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Multi-band CMOS Sensor simplify FPA design

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ABSTRACT

Push broom multi-band Focal Plane Array (FPA) design needs to consider optics, image sensor, electronic, mechanic as well as thermal. Conventional FPA use two or several CCD device as an image sensor. The CCD image sensor requires several high speed, high voltage and high current clock drivers as well as analog video processors to support their operation. Signal needs to digitize using external sample / hold and digitized circuit. These support circuits are bulky, consume a lot of power, must be shielded and placed in close to the CCD to minimize the introduction of unwanted noise. The CCD also needs to consider how to dissipate power. The end result is a very complicated FPA and hard to make due to more weighs and draws more power requiring complex heat transfer mechanisms. In this paper, we integrate microelectronic technology and multi-layer soft / hard Printed Circuit Board (PCB) technology to design electronic portion. Since its simplicity and integration, the optics, mechanic, structure and thermal design will become very simple. The whole FPA assembly and dis-assembly reduced to a few days.

A multi-band CMOS Sensor (dedicated as C468) was used for this design. The CMOS Sensor, allow for the incorporation of clock drivers, timing generators, signal processing and digitization onto the same Integrated Circuit (IC) as the image sensor arrays. This keeps noise to a minimum while providing high functionality at reasonable power levels. The C468 is a first Multiple System-On-Chip (MSOC) IC. This device used our proprietary wafer butting technology and MSOC technology to combine five long sensor arrays into a size of 120 mm x 23.2 mm and 155 mm x 60 mm for chip and package, respectively. The device composed of one Panchromatic (PAN) and four different Multi-Spectral (MS) sensors. Due to its integration on the electronic design, a lot of room is clear for the thermal design. The optical and mechanical design is become very straight forward. The flight model FPA passed all of the reliability testing.

Keywords: FPA, CCD, CMOS Sensor, MSOC, PAN, MS, LVDS, APS, PGA

1. INTRODUCTION

Remote sensing is related to the acquisition of information about an object without making physical contact with the object. In modern usage, the term generally refers to the use of aerial sensor technologies to detect and classify objects on Earth (both on the surface, and in the atmosphere and oceans).

There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive remote sensing detects natural radiation that is emitted or reflected by the object or surrounding areas. Reflected sunlight is the most common source of radiation measured by passive sensors. Examples of passive remote sensors used in the passive remote sensing include film photography, infrared, and charge-coupled devices (CCD). Active remote sensing, on the other hand, emits energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target. Radar is an example of active remote sensing, where the time delay between emission and return is measured, establishing the location, height, speed and direction of an object being radiated by the emitted energy (electromagnetic waves).

One of the passive remote sensing techniques is to use what is commonly referred to as Remote Sensing Instrument (RSI) that includes multiple linear image sensors to capture a ground scene. A satellite map or image is then formed from respective signals of the multiple linear image sensors. For example, an exemplary RSI may use one panchromatic (PAN) signal and four Multi-Spectral (MS) signals from the multiple linear image sensors. In general, besides the PAN signal, there are four MS signals: Blue (B), Green (G), Red (R), and Near Infrared (NIR), which are used to create a colorful satellite image. In a high resolution and high performance RSI, the instrument needs 5 individual linear sensor arrays. The pixel size and number of pixel element are determined by the optical system for the individual linear sensor arrays, the satellite orbit and the swath width. For imagery at 720 km above the earth, the optical reduction is about

200,000. The pixel size of 10 um represents 2 meters resolution on the ground. For a linear sensor of 12,000 pixels, the image swath width is 24 km. The resolution of the PAN signal is normally higher than that of the MS signals. Thus the pixel size generating the MS signals is typically larger and the pixel number is smaller than that of the pixel size for the pixels generating the PAN signal.

The RSI has two units: the telescope and the electronic unit (EU). The telescope unit contains optical elements, i.e., mirrors and lens, and the Focal Plane Assembly (FPA) that contains sensor, driving circuitry, gain control circuitry, analog-to-digital converter (ADC), house keeping function, output formatter and etc. The EU conducts function of data compression, packetization, encryption, storage, file management, channel coding, and the QPSK X-band interface as well as conducts the functions of DC / DC power supply, camera control, house keeping, command buffer, and the thermal control of the telescope. The EU will interface with FPA by unregulated power, master clock, and camera link interface which is used to transfer image data, commands and telemetry between FPA and EU. As the sensor arrays used in the current FPA are commonly CCD-based devices while other circuits (e.g., AGC and amplifiers) are CMOS-based. It is well known that the integration of the CCD sensors and the CMOS-based circuitry requires very sophisticate skill sets given the working conditions in which a FPA operates. The FPA needs to operate in space, thus the FPA system designs are required to consider the thermal, structure and mechanical extremes in the space. These considerations and resulting design parameters often cause the FPA designs very complicated, hard to make and bulky. The current RSI uses folding mirrors to guide the different ray traces (incoming lights) to different optical planes, where one or more individual sensor arrays are positioned. Figure 1 shows a mirror block to fold different ray traces (via respective filters) and project a corresponding colored ray onto one designated sensor array. Each of the MS CCD-based array is located on an independent optical plane. Figure 2 shows another way to use folding mirrors to design a RSI. The folding mirror guiding the PAN ray to a PAN focal plane while the MS folding mirrors direct the MS ray to the MS focal planes. The focal planes of PAN and MS are different optical planes. The folding optical methods require very complicated optical system design.

