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NEW SWIR STARING ARRAYS FOR EARTH OBSERVATION SPACE APPLICATIONS AT LYNRED

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NEW SWIR STARING ARRAYS FOR EARTH OBSERVATION SPACE APPLICATIONS AT LYNRED

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ABSTRACT

LYNRED (formerly Sofradir) is a global leader in designing and manufacturing high quality infrared technologies for aerospace, defense and commercial markets. Its vast portfolio of infrared detectors covers the entire electromagnetic spectrum from near to very far infrared, especially thanks to a well-mastered wavelength tunable MCT technology.

Over the past 20 years, LYNRED has been involved in numerous space applications requiring SWIR detectors for Earth observation like atmosphere chemistry (such as TROPOMI instrument on-board Sentinel 5 precursor satellite) or hyperspectral imaging (such as PRISMA or HYSIS satellites). Most of these instruments used the well-known SATURN detector. These kind of missions are increasing and will keep growing in the near future in order to provide new measurement tools to control, measure and preserve our environment.

Pulled by this trend, the need corresponding to short wavelength infrared detectors is evolving in order to match with these mission's expectations. In particular, spatial and spectral resolutions of instruments are more demanding, resulting in requirements for larger detectors with better radiometric performances.

In this paper, we introduce our new generation of SWIR detectors answering future Earth observation missions. In the first part, we will describe the key requirements to be considered when developing infrared sensors for such applications. We will then present our dedicated space product line based on the mature NGP detector (1024x1024, 15µm pixel pitch) that is currently in production and the new COBRA detector proposed in two versions (COBRA-L = 1840x1112 and COBRA-S = 1380x640, 20µm pixel pitch). Their state-of-the-art features and main performances will also be detailed. Finally, examples of passive and active detector packages well adapted to these IRFPAs will be proposed.

Keywords: Space infrared detectors, MCT, SWIR, multispectral, hyperspectral, spectrometer.

1. INTRODUCTION

Space-based Earth observation missions, using satellites to monitor Earth's physical and chemical environment, have proven to be a fast, accurate and cost-efficient way to gather numerous and various data in order to enhance meteorological knowledge, weather forecast and climate change understanding. Each specific mission requests a unique payload where infrared sensors are embedded in panchromatic (black and white imagery), multispectral (acquisition of multiple images of a scene simultaneously at specific spectral bands), hyperspectral (acquisition of multiple images of a scene simultaneously in hundreds of continuous narrow spectral bands) or spectrometer instruments. These infrared sensors can operate in SWIR, MWIR, LWIR or VLWIR spectral bands, the former band being usually the preferred choice to provide the strong contrast needed for high resolution imaging solution or to measure pollution levels, greenhouse gases and aerosols in the atmosphere.

To address this SWIR Earth observation market segment, LYNRED developed in the early 2000 a first Infrared Focal Plan Array (IRFPA) detector named SATURN (1000x256, 30µm pixel pitch) that has been successfully used in numerous space missions like TROPOMI, PRISMA or HYSIS missions. A mid-format detector named NEPTUNE (500x256, 30µm pixel pitch) has also been derived and proposed in missions like Hayabusa, Chandrayaan or Spirale missions.

Technical requirements for these detectors evolved over the years and LYNRED started in 2011 the development of a new IRFPA named NGP (1024x1024, 15µm pixel pitch). This detector, validated in harsh space environmental conditions, is still in production and has been selected up to now for the Copernicus Sentinel-5, MicroCarb and CO2M missions. A detailed presentation of this component, including measured electro-optical performances, is proposed in this paper.

As the trend towards higher performances detectors continues, a new IRFPA development has been initiated in 2020. This large format detector named COBRA comes in two versions (COBRA-L = 1840x1112, 20µm pixel pitch and COBRA-S = 1380x640, 20µm pixel pitch) and perfectly matches the future needs of components featuring better spatial and spectral resolution as well as improved radiometric performances. More information about this detector are detailed in the next paragraphs.

Finally, different packages adapted to NGP and COBRA detectors are presented in the last paragraph. These products are proposed in passive version, an architecture composed of an IRFPA integrated on a baseplate with a detection cold wiring, or in active version, an architecture where the IRFPA is housed in a Dewar combined with a long-life low micro-vibrations pulse-tube cooler.

