A High-Speed MWIR Uncooled Multi-Aperture Snapshot Spectral Imager for IR Surveillance and Monitoring

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***Abstract*—This work describes the development of a modular, compact and cost effective snapshot multi-spectral imaging camera in the short and mid-wavelength infrared (S/MWIR) range. The solution combines an array of six uncooled PbSe focal plane arrays (FPAs) with a multi-aperture optical arrangement, and it is endowed with embedded processing capabilities to perform computational imaging. The spectral imager performance allows high-speed multi-spectral video acquisition at a maximum rate of 1000 frames per second. With this approach, the aim is to provide a versatile and easily customizable device for different applications. To demonstrate the performance of the camera, high temperature measurements of a blackbody were carried out. Taking advantage of the spectrally resolved measurements, a procedure for increasing the dynamic range and sensitivity of the sensor is proposed. Combining the response from 4 detectors in different MWIR narrow bands, an increase of 60% in the dynamic range is obtained.**

I. Introduction

Infrared (IR) imaging has an increasing demand from different key sectors, specially due to increasing requirements on safety and security. In addition to defence applications, monitoring of civil infrastructures and advanced control of industrial processes are becoming a major area of application [1] [2].

The mid-wavelength infrared (MWIR) band has demonstrated unique capabilities for surveillance applications, providing better contrast than other IR regions and robustness to variable visibility conditions. It is the preferred band when inspecting high temperature objects [3]. Spectrally resolved IR imaging in the MWIR has the advantages of first a better-defined emissivity due to the reduced bandwidth. Second, it can drastically increase the signal-to-background ratio by only detecting signal changes in the relevant part of the spectrum. MWIR spectroscopy has a great potential for gas detection and identification, since most gases have unique absorption features in the spectral region between 3-5 microns [4].

The majority of the MWIR cameras require cooling, increasing the size and cost of the systems. The use of spectral band pass (BP) or narrowband pass (NBP) filters is the easiest way to perform spectrally resolved MWIR imaging [1]. Commercial cameras incorporate a filter wheel offering the possibility to mount several cold filters (with temperatures close to the detector temperature) between the camera lens and the detector, like the FLIR SC6000 or Xenics Onca family. The need of a cryogenic cooling system that contribute to size, weight, and power, together with the filter wheel that reduces the acquisition rate of multi-spectral IR images, are the major shortcomings of current sensors. The lack of affordable MWIR focal plane arrays (FPAs) has prevented the development of MWIR tools and the span of applications.

Uncooled IR detectors are an alternative solution to cooled sensors for a wide range of thermal applications, drastically reducing the size, weight, power and cost. To the best of authors knowledge, there are only two uncooled MWIR detectors reported in the literature [5], [6]. The first work describes a microbolometer detector, more suited for the LWIR band than for MWIR, while the second detector is based on a MWIR-optimized photomechanical sensor chip. New Infrared Technologies (NIT) offers a new type of uncooled PbSe-based FPA quantum detector for the MWIR range. Today, with microbolometers (LWIR 8-12 microns), NITs Vapor Phase Deposition (VPD) PbSe-based FPA is the only IR technology able to fulfill mass market requirements in terms of cost and production volumes. One of the unique features of NIT's PbSe-detector is the high speed acquisition, able to achieve up to 10000 frames per second (FPS).

In this work we describe the development of a SWaP-C (Size, Weight, Power and Cost) snapshot spectral imager for the MWIR range. The solution combines six uncooled PbSe-based FPAs from NIT, a multi-aperture optical arrangement, and it is equipped with embedded processing capabilities to perform computational imaging. To demonstrate the performance of the camera in a sample application, we have measured the temperature of a blackbody. Similarly to super-framing [7], and taking advantage of the multi-aperture, we propose a technique for enhancing the dynamic range of the camera by combining the response of the detectors in different narrow spectral bands. The dynamic range increased by 60%, with a resolution of $< 1^{\circ}C$ in the $[200-1000]^{\circ}C$ temperature range.

