DEVELOPMENT OF STATE-OF-THE-ART CHARACTERIZATION TEST BENCH FOR INTEGRATED DETECTOR DEWAR COOLER ASSEMBLY BASED INFRARED FOCAL PLANE ARRAYS

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ABSTRACT: Large format Infrared Focal Plane Arrays (IRFPAs) are envisaged to be used in ISRO's future remote sensing programs for multispectral and hyperspectral imaging applications. These IRFPAs consists of two dimensional (2D) photodiode array hybridized with high performance Read-out Integrated Circuits (ROICs). An Integrated Detector Dewar Cooler Assembly (IDDCA) is essential to characterize such IRFPAs at desired cryogenic temperature in lab conditions. In an IDDCA, the FPA sits over the cold tip of an active cryo-cooler and the detector cooler assembly is vacuum sealed in a thermally isolated Dewar. Characterization of such IDDCA based IRFPAs require tremendous expertise in the fields of optics, thermal, mechanical and electronics. A test bench is developed to characterize electrical, electro-optical, mechanical and thermal characteristics of IDDCA based IRFPAs. The setup is designed with a modular approach whereby the required equipments can be connected depending on the parameter to be measured. Major features of the developed test bench are: (i) FPA operating temperature and Cooler skin temperature control, (ii) Cooler cool down curve and thermal characteristics measurement, (iii) Generation of low noise tunable bias and programmable timing and control clocks for FPA operation, (iv) ROIC on-chip register programming for gain, integration time, frame rate and windowing control, (v) Multi-port video data digitization, (vi) Digital data acquisition and (vii) Online data processing. Validation of the developed test bench was carried out by characterizing a large format SWIR IDDCA where the FPA is operating at 150K. This paper gives design details and validation test results of the developed IDDCA characterization test bench.

1. INTRODUCTION

A detector is a prime element of an imaging system and its performance defines the major quality parameters of the image data produced. Detailed characterization of detectors is essential not only for selection of the most suitable detector from a range of those available, but also for assessing their usability in the imaging system. A detector characterization test bench is a system which facilitates testing and measurement of various performance parameters of the detector under different operating conditions (Jain, 2012). Characterization of first generation discrete element infrared detectors can be carried out in lab Dewar assemblies due to less number of interconnections associated with these detectors. Second and third generation infrared detectors consists of large number of small size pixels hybridized with high performance Read-out Integrating Circuits (ROIC), known as Focal Plane Arrays (FPA) (Rogalski, 2009). An Integrated Detector Dewar Cooler Assembly (IDDCA) is essential to characterize such large format FPAs at desired cryogenic temperature. In an IDDCA, the FPA sits over the cold tip of an active cryo-cooler and the detector cooler assembly is vacuum sealed in a thermally isolated Dewar. The IDDCA concept isolates the FPA from its surroundings thereby reduces thermal load on cooler cold finger which in turn enhances cooler performance. Characterization of such IDDCA based IRFPAs is quite challenging as it involves active cooler vibration and thermal management in both lab ambient as well as vacuum conditions. An indigenous test bench is developed to characterize various electrical and electro-optical parameters of IDDCA based IRFPAs. This paper gives design details and validation results of the developed test bench.

2. IDDCA CHARACTERIZATION TEST BENCH

2.1 SWIR IDDCA

The IDDCA test bench is developed considering the major requirements for operating the active cooler and IRFPA of a SWIR IDDCA custom developed by Sofradir for ISRO's upcoming space based Hyper Spectral Imager.

Photograph of the SWIR IDDCA is shown in Figure 1. It consists of a two dimensional array of 1000 x 256 pixels with pixel pitch 30μm sensitive in SWIR spectral band of 0.9μm to 2.5μm. The sensor array is hybridized to a Si Read-out Integrated Circuit (ROIC) which facilitates integration of photo-generated charge, charge-to-voltage conversion, signal amplification and multiplexing. Analog video output is available at four output ports. The FPA is operated at 150K temperature using a long life high reliability linear Stirling cooler from Thales cryogenics. A linearly variable Order Sorting Filter (OSF) is placed just above the FPA inside the Dewar to suppress the higher orders of incident radiation other than the desired one and maintain its spectral purity. A baffled tele-centric cold shield is also placed over the FPA inside the Dewar to restrict detector field of view and suppress any stray light. Both OSF and cold shield are attached to cooler cold finger and cooled to cryogenic temperature to minimize their self-emission.