2. FROM SWIR EARTH OBSERVATION APPLICATIONS TO NGP AND COBRA DETECTORS

2.1 Two main kinds of applications

Earth observation applications can be splitted in two different categories: atmosphere and ground observation.

The main objective of atmosphere observation is to identify the structure of the chemical and aerosol composition of Earth's atmosphere. Most of the optical instruments operating in the SWIR spectral band and answering theses needs are based on a spectroscopy concept in order to analyze the atmosphere composition through infrared radiations that are absorbed by the different species. This kind of applications requests detectors that are large enough to cover the swath of the instrument and with radiometric performances compatible with a low level of infrared signals, an intrinsic characteristic of this type of applications. The TROPOMI instrument on-board Sentinel 5 precursor satellite as well as Sentinel 5 or more recently CO2M mission in the frame of the European Copernicus program are good examples of atmosphere observation systems.

Regarding ground observation, the main objective is to provide imaging services for a range of applications in agriculture, forestry or assessment of coastal zones evolution to name just a few. Two sub-categories can be identified according to the number of spectral bands that are used in the optical instrument: multispectral or superspectral applications and hyperspectral ones. While multispectral or superspectral applications correspond to space observation of Earth in a few number of spectral bands like in Sentinel 2 mission, hyperspectral applications correspond to Earth observation from space in hundreds of continuous spectral bands inside the overall SWIR spectral range. PRISMA or HYSIS missions are typical examples of SWIR hyperspectral missions.

2.2 Key requirements for SWIR Earth observation missions

Hyperspectral instruments provide images of the observed scene with a high number of continuous spectral channels and with a high spectral resolution (typically 10 to 15 nm) in the considered waveband. Thus, detectors used in these instruments are two-dimensional arrays with an adapted spectral response to fit the instrument waveband. Specific functions concerning the control of the detector are required. Among them, one can mention:

- A function enabling the selection of the lines to be output in order to remove the lines that are useless as they correspond to uninteresting spectral bands.
- A function enabling to select the gain of one line among the others.
- A rapid operation of the detector with typical frame rates as high as 150 Hz or even 200 Hz typically.

LYNRED developed its SATURN detector to satisfy these requirements and has acquired thanks to it a large experience in the field of SWIR detectors for hyperspectral applications.

Spectro-imagery instruments used for Earth atmosphere observation provide spectrograms of the observed scene with a typical spatial resolution of some kilometers. As an example, the CO2M mission contains an infrared spectrometer enabling to measure the quantity of CO2 in the atmosphere with a ground resolution of 4 km². Here also, the detectors that are used in these instruments are two-dimensional arrays with an adapted spectral response to fit the waveband of interest depending on the species that are observed. Some specific characteristics and performances are required at detector level to satisfy these applications:

- A high number of pixels in both directions of the array in order to meet the ground spatial resolution as well as the spectrogram required resolution.
- Stringent radiometric performances and in particular a very low noise of the detector correlated with an excellent linearity in order to provide a consistent operation of the detector being given the low flux levels that are generally encountered in these applications.

For this second category of applications, the SATURN detector has also been widely used like in TROPOMI instrument on Sentinel 5 precursor satellite or in 3MI instrument on Sentinel 5 satellite.

2.3 Next generation SWIR staring arrays for Earth observation

Anticipating the evolution of future SWIR Earth observation missions, LYNRED started the development of a new generation of SWIR staring arrays around 2011 with the NGP detector and more recently with COBRA. Figure 1 presents a chronology of these different developments with some examples of missions using each of these detectors.

