelength range have been implemented in two different formats, 640×512 , $15 \mu\text{m}$ pitch (VGA) and 2040×512 , $15 \mu\text{m}$ pitch (space prototype). Excellent performances have been shown repeatedly in production of such FPAs, including QE values $> 70\%$, PRNU $< 2\%$, MTF $> 60\%$ at Nyquist and great correctability (low RFPN), which all contribute to the excellent imaging quality observed with these detectors.

For MWIR, the state-of-the-art performances of SXGA format (1280×1024 , $10 \mu\text{m}$ pitch) detectors (Njord), with high sensitivity ($NETD < 25 \text{ mK}$ at 130K, F/4, 60 Hz), excellent uniformity (PRNU $< 1\%$), demonstration of long-term stability with maintained low RFPN over 71 days of testing and MTF values higher than 60% at Nyquist, which is a result of mature design and production of MWIR T2SL at IRnova for more than a decade. Also for these detectors, T2SL material and ROIC designs compatible with earth observation missions have been selected.

For LWIR, evaluation of IRnova's first LWIR T2SL FPAs shows maintained good correctability and anticipated high MTF ($\sim 60\%$ at Nyquist, extracted from simulations), resulting in nice high-resolution images. The uniformity (PRNU $< 4\%$) and operability ($\sim 99\%$) values are also competitive to other technologies, but slightly lower than for the more mature eSWIR and MWIR T2SL detectors. Optimization of the LWIR production chain, including T2SL design, growth and fabrication, is hence ongoing to reach the high performance significant for T2SL also in this wavelength band.

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