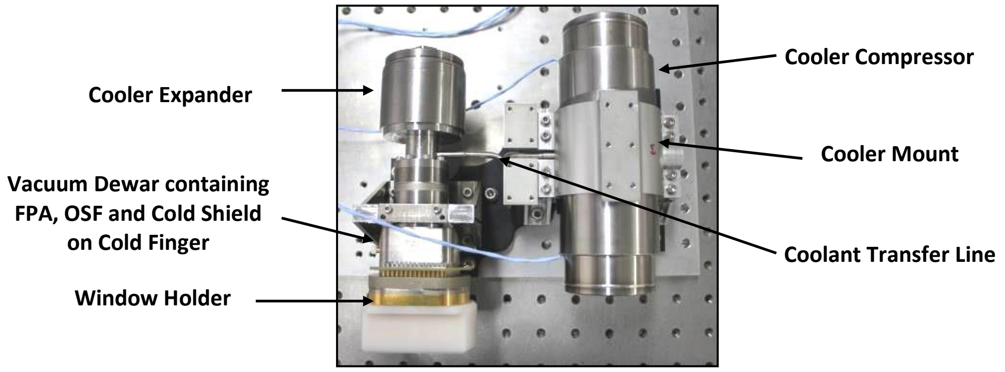


Figure 1 SWIR IDDCA

2.2 Test Bench Implementation

Test bench was developed to interface and power the SWIR IDDCA with cooler drive electronics and detector front-end electronics for characterizing cooler and FPA electrical and electro-optical parameters. Photograph of the developed test bench is shown in Figure 2 below.

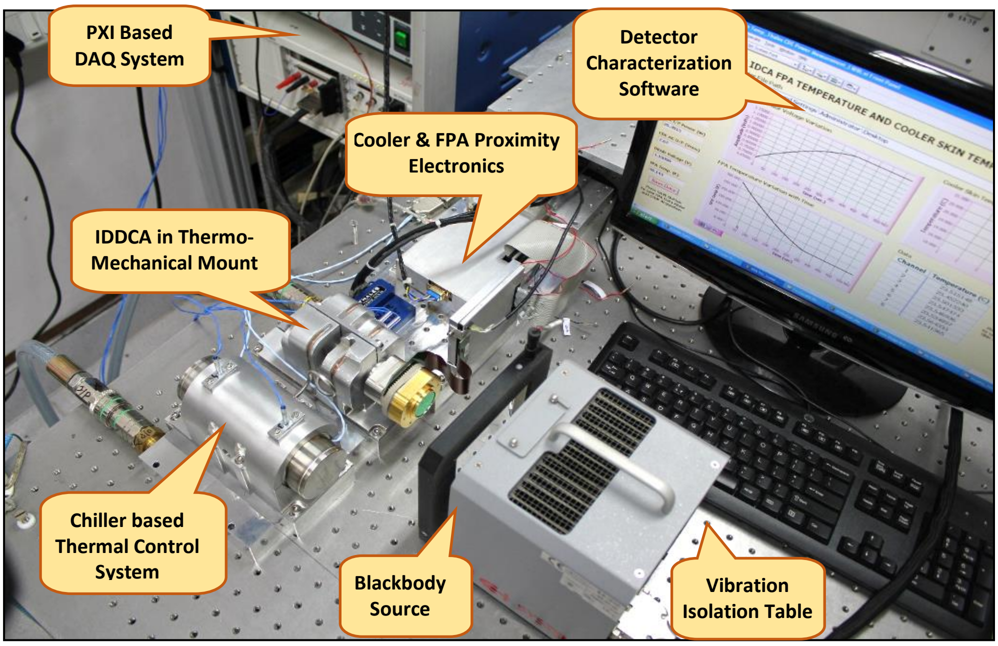


Figure 2 SWIR IDDCA Characterization Test Bench

As shown in Figure 2, the test bench consists of:

i. SWIR IDDCA held in a rigid thermo-mechanical mount
ii. IDDCA front end and processing electronics
iii. Cooler drive electronics
iv. Digital data acquisition system
v. Detector programming and characterization software

Description of each component of the setup is given below:

i. **IDDCA Thermo-Mechanical Mount:** The SWIR IDDCA is rigidly fixed in a mechanical mount and placed on a floating vibration isolation table. A few iterations in mount design were carried out to arrive at an optimum design to reduce cooler vibrations and have provision for thermal interfaces (mount design is out of the scope of this paper).