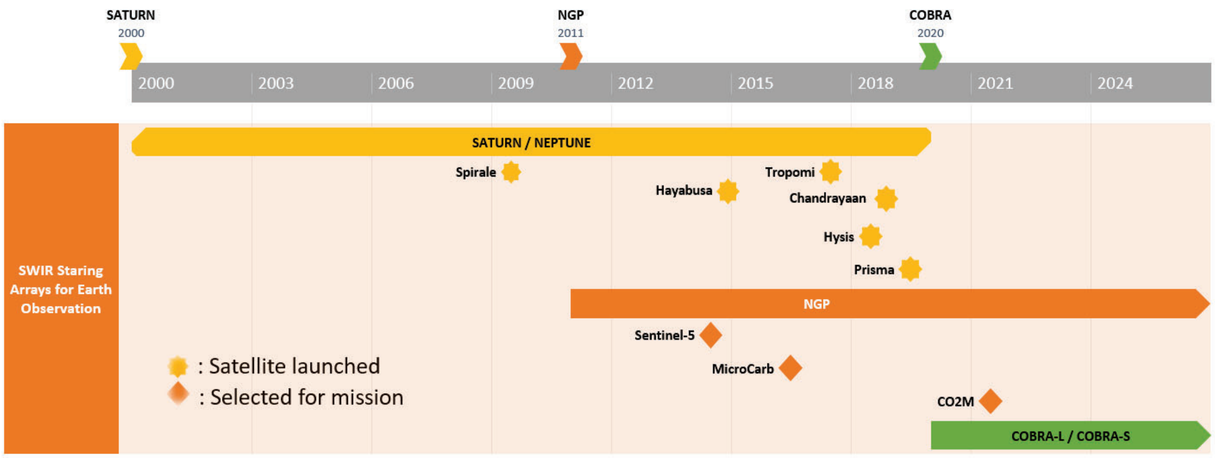


Figure 1. SWIR staring arrays development roadmap, including examples of mission using these detectors.

For these two next-generation detectors, the goal is to develop SWIR staring arrays answering most of the requirements for both hyperspectral and spectro-imagery applications described above. The main ones are highlighted hereafter:

- Enlarge the array format to $1k^2$ minimum and up to around 2k x 1k in order to provide more spectral channels and/or the highest spatial resolution / satellite swath.
- Define a pixel size between 15µm and 20µm with a trade-off on the functionalities implemented in the pixel in order to meet application’s needs in terms of radiometric performances.
- Provide a low noise and low consumption ROIC while the format of the detector is significantly increased compared to previous SATURN detectors generation.
- Ensure good electro-optical performances such as Photo Response Non Uniformity (PRNU), Dark current and Dark Signal Non Uniformity (DSNU) at operating temperature.

3. NGP AND COBRA SWIR IRFPA DESCRIPTION

3.1 NGP and COBRA IRFPA basic architecture and manufacturing process

As mentioned previously, two different NGP and COBRA IRFPAs are proposed by LYNRED for SWIR Earth Observation missions. Even if they differ in size and performances as we will see later in this paragraph, they both rely on the same basic hybrid structural architecture composed of a Detector Circuit connected with a Read-Out Integrated Circuit (ROIC) thanks to indium bumps as illustrated in Figure 2.

The Detection Circuit is manufactured by using LYNRED well-mastered wavelength tunable HgCdTe (Mercury Cadmium Telluride or MCT) technology: n-type photodiodes are formed thanks to a ion implantation process on a thin p-type MCT epitaxial layer that has been grown on a CdZnTe substrate, the IR sensitivity range being tailored to the desired wavelength range by adjusting the MCT layer material composition.

The ROIC on its side is manufactured by using a specific silicon CMOS foundry process and additional under bump metallization (UBM) post-processing steps to facilitate the flip-chip hybridization.

An anti-reflective coating in either single-layer (SLARC) or multi-layer (MLARC) version is finally added on top of the Detection Circuit to minimize the average reflectivity over a selected wavelength range.