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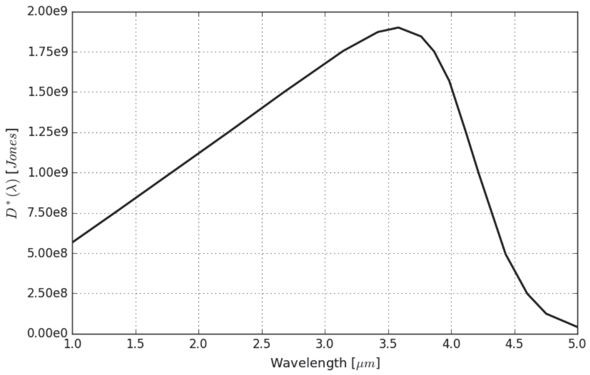


Fig. 1: PbSe typical detector response (specific sensitivity)[$D^*(\lambda_{peak})(500K, 1000H_z, 1H_z)$].

II. Multi-aperture sensor outline

In this section we outline the design of the multi-aperture spectral imager in the MWIR range. The camera was designed to fulfill the following requirements:

- Compact Size
- Low power
- Snapshot multi-spectral acquisition (up to 6 spectral bands in the 1-5 μm range through the use of specific filters)
- High speed data acquisition up to 1000 frames per second
- Integrated shutter for non uniform correction (NUC)
- USB-HS for power, control and data communication

A. PbSe-based FPA

NIT has a patent which develops an innovative process for the manufacture of uncooled MWIR detectors, through deposition of a polycrystalline material (PbSe) by thermal evaporation. The PbSe is known by its good high-temperature thermoelectric performance [8]. NIT's vapor phase deposition (VPD) technology is compatible with CMOS substrates which allows manufacturing even few detectors at a very low cost. The VPD-PbSe uncooled detector provides greater stability and allows high acquisition rates. The detector has good responsivity at room temperature in a wide spectral band ranging from 1-5 microns, with the peak around 3.5, allowing it to compete with other technologies in the SWIR band. Figure 1 shows the typical detector response. The main characteristics of the VPD-PbSe detector are:

- Uncooled operation at room temperature
- Detection in the 1-5 micron window
- No vacuum packaging required (lower manufacturing costs)
- Extremely fast and responsive (photonic)

NIT offers optimized electronic systems for each detector type. The multi-spectral camera is built based on the Tachyon 1024 μCore, an IR module designed for system integration with control and communications interface for the current generation of FPAs, see Table I.

TABLE I: Tachyon 1024 FPA specifications

Parameter	Value	Units
Model	Tachyon 1024	
Technology	PbSe	
Spectral range	1.0 to 5.0	μm
Resolution	32x32	pixels
Pixel pitch	135	μm
Package size	14.2 x 14.2	mm^2
Readout method	snapshot	
Frame rate	1000	fps
Digital resolution	14	bits
Power	$<$0.5	watts
Integration time	100-1000	μs
Data output	16	lines

B. Multi-aperture arrangement

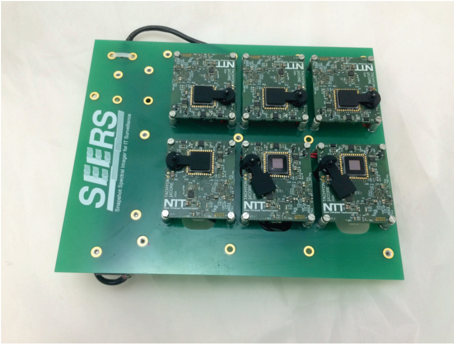
The multi-aperture camera module consists of an array of 6 Tachyon 1024 μCores mounted on a common board, with an enclosure supporting the front-plate that holds the optics. The use of specific filters in front of the optics are the basis of the spectroscopy operation. The geometrical arrangement of the module was defined to keep the distance between contiguous FPAs centres below 40 mm. This design was adopted for two reasons: to maintain an overall compact size and to be compliant with the requirements of super-resolution techniques [9] [10]. A specific circuitry was designed and implemented on the main-board with the objective of combining the 6 digital outputs into a single high speed USB port to plug on to the processor system. The main-board incorporates the electronics necessary for powering the 6 sensors. Figure $2a$ and $2b$ show the 6 PbSe modules mounted on the main-board and the front-plate supporting the optics.

C. Embedded processing module

To handle the high speed synchronized data acquisition and run computationally intensive image processing algorithms a powerful embedded board equipped with a graphics processing unit (GPU) has been integrated in the camera, the Nvidia Jetson TX1.

The software, running in the embedded system, is responsible for multi-camera control and management, data acquisition and transmission, and image processing. It was designed and implemented to achieve the following goals: synchronized acquisition from the 6 sensors at maximum data rate (1000 FPS), and to provide an efficient data flow enabling the implementation of processing algorithms achieving video-rate performance.