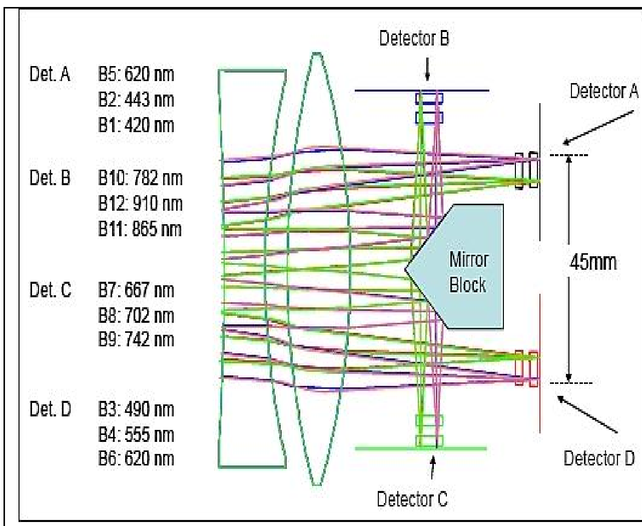

Figure 1. Optical system to use multiple CCD.

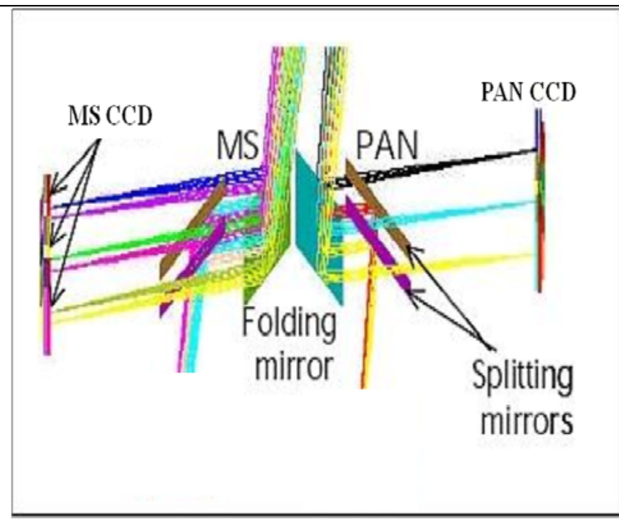

Figure 2. Optical system to use PAN and MS CCD.

There is thus a great need for different architectures of FPA that may have small footprint, broad operating wavelength range, enhanced impact performance, lower cost, and easier manufacturing process. Section 2 describes five band of the CMOS Sensor. The electronic, mechanic, thermal, and optic design of the FPA is presented in section 3. The environmental testing of the FPA is shown in section 4. Section 5 explains the summary of this work.

2. C468 (FIVE BANDS CMOS SENSOR)

Microelectronic technology is proposed to design five bands of the sensor array and its peripheral circuitry. Instead of discrete CCD array, five rows of the CMOS Sensor with digital output were design into a tiny silicon chip. Figure 3 shows an array of the multi-band sensors. As shown in figure 3, the array of multi-band sensors includes five image sensors disposed in parallel, separated by a corresponding support circuit for each sensor. These five sensors are respectfully referred to as a PAN sensor and four color-band sensors. Depending on implementation, the sensors may be separately coated with a filter designed to pass through a specified frequency band or disposed behind a special filter. While the PAN sensor is designated to sense a broad spectrum, often resulting in a visually grey image of a scene, each of the color-band sensors produces an image within one frequency band from sensing the same scene. Three of the color-band sensors produce images in red, green and blue and the fourth one produces an image in infrared. When five images from the sensors are properly combined, a multi-spectral image is produced. When the array of sensors is used in remote sensing, a satellite image can be obtained.

