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Development of A Hermetically Packaged 13μm Pixel Pitch 6000-Element InGaAs Linear Array

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ABSTRACT

In this paper, we present the test results of a flight-grade 13µm pixel pitch 6000-element 1.7μm InGaAs linear array in a hermetic package, designed and developed for space remote sensing and imaging applications. The array consists of a single 13µm pixel pitch 6000-element InGaAs linear array and a custom single digital 2.0 Me- capacitance trans-impedance amplifier (CTIA) readout integrated circuit (ROIC) with four gains. We have achieved greater than 80% peak quantum efficiency and higher than 1100 signal-to-noise ratio (SNR) at 90% well fill. The focal plane array is in a vacuum hermatically sealed package with an anti-reflective (AR)-coated Sapphire window and 29 pins, including four for low voltage differential signaling (LVDS) outputs.

Keywords: Monolithic Array, Linear Focal Plane Array, InGaAs, Hermetic Package, Remote Sensing, Infrared Sensor Imager

1. INTRODUCTION

In recent years, there has been increased demand for the large swath, high-resolution push-broom detector linear arrays for earth observing and remote sensing applications. An instrument with a large linear array can operate without the need for a scanning mirror; therefore reducing the instrument's complexity and cost. InGaAs focal plane arrays are sensitive to near-infrared, with little or no cooling requirements. Linear arrays up to 6000 elements with 12µm to 15µm pixel pitch have been constructed by integrating multiple staggered or butted small linear arrays, for instance using six 1024-element arrays [1] [2] or three 2048-element arrays. We have pushed the state-of-the-art technologies and successfully developed a monolithic continuous 13µm pitch 6000-element InGaAs linear array in an f/3 hermetically sealed, high-reliability nitrogen back-filled package. The 1.7µm cutoff InGaAs short wave infrared (SWIR) sensor was integrated on an instrument payload and launched in 2017 for a civil earth resource observation mission.

2. 6000-ELEMENT InGaAs LINEAR ARRAY

The linear array is an 87mm long single hybrid consisting of a backside illuminated, monolithic, continuous 13µm pitch 6000x8 element 1.7µm cutoff InGaAs linear array with pixel format matching a single silicon readout integrated circuit (ROIC) chip. The 6000x8 pixel format allows selection of a single primary operating row for imaging and allows substitution of bad pixels in the primary row with good pixels from neighboring (redundant) rows to achieve high operability. The detector has a wavelength spectral response ranging from 1.0µm to 1.7µm at an operating temperature around 22°C. The ROIC is a 4-gain capacitance trans-impedance amplifier (CTIA) type ROIC, designed to allow sequentially read out of correlated double sampled (CDS) output at individual pixels. The ROIC's readout mode is "read while integrating (RWI)." The sensor array has two 14-bit uni-encoded serial LVDS outputs. In Fig.1, we show the schematic diagram of the 6000x8 element ROIC. The readout chain includes a four gain CTIA with CDS and 8 to 1 element multiplexer, a unit gain switch, a single slope 14 bits ADC and two LVDS outputs.