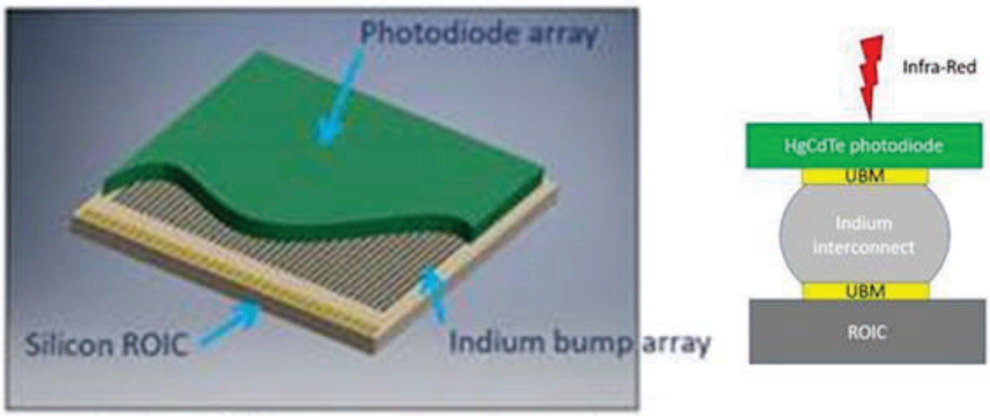


Figure 2. Basic hybrid IRFPA structural architecture.

3.2 NGP and COBRA Detection Circuits and related performances

The NGP and COBRA-L IRFPAs presented in Figure 3 are respectively 1024x1024 and 1840x1112 detection arrays with square-shaped pixel pitch of 15µm and 20µm. Designed for a targeted operational temperature around 150K, they both rely on the Detection Circuit and associated performances detailed hereafter.

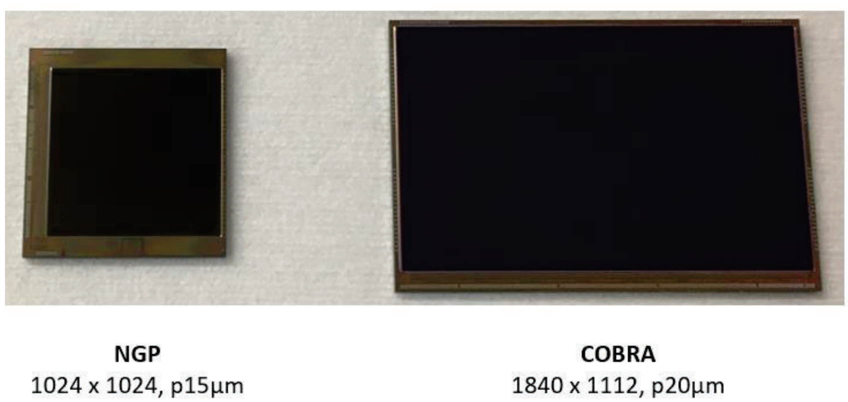


Figure 3. NGP (1024x1024, 15µm pixel pitch) and COBRA-L (1840x1112, 20µm pixel pitch) IRFPAs.

LYNRED has a strong experience with SWIR MCT technology and production that was gained through numerous flight models already delivered (more than 80 flights models have been shipped and ~50% of them have already been launched into space). Most of them use a 2.5µm cut-off material. NGP and COBRA detectors benefit advantageously from this highly mature technology building block and its associated heritage including space qualification. Figure 4 presents the typical spectral response of NGP and COBRA detectors with SLARC @150K.

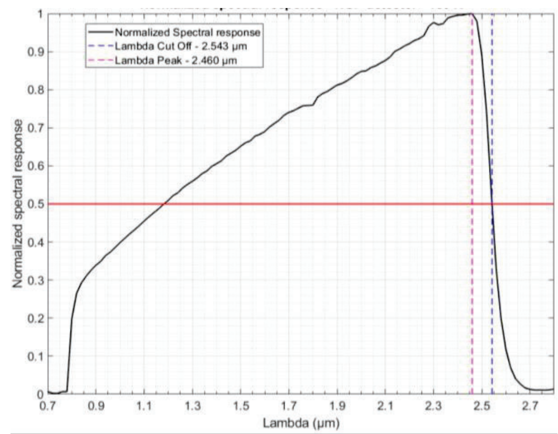


Figure 4. Typical normalized spectral response of a SWIR Detection Circuit with SLARC @150K.

Even if the dark current is generally less critical for SWIR applications compared to LWIR/VLWIR ones, its contribution to the global signal can be close to the minimum photonic flux and a monitoring of this performance remains necessary. The next figure illustrates the dark current density values as a function of the IRFPA temperature: we have ~2.4 10^{-3} fA/µm² at 150K.