One of the objects, benefits and advantages of the array of multi-band sensors is that all the sensors are disposed on one image plane, resulting in a much simpler optical system design, hence small footprint, broad operating wavelength range, enhanced impact performance, lower cost, and easier manufacturing process. Further the sensors are CMOS-based and packaged in one unit, making it easier to operate with other CMOS-based circuits. The pixel resolutions of the sensors are designed to be different to accommodate different applications. In one application, the pixel resolution of the PAN sensor is different from that of the color-band sensors, where the resolution is twice that of the color-band sensors.

2.1 Silicon chip

The C468, five bands image sensor array consists of five independent sensor lines: one PAN band and four MS band which designates as B1, B2, B3 and B4, packaged in a ceramic substrate as shown in Figure 4. The PAN band has a total of 12,000 pixels, the pixel size is 10 μm square on a pixel pitch of 10 μm. The multi-spectral (MS) bands, (B1 ~ B4), each band has 6000 pixels, the pixel size is 20 μm square on a pixel pitch of 20 μm. Five bands arranged on B1, B2, PAN, B3 and B4 sequence. The spacing between each band to neighbor band (B1 to B2, B2 to PAN, PAN to B3, and B3 to B4) is 4 mm. Thus, the focal plane (image sensor area) is 120 mm x 16.02 mm. A 132 pin of Pin Grid Array (PGA) ceramic package is used to house the silicon chip. The space qualified radiation hardness glass window with double side AR coating is used to seal the silicon sensor. The device after package is 155 mm x 60 mm x 8.77 mm.

The device uses our proprietary technologies (e.g., wafer butting, multi chip butting, and multiple readout) to achieve the requirement of gapless image pixel line and very short integration time. The array is designed to provide a high resolution, low power consumption for high attitude (~ 720 km) earth orbit RSI application. The C468 is mixed mode MSOC IC that integrates active pixel sensor (APS), programmable gain amplifier (PGA), 12 bit analog to digital (ADC), voltage regulator, low voltage differential amplifier (LVDS) and timing generator together. The C468 is also built with power down mode that will consume a very small of power while the focal plane array (FPA) is not active. The device is response over the spectral wavelength of 450 to 900 nm with five different bands. With external multi mode filter, it is defined as: PAN (450 ~ 700 nm), MS1 (455 ~ 515 nm), MS2 (525 ~ 595 nm), MS3 (630 ~ 690 nm), and MS4 (762 ~ 897 nm). All five bands are total isolated and electrically isolated. The user can power on any band of the sensor array independently. This functionality allows the user to read different colors from the imager.

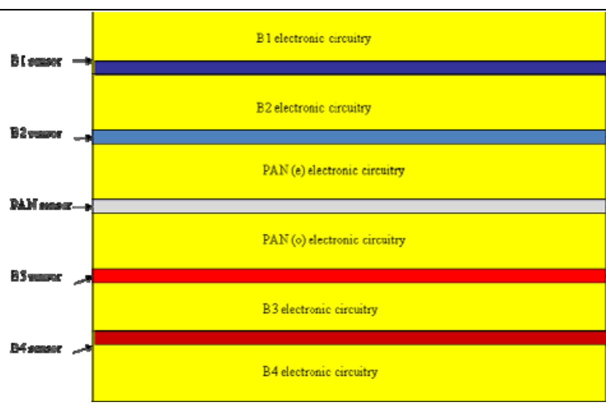

Figure 3. Array of multi-band sensor.

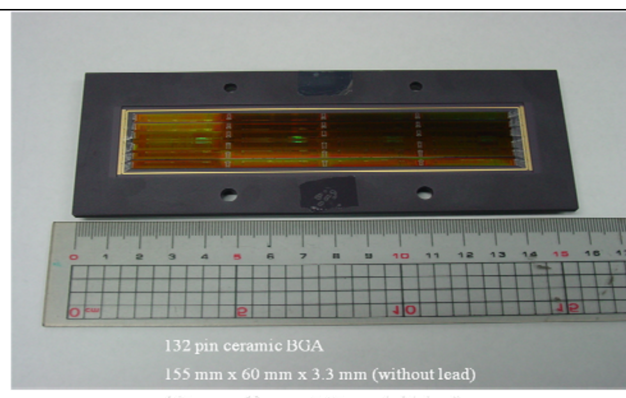

Figure 4. C468 (five band CMOS Sensor) photo.

2.2 Ceramic package

The C468, CMOS image sensor, chip is a mixed mode IC. It integrates sensor array, digital circuitry and analog circuitry together into a tiny silicon chip. The switching of the digital circuitry generated glitch to the power supply and injected the charge to the silicon substrate. This will impact to the analog signal line and cause high noise problem on the CMOS image sensor device. A large, low equivalent series resistor (ESR) de-coupling capacitor is normally used to connect from power supply to ground to reduce the noise problem. This de-coupling capacitor need to close to the silicon chip. In additional, the low voltage differential signal (LVDS) input and output of the CMOS image sensor also required resistor matching and termination resistor close to the silicon chip.