The motor inside an active cooler consumes electrical power to generate required cooling at the cold tip. Efficiency of a Stirling cryocooler is typically 5% to 8% which means most of the power consumed is dissipated in the form of heat. Cooler efficiency, life and vibrations generated depend on cooler skin and ambient temperature. A chiller based thermal control system with base plate cooling is developed to control IDDCA skin temperature during operation. A liquid coolant from the chiller circulates in a jacket / heat sink wrapped around the cooler parts and a Programmable Logic Control (PLC) inside the chiller senses and controls the coolant temperature through calibrated temperature sensors at its entry and exit ports. The thermal control system is developed considering following prime requirements:

- ✓ it should control the IDDCA skin temperature to $\leq$ 25°C in both cool down (peak power) and regulation phases of operation in lab ambient conditions,
- ✓ it should be flexible enough to avoid any stresses on IDDCA,
- ✓ it should not cause any condensation on IDDCA (especially on optical parts) during thermal control,
- ✓ it should not impart any vibrations due to coolant flow around the IDDCA,
- ✓ it should not cause any contamination and
- ✓ it should be corrosion and oil/lubrication free.

ii. **Front end and Processing Electronics:** The front end and processing electronics is interfaced with IDDCA through a 10cm. long flexi-rigid PCB. The flexi-rigid PCB contains socket pins for interfacing with detector pins. The front end electronics performs following functions:

– Provides low noise regulated biases and control clocks required for FPA operation.
– Facilitates FPA characterization at variable integration times, frame rates and read-out rates through serial programming.
– Receives FPA video signal available at four ports, digitizes the analog video signal and multiplexes the digital video stream.
– Provides interface for FPA temperature control and monitoring.

iii. **Cooler Drive Electronics (CDE):** The CDE consumes DC electrical power (+24V / 10A) and generates AC signal at a fixed frequency required for cooler operation. It uses a PID controller to control the FPA temperature to 150K +/- 1K in close loop using feedback from temperature sensor available at FPA. CDE has a ‘soft start’ feature where the cooler is provided with a low input power from CDE at the beginning, to protect the compressor from potential internal shocks at high power, followed by a ramp-up to the maximum power.

Two 2N2222 type temperature sensors are glued at chip carrier close to the FPA for FPA temperature control and monitoring. Both sensors are calibrated with different bias currents at different temperatures inside a lab Dewar and optimum sensor bias is arrived at considering drop at resistances in sensor read-out path. The CDE provides optimized bias current to temperature sensors to read sensor voltage and the sensor voltage can be converted to equivalent temperature using polynomial given in Equation (1).

$$T(K) = -642.51V_d^4 + 1826.8V_d^3 - 1959.2V_d^2 + 399.8V_d + 488.91 \quad (1)$$

where, ‘T(K)’ is the temperature in Kelvin and ‘V_d’ is the 2N2222 sensor voltage.

iv. **Digital Data Acquisition System:** The 14-bit parallel digital video data is acquired using National Instruments NI PXI 6541 high speed digital data acquisition system. The DAQ has 32 input channels and is capable of acquiring 1.8V, 2.5V, 3.3V and 5.0V TTL signals at a maximum rate of 50MHz. Detector generated synchronization clocks like frame sync and line sync are used for synchronizing data frames and for extracting useful pixel data from a frame. Multiple frame data can be acquired and stored simultaneously with the initiation of trigger pulse.

v. **Detector Programming and Characterization Software:** The detector programming and characterization software is developed in LABVIEW environment in the form of multiple Graphical User Interfaces (GUIs), as shown in Figure 3, for detector programming, process control, real time digital data acquisition, data processing and image display. The software facilitates programming various ROIC features like variable readout rates, variable integration times, bias adjustment, gain selection, row selection etc. by setting the fields of an on-chip serial control register through a serial programming link. It also facilitates digital data acquisition and on-line raw image and dark corrected image display.