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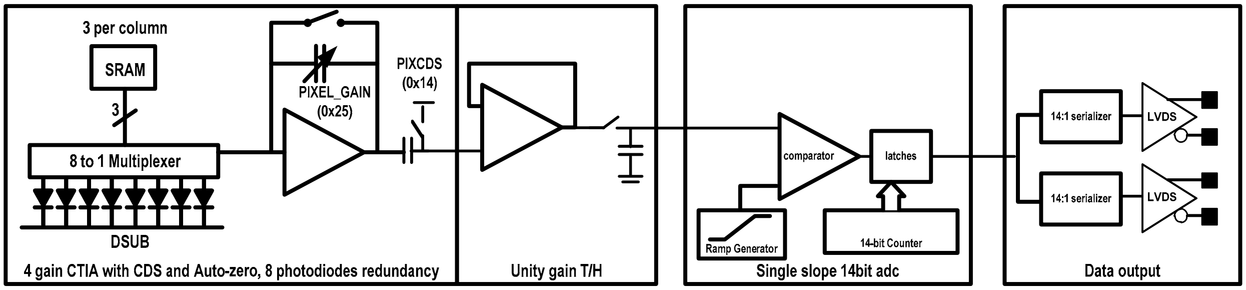
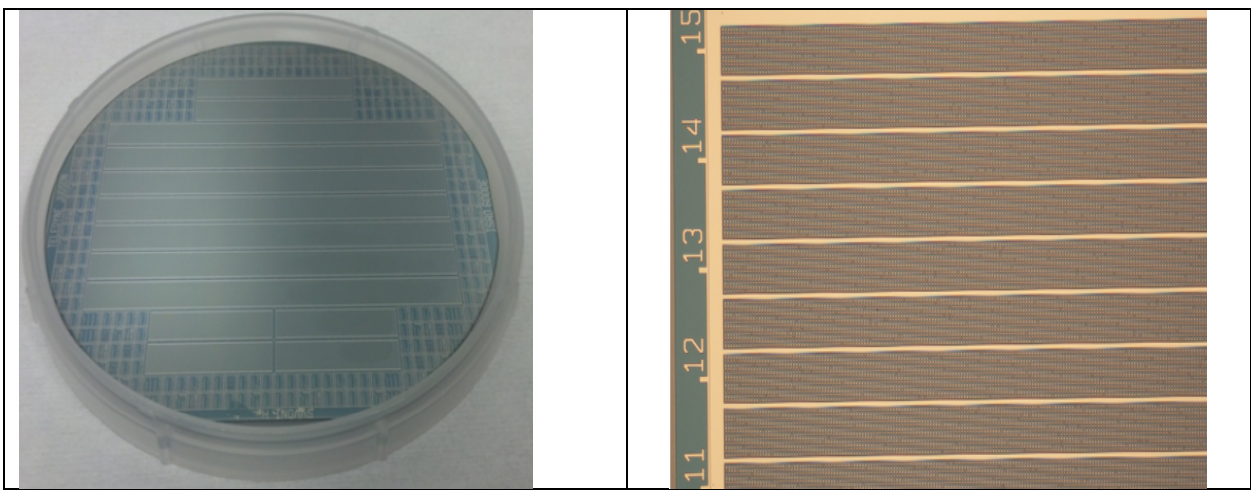


Fig. 1 Readout chain of the Teledyne 6000 x 8 element ROIC

2.1 Performance Evaluation Chips (PEC) Dark Current and Quantum Efficiency

The detector arrays were fabricated from 4-inch diameter InGaAs wafers and patterned as shown in Fig. 2



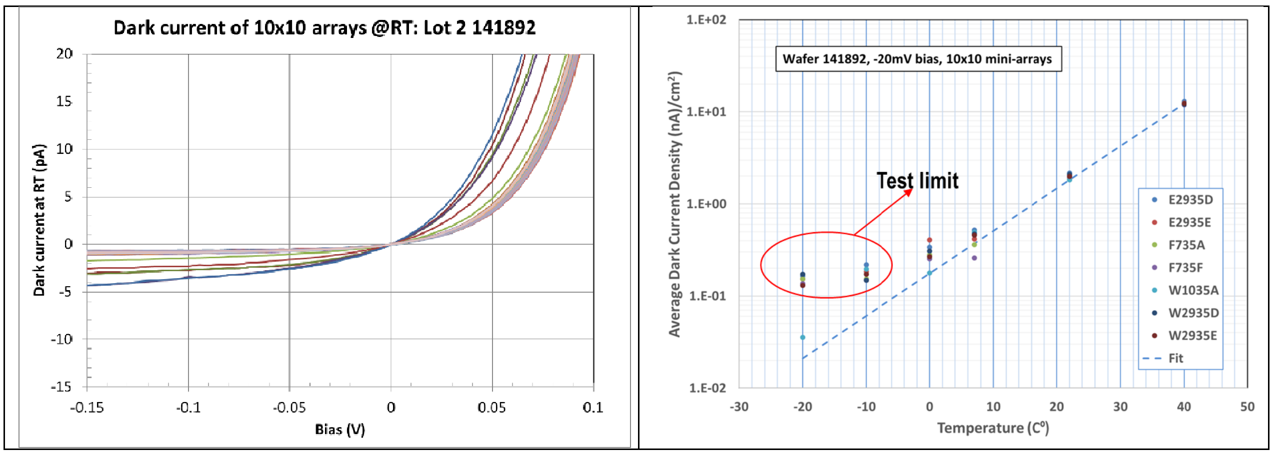
(a) (b)