The aim is to provide an integrated and flexible solution delivering different image products depending on the application. The current processing chain includes basic preprocessing algorithms, such as fixed pattern noise (FPN) and non-uniformity correction (NUC) [11]. Advance computationally demanding image processing techniques, like super-resolution [9] [10], automatic determination of temperature and emissiv-



(a)

(b)

Fig. 2: (a) Multi-aperture module layout. (b) Optics front plate.

ity [12], feature extraction [4], band fusion [13] [14], and a digital lock-in amplifier to increase the sensitivity [15] are part of the ongoing work.

III. Temperature measurement

Robust temperature measurement of hot objects is one of the potential applications of the spectral imager. Accurate temperature measurement with thermography is based on emissivity. Unfortunately, the emissivity of an object is difficult to determine, since it depends on many parameters: material, surface structure, viewing angle, geometry (e.g. grooves), wavelength and temperature [1]. In practice, this material property is usually assumed known, guessing the emissivity from available tables for different materials, which may lead to erroneous results. One advantage of using spectrally resolved IR measurements is to better defined object emissivity due to the reduced bandwidth. Methods for temperature measurement combining the response at different wavelengths, without known objects emissivity and with emissivity varying during a measuring, have been used with pyrometers with good results [16] [12].

One limitation of the PbSe detector, and in general of any uncooled FPA, is the reduced dynamic range with respect to the large range of temperatures that can be present in a real scene. For instance, monitoring a plane propeller. A popular technique to increase the dynamic range of a photonic detector is called superframing. Superframing consists of varying the integration time of the camera from frame to frame in a cyclic manner, then combining the resulting subframes into single superframes with greatly extended dynamic ranges [7]. A drawback of the method is the reduction of the acquisition frame rate of the camera, inversely proportional to the sum of all the integration times. Besides, the PbSe detector is very sensitive to the integration time, only small range of integration times can be used without heavily degrading the SNR, which limits the application of the method. Alternatively, a similar effect can be obtain by combining the response at different wavelengths using narrowband pass filters [1]. This approach is the strategy adopted in this work. Thanks to the multi-aperture arrangement and the possibility of using several filters simultaneously, the method enhances the dynamic range while keeping the maximum FPS.

The most effective measurement for a particular temperature should be performed for the wavelength at which most intensity is emitted [3]. The electromagnetic radiation emitted by a blackbody in thermal equilibrium is described by Planck's law [3],

$$W_{\lambda b} = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda k_B T)}-1}, \qquad (1)$$

where k_B is the Boltzmann constant, h the Planck constant, λ the wavelength, T the absolute temperature in Kelvin, and c the speed of light in the medium. Figure 3a shows the distribution of electromagnetic radiation emitted by a blackbody at different temperatures. The higher the temperature of a body the more radiation it emits at every wavelength. The peak of maximum radiation intensity at a specific wavelength depends on the temperature; the higher the temperature, the shorter its wavelength. Formally, Wien's displacement law states that the spectral radiance of blackbody radiation per unit wavelength, peaks at the wavelength $\lambda_{\max}$ is given by:

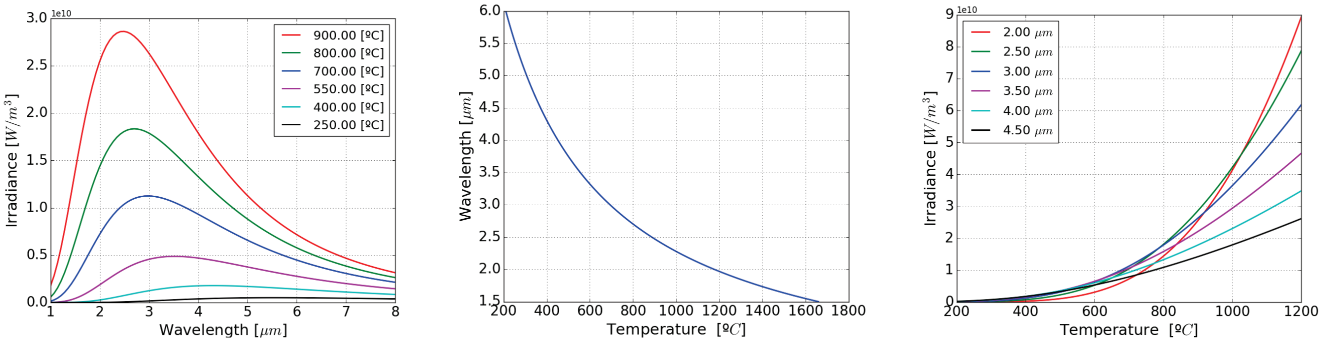
$$\lambda = \frac{b}{T}, \qquad (2)$$

where T is the absolute temperature in Kelvin and $b \approx 2.898^{-3} mK$ is the Wien's displacement constant.

