Two-color quantum well infrared photodetector focal plane arrays

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ABSTRACT

QmagiQ LLC, has recently completed building and testing high operability two-color Quantum Well Infrared Photodetector (QWIP) focal plane arrays (FPAs). The 320 x 256 format dual-band FPAs feature 40-micron pixels of spatially registered QWIP detectors based on III-V materials. The vertically stacked detectors in this specific midwave/longwave (MW/LW) design are tuned to absorb in the respective 4-5 and 8-9 micron spectral ranges. The ISC0006 Readout Integrated Circuit (ROIC) developed by FLIR Systems Inc. and used in these FPAs features direct injection (DI) input circuitry for high charge storage with each unit cell containing dual integration capacitors, allowing simultaneous scene sampling and readout for the two distinct wavelength bands. Initial FPAs feature pixel operabilities better than 99%. Focal plane array test results and sample images will be presented.

Keywords: QWIP, GaAs/AlGaAs, readout integrated circuits, focal plane arrays, dual band, two-color

1. INTRODUCTION

The easily tunable and relatively narrow spectral absorption band of GaAs based QWIPs coupled with the mature state of GaAs processing techniques provides a ready basis for fabricating large and complex FPAs optimized for a variety of unique systems and applications. QmagiQ LLC, began producing commercially available QWIP FPAs in 2003, the first of which was a small format 320x256 long wave (LW) infrared imaging array using the ISC9705 silicon readout integrated circuit (ROIC). The large format 640x512 LW FPA product followed using the ISC9803 ROIC. A joint program involving QmagiQ LLC, and FLIR Systems, Inc. lead to the development of a small format midwave (MW) FPA and a dual-band or 2-color (MW/LW) FPA using the ISC0006 ROIC. The resulting 2-color device contains a 320x256 array of spatially registered dual wavelength detectors that have high pixel uniformity and operability approaching those of their single color precursors, making them well suited for a variety of imaging applications. The fabrication and performance results of these 2-color infrared imaging FPAs are discussed.

2. FPA OVERVIEW

Creating the 2-color QWIP FPA involves flip-chip hybridizing individual QWIP detector array die to ISC0006 ROIC die, making electrical and structural contact between each QWIP pixel in the detector array and its respective charge integration unit cell circuit in the readout chip. After subsequent removal of the GaAs substrate from the back of the detector array, the completed FPA is ready for operation. A diagram of the hybrid chip unit cell is shown in Figure 1. The three terminal stacked QWIP pixel is attached to the ISC0006 ROIC such that one terminal of the MW QWIP connects to the Channel A bias and integration control, one terminal of the LW QWIP connects to Channel B, and the shared terminal between the two QWIPs connects to a global detector common (detcom) line.

This architecture allows an external voltage bias to be applied to the entire detector array with the capability of adjusting the effective bias for each color through digital controls in the ROIC. In addition to separate voltage bias controls, the ISC0006 provides independent integration time settings for each of the two channels. This versatile set of FPA controls allows a wide range of QWIP combinations to be operated effectively. The electrical characteristics of QWIPs depend largely on their operating temperature as well as the details of the specific detector design and what optical parameters that design has been tuned for (peak wavelength, spectral width, etc.). Inherent in the physics of multi-color QWIP arrays is the need to operate each color at a different bias to achieve optimal performance. Even the same FPA can be