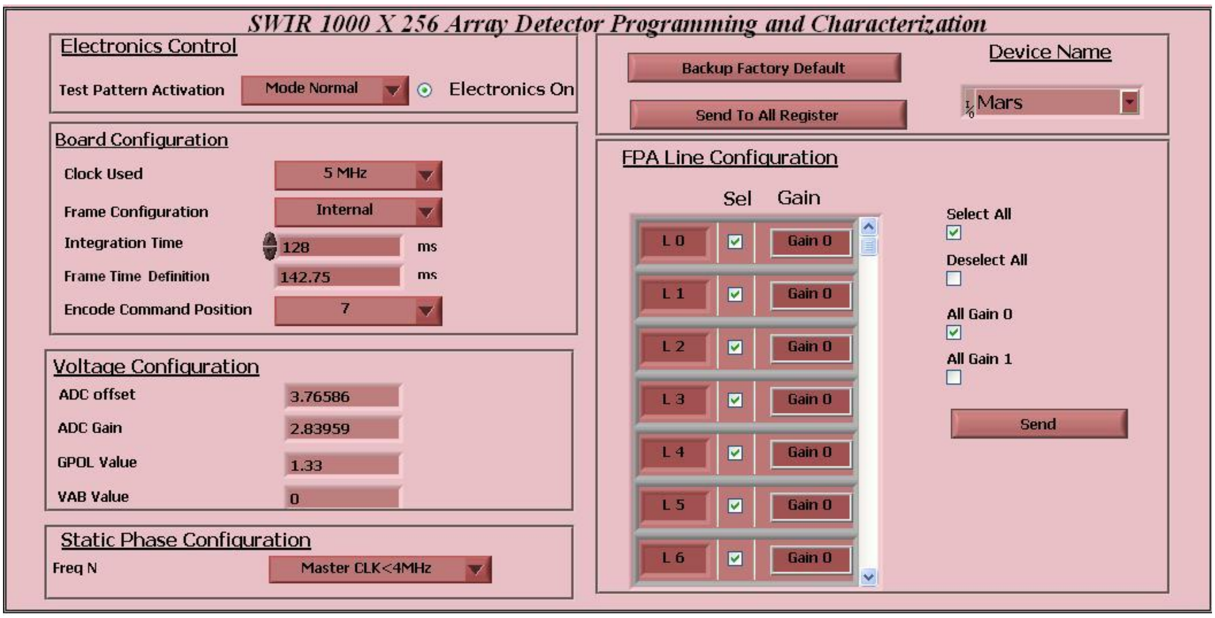


Figure 3 Screen Shot of Detector Programming and Characterization Software

2.3 Test Bench Configuration

The test bench is developed with a modular approach and it can be configured as per the parameter to be measured (Wilinsky, 1995). Broadly it is configured for following measurements:

- ✓ Test bench for cooler parameters measurements
- ✓ Test bench for FPA radiometric measurements
- ✓ Test bench for spectral response measurements

i. Test Bench for Cooler Parameters Measurement

The test bench is configured for measuring various cooler parameters like cooler AC input power, CDE DC input power, FPA operating temperature, FPA cool down time, cooler skin temperature at various locations etc.

CDE DC input power can be measured by sending serial commands to the CDE through RS232 port and reading instantaneous DC voltage and current. Cooler AC input power is measured using Tektronix TCPA300 current probe. A Hall sensor probe across the cooler cables senses the AC current flowing through the cables which is converted to voltage and amplified by the Tektronix amplifier. RMS value of both AC voltage and current and the phase difference between the two waveforms are measured on an oscilloscope. AC input power to the cooler is then computed by equation given in (2).

$$\text{Cooler AC power (Wac)} = \text{Vrms X Irms X Cos}\varphi \qquad (2)$$

where, Vrms = Cooler AC RMS voltage
Irms = Cooler AC RMS current
Φ = Phase difference between the voltage and current waveforms

Cooler skin temperature is monitored at 8 different locations on the IDDCA using YSI make 10K precision thermistors. All thermistors are connected through a harness to an 8-channel scanner card of Keithley digital multimeter. The multimeter is interfaced with PC through GPIB to read IDCA skin temperature. Photograph of the test bench for cooler power and skin temperature measurement is shown in Figure 4.