Fig. 2 Teledyne InGaAs detector format and pattern: (a) Patterned 4-inch diameter wafer, and (b) detector die pattern

The desired linear array format for imaging is 6000x1 pixels with 13µm pitch. In order to maximize operability, we chose a 6000x8 format for each array dies, as shown in Fig. 2a. Four inch InGaAs epi-wafers were used to achieve an array length of >78mm active area. The InGaAs epi-layer was grown on InP substrate by Metal Organic Chemical Vapor Deposition (MOCVD). The 50% cutoff wavelength of InGaAs was slightly extended from 1.66-1.67µm of lattice matched InGaAs to nearly 1.7µm at room temperature, to enhance quantum efficiency (QE) around 1.7µm. An N^+ InP buffer layer, a low doped n-InGaAs absorption layer, and an N-InP cap layer were consecutively grown on an N^+ InP substrate.

The detector arrays were fabricated using Teledyne Judson Technologies' large format small pixel InGaAs array fab process [3]. A planar P^+ region was formed through the N-InP cap layer by Zn diffusion to produce a P^+-n-N^+ junction structure. Both P-metal and N-metal contacts were formed on the frontside of the array, to complete a fully planar structure. The completed array die size was 79.3mm x 6.8mm.

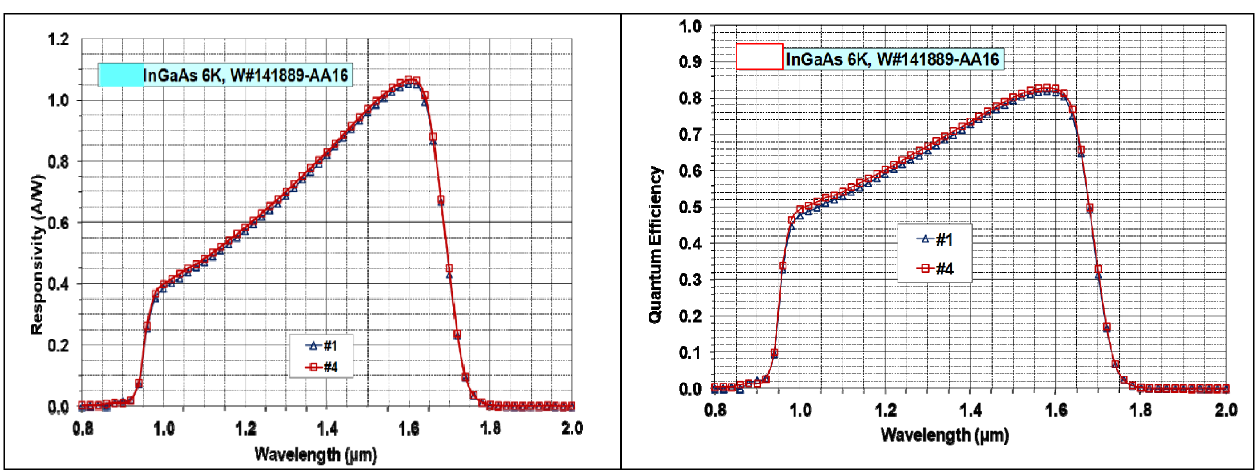
Performance evaluation chips (PECs) were designed around the large arrays on the same wafer, as shown in Fig. 2a. Dark current data were taken on 10x10 PEC mini-arrays of 13µm pitch, spread around the four sides of the wafer. Spectral QE data were taken on 15x15 mini-arrays of 13µm pitch. Also, variable pixel sizes of mini-arrays were designed for evaluation of surface/perimeter effect on the dark current. Low dark current density (Jd) was achieved with typical average Jd ~ 2nA/cm^2 at -20mV bias and room temperature. The 2nA/cm^2 dark current density is equivalent to 3.4fA dark current for the 13µm pitch pixel. As can be seen from the I-V curves obtained from measurements of a group of PECs in the same manufacturing lot, the dark current appears insensitive to the bias voltage; this characteristic has the advantage of allowing flexible bias voltages from zero to 100 mV. Fig. 3b shows the temperature dependence of dark current density measured from seven 15 x 15 PEC arrays. The circled data points achieve test setup limited dark current.



