Extended short wavelength spectral response from InGaAs focal plane arrays

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ABSTRACT

InGaAs detector material used in near infrared focal plane arrays (NIR FPAs) has typically been limited in spectral response to a range from approximately 900 nm to 1700 nm. Through special processing techniques, the spectral response can be extended down through the visible spectrum and into the ultraviolet. Test results showing preliminary spectral response from 350nm to 1700 nm, responsivity, sensitivity, corrected uniformity and simultaneous imaging of NIR and visible signals will be presented along with a discussion of anticipated applications for this new sensor technology.

Keywords: InGaAs, NIR, FPA, spectral response, VisGaAs

1. INTRODUCTION

InGaAs FPAs and the imaging systems into which they are incorporated are used in a variety of commercial and military applications. These applications include various types of laser imaging including characterization of the beam and imaging with NIR laser illumination. [1] Other applications include imaging through paint for forensic analysis, outdoor imaging using nightglow and incorporation into spectroscopic instruments. [2] While other sensor technologies are equally capable of covering all or parts of the NIR spectrum covered by standard InGaAs FPAs (900 to 1700 nm), most other technologies have some drawback that make then less attractive. InSb can be used to cover the same range with a high performance sensor but requires cryogenic cooling, resulting in a higher cost, and lower reliability camera due to the sterling cooler. Short wavelength HgCdTe, like InGaAs does not require cryogenic cooling, but is relatively more expensive due to limited commercial availability of he detector material. Pyrometers can be used in many NIR applications, but offer significantly reduced sensitivity when compared to photon detectors.

While standard InGaAs imaging systems are a good match for many applications, there are some applications that require or would benefit from enhancement of the spectral response of commercially available InGaAs FPA and cameras. Specifically standard InGaAs is not ideal if the application requires imaging 850 nm laser designators along with other longer wavelength NIR lasers. A second camera would be required to provide high sensitivity imaging of the 850 nm laser. In other instances, NIR imaging under daylight conditions provides an excellent high contrast image, but will not accurately reflect a scene's visible information content due to differences in spectral reflectivity and absorptivity of the objects in the scene. For example, painted-on numbers and letters may not be detectable with a NIR-only camera.

With these applications in mind and others yet to be discovered, Indigo Systems has developed a method for processing standard InGaAs detector material. This processing method enhances the short wavelength spectral response, extending the cut-on wavelength down to 350 nm. To distinguish the InGaAs material processed to detect shorter wavelengths from standard InGaAs, J. Barton has coined the term VisGaAs. This term will be used throughout the paper and InGaAs used to describe either the standard spectral response material or as a reference to the chemical composition of both detector types.

This paper details the test results for two different processing runs of VisGaAs detectors built into FPAs and integrated into camera systems. Measurements include, spectral response, responsivity, uncorrected uniformity, sensitivity, pixel operability, and corrected uniformity. These performance results will be discussed with respect to standard InGaAs

Infrared Technology and Applications XXIX, Bjørn F. Andresen, Gabor F. Fulop, Editors,
Proceedings of SPIE Vol. 5074 (2003) © 2003 SPIE · 0277-786X/03/$15.00

performance on the same readout integrated circuit (ROIC) and as they relate to performance requirements for imaging applications. Still images of scenes having both visible and NIR spectral content are also presented.

2. SENSOR PERFORMANCE MEASUREMENTS

2.1 Configuration

2.1.1 VisGaAs FPA overview

Die from VisGaAs detector material from the first two processing runs were hybridized with Indigo Systems ISC9809 readout integrated circuits to form FPAs. The first processing run yielded one FPA designated ENG 1. The second processing run yielded two FPAs, S/N 467 and 468. Data in this paper is from ENG 1 and S/N 467. The performance of S/N 468 was similar, but that FPA was not characterized as completely, as was S/N 467. Standard InGaAs FPAs are typically finished with an anti-reflective (AR) coating to enhance quantum efficiency and minimize image artifacts that may result from excessive energy being reflected off the FPA surface. This AR coating has been optimized for 900 to1700 nm performance, but has significant reflectance in the visible spectrum. In order to get meaningful spectral response data both VisGaAs FPAs were fabricated with no AR coating.