The above requirement can be solved by used ceramic Pin Grid array (PGA) package to house the silicon chip. The PGA package is formed by more than ten thin layers of the ceramic plate and metal tray. They are the best material to design a decoupling capacitor and resistor network. The package included at least 10 different ceramic layers. By print the metal tray to top and bottom of the dielectric ceramic plate, one can generate a capacitor with value of $C = \varepsilon\ (w / d)$. Where C is the decoupling capacitor value, ε is ceramic dielectric constant, w is area of the metal trace and d is the thickness of the ceramic layer. Higher decoupling capacitor is possible by add several ceramic capacitors parallel together. The metal tray on the ceramic PGA package also can be design to match the LVDS input and output. By proper design of the PGA package to form an embedded suitable de-coupling capacitor and resistor network, the external R, C components is not necessary. Due to this fully integration between sensor chip and ceramic PGA package, the C468 is able to connect thru soft PCB to other electronic circuitry. This simplifies the electronic design on the FPA.

2.3 Device specification

The specification of the C468 device is displayed in table 1.

Item	Specification	
Readout mode	Snap shot operation; Start and stop integration of all pixels simultaneous	
Integration time	PAN	297 us ± 5%
	MS (MS1 ~ MS4)	594 us ± 5%
Dark Current	≤ 1000 electrons / s /pixel for all pixels of the array	
PSRR of the device	≥ 60dB on all the supply lines at readout frequency	
Power consumption	PAN	1.6 W
	MS1	0.8 W
	MS2	0.8 W
	MS3	0.8 W
	MS4	0.8 W
	Total	4.8 W
Full well capacity	PAN	32,000 electrons
	MS1	95,360 electrons
	MS2	138,000 electrons
	MS3	132,000 electrons
	MS4	123,000 electrons
Dark offset non-uniformity	Dark signal variation is less than 5 times its noise level at mean radiance.	
Residue (Line to Line)	< 1% when alternate Lines are illuminated up to 90% of Full Well	
Non-linearity	< 1% in 10% to 90% of Full Well for any pixel	
Maximum non-uniformity	< 1% RMS including FPN	
Anti-blooming	On chip lateral anti-blooming structure	

Band	Band definition (nm)	Mean irradiance (W/m^2)	Saturation irradiance (W/m^2)	SNR @ mean irradiance
PAN	450 ~ 700	0.1820	0.5460	> 93
MS1	455 ~ 515	0.0397	0.1193	> 100
MS2	525 ~ 595	0.0467	0.1402	> 100
MS3	630 ~ 690	0.0413	0.1239	> 100
MS4	762 ~ 897	0.0815	0.2445	> 100

PAN @ 50 lp / mm						
	450	500	550	600	650	700

Min MTF	0.723	0.694	0.664	0.604	0.538	0.507
MS @ 25 lp / mm						
	MS1	MS2	MS3	MS4		
Min MTF	0.78	0.766	0.716	0.655		

Table 1. C468 specification

3. FPA DESIGN AND FABRICATION

The whole FPA consists of (1) FPA mechanical structure; (2) FPA electronic circuitry; (3) C468 (5 bands of the CMOS Sensor); (4) thermal control hardware: included heater, temperature sensor, ..; (5) filter; (6) interface for electronic, mechanical, optical, thermal. The FPA structure shall be able to attach FPA to main plate and place image sensor to focal plan of telescope. The thermal hardware shall contain heater, temperature sensor, heat path, radiator and necessary thermal design such that FPA can maintain its thermal environment to keep its performance. The FPA shall be able to provide the following operation mode. They are (1) test mode; (2) standby mode; (3) MS imaging only mode; (4) PAN imaging only mode; (5) Simultaneous PAN and MS imaging mode; and (6) Off mode. Based on the above requirement, The FPA design needs to consider electronic design, mechanic design, structure design, thermal design and optical design. A five band CMOS Sensor (C468) is used to design FPA.