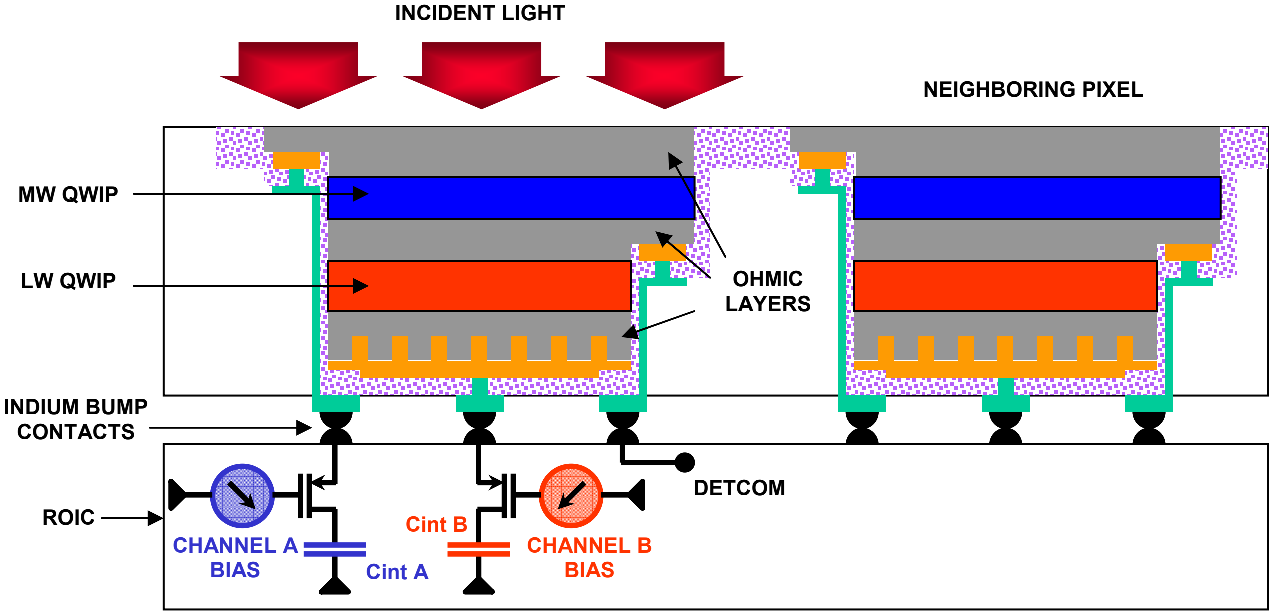

Figure 1 – 2-Color FPA Unit Cell

optimized for its specific application through the use of the independent bias and integration time controls available. For example, true spatially and temporally registered scene images can be obtained by setting the same integration times for both channels then adjusting the bias controls to optimize the charge collected from each spectral band.

The captured image information is read out of the FPA on two separate output lines, one for each color channel. The resulting data streams are time synchronized such that the integrated charge levels for both colors of any given pixel appear simultaneously at the output. Subsequent post processing can be performed in real time on a pixel-by-pixel basis without the need to analyze the two images as a whole after the entire frame has been read out.

3. READOUT INTEGRATED CIRCUIT

The ISC0006 is a high performance 2-color CMOS readout integrated circuit (ROIC) designed for use with QWIP GaAs/AlGaAs detectors. There are 320 by 256 pixels for each color on a 40 micron pitch with a shared unit cell. For each detector there is a p-channel direct injection input circuit supporting simultaneous, snap shot integration for both colors. The ROIC is designed for MWIR (color A) and LWIR (color B) spectral bands where the two colors are in the range of 4-5 and 8-9 microns, respectively. The input charge-handling capacity is > 17e6 carriers for the MWIR input and > 87e6 carriers for the LWIR.

The electrical interface of the ISC0006 consists of 4 clocks and 7 unique biases, of which 5 are fixed and 2 are user adjustable. The device operates in an integrate-then-read mode with variable integration time adjustments for each color. A 30Hz frame rate is supported for full frame readout. The ISC0006 employs advanced features such as on-chip skimming for dark current correction, adjustable detector bias and selectable gain for each color, an anti-blooming circuit, adjustable bias supply and power dissipation levels. The operating modes of the chip are controlled via a serial control register, a simple user interface.

The ISC0006 is fabricated using a standard mixed-signal 0.5-micron process with 3 metal and 2 polysilicon layers. The expected operating temperature range is 60 to 75K. In addition to the standard imaging mode, the chip also supports a test mode. This mode is set by a bit in the serial control register which converts the bloom gate to a unit cell test function, controlled via the detector bias circuit.

3.1 Analog Design

The ROIC is designed to interface with 2-Color 320 X 256 MWIR / LWIR QWIP GaAs/AlGaAs detectors with the input circuit configuration as direct injection (DI) for high density and high charge storage. The unit cell contains two integration capacitors, one for each color, which also operate as sample and hold capacitors supporting snap shot integration. The unit cell signal is read out in charge mode by a column charge amplifier during the interline dead time. The column amplifiers have a programmable gain (0.444x – 1.78x) and contain a voltage skimming function for removing dark current. The column output voltage is sampled, buffered, and then multiplexed to high bandwidth output amplifiers. The multiplexed signals are readout of the chip as analog voltages at a data rate of up to 6.25MHz. Figure 2 shows a block diagram of the signal chain.