Because FPA capability and performance is closely tied to the performance and capability of the ROIC, it is useful to review the specifications (Figure 1) of the ISC9809 ROIC. [3] This device was originally designed for use with InGaAs detectors and as such is also ideally suited for use with VisGaAs detectors. The ISC9809 is also one of several ROICs that interface to the Indigo Systems Phoenix camera allowing the FPA to be integrated into a complete camera system.

Parameter	Specification
FPA format	320 x 256 pixels
Pixel pitch	30 x 30 microns
Storage capacity, high gain	1.7E3 electrons
Storage capacity, low gain	3.5E6 electrons
Input circuit	CTIA
Integration type	Snapshot
Integration mode	Integrate then read, Integrate while read
Integration time	Adjustable > 500 ns
On-chip adjustable gain	1x (low) , 20 x (high)
Windowing	Dynamic adjustment of position and size
Number of outputs	1,2,or 4
Maximum frame rate	340 Hz (full frame)
FPA parameter control	32 bit serial data word

Figure 1: Specifications of the ISC9809 ROIC

2.1.2 Phoenix camera overview

By integrating the VisGaAs FPA into a Phoenix camera head (front end) and configuring the camera to operate with a Phoenix Real Time Imaging Electronics (RTIE or backend) video processing unit, complete camera level performance was obtained and compared to commercial Phoenix InGaAs systems. Because the relevant FPA mechanical dimensions are the same between InGaAs and VisGaAs FPAs, no modifications to either the FPA package or the Phoenix Camera head were required.

The Phoenix camera head consists of an FPA package, power supply and digitizer electronics assembled into a sealed ruggedized housing. The FPA package is a vacuum evacuated assembly that contains the FPA mounted on a thermal electric cooler for temperature stabilization and isolation from the external environment. The digitizer electronics provides all the necessary clocks, and biases to the FPA and performs the analog to digital conversion of the FPA output.

The Phoenix RTIE receives the digitized output from the camera head and performs various digital signal processing on the uncorrected signal (See Fig. 2). [4] The first step in this processing is the application of a non-uniformity correction (NUC)to each pixel in the data stream in real time. Right after NUC, any bad pixels in the image are replaced. This allows both analog and digital video to have both NUC and bad pixel replacement applied. Both of these functions can be user disabled/enabled independently on either the analog or digital video output. It is the digital output that was used for data acquisition. Refer to figure 3 for a listing of Phoenix camera specifications