(a) (b)

Fig. 3 The dark current of a 13µm pitch 10 x 10 array (a) as a function of reverse bias voltage, and (b) as a function of operating temperature.

We have also demonstrated greater than 80% QE at peak wavelength and a minimum QE of 50% within the wavelength range from 1.0µm to 1.68µm at 22ºC. We measured QE on a test station is equipped with a calibrated IR monochromator, a tungsten IR source and an optical beam collimator. In Fig. 4, we show the spectral responsivity and QE as a function of wavelength (microns), respectively.

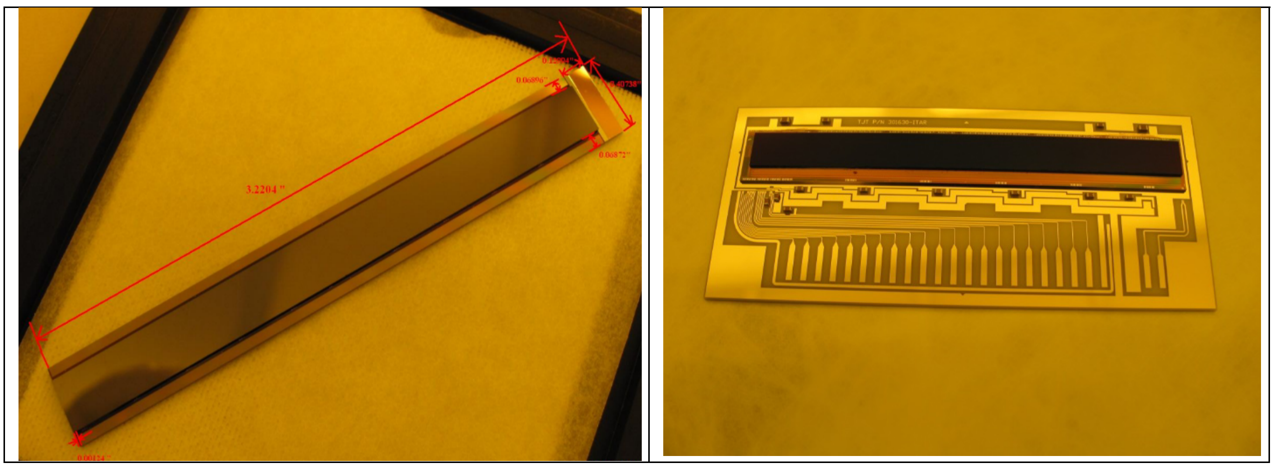


(a) (b)

Fig. 4 (a) Spectral responsivity of a Teledyne 6000-element InGaAs array as a function of wavelength, and (b) quantum efficiency as a function of wavelength