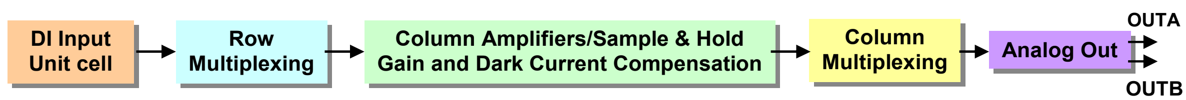

Figure 2 - ISC0006 Signal Chain Block Diagram

Several analog controls are available through external pads and the serial control register. These include power adjustment register bits to optimize power dissipation while achieving desired performance. The power adjust circuits can set currents in specific circuits to optimize column amplifier slewing and settling time requirements, multiplexer buffer drive conditions and analog output drive conditions. The master current of the chip can also be adjusted both through register bits and the external IMSTR_ADJ pad. Typically any adjustment for the master current source is to account for internal master resistor process variations. Register bits are also available to independently adjust the current in portions of the signal chain, such as the column amplifiers, multiplexer buffers, and analog output buffers. The chip's four gain states are set by bits in the serial control register with separate settings for each color. Also in the serial control register are bits for enabling the skimming function, used to adjust global offset independently for each color. Once enabled, the skimming level is controlled through the VOSA and VOSB pads by applying a voltage between VREF4 (3.6V) and VNEG, corresponding to skimming 0 to 100% of full well. The final analog adjustment is the detector bias and it can be controlled either through the serial control register bits or by applying a voltage to two VDET_ADJ pads. Each color has independent detector bias control, with the detector common voltage the same for both colors. The detector bias adjust controls the gate potential of the DI input stage.

3.2 Digital Design

As discussed in the previous section, the ISC0006 utilizes a serial control interface for adjusting parameters of the chip. Data is clocked into the serial control register through the DATA input pad. The seventy-four bit data word controls variable integration time, programmable on-chip gain, variable detector bias, skimming enable, programmable test and master reset. A control word is loaded once during a frame time and is only required when settings are changing. The chip operates in integrate-then-read (ITR) mode where TFrame ~ T_{Read} + T_{Int} + T_{Dead} as shown in Figure 3.

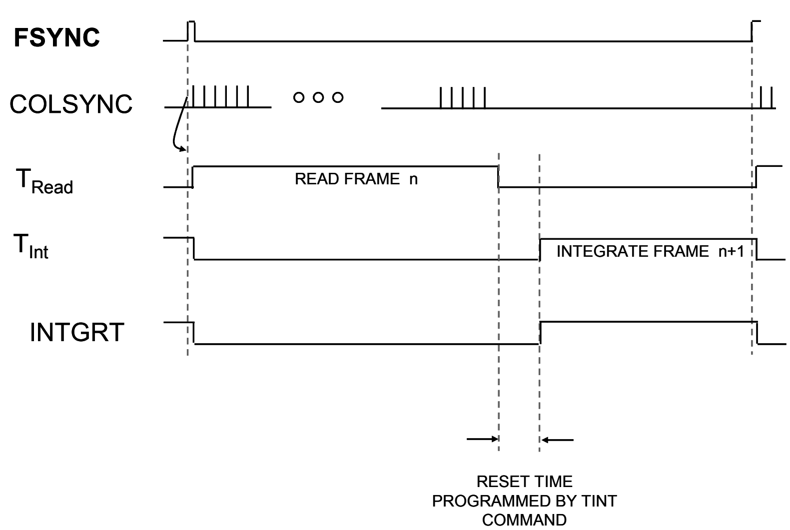

Figure 3. – Integrate-Then-Read Timing

The start of integration is programmable for each color and is controlled by the serial word command register. The rising edge of the FSYNC input clock triggers the global stop and hold of the integrated signal and the register word programs the number of lines of reset as shown in Figure 3. Integration ends simultaneously for both colors. The integration capacitor is reset on a row to row basis after being read out. An additional feature accessed via the serial control register is the vector enabled test used to monitor thirty-two internal signals through a switch matrix addressed by the VADD(4-0) register bits and monitored by the TESTOUT pad. A master reset command is also available by setting a bit of the serial register. This setting causes an internal circuit to generate a reset pulse upon power up of the chip. This resets all shift registers and control logic, applies default command settings (except VADD[4-0]) but does not reset the analog sample and hold values.