3.1 Electronic design and fabrication

The FPA electronic circuitry need to provide the power and control signal to operate C468 sensor; manipulate the image data from C468 and transfer it to EU. The electronic circuitry also needs to receive the command from EU to switch different operation mode and report the FPA health condition to EU. The circuit design needs to consider the power supply stability to reduce noise, over voltage and over current protection to protect FPA. Figure 5 shows the block diagram of the electronic circuitry. Except sensor array, all of the electronic circuitry built two sets to increase reliability. The set of the electronic circuit are identical. One set is in operation; the other is redundancy. It is dedicated as A side and B side. Ground command can switch the FPA to operate either A-side or B-side. When one side is failed, ground operator can turn on to the other side. Each side include (1) power supply selection to select either A or B; (2) FPA power supply; (3) C468 sensor power supply; (4) clock signal; (5) FPGA; (6) Buffer and LVDS interface circuitry; (7) temperature sensor; and (8) heater. The electronic interface for input / output and power supply is thru 2 sets of 104 pin connector to EU. The thermal control interface is thru one set of 26 pin D-sub connector to EU.

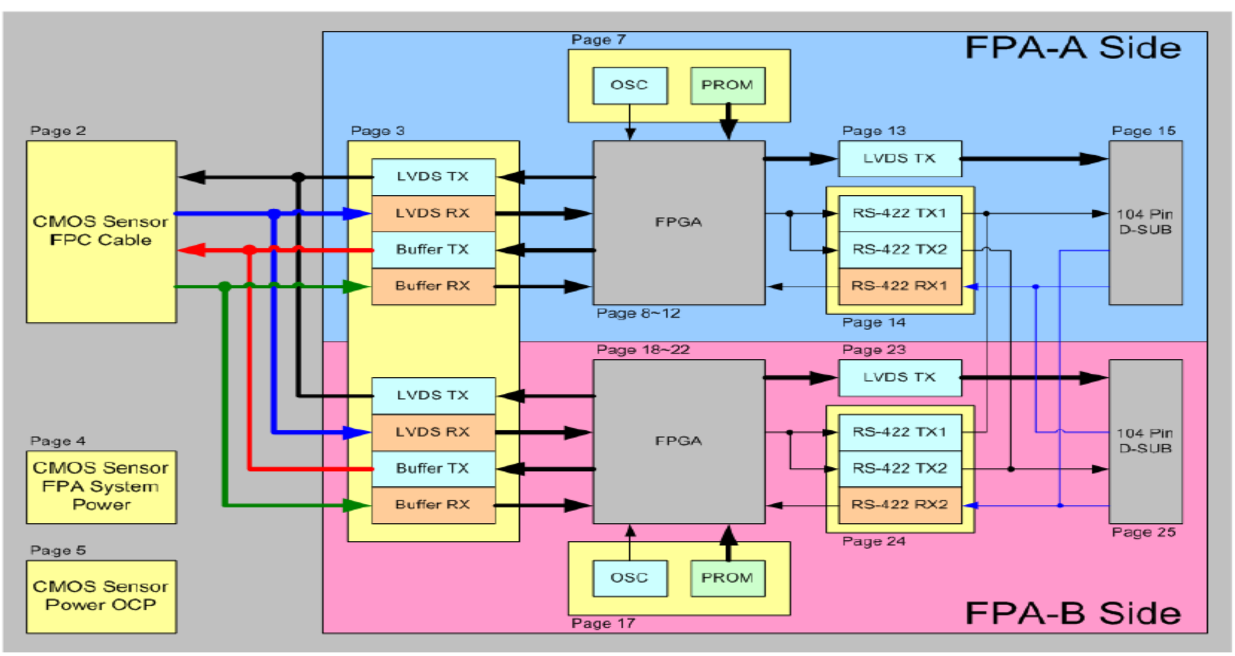

Figure 5. Block diagram of the electronic circuitry.