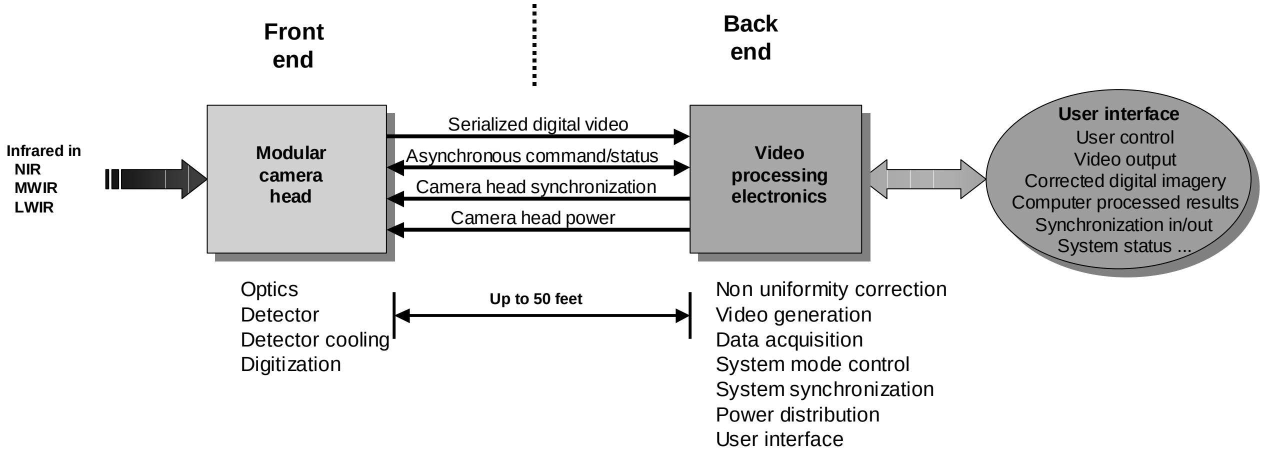

Figure 2: Phoenix RTIE camera architecture overview

Parameter	Specification
Detector types supported	InGaAs (VisGaAs), QWIP, InSb, other P-on-N / N-on-P photo-detectors
FPA formats	320 x 256 or 640 x 512
Sensor cooling method	Thermal electric stabilization (InGaAs), Sterling cycle (InSb, QWIP)
Optical interface	C-mount (InGaAs), bayonet (InSb, QWIP)
Video output	NTSC, PAL, RS-170, S-video
Digital output	14 bit non-uniformity corrected
Non-uniformity correction	Gain and offset per pixel in real time
Corrected uniformity	<0.2% low gain, <0.35% high gain (for InGaAs)
Sensitivity (noise equivalent irradiance)	<1.5E-7 Watts/(cm^2) low gain, <3.0E-10 Watts/(cm^2) high gain
Automatic gain control	Linear and non-linear histogram based algorithms, manual control
Bad pixel replacement	Nearest neighbor algorithm applied to analog and digital video
Triggering capability	External sync to start integration, genlock
Camera control	Via RS-232 port

Figure 3: Specifications of the Phoenix RTIE camera system

2.1.3 Measurement hardware, software and data collection

In addition to the Phoenix camera already described, several other pieces of hardware and software were used to gather and analyze the data. To provide quantifiable amounts of input energy to the sensor both a cavity type blackbody and a visible light integrating sphere were used. The blackbody was an Infrared Industries, 1 inch high temperature cavity style blackbody, model number IR201. The integrating sphere consists of a 1.7 inch diameter head, model number 11601 and a controller, model number 912G both manufactured by Santa Barbara Infrared. The 14 bit digital video from the RTIE was acquired using a Bitflow Roadrunner model RUN-PCI-12 M. Acquisition sequences up to 128 consecutive frames were to measure noise, responsivity and uniformity.

2.2 Spectral response

Spectral response was measured for FPAs ENG1 and S/N 467. The integrating sphere was used to provide broadband signal of sufficient intensity to narrow band-pass spectral filters to provide signal at distinct wavelengths across the uv, visible and NIR bands. The filters were placed directly in front of the sensor with only the FPA package window in between the filter and FPA. Since each filter had a bandwidth of 40 nm, care was taken to minimize light leaks that would otherwise contaminate the measurement. Each filter was scanned for transmission and out of band leakage to allow accurate calculation of expected photon flux at the FPA. The FPA window is made of BK-7 glass with a broadband anti-reflective coating on both sides. Measurement of the window indicated that it would not interfere with spectral response measurements.

Figure 4 shows the normalized response versus wavelength of FPAs ENG 1 and S/N 467. For reference a plot of the spectral response of standard InGaAs is also provided on the same chart. Data markers on each plot indicate the wavelengths where data was taken. Since InGaAs FPAs are photon detectors the un-normalized response data was measured in units of quantum efficiency, electrons per photon.