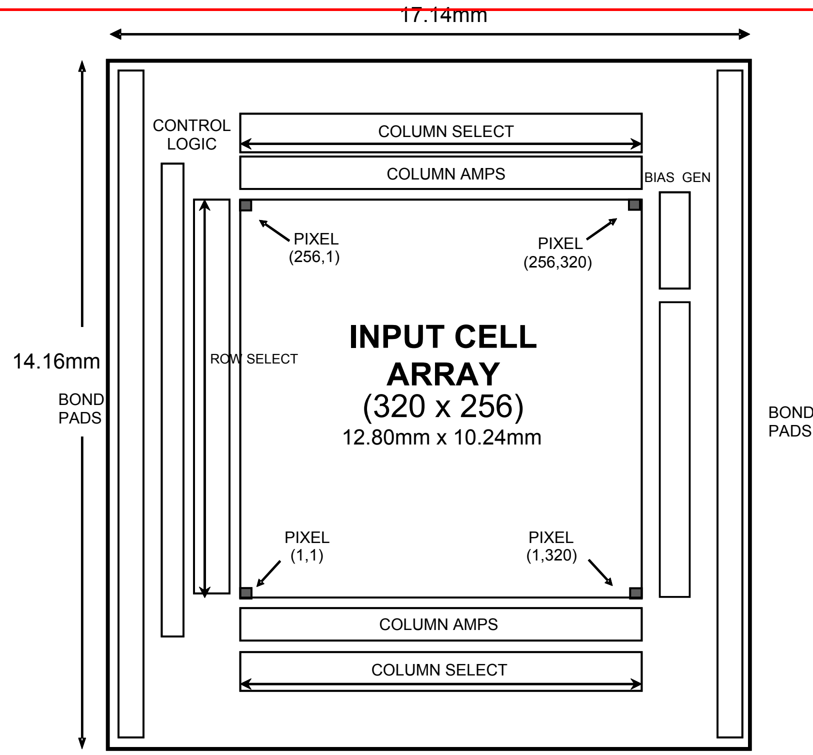

Figure 4 - ISC0006 Layout Block Diagram

3.3 Physical Design

The ISC0006 is fabricated on 200mm (8-inch) wafers using AMI's standard C5, 3 Metal / 2 Poly, N-well, standard mixed-signal process. The die size is 17.14mm x 14.16mm as measured to edge of scribe lane, resulting in 92 die per 8-inch wafer with a 90 micron scribe lane in X and Y directions. Figure 4 shows a block diagram of the chip layout.

The detector interface to the ISC0006 is an array of 328x264 pixels but has indium bumps only for the 320x256 array. Each 40-micron pixel contains two pads, one for each color, and a detector common pad. The indium bump pads on the readout are 9 x 9 microns with 5 x 5 micron pad openings. A detector unit cell quad is shown in Figure 5. For detector testing, 3 test detectors are included on the chip with 3 sets of pads for direct access to these QWIP detectors.

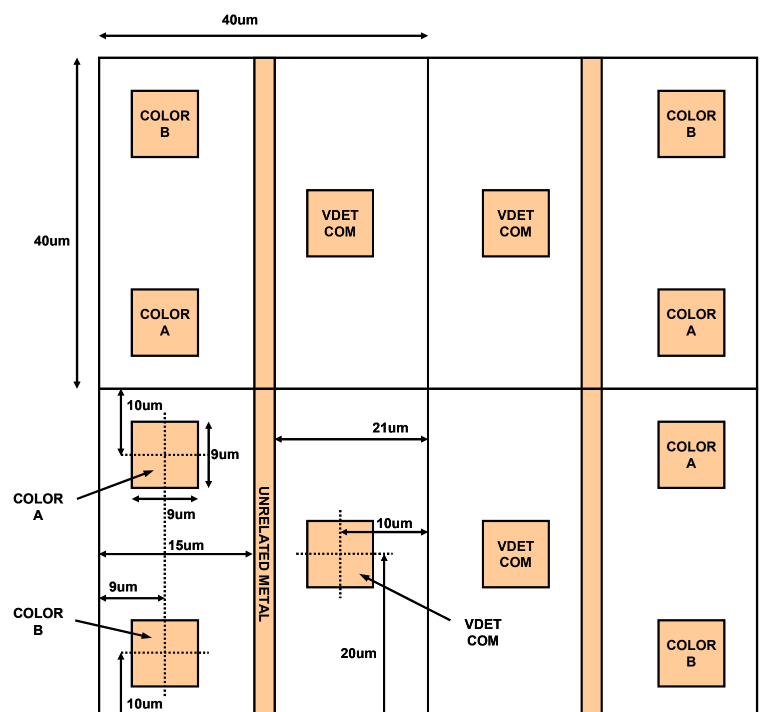

Figure 5 - Detector Unit Cell Quad Layout

4. DETECTOR AND FPA FABRICATION

The detector material is grown in production molecular beam epitaxy (MBE) reactors on 6-inch GaAs wafers. A single growth session yields the entire complex dual-band detector structure of bottom ohmic layer, MW InGaAs/GaAs/AlGaAs QWIP stack, middle or common ohmic layer, LW QWIP stack, and top ohmic layer. The front side detector wafer processing is all performed at the 6-inch wafer level using modern stepper lithography and dry etching techniques. These methods yield well controlled, highly uniform, and precisely defined detector device features, including the detector array pixelization, the vias needed to make electrical contact to the middle and bottom ohmic layers, and the optical coupling grating, all of which results in high pixel operability and performance uniformity across individual detector arrays as well as over the entire detector wafer. Deposited metal lines and indium bumps provide the electrical and mechanical features needed to connect the detector array to the ROIC.

Individual detector arrays are paired with ROIC die which have been similarly prepared with indium bump array contacts. A precision alignment compression technique brings the detector array and ROIC together, welding the indium contacts and forming the hybrid device. An epoxy underfill strengthens and supports the hybrid bond before the device undergoes a backside process to remove the GaAs substrate from the epitaxially grown detector material. This combination of mechanical and dry etch steps yields a completed FPA in which just a few microns of detector material remain on the surface of the ROIC.