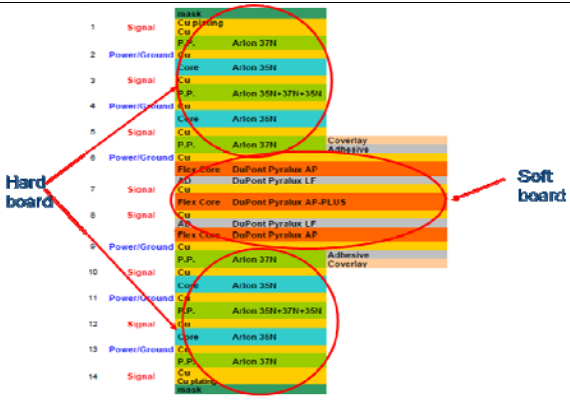

Figure 6 (a) Hard / soft board

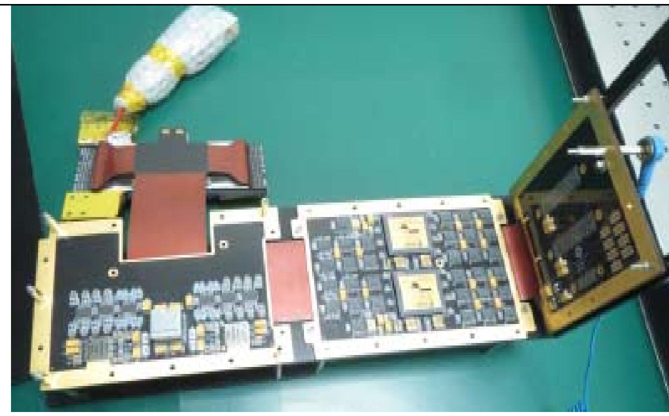

Figure 6 (b) hard / soft PCB of the electronic circuitry

As shown in figure 6(a) and 6(b), a hard / soft board combination is used to design the Printed Circuit Board (PCB) for the electronic circuitry. The main board to C468 sensor and board to board is connected thru soft PCB. This design eliminates the connector and increases the FPA reliability. The electronic assembly is simple and reliable.

3.2 Mechanic, structure and thermal design and fabrication

The mechanic and structure design need to meet the stiffness requirement for first eigen-frequency with all the supported items, fixed on a rigid support shall be higher than 160 Hz in all dimensions. The thermal design shall provide its own thermal control to maintain the thermal condition such that it meets the interface requirement and provide suitable environment to achieve the performance requirement. Under those requirements, the mechanical interface design needs to consider (1) the stability of the focus plane (2) stress free during focal plane assembly, (3) the FPA accuracy during satellite transportation and launch, (4) focal plane accuracy during operation. The opto-mechanical interface consists of (1) filter interface with FPA; (2) Sensor interface with FPA and (3) filter interface with 5 bands of the sensor.

Thermal interface design need to consider (1) thermal control to control sensor temperature within a particular range; (2) all of the components on the PCB need to operate in a particular range; and (3) Sensor need to operate in a particular range even when satellite is rotate. Each phase of the temperature is varied at this condition; and (4) FPA shall be thermally isolated in the mounting area to avoid thermal distortion of telescope.

Figure 7 shows the whole focal plane assembly. Without four mounting area, the FPA dimension is 20 cm x 20 cm x 15 cm. The total weight is less than 6 kg. The peak and average power dissipation is less than 12 and 2.5 watt, respectively.

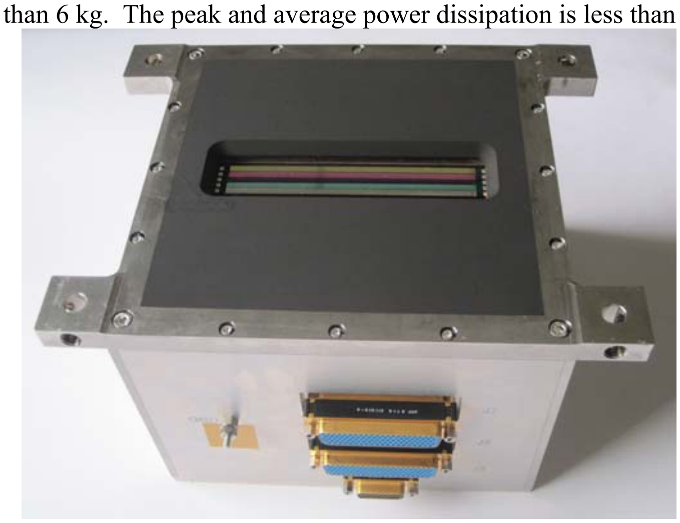

Figure 7. FPA photo

3.3 Optical design

Figure 8 (a) presented the optical focal plane with C468 multi-band sensors. The optical focal plane is about 121 mm. This allows a smaller lens and mirror to cover the whole sensor array. The telescope lens system is shown in figure 8(b). Reflected lights are coming from a scene and captured by one or more lenses to focus the reflected lights to a mirror that directs the focused lights to a lens that further focuses the lights onto the multi-band sensors. As shown in the above figure, the optical system to design FPA is much simpler than conventional method.

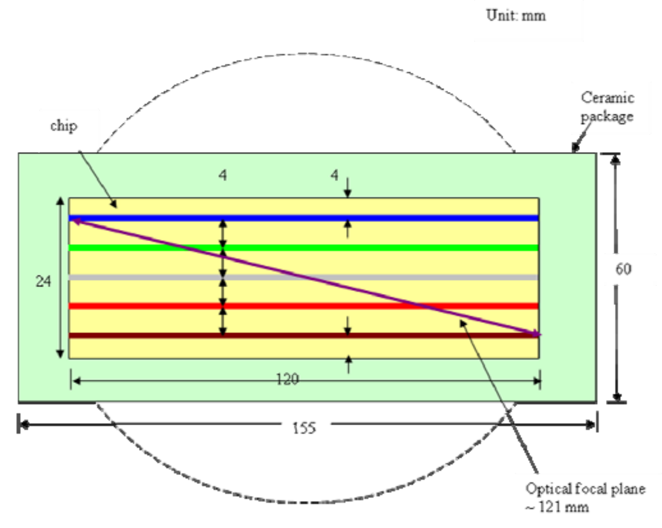

Figure 8(a). Optical focal plane.