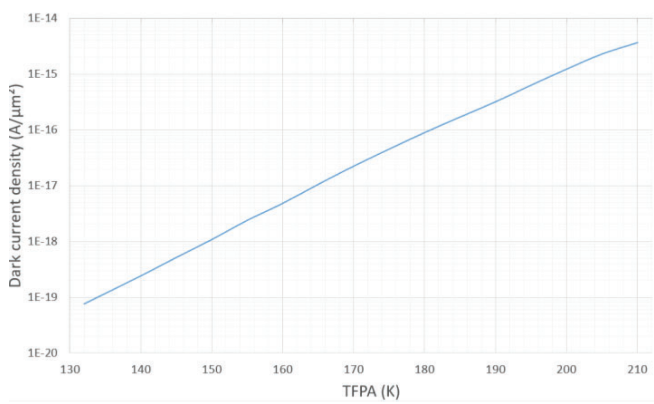


Figure 5. Typical Dark current densities of SWIR Detection Circuit vs operational temperature.

Spectral Detection Efficiency (SDE) is defined as the ratio of the amount of collected electrons over the amount of incident photons considering an ideal fully sensitive photodiode area (15x15 µm² for NGP and 20x20 µm² for COBRA). The figure hereafter illustrates the typical measured SDE evolution vs wavelength of IRFPAs including a ZnS quarter-wavelength SLARC added to minimize the average reflectivity and optimize the Quantum Efficiency. The typical PRNU is 1-3%.

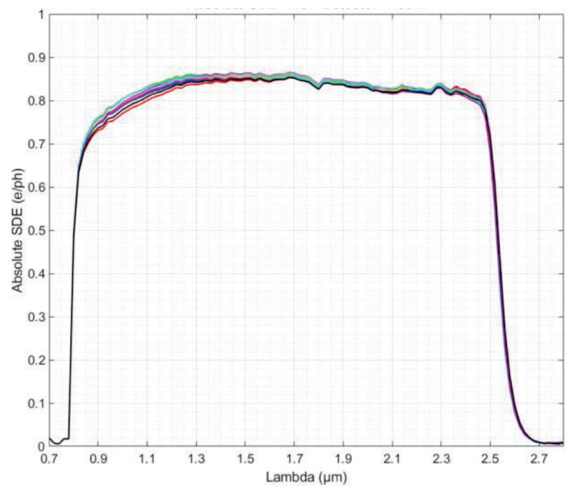
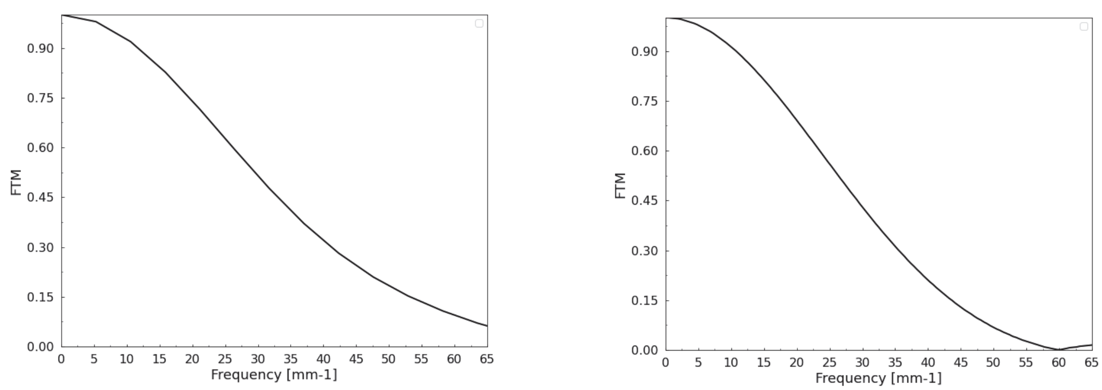


Figure 6. Typical measured Spectral Detection Efficiency at different positions on the IRFPA with SLARC (@150K).