5. PERFORMANCE

Detector characterization is performed on completely processed detector arrays that get hybridized to silicon fanout chips. These fanout chips mimic an actual ROIC such that the resulting fanout array sees the same processing steps that subsequent FPAs do, but it provides direct electrical connections to individual detector pixel contacts in the array, allowing the detector to be analyzed independent of the ROIC. These spectral response curves are shown in Figure 6 and include the effects of the pixel cavity, optical coupling grating, and epoxy absorption.

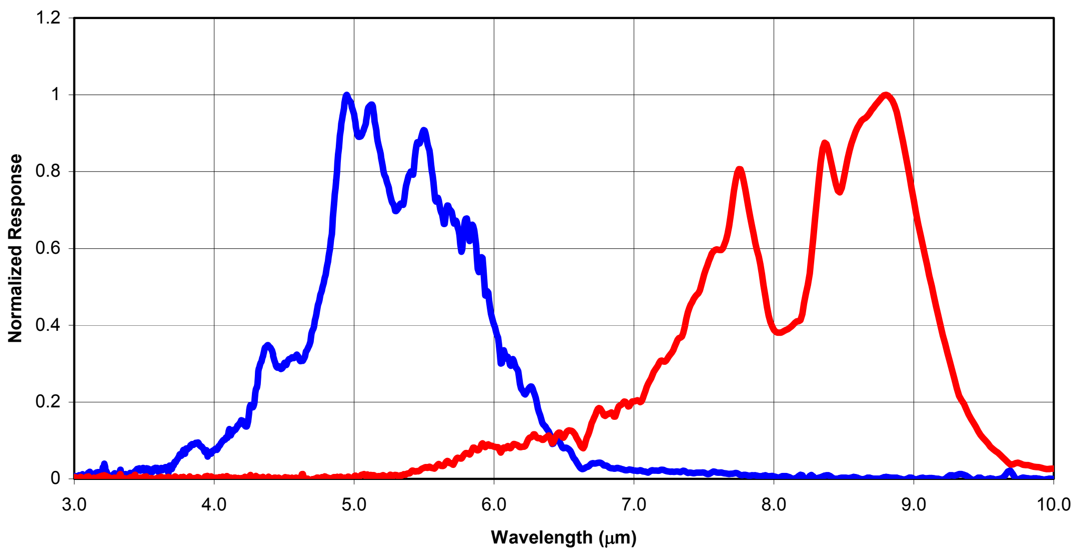

Figure 6 – 2-Color Spectral Response

The characteristically narrow spectral response of QWIP detectors leads to performance metrics that are defined in a slightly different way from their meaning in conventional wideband photodiodes or photoconductors. The blackbody response of a given pixel is the magnitude of the photocurrent resulting from the total (i.e., spectrally integrated) incident photon flux (determined by the source temperature, the dimensions of the pixel, and the geometry of the cold shield).

The peak response is calculated as the ratio of the photocurrent to the in-band incident optical power, determined by the spectral response specific to the detector. The external conversion efficiency is defined as the number of electrical charges collected in the external circuit per unit time normalized to the number of in-band photons striking the pixel. It is to be distinguished from the internal quantum efficiency, which is the ratio of the number of carriers photoexcited in the active region of the pixel per unit time normalized to the number of in-band incident photons. The conversion efficiency is normally smaller than the quantum efficiency because some of the photoexcited carriers disappear before they have a chance to reach the electrical contacts.

Completed FPAs are packaged in leadless chip carries for final test and characterization. The FPAs are operated at a temperature of 68K and characterized using an extended black body radiation source to generate uniform scene temperatures across a typical range of 10-50C. A sample test report describing the performance of a QmagiQ 2-color (MW/LW) FPA is included in Appendix I. Some points of note are the high pixel operabilities (>99.5%) and low noise equivalent temperature differences (NETD <45mK).

6. APPLICATIONS

Integration of the ISC0006 based 2-color QWIP FPA into an IDCA package has been undertaken at FLIR systems Boston site. The IDCA engine is based on FLIR's MC-5 family of high efficiency sterling rotary coolers. The gross cooling capacity of the MC-5 class is 650mW with a steady state input power of approximately 4W operating in a normal room temperature ambient. Based on FLIR Boston's extremely lean dewar design, the expected cooldown time for the coldtip is <5 minutes to achieve QWIP operating temperatures, typically about 70K. The entire IDCA package is approximately 500 grams in mass and is hand-sized.

Applications for a 2-color FPA based imaging system are operationally diverse. They stretch across commercial and military uses.