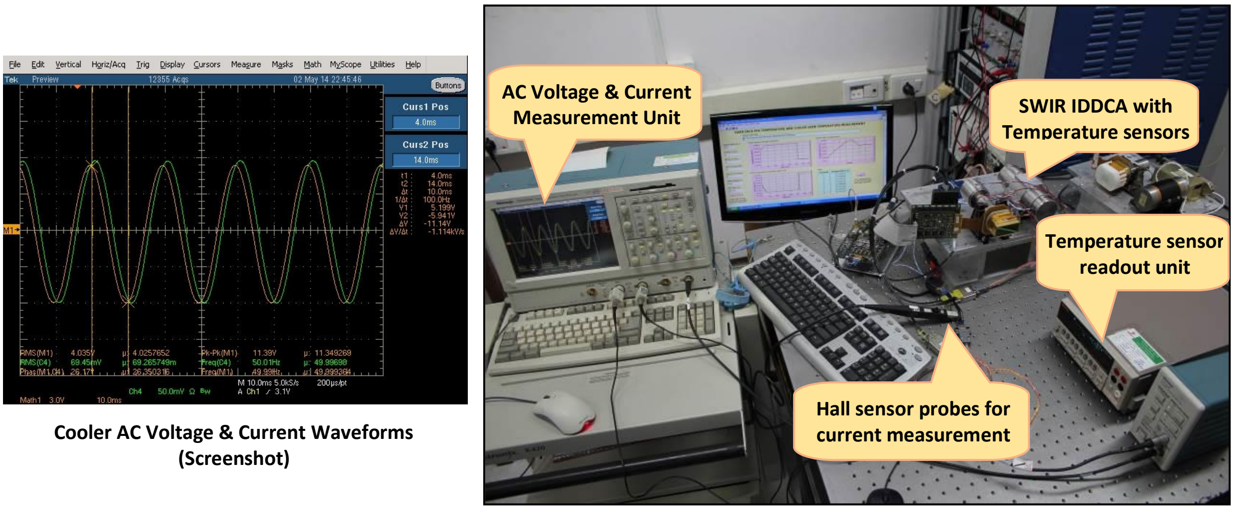


Figure 4 Test Bench for Cooler AC Power and Skin Temperature Measurement

ii. Test Bench for FPA Radiometric Measurements

The FPA radiometric test bench facilitates measurement of various FPA electro-optical parameters like dark offset, dark noise, signal-to-noise ratio (SNR), photo-response non-uniformity (PRNU), non-linearity etc. An extended area blackbody with 100 x 100 mm. aperture size is used as radiation source. The blackbody is able to reach +15°C to +100°C with a accuracy of 1mK and temperature stability of 10mK. Photograph of the FPA radiometric test bench is shown in Figure 2.

iii. Test Bench for Spectral Response Measurements

Spectral response measurement is important to find out in-band and out of band response of the FPA. For this a grating based double monochromator system is used to obtain a monochromatic light at required resolution. Tungsten halogen lamp is used as radiation source to cover the spectral range from 700nm to 2800nm. An IR collimator is placed at the exit port of monochromator to obtain collimated light covering the entire FPA. A standard pyroelectric detector is used to calibrate the source radiance. Photograph of the spectral test bench is shown in Figure 5.

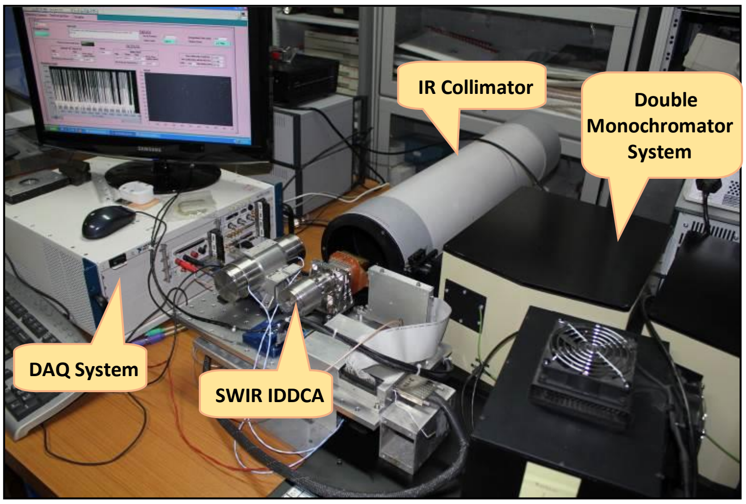
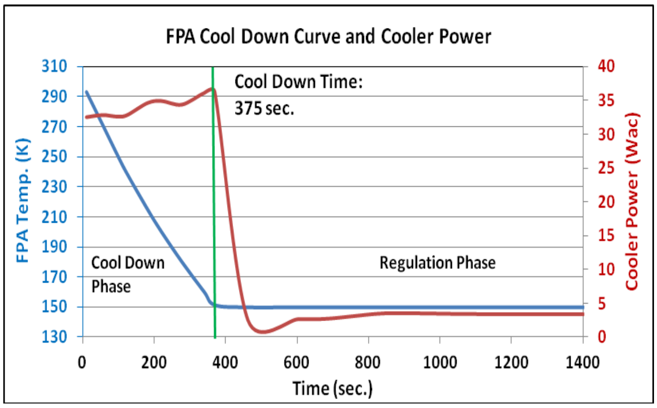