Given the difference in pixel size between NGP and COBRA IRFPAs, the MTF which is a detector geometrical parameter must be analyzed specifically for each of them. The next figure illustrates typical MTF performances at the Nyquist frequency with the potential dispersion:

- For NGP, measured MTF values are higher than 0.45 at pixel level.
- For COBRA, evaluated MTF values from simulations and measurements are higher than 0.5 at pixel level.



NGP: 1024x1024, 15µm pitch   COBRA: 1840x1112, 20µm pitch

Figure 7. Typical MTF of NGP and COBRA detectors.

3.3 NGP's ROIC

The other key IRFPA subpart is the ROIC, the brain of the component that is needed to integrate the electrons generated by the detector, amplify the different signals and multiplex them. As explained in paragraph 2, a specific attention was paid to the architecture, functionalities and performances of the NGP ROIC in order to adapt the detector design to the targeted applications. In particular, the ROIC enables to provide the user with essential functions like integration while readout operation, line selection, non-destructive multi-reading… Its architecture, based on an advanced CMOS technology process combined with a radiation hardening strategy inherited from previous space programs, was defined to obtain the following characteristics and performances.

- Analog chain:
    - Photodiode biasing is done thanks to a CTIA (Capacitive TransImpedance Amplifier) input stage that converts the current from the photodiode to a voltage by using the ~650ke- conversion capacitance. This CTIA architecture provides a very good linearity and is well adapted to low flux conditions encountered in hyperspectral and spectro-imagery applications.
    - Currents of each photodiode are integrated simultaneously (snapshot mode), the reading of a frame can be made through IWR or ITR modes, with one reading or non-destructive multi-reading alternative that allows to perform several readings during one integration phase in order to improve the noise performance.
    - To limit the risk of blooming of the photodiodes, an anti-blooming system has been implemented to control the saturation level of the pixel output.
    - The ROIC has 4 analog outputs operating at up to 8 MHz.
- Digital chain:
    - The digital block generates the different internal signals necessary for the integration and readout sequence. The serial programming interface is also implemented into this block and uses a serial physical link (Serdat link).
    - The maximum master clock frequency is 8 MHz.
    - The Serdat link is used to set the requested configuration such as:
        - Line selection.
        - Power management of the input stages and video out amplifiers.
        - Integration time adjustment.
- Power consumption and noise performances:
    - The mean power consumption of the detector ROIC is 115mW for a pixel frequency of 3 MHz and nominal power management.
    - The typical readout noise, one of the key parameter to obtain good detector especially in low flux condition, is 140e- with an homogenous distribution as illustrated on the next figure.

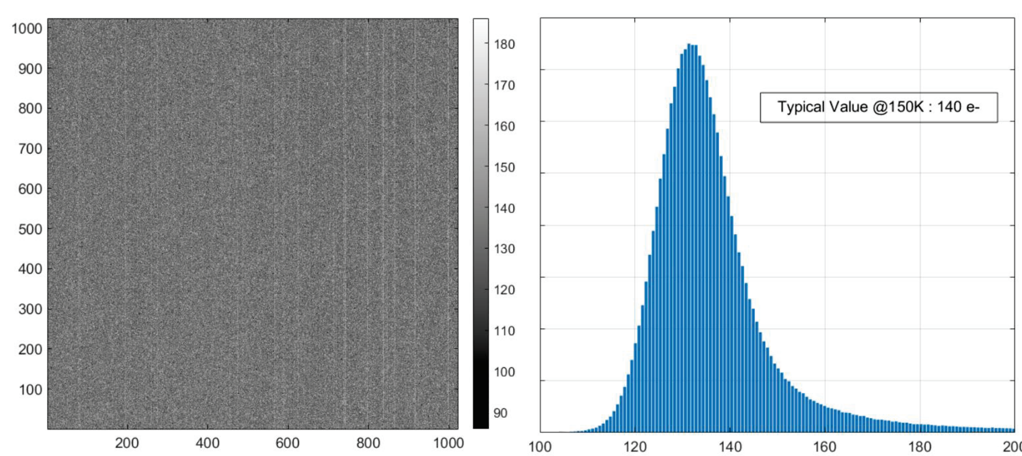


Figure 8. NGP ROIC noise cartography and histogram.