In the commercial markets, thermographic applications would benefit greatly from this technology. Emissivity is of primary importance in attempting to ascertain accurate and true object temperatures. Single color or single band optical radiometers rely on user knowledge or close estimate of the target emissivity in order to accurately determine true target temperature. Two color imagers make use of ratio-metric imaging (using the "2" spectral bands of the imager) to eliminate the need to know a target's emissivity and still determine its temperature. The basic requirement for a ratio-metric imager is that the target be a grey-body emitter or that the emissivity in both spectral bands be the same. Further, multi-band FPAs can be used to uniquely acquire imagery that is both temporally and spatially registered in two spectral bands. This type of highly correlated imagery can then be post processed to increase the user's knowledge of the target or scene of interest – this is especially important when considering ratio-metric imaging applications. Additionally, FLIR has recently introduced a new product line designed around imaging the spectral absorption of greenhouse gases and other volatile pollutants. Speciation and quantification of these types of emissions are further possible with a 2-color QWIP device. Multiple, simultaneous spectral imaging would permit more then just "seeing" the presence of a pollutant; with the right algorithmic processing, it could enable estimates of its mass over the optical path and its chemical composition.

In the military arena, this type of multi-spectral sensor technology has a wide range of potential uses: threat identification and discrimination, missile warning, simultaneous hard-body and plume imaging, reduction of IR clutter, extended environmental and battlefield imaging applications, mine detection, etc. The key to success in many of these applications is the judicious selection of the appropriate spectral bands. Different applications are better suited by various combinations of MW and LW spectral bands (i.e., MW/MW, MW/LW, LW/LW, etc.). Through a combination of modeling and field measurements, the optimum spectral band combinations can be determined. Two-color QWIP technology is well suited to band optimization with FPAs already built and fielded in a wide range of band combinations across the 3 – 12um region.

One of the challenging areas related to 2-color IR systems is the design and development of 2-color optical lenses. Mirror systems (which do not suffer from chromatic aberrations) are not always the best choice for small, compact 2-color sensors. Refractive optics are typically sought after, but their design must always consider the ability to achieve spectral parfocality so that both images are always in simultaneous focus. This can be difficult, especially for spectral bands that are widely separated. Further, depending upon the intended application, there could be substantially conflicting requirements for optical aperture or F/# in a two color system – this must also be properly addressed to achieve an effective 2-color sensor system.

CONCLUSIONS

The 2-color pixel registered QWIP FPAs described here provide a previously unavailable option for the diverse application space of 2-color imagers. Many of the 2-color imagers to date have been used for research applications, application-specific field measurement programs, and laboratory experiments. In the future, these types of systems will be more commonplace and raise-the-bar on IR sensor imaging capabilities.

Until these sensors are out in the field in larger numbers, many of the applications and true potential of this technology won't be discovered or fully exploited. It is clear, however, that once a technology like this becomes part of our everyday IR arsenal, more and more applications will emerge.

ACKNOWLEDGMENTS

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APPENDIX I
DUAL-BAND MW-LW

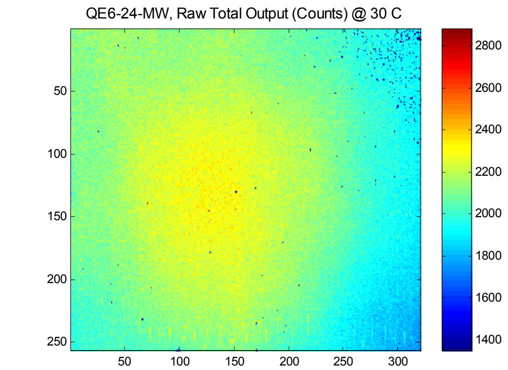
Midwave Summary

QE6-24-MW
320x256
ISC0006 ROIC

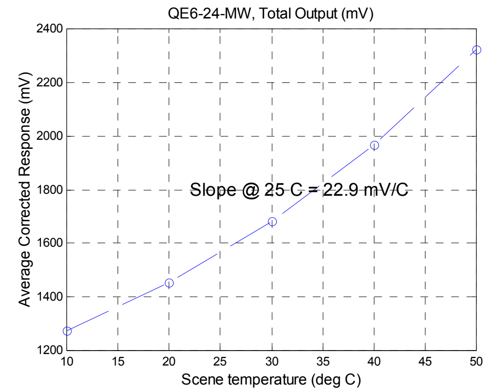
PARAMETER	VALUE	UNITS	CRITERIA
Active array size	320 x 256	-	
F/number	2.3	-	
ROIC gain setting	1.33	-	
Integration time	17.78	ms	
Frame rate	31	Hz	
FPA Temperature	68	K	
QWIP bias	0.55	V	
Aperture-corrected DC output μ	1685.7	mV	
Aperture-corrected DC output σ	42.2	mV	
Aperture-corrected DC output σ/μ	2.50	%	
Differential response mean μ	22.9	mV/°C	
Differential response st. dev. σ	1.1	mV/°C	
Differential response σ/μ	4.82	%	
Mean blackbody responsivity†	6.0	mA/W	@ -1V bias
Mean peak responsivity†	74.7	mA/W	@ -1V bias
Mean conversion efficiency	1.00	%	@ actual bias
Differential response failures	298	-	>± 3 σ
Mean rms noise	5.8E-11	mA	
Mean temporal NEΔT	42.2	mK	
Mean noise-equivalent power	7.7E-13	W	@ actual bias
Mean peak D*	2.6E+10	cm-Hz$^{1/2}$/W	
Spatial NEΔT mean μ	76.8	mK	
Post NUC nonuniformity (σ/μ)	0.18	%	
ROIC power dissipation	78.3	mW	
Number of defective pixels	298	-	
OPERABILITY	99.64	%	