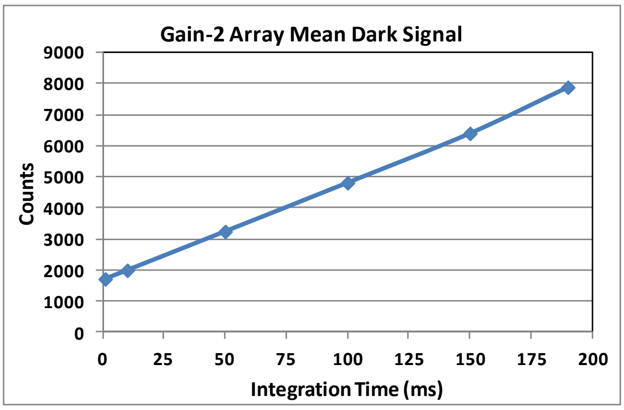
Figure 5 Spectral Response Measurement Test Bench

3. TEST BENCH VALIDATION AND DISCUSSIONS

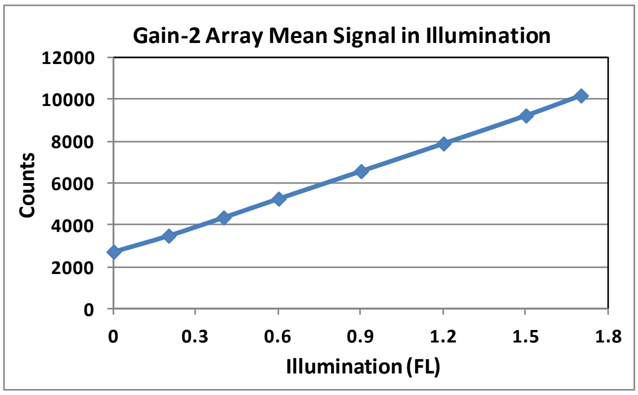
Validation of the developed test bench is carried out by characterizing a lab model SWIR IDDCA in lab ambient conditions. Various cooler and FPA parameters as described in section 2 were measured. Preliminary characterization test results are shown in Figure 6(a) to 6(e) below.