3.4 COBRA's ROIC

Anticipating the evolutions of future Earth observation missions, Lynred started the development of the COBRA detector beginning of 2020. This detector will provide another improvement step in order to fit new hyperspectral and spectro-imagery space missions. In particular, this detector will provide the following main features:

- A larger format with two possible configurations: 1380x640 (COBRA-S) and 1840x1112 (COBRA-L).
- A pixel pitch of 20µm enabling to propose a double gain configuration with one high gain and one low gain.
- A CDS (Correlated Double Sampling) function operating with the highest gain.
- A line selection function.
- A gain selection on a line by line basis.
- Improved ROIC noise performances.
- Several and configurable number of outputs enabling to adjust the detector configuration to each kind of missions needs.

As explained above, the COBRA detector is proposed in two versions in order to offer two different formats depending on the mission's needs. Of course, all functionalities and performances for both versions are strictly identical.

This ROIC architecture, based on an advanced CMOS technology process offering stitching capabilities needed to obtain a ROIC bigger than the reticule format, has been defined to obtain the followings characteristics and performances.

- Analog chain :
    - Similarly to the NGP ROIC, the analog chain is based on a CTIA (Capacitive TransImpedance Amplifier) input stage also. In order to offer a higher versatility with respect to space missions requirements and thanks to the choice of a 20 µm pixel pitch, two gains have been implemented. As a matter of fact, the detector presents two conversion gains depending on the conversion capacitance chosen among the two available: 120ke- (high gain) and 1.2Me- (low gain). In addition, the architecture also provides a CDS on chip functionality in high gain mode, a solution to further decrease the ROIC noise in case of use with very low fluxes like in atmosphere observation missions.
    - Currents of each photodiode are integrated simultaneously (snapshot mode), the reading of a frame can be made through IWR or ITR modes, with one reading or non-destructive multi-reading alternative that allows to perform several readings during one integration phase in order to improve the noise performance.
    - An anti-blooming system has been implemented to control the saturation level of the pixel output.
    - The ROIC offers two outputs mode: one with 8 analog outputs and one with 16 outputs for hyperspectral applications. Coupled to an operation up to 10 MHz, this 16 output mode enables to fit the need of high frame rates for hyperspectral applications.
- Digital chain:
    - The digital block generates the different internal signals necessary for integration and readout sequence. The serial programming interface is also implemented into this block and uses a SPI physical link.
    - The maximum master clock frequency is 10 MHz.
    - The SPI link is used to set the requested configuration such as:
        - Line selection and line inversion mode.
        - Power management of the input stages and video out amplifiers.
        - 8-16 outputs selection.
        - Gain selection + CDS mode.

- Power consumption and noise performances:
    - The expected mean power consumption for a focal plane temperature of 150K is 220mW for a pixel frequency of 3 MHz with 8 outputs mode. Considering an operation of the detector at 8 MHz, the power consumption is 260mW with 8 output mode. Finally, with 16 outputs and an operation at 8 MHz, the power consumption is 330mW.
    - The expected readout noise at 8MHz is 70e- in high gain without CDS (50e- with CDS) and 250e- in low gain mode.

On a programmatic point of view, the ROIC functionalities and performances at ambient and operational temperature have been successfully verified. The final validation of the IRFPA is now on-going in order to confirm its overall characteristics.

3.5 Overview of Key Parameters for NGP and COBRA IRFPAs

The Table 1 hereafter summarizes the key features, parameters and performances of both IRFPAs intended to SWIR Earth observation missions.

Table 1. Summary of key parameters for NGP and COBRA IRFPAs.