2.2 Sensor Chip Assembly (SCA)

The following is a description of the process we have developed: after the initial performance evaluation is completed on InGaAs detector PECs and the ROIC wafer, we dice the InGaAs wafer into detector chips and the Silicon wafer into ROIC chips. After chip cleaning and inspection, each ROIC is hybridized to a detector array, to form a hybrid such as the one shown in the picture of Fig. 5(a). Hybridizing such long stripe ROIC and InGaAs could be very challenging. However, Teledyne's advanced technique and unique process made it a high yield process. The hybrid's physical dimensions are 10.57mm x 80.86mm. Before the hybrid is enclosed in a hermetic package, it is mounted and wire bonded to a metallization-patterned ceramic motherboard. The hybrid-motherboard assembly is called "sensor chip assembly" (SCA), shown in Fig. 5(b). On the SCA board, there are 29 wire bond pads, to be electrically connected to the 29 pins on the hermetic package. Surface flatness is paramount to the sensor. On the single hybrid with an aspect ratio of almost 8:1, we achieve peak-to-valley flatness of smaller than 2µm, which results in a negligible impact on the imaging quality of an optical camera with a typical focal depth of 100µm.



(a) (b)

Fig. 5 (a) Teledyne 6000x8 element hybrid chip before mounting on a custom ceramic motherboard, and (b) a sample 6000x8 element hybrid mounted on a patterned ceramic motherboard. The assembly in (b) is a sensor chip assembly (SCA).

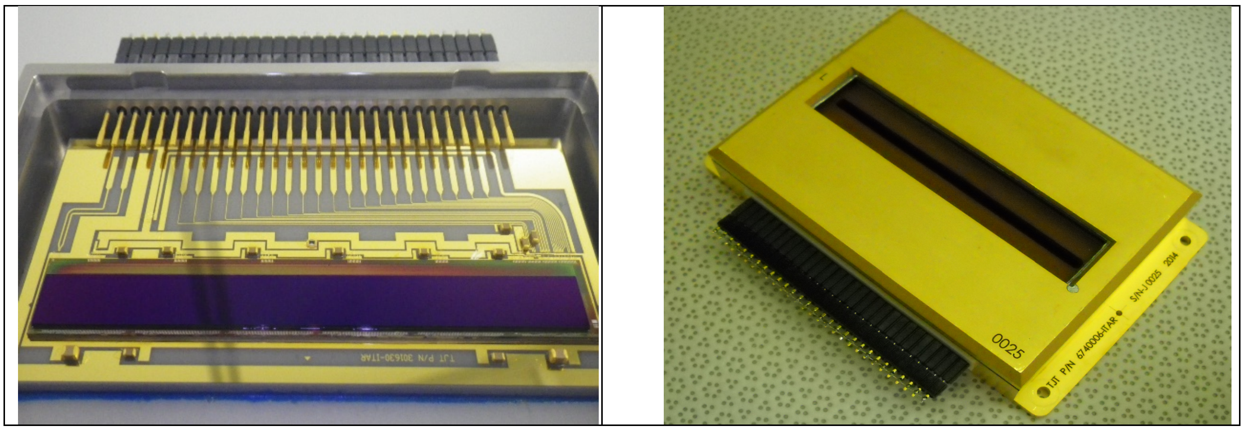
2.3 Hermetic Package

Teledyne's 6000-element array hermetic package consists of a sensor chip assembly (SCA), a package housing, an optical slit, a shim and an optical window subassembly.

The package housing consists of a Kovar single in-line header with twenty-nine high vacuum feed-thru pins glassed into the header base for electrical signals and returns. The hermetic seal for this type of package construction has been qualified to be hermetic for ten years of vacuum life. The vacuum evacuation tube is soldered to the copper base and is helium leak checked. Preprocessing of the evacuation tube allows for pinch off or cold weld sealing. To reduce outgassing from the materials in the package cavity, we backfill dry, pure Nitrogen gas in the cavity after the package is vacuumed and baked.