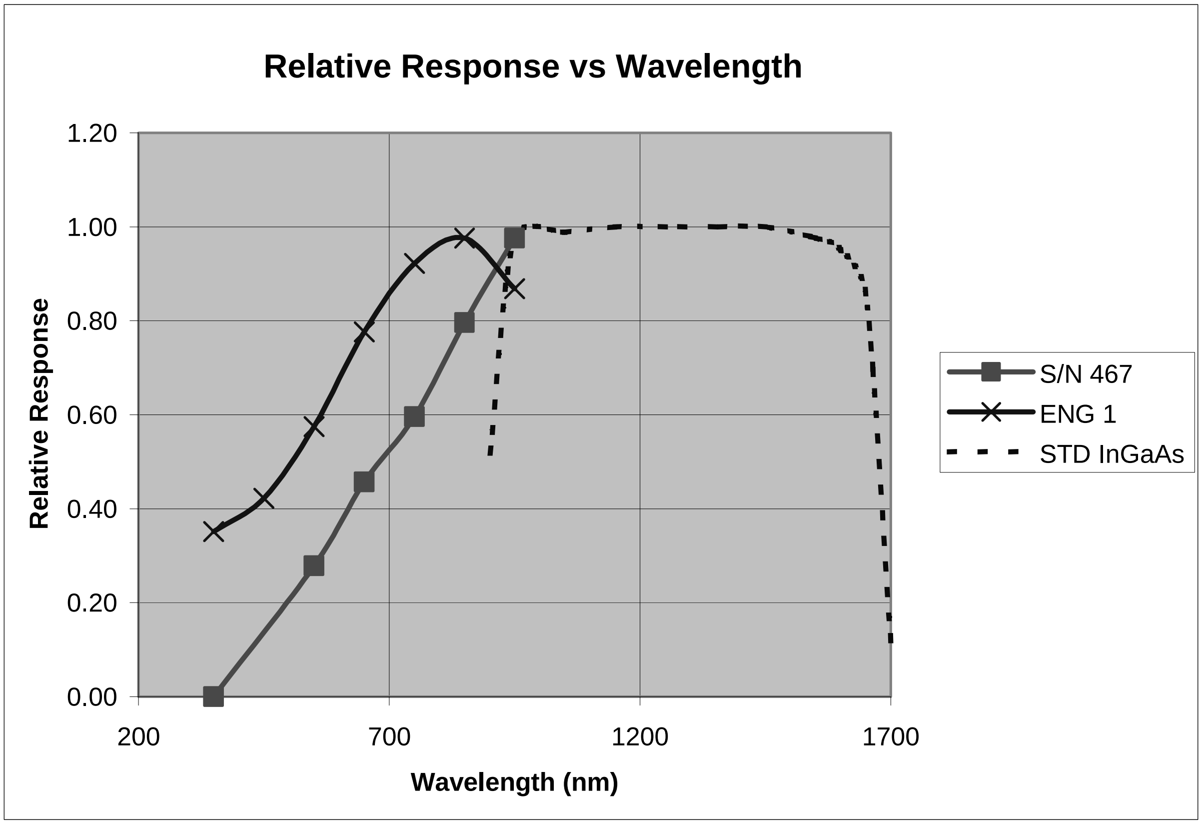

Figure 4: Spectral response of VisGaAs FPAs S/N 467 and ENG1

As can be seen from Figure 4, both VisGaAs FPAs show enhanced short wavelength spectral response beyond the wavelength where standard InGaAs cuts off. Spectral response was not measured at wavelengths beyond 950 nm due to a lack of longer wavelength narrow band-pass filters. However, FPA S/N 467 was measured for broadband NIR quantum efficiency from 1276 to 1605 nm with an average value across 3 measurements of 0.60. This value agrees fairly well with 0.67, the value expected for uncoated InGaAs based on Fresnel reflection losses.