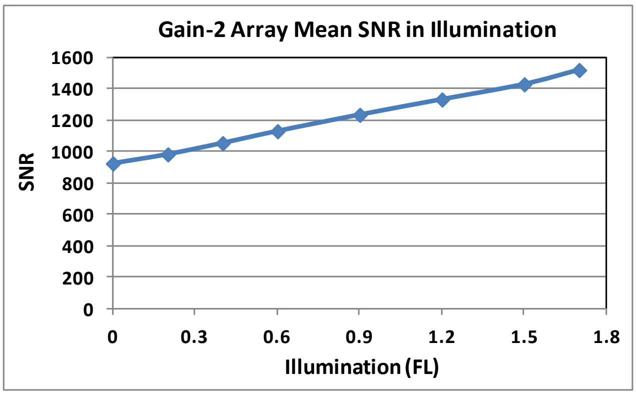
(a) FPA Cool Down Time and Cooler Power



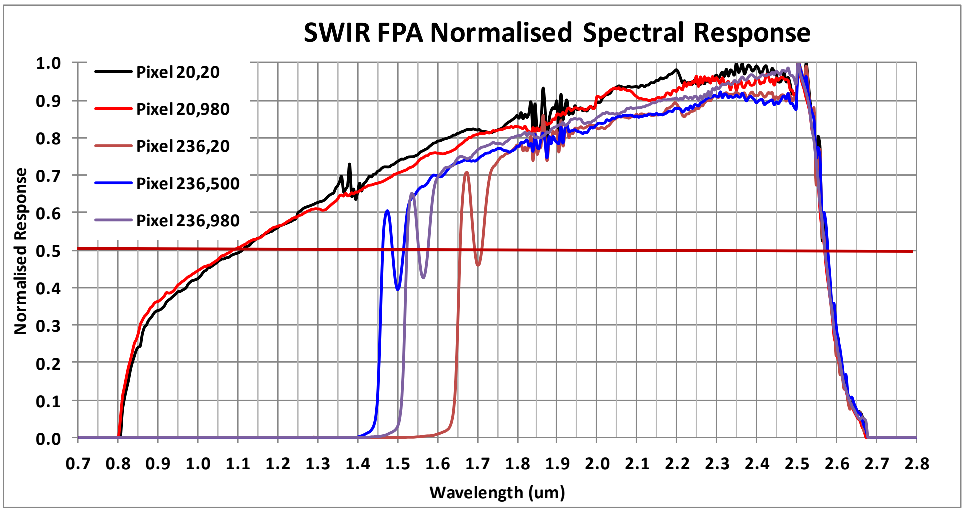
(b) Dark Signal Variation with Integration Time



(c) Mean Signal Variation with Illumination



(d) SNR Variation with Illumination



(e) Normalized Spectral Response

Figure 6 SWIR IDDCA Preliminary Characterization Test Results

Fig. 6(a) shows measured FPA cool down time and cooler power during cool down and regulation phases. The FPA cools down from lab ambient temperature 293K to 150K in 375 seconds. The achieved temperature stability at 150K is 0.5K. The Stirling cooler consumes about 36Wac power during cool down phase and only 4Wac during regulation phase of operation. Fig. 6(b) shows variation in FPA mean dark signal with integration time and Fig.6(c) shows variation in array mean signal output with illumination. The non-linearity in the output signal was computed using linear regression method and found less than 0.5% of full scale value. Fig. 6(d) shows variation in SNR with illumination. Measured SNR near saturation is about 1500. Fig.6(e) shows measured spectral response of five different pixels of SWIR FPA at integrated level. Since, the order sorting filter (OSF), placed above FPA inside

Dewar, is a linearly variable high pass filter, the cut-on response of pixels in different detector rows will be different. Variation in cut-on wavelength for pixels in same row determines non-uniformity in cut-on wavelength along spatial direction. From the Fig.6(e) it is found that the cut-on wavelength for pixels on row 20 is 1.1µm and for pixels in row 236 is varying from 1.45µm to 1.65µm. This variation in cut-on wavelength is due to filter characteristics. The cut-off wavelength for all pixels is about 2.55µm which is due to MCT material characteristics. A brief summary of measured SWIR IDDCA parameters is given in Table-1 below.

Table-1 Summary of Measured SWIR IDDCA Parameters

S.No.	Parameter	Unit	Specification	Measured Value
1	Cool Down Time	minutes	≤ 10	6’15”
2	Cooler Power - During Cool Down Phase - During Regulation Phase	 Wac Wac	 ≤ 50 ≤ 20	 36.2 4.2
3	FPA Temperature Stability	K	± 1	± 0.5
4	FPA Mean Dark Signal (at minimum integration time)	Counts	≤ 2000	1754
5	FPA Dark Signal Non-uniformity	%	≤ 5	3.5
6	ROIC Full Well Capacity	e-	≥ 2 million	2.2 million
7	SNR (near saturation)	-	≥ 1000	1558
8	Photo Response Non-uniformity	%	≤ 10	5.2
9	Non-linearity	%	≤ 1	0.48
10	FPA Spectral cut-off	µm	≥ 2.5	2.55

4. CONCLUSION

Next generation Infrared focal plane arrays consist of a 2D mosaic of photodiodes coupled with high performance ROIC and cooled to cryogenic temperatures using an integrated Dewar cooler assembly. Detailed characterization of such assemblies is required to assess their usability in intended application. A test bench is developed to characterize various electrical and electro-optical parameters of such IDDCA based IRFPAs. Test bench validation is carried out by characterizing a lab model SWIR IDDCA. This paper gives design details and validation test results of developed IDDCA characterization test bench.

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