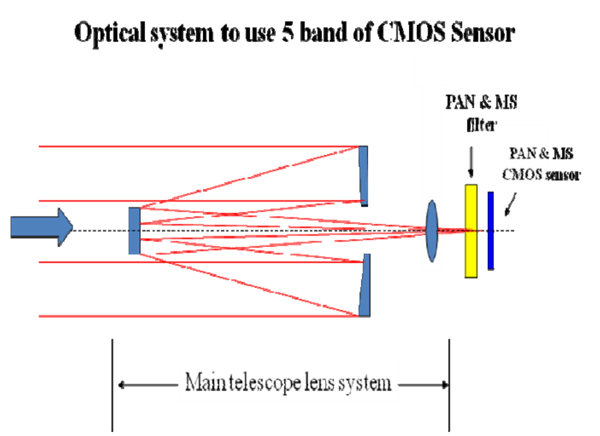

Figure 8(b). Optical system to use 5 band of CMOS Sensor.

4. ENVIRONMENTAL TESTING

The FPA can meet the specification of the electronic and opto-electronic requirement. For space application, the FPA also need to pass a lot of environmental testing to make sure the device can survive during launch and operate in the space. The environmental testing includes (1) mechanical testing, (2) thermal vacuum testing, and (3) EMC testing. The FPA pass the mechanical testing and EMC testing. The thermal vacuum (TV) testing is the most important for the space application and need to address in the following section.

4.1 TV testing setup and description

This testing is to achieve the FPA qualification level cold and hot temperature extremes 8 times to verify the FPA EM workmanship and reliability. For FM, it will be performed at flight level cold and hot temperature extremes 8 times. During the thermal cycle test, the mounting interfaces of FPA will be subjected to the thermal extremes under vacuum conditions. Thermal Vacuum Chamber (TVC) thermal base-plate and test adapter will be thermally controlled to provide simulated mounting interface temperatures. The completion criteria are to obtain test thermocouple readings held for 2 hours (dwell or soak) at hot and cold plateaus of each cycle after the wall within the tolerance of the soak temperature. Besides, no critical anomaly happens in this phase.

The test article will be mounted on test adapter with thermal filler between them. Test adapter will be mounted on thermal base-plate, which is in TVC. Test thermal blankets (MLI) will cover the external surfaces of test articles.

The test article shall be subjected to a total of eight (8) temperature cycles. A temperature cycle begins at room ambient temperature, proceeds to hot test temperatures, then to cold test temperatures, and finally back to room ambient. Figure 9 shows the testing profile. If the FPA has problem need to be solved during the thermal vacuum test, the safe temperature for FPA debug can be adjusted in the room temperature.

4.2 TV testing data

Seven components on the electronic circuitry have higher power consumption. They are selected to add the temperature sensor on each component to monitor the temperature under TV chamber. Figure 10 displayed the temperate profile for each testing point. All of the temperature for each critical component is less than 60 ºC under environmental temperature of 45 ºC. The temperature raise is less than 15 ºC. This indicates that all electronic components can operated in the normal condition under thermal vacuum condition.