ENG 1 showed relatively better short wavelength response than S/N 467 and was able to image wavelengths as short as 350 nm (Fig. 5). Both sensors showed no response at 250 nm. The slight upturn in response on ENG 1 at 350 nm is attributed to a light leak not found in the test configuration at the time of that measurement. Subsequent outdoor imaging with ENG 1 indicated slight image retention when viewing scenes of high intensity and significant short wavelength spectral content for extended periods. The image retention can be seen when moving off to a low contrast low intensity scene and is of the order of 10 counts higher intensity than the uniform low intensity scene. Initial speculation on the effect was that it was related to the uv response. S/N 467 was fabricated at a later date with a slightly modified process to reduce the uv response and image retention. Initial image retention tests on S/N 467 performed imaging the sun, indicate that image retention is completely eliminated, though further investigation is required.

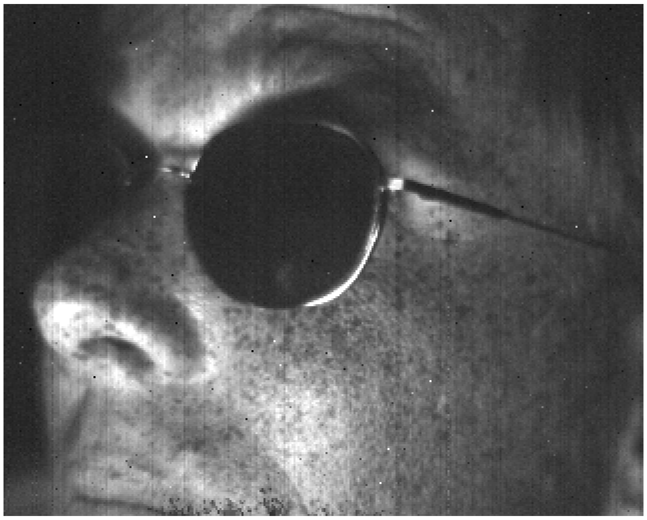

Figure 5: A face illuminated with a uv light, imaged by ENG 1. Dark skin blotches are sun damage revealed by uv illumination. [5]

2.3 Responsivity

The responsivity of FPA S/N 467 was measured by uniformly illuminating the FPA with broadband light from the integrating sphere. No filters were used in this measurement. Two levels of illumination were selected and a sequence of 64 frames was captured at each illumination level. Each frame sequence was averaged together and then the two frames were subtracted from each other. By controlling the illumination levels, the FPA integration time, knowing the spectral response and the internal transfer function of the FPA, responsivity in units of Amps/Watt can be calculated. Figure 6 shows a histogram of responsivity values. The average value of 0.35 A/W is comparable to standard InGaAs, as expected. As important than the mean value of responsivity is the uniformity. The responsivity uniformity is a significant driver in the overall amount of non-uniformity before correction. If there is a significant amount of pre-NUC non-uniformity, the total system dynamic range will be unacceptably reduced by individual pixel output variations at the A/D converter. The responsivity non-uniformity is typically defined to be the standard deviation divided by the mean, resulting in a value of 2.6%. This value is well below 5%, the usual specification set by Indigo for InGaAs and InSb FPAs.

Lastly, the responsivity measurement gives a first indication of total FPA operability by screening for pixels with low (no) responsivity. A typical requirement for operability is that a pixel have responsivity of at least 50% of the mean responsivity to be considered operable. Using this definition approximately 0.2% of the pixels are classified as inoperable or 99.8% of the pixels are operable. This value exceeds Indigos present operability specification of 99.5% for standard InGaAs FPAs and is a good indicator that the VisGaAs process does not negatively impact operability.