			COBRA	
		NGP	**COBRA-L**	**COBRA-S**
Spectral band (µm)		0.9 - 2.5	0.9 - 2.5	0.9 - 2.5
Format	Colums x Rows	1024 x 1024	1840 x 1112	1380 x 640
	Pixel pitch (µm)	15	20	20
Temperature (K)		150 typical [140-200] on demand	150 typical [140-200] on demand	150 typical [140-200] on demand
Detection Circuit Key Parameters	Lc @TFPA (µm)	2.5	2.5	2.5
	SDE	0.85	0.85	0.85
	PRNU (%)	1-3	1-3	1-3
	Idark density (fA/µm²)	$2.4\ 10^{-3}$	$2.4\ 10^{-3}$	$2.4\ 10^{-3}$
	DSNU (%)	15	20	20
	MTF (@Nyquist)	0.45	0.5	0.5
	Reflectivity mean (%)	8	8	8
ROIC Key Parameters	Functionalities	Snapshot integration, IWR/ITR/multi-reading readout/CDS modes (on chip for COBRA), line selection, anti-blooming		
	Pixel rate	8 MHz	10 MHz	10 MHz
	Number of outputs	4	8 - 16	6 - 12
	Charge Handling Capacity (CHC)	~650ke-	120ke- (high gain) 1.2Me- (low gain)	
	Readout Noise (TRON)	~140e-	~70e-, ~50e- with CDS (high gain) ~250e- (low gain)	
	Power dissipation	115mW @3MHz 125mW @7.5MHz	8 outputs: - 220 mW @3MHz - 260 mW @8MHz 16 outputs: - 330 mW @8MHz	6 outputs: - 120 mW @3MHz - 145 mW @8MHz 12 outputs: - 200 mW @8MHz

4. DETECTOR CONFIGURATIONS FOR SWIR APPLICATIONS

Different package architectures can be considered to accommodate NGP or COBRA IRFPAs and facilitate their integration at instrument system level:

- A passive version composed of a baseplate, offering appropriate mechanical and thermal interfaces, and a Detection Cold Wiring (DCW) composed by a flexible harness and a connector to insure the electrical interface with the driving electronics. Depending of the optical requirements, a specific cold shield as well as a window can be added: the cold shield limits the parasitic flux and provide a protection of the wirebondings used between the ROIC and the flex, whereas the window helps to obtain an hermetic solution.

  An example of a space-validated solution is presented in Figure 9. This detector package is based on a concept used in the LSTM NIRSWIR instrument and previously validated in the frame of METIMAGE mission. It consists of a Molybdenum baseplate and its associated DCW. This alternative is well suited to obtain versatile focal plane architectures illustrated in Figure 10 where several detectors are assembled in a staggered/butted configuration.

Figure 9. Example of a passive Detector Packages.

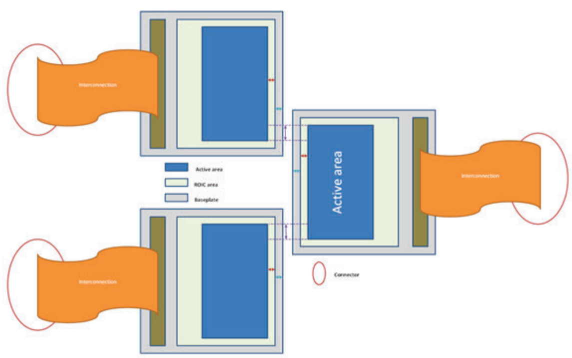


Figure 10. Illustration of a staggered/butted configuration composed of 3 Detector Packages.

- An active version where the IRFPA is housed in a Dewar combined with a Linear Pulse-Tube (LPT) cryocooler. Compared to previous SATURN detectors that were based on a traditional Linear Flexure bearing split Stirling (LSF) configuration, this LPT technology without any moving parts in the cold finger helps to reach an extremely long-life time and availability as well as low microvibrations.

  A product configuration, well adapted to integrate either NGP or COBRA IRFPAs, is presented in Figure 11.

Figure 11. Active Detector Package composed of a Dewar and a LPT cooler for NGP and COBRA detectors.

5. CONCLUSION

LYNRED has developed and manufactured for more than 25 years IRFPAs and Detector Packages dedicated to space applications. Based on a well-mastered wavelength tunable MCT technology and appropriate CMOS processes, two staring arrays named NGP and COBRA have been presented in this paper: they both propose state of art characteristics, high electro-optical performances and superior reliability that are fully aligned with the most recent and future space-based Earth observation missions requiring improved spectral and spatial resolution.

Examples of passive and active Detector Packages proposed in our product portfolio have also been detailed: their versatile architectures can be modified upon request to better fulfil any specific mission needs.

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