An anti-reflection (AR) coated sapphire window is soldered to a compatibly matched iron-nickel alloy material to mitigate any coefficient of thermal expansion (CTE) mismatch of this soldered interface. The purpose of matching the CTE of the window and package is to relieve stress on the solder interface, which in turn increases the hermetic lifetime of the package. The window subassembly is then leak-checked and pre-baked, to remove all atmospheric water molecules within the detector package. The window subassembly can then be laser-welded to the package after completing the detector array centering and wire bonding. Fig. 6 (a) shows the 6000-element array package at precap, and Fig. 6 (b) shows a fully assembled package.

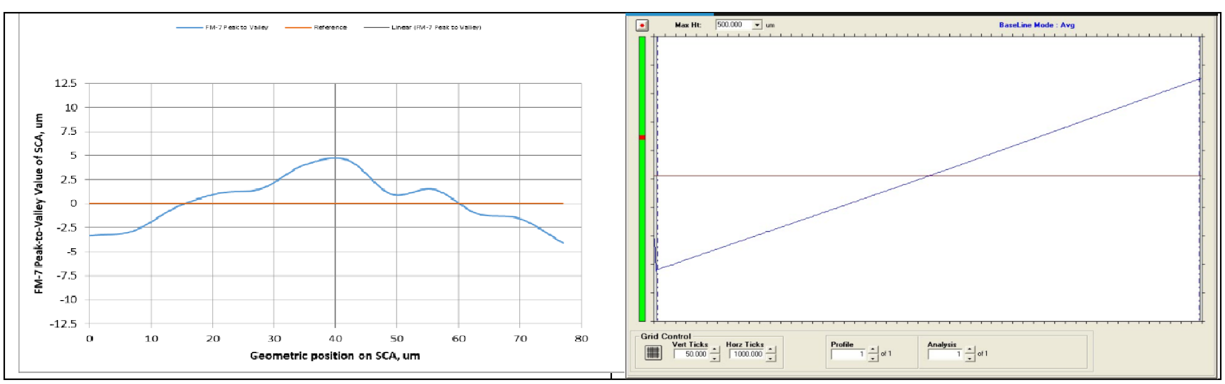
A blackened and pre-baked optical slit serves as a field of view optical slit with an f-number of 3.0. The AR coated Sapphire window has a minimum transmittance greater than 95% over the entire wavelength range from 1.0µm to 1.8µm.



(a) (b)

Fig. 6 The Teledyne 6000-element array assembly package (a) pre-cap and (b) post seal

The flatness of the focal plane array optical surface and the optical window surface in the package is critical for sensor imaging quality. At the package level, we have repeatedly achieved flatness of fewer than 10µm (peak-to-valley) on the SCA and less than 1 micron on the package window. In Fig. 7, we show the measured SCA surface flatness using a Nikon microscope and the measured optical window flatness using a laser scanner, for a typical array.



(a) (b)

Fig. 7 Measured surface flatness in length direction for (a) an SCA surface profile, and (b) window surface profile

3. ELECTRO-OPTICAL PERFORMANCE

We performed testing on the fully packaged sensor, to characterize electro-optical performance. The performance of key parameters is summarized in Table 1 below.