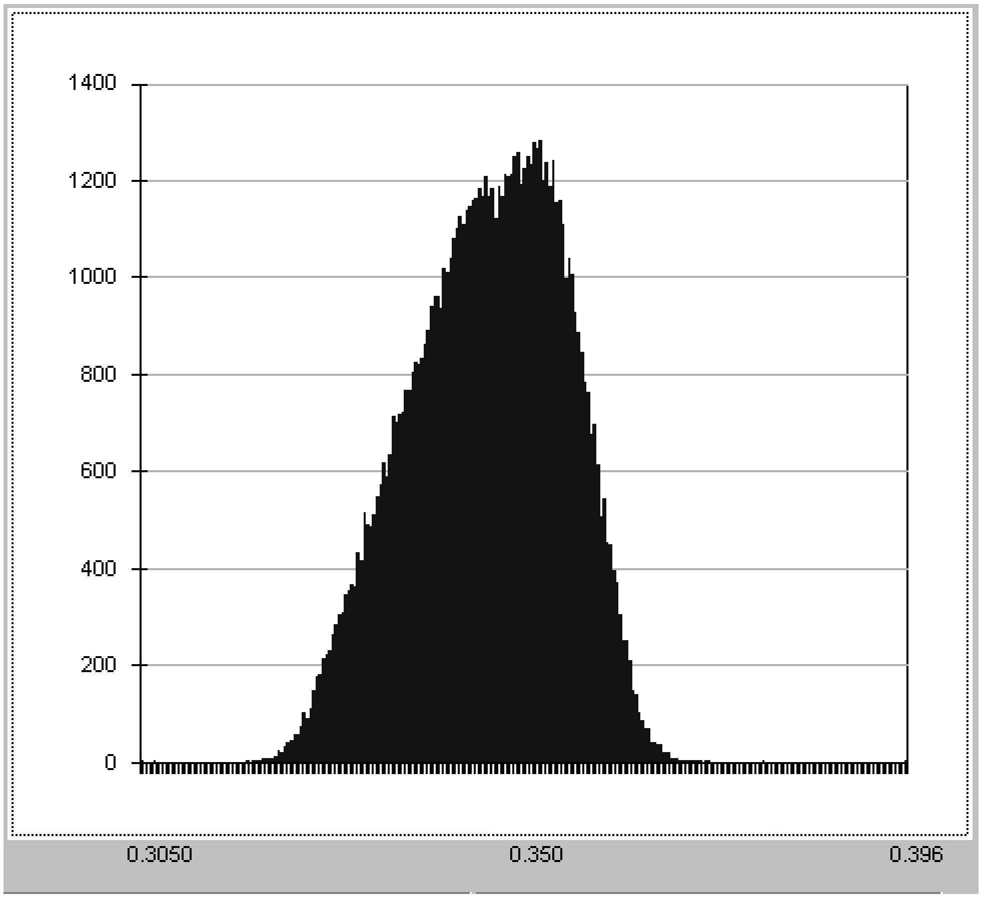

Figure 6: FPA S/N 467 responsivity histogram

2.4 Sensitivity

Sensitivity is a critical performance parameter for FPAs and camera systems. It defines the camera's capability to resolve small changes in scene intensity. A typical figure of merit used to quantify sensitivity is noise equivalent irradiance (NEI) expressed in terms of watts per square centimeter. NEI is the change in received power at the FPA surface required to generate a change in signal equal to the temporal noise level for that particular set of operating conditions. NEI was measured as a function of wavelength for FPA S/N 467, using the filters described in section 2.2. Figure 7 shows a plot of FPA average NEI versus wavelength in both high and low gain modes. As expected, the high gain mode shows better sensitivity at every wavelength. The values plotted at 1445 nm are from the broadband 1276 to 1605 nm filter. This is the same filter used for testing standard InGaAs FPAs. The values at 1445 nm of 1.6E-9 W/cm^2 and 3.5E-10 W/cm^2 meet Indigo's published specification for standard InGaAs FPAs, indicating excellent NIR sensitivity. The general trend to higher NEI values at shorter wavelengths is explained partly by the reduced quantum efficiency at shorter wavelengths. At first glance, there appears to be a very significant reduction in sensitivity. However, much of the trend to higher NEI at shorter wavelengths can be explained by the higher energy per photon at shorter wavelengths, making the upward curve an artifact of the units (watts) chosen to express NEI.