† Normalized to 1-V bias and unity mux gain.

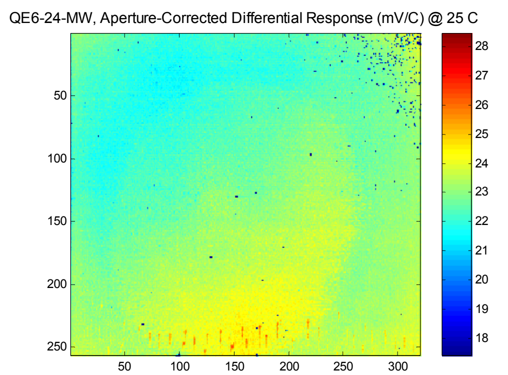
Midwave Details



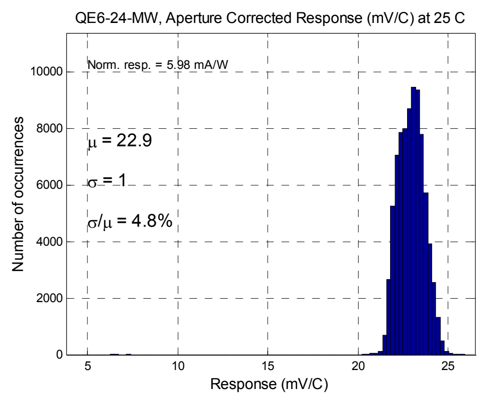
2-D plot of total output.



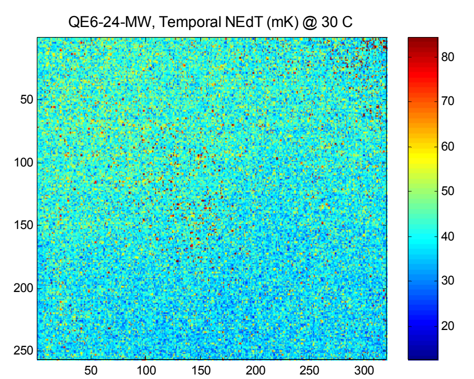
Average output vs. scene temperature.



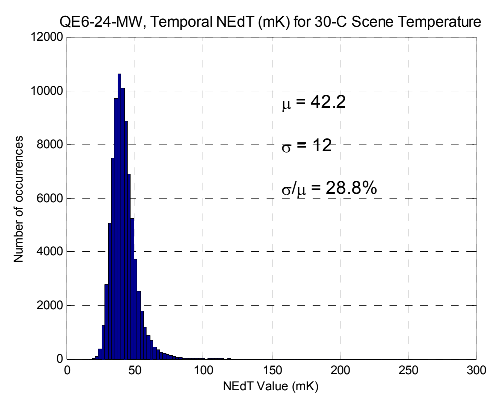
2-D plot of aperture-corrected optical response.



Histogram of aperture-corrected optical response.



2-D plot of NEΔT.



Histogram of NEΔT.