Infrared measuring devices usually use either MWIR or LWIR. MWIR devices are used for high-temperature readings, while LWIR is used for ambient temperatures. In the same manner, the use of narrowband regions within a wide band, can increase the sensitivity at a specific temperature. The selection of the proper wavelength for the specific temperature must take into account both the theoretical irradiance at the given temperature and the detector response. Figure 3c, shows the electromagnetic radiation emitted by a blackbody at several wavelengths for the typical range of temperatures measured in the MWIR.

A. *Experimental Test*

To demonstrate the performance of the multi-spectral MWIR camera, we have measured the temperature of a cavity blackbody. Taking advantage of the multi-aperture approach, we combine the response of several detectors, using specific NBP filters, to increase the overall sensor sensitivity and



(a) (b) (c)

Fig. 3: (a) Planck's law accurately described a blackbody radiation. (b) Wien's law describes the shift of the peak of radiation in terms of temperature. (c) Theoretical radiation of a blackbody in thermal equilibrium at a specific wavelength in terms of temperature.

extend the dynamic range. We have considered 5 narrowband pass filters with central wavelengths at $2.00, 2.50, 3.00, 4.00$ and 4.50 μm, and a common filter bandwidth of 0.5 μm, keeping one aperture without filter. The integration time of the detectors was fixed to 500 μs. The multi-aperture module was placed in front of the cavity blackbody at a distance of 50cm. After image registration, the image-based measurements were performed on a small region of interest of 3x3 pixels, common to all the detectors.

First, we evaluate the response of the PbSe detector with no filter to the radiation of a blackbody at different temperatures in the range of $[150 - 982]$°C in steps of $50°$, Figure 4. The sensor shows a good linear response from $200°$ to $600°$C, but rapidly saturates beyond $600°$C. Figure 5 shows the sensors' response to the blackbody radiation for each wavelength. The response using filters at 3.00 and 4.00 saturate around $800°$. On the other hand, the curves at 2.00, 2.50 and 4.50 do not saturate the output of the detector for high temperatures, up to the maximum provided by the blackbody, but produce a low response, similar to the noise level, below $450°$. The 2.50 and 2.00 bands have the peak of radiation around 900 and $1200°$ respectively (see Figure 3b), which corresponds to the maximum sensitivity (slope of the curve) obtained with the PbSe sensor in these bands. The response in the 4.50 μm band, which is close to the cut-off band of the PbSe sensor (Figure 1), provides poor sensitivity for the whole range of temperatures as expected.

To increase the dynamic range of the camera, keeping a high sensitivity for the whole range, we combine the response of several sensors at different wavelengths. Figure 6(top) shows the detector sensitivity obtained for each wavelength vs the temperature, which helps us to identify which filter is more appropriate for measuring a specific temperature. The range of temperatures is divided in four intervals, ([200-500],[500-740],[740-910],[910-1000]), where the response providing the highest sensitivity are the associated to the sensors with: no filter, 3.00, 2.50 and 2.00 μm respectively. Combining

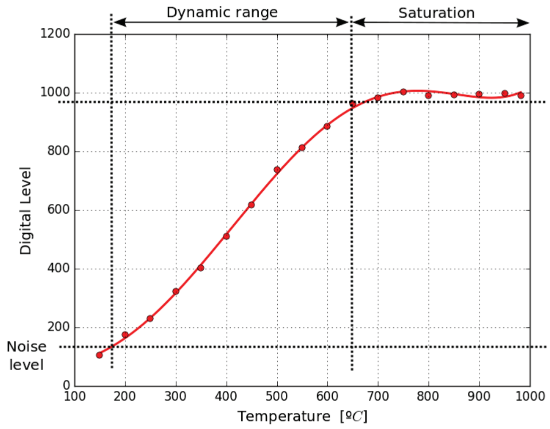


Fig. 4: PbSe-based sensor response to blackbody radiation.