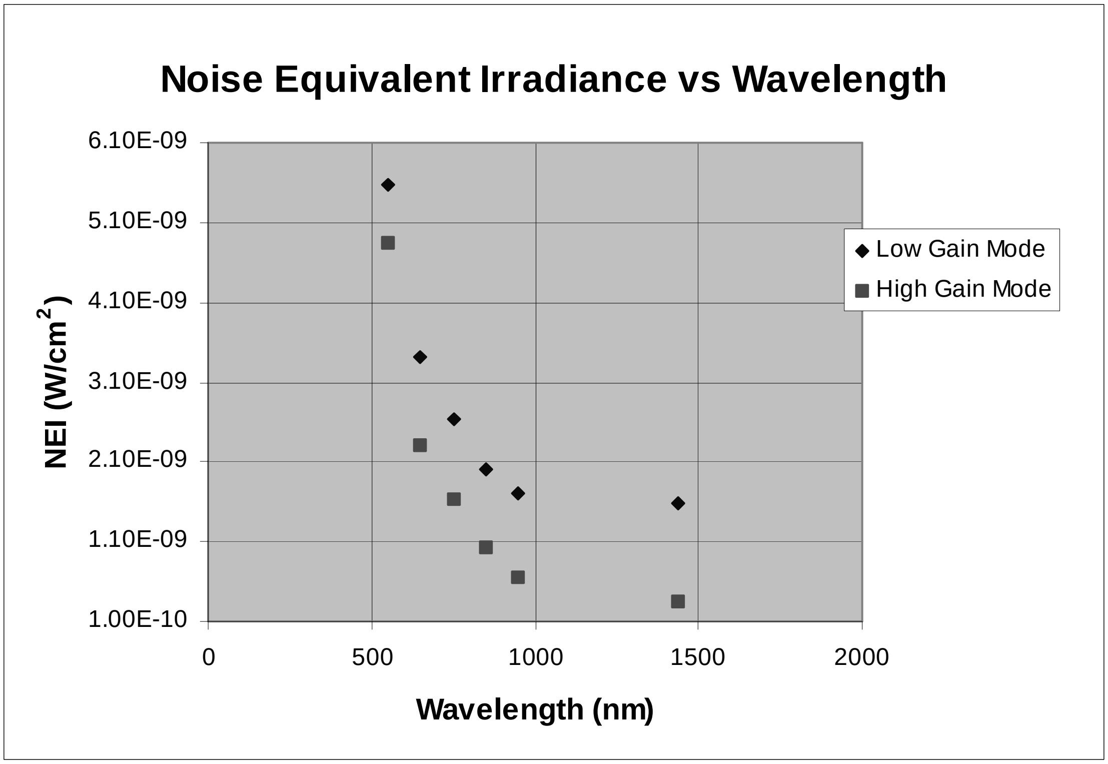

Figure 7: Camera sensitivity as a function of wavelength

2.5 Corrected uniformity

While mean per pixel sensitivity is a crucial aspect of camera performance, the sensitivity can only be put to use if the camera also has excellent uniformity. Without excellent uniformity, pixel-to-pixel variations in the camera's output when viewing a uniform scene make it difficult to distinguish between small variations in actual scene intensity and small differences between pixels. Since detector characteristics can influence parameters like linearity, which have a direct influence on uniformity, it is important to characterize uniformity for new FPA types.

Typically uniformity is measured by calculating the standard deviation in pixel output across the FPA when viewing a uniform source. If a NUC has been applied to the image, this measurement is often described as residual non-uniformity after correction or fixed pattern noise. On a frame-by-frame basis image uniformity is also reduced by pixel-to-pixel temporal variations (temporal noise). Since temporal noise variations place a limit on frame-to-frame uniformity, it can be useful to plot fixed pattern noise together with temporal noise across a sensor's dynamic range. In general, if the fixed pattern noise value is less than the temporal noise value then the non-uniformity correction is sufficient. By calculating the square root of the sum of the squares of the temporal noise and fixed pattern noise values at each point in the dynamic range a value for total noise can also be found.