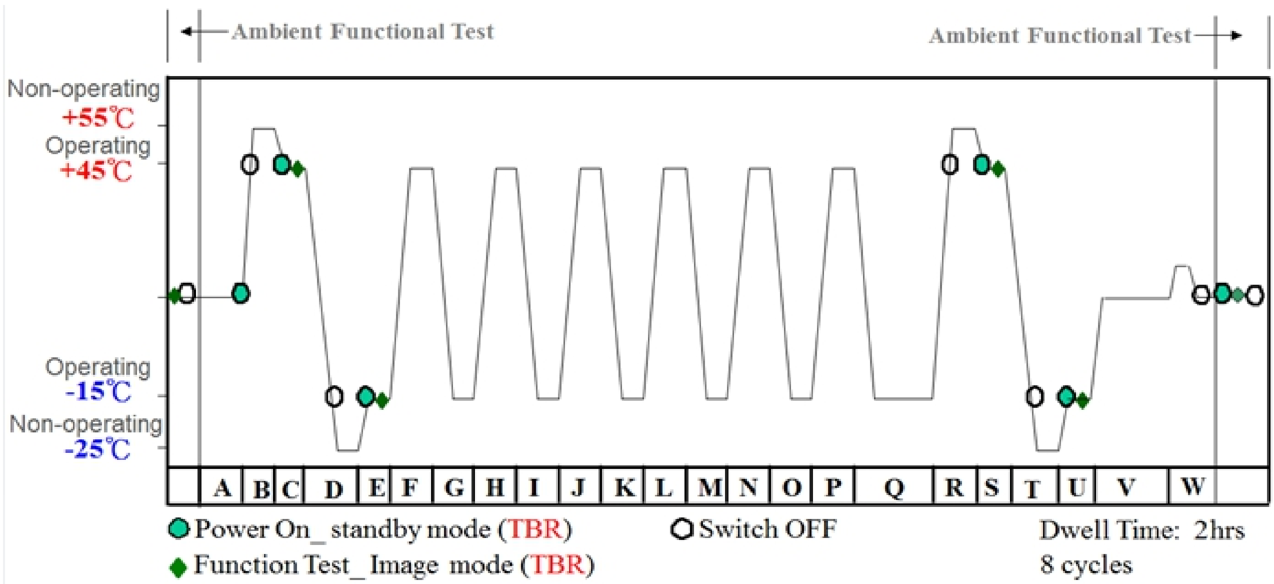

Figure 9. Thermal vacuum testing profile.

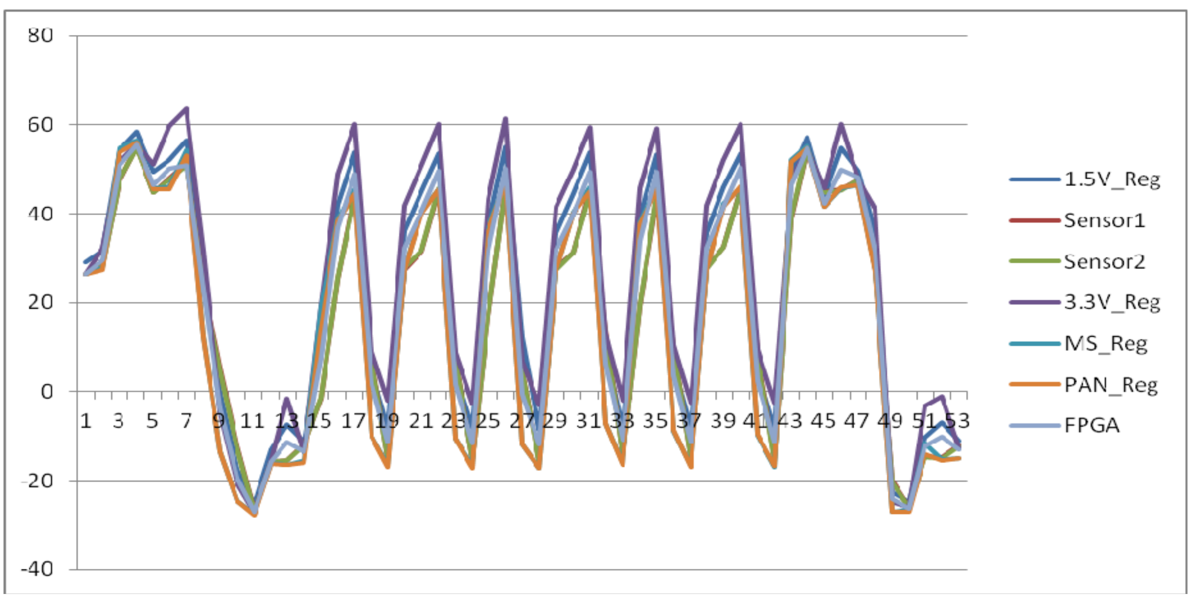

Figure 10. Measured temperature profile on each high power component.

4 SUMMARY

The multi band focal plane array was designed and fabricated for space RSI satellite imaging application. The sensor chip used on the FPA is 5 bands of CMOS sensor. The image quality and device performance can compete with CCD. Since CMOS Sensor is able to integrate sensor array, analog circuitry and digital circuitry into a tiny silicon chip, the support circuitry to operate the CMOS is very simple. A ceramic package is used to house not only silicon chip but also provide the R-C network for the CMOS Sensor chip. Due to its integration, a soft / hard PCB design is available for the electronic design. The result is mechanical design, thermal design and optical design of the FPA become very simple and reliable. The whole FPA dimension is 20 cm x 20 cm x 15 cm. The weight is less than 6 kg. The overall peak and average power dissipation is less than 12 watt and 2.5 watt, respectively. This work provides an evidence for CMOS Sensor as an alternate solution other than CCD device for RSI applications.

ACKNOWLEDGEMENT

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