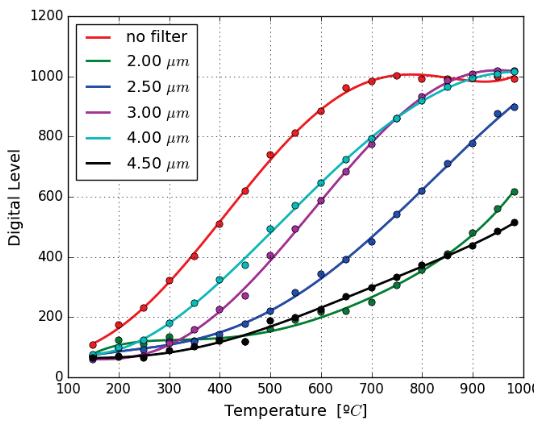


Fig. 5: PbSe-based sensor response with different narrowband filters.

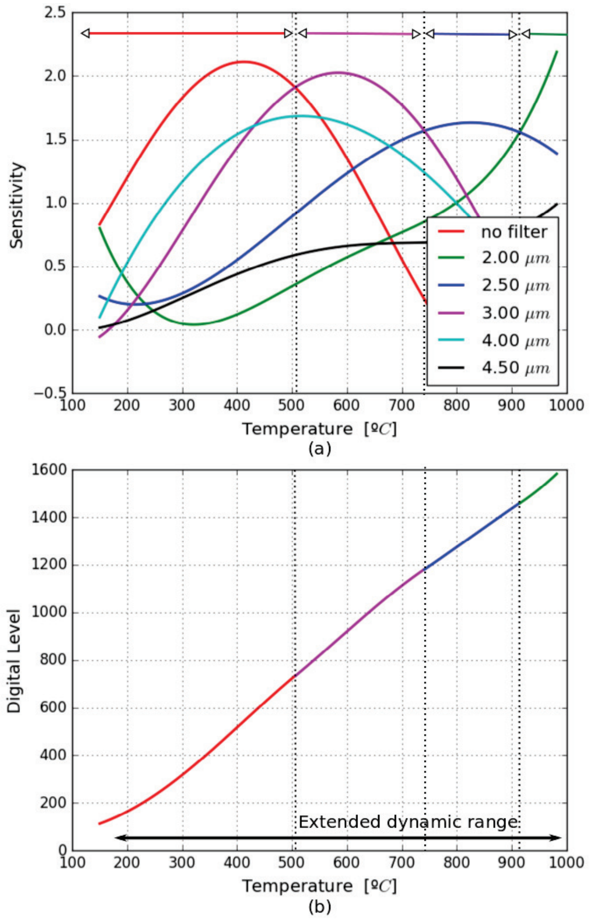


Fig. 6: Combined sensor response: (a) sensor sensitivity using different narrowband filters, (b) combined sensor response with extended dynamic range.

the output of these four sensors, we obtained the piecewise function in Figure 6(bottom). The combined response keeps a sensitivity higher than 1 in an extended dynamic range of [200-1000]°C.

IV. Conclusion

In this work we have shown the ongoing work in the development of a low cost uncooled multi-aperture spectral imager in the MWIR. The module comprises six FPAs with a multi-aperture optical arrangement. The sensor provides high-speed (1000fps) multi-spectral video. Potential applications include gas detection and identification, robust temperature measurement and industrial process control.

As an example application, we have shown the capabilities of the MWIR module for high temperature measurement. Exploiting the multi-aperture arrangement, we propose a procedure for enhancing the dynamic range and sensitivity of the camera, by combining the responses of several detectors using specific NBP filters. We show that combining the response of four sensors, one without filter and three with NBP filters at 2.00, 2.50 and 3.00 μm, we obtain an extended dynamic range of [200-1000]°C (increased by $\%60$) with high sensitivity. The procedure is extensible to higher temperature ranges using an appropriate selection of NBP filters.

While the current imager is based on the 1024 FPA detector from NIT, the next generation ROIC (2.5G), Tachyon 16K, will include several improvements over the previous generation: higher resolution 128x128 pixels, smaller pixel pitch 50μm, and better linearity on the integrator stage. Since both detectors have similar package size and digital interface, that will allow the replacement of the current detector by the new generation when it will be available.

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