We adopted the Photon Transfer Conversion method [4] to measure array conversion gain in e-/ADU. Conversion gain (ADU/e-) is the slope of the linear fit of the array's median noise versus the median array signal. The readout chain gain is dependent on an external ceramic capacitor, compliant to MIL-PRF-123, with ±10% tolerance. Therefore, the overall conversion gain could vary from array to array by the same percentage. The test data and plots presented in Fig. 8 were from a flight grade unit. Fig. 8(a) shows the dark signal image of selected 6000 pixels in the linear array. It is worth noting that in the test software, the highest ADU count value corresponds to the lowest signal or noise value and vice versa. Fig. 8(b) shows the measured noise variance versus output signal in ADU, which derives the pixel full-well capacity, i.e., the product of the dynamic signal range from the minimum to the maximum and the conversion gain. For the unit under test, the conversion gain and the full signal range is 225 E-/ADU and 9656 ADU, respectively, so the array's pixel full-well capacity is 2.172600 Me-. Fig. 8(c) shows the measured QE at five different wavelengths. The QE values are 82.0% at 1550 nm; 76.2% at 1575nm; 69.4% at 1600 nm, 57.6% at 1640 nm and 44.0% at 1685 nm. The QE measured on the full array is consistent with that of the detector PEC. Fig. 8(d) shows the computed signal-to-noise ratio (SNR) [4] using the measured signal and noise value at the lowest CTIA gain setting. At 90% well fill, the SNR is 1129 for this unit. At high well fill, the photon shot noise is the dominant noise source.

Table 1 Typical Performance of a Teledyne 6000-Element InGaAs Array

Parameter	Typical Value
Sensor Spectral Range (μm)	1.00 - 1.69
Upper cut-off (50% peak responsivity) wavelength (μm)	≥1.68 @ 22ºC
Photodiode Well Capacity (FWC)(e-) at gain 1	≥2.0 million at lowest CTIA gain (gain code =0, 1, 2,3 representing the gain from low to high)
Photodiode Well Capacity (FWC)(e-) at gain 2	≥1.50 million at gain 1
Photodiode Well Capacity (FWC)(e-) at gain 3	≥ 0.85 million at gain 2
Photodiode Well Capacity (FWC)(e-) at gain 4	≥0.50 million at gain 3
Average SNR @ 1kHz frame rate	SNR FWC >1000 @90% of Full well capacity, gain=0
Mean Quantum Efficiency over the range 1.55 - 1.69μm	≥65%
Minimum Quantum Efficiency over 1.00 - 1.70μm	50%
Peak quantum efficiency	>=80%
Read Noise (e-)	<= 740e- @gain=0; ≤600e- @ gain=1;<=370e- @gain=2; <=240e-@gain=3
Photodiode Bias	Internally adjusted to ±1000μV with Auto-Zero
Pixel operability in a row, without noise taken into account	>=99.95%

Pixel operability in a row, with noise taken into account, 2x read noise	>=95%
Number of Output Port	1-2 outputs digital LVDS, 14 bits
Maximum Pixel Readout Rate	16 Mega Pixels/sec
Sensor Power dissipation at the nominal frame rate (1KHz)	≤500mW
Supply Voltage	3.3V ± 10% from VDD to VSS, 40 dB PSRR