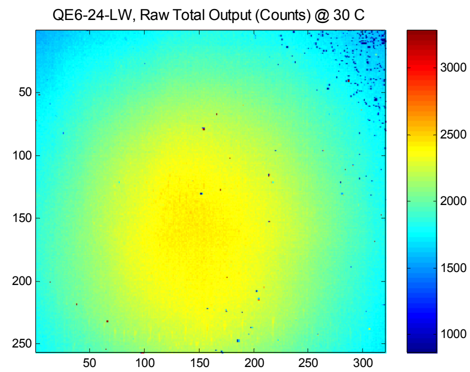
Longwave Summary

QE6-24-LW
320x256
ISC0006 ROIC

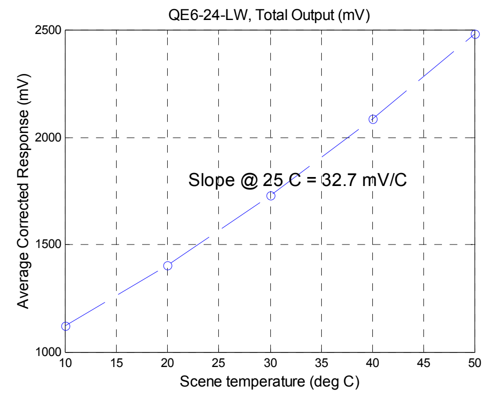
PARAMETER	VALUE	UNITS	CRITERIA
Active array size	320 x 256	-	
F/number	2.3	-	
ROIC gain setting	2	-	
Integration time	17.78	ms	
Frame rate	31	Hz	
FPA Temperature	68	K	
QWIP bias	1.06	V	
Aperture-corrected DC output μ	1732.9	mV	
Aperture-corrected DC output σ	23.8	mV	
Aperture-corrected DC output σ/μ	1.37	%	
Differential response mean μ	32.7	mV/°C	
Differential response st. dev. σ	1.3	mV/°C	
Differential response σ/μ	3.95	%	
Mean blackbody responsivity†	14.6	mA/W	@ -1V bias
Mean peak responsivity†	117.0	mA/W	@ -1V bias
Mean conversion efficiency	1.78	%	@ actual bias
Differential response failures	377	-	>± 3 σ
Mean rms noise	2.2E-10	mA	
Mean temporal NEΔT	34.1	mK	
Mean noise-equivalent power	1.9E-12	W	@ actual bias
Mean peak D*	1.1E+10	cm-Hz$^{1/2}$/W	
Spatial NEΔT mean μ	71.5	mK	
Post NUC nonuniformity (σ/μ)	0.21	%	
ROIC power dissipation	78.3	mW	
Composite number of bad pixels	377	-	
COMPOSITE OPERABILITY	99.54	%	

† Normalized to 1-V bias and unity mux gain.

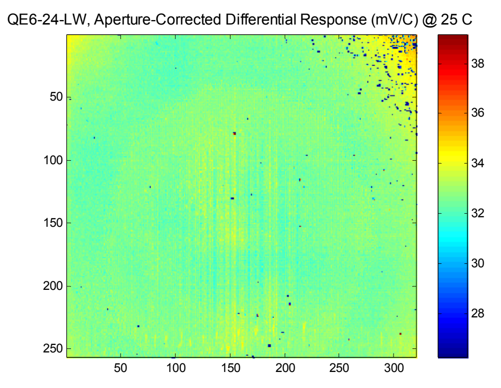
Longwave Details



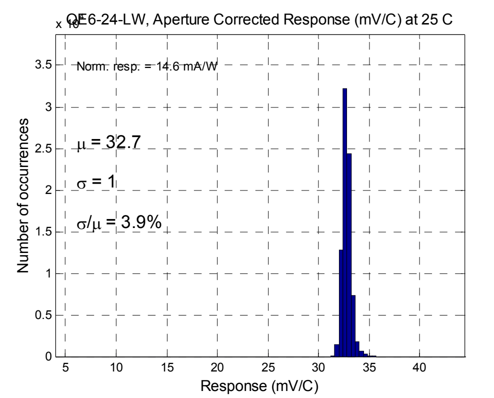
2-D plot of total output.



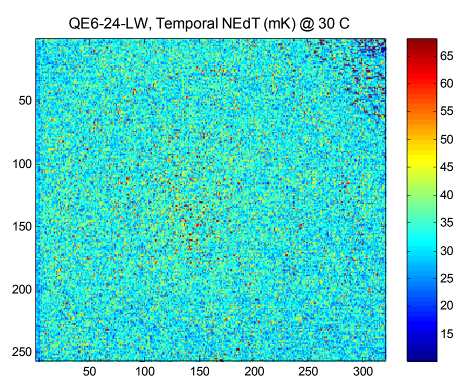
Average output vs. scene temperature.



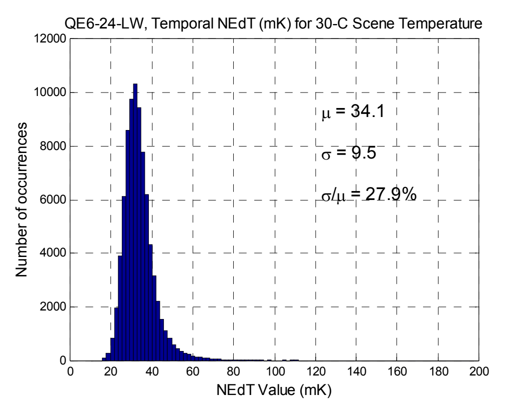
2-D plot of aperture-corrected optical response.



Histogram of aperture-corrected optical response.



2-D plot of NEΔT.



Histogram of NEΔT.