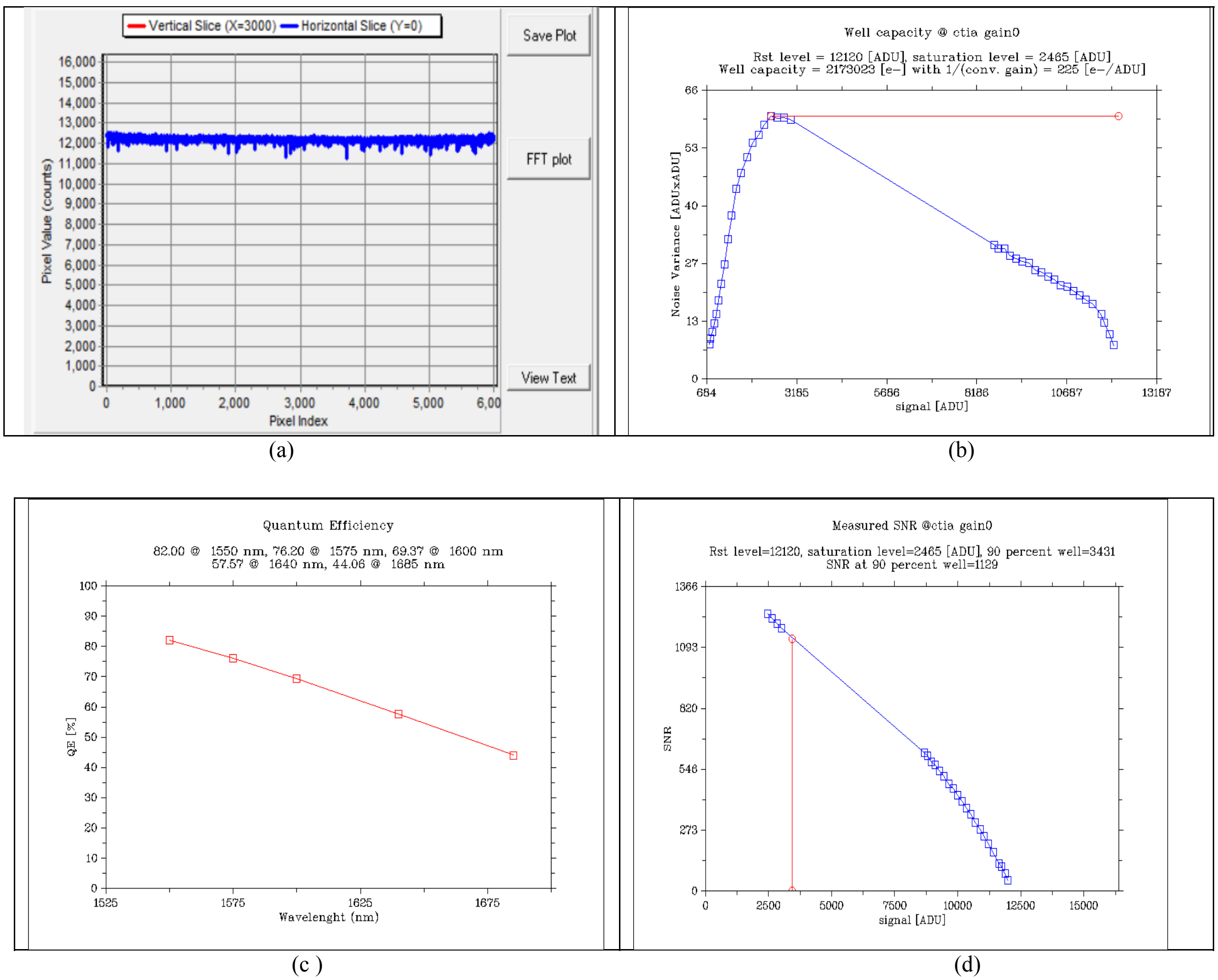


Fig.8. Electro-optic performance of a fully packaged Teledyne 6000 element InGaAs array: (a) dark signal image of selected 6000 pixels, (b) Noise variance (in ADU x ADU) versus signal (in ADU), (c) QE at 22ºC; and (d) SNR versus signal (in ADU).

4. CONCLUSION

Teledyne has developed a monolithic continuous 6000x8 element 13μm pitch InGaAs focal plane array image sensor and successfully packaged the sensor array in a back-filled hermetic package. The imager sensor chip assembly consists of a 6000x8-element InGaAs-ROIC hybrid, a patterned ceramic motherboard, and CTIA capacitors. The full sensor package includes an image sensor chip assembly, an optical slit, and an AR-coated sapphire window. The 6000x8-element assembly is capable of operating at any of the four CTIA gains on "read while integrating (RWI)" mode and offers two 14-bit uni-encoded serial LVDS outputs. We have achieved an ultra-low dark current of less than 3.5fA at 22ºC and a high QE greater than 80% at a wavelength near 1.58μm. The array sensor is highly responsive to IR signal in the wavelength range of 1.0μm to 1.68μm. The array sensor has a typical pixel full well capacity greater than 2 Me- and read noise lower than 600e-. The array sensor can be operated at 1kHz frame rate with an integration time close to one millisecond. The 6000-element array assembly is a ruggedized package suitable for commercial imaging and space remote sensing applications.

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