Figures 8 and 9 are plots of uniformity as a function dynamic range in high and low gain modes respectively. In the case of high gain mode operation, the temporal noise exceeds spatial noise across nearly the entire range of the FPA, indicating an excellent non-uniformity correction can be achieved with VisGaAs FPAs. The flux range spanned in high gain mode was from 1E6 to 2E7 photons/(pixel*sec). The uniform illumination was produced by the integrating sphere with no filters in the optical path. In the case of low gain mode operation, the temporal noise exceeds the spatial noise from 20% in the dynamic range to the 80% point in the dynamic range. While not as good as high gain mode, this level of performance is similar to standard InGaAs and again indicates that VisGaAs FPA uniformity meets the requirements of a high performance camera system. The flux range in the low gain measurement was from 2E7 to 2E8 photons/(pixel*sec).

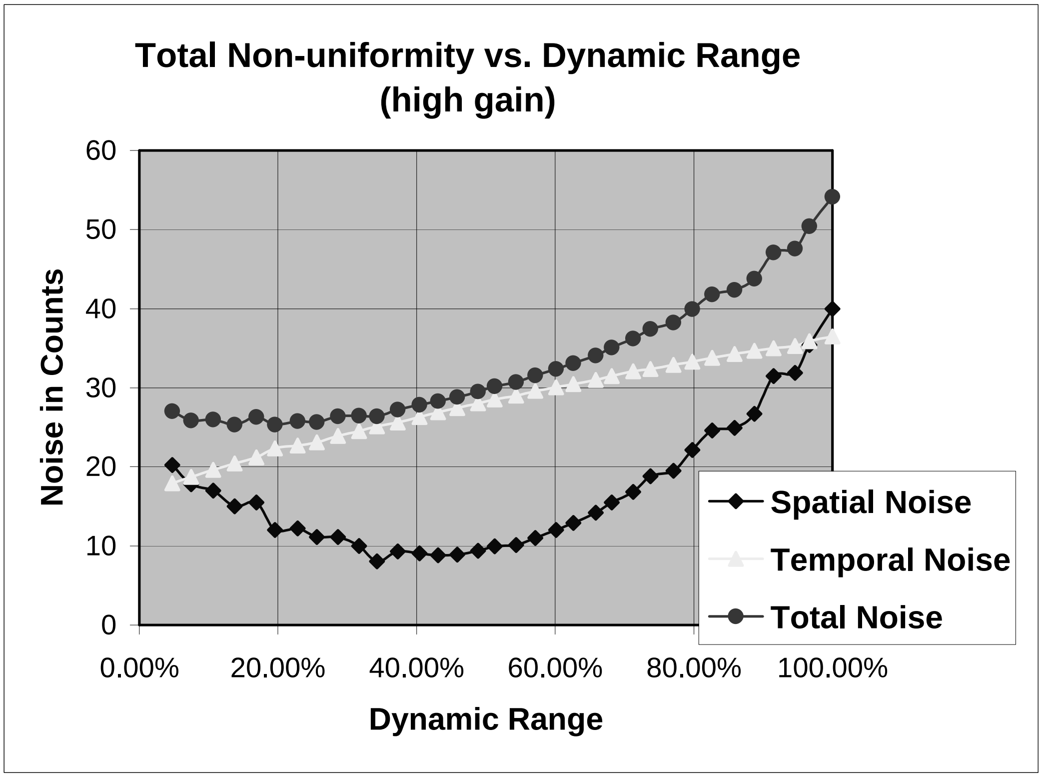

Figure 8: Non-uniformity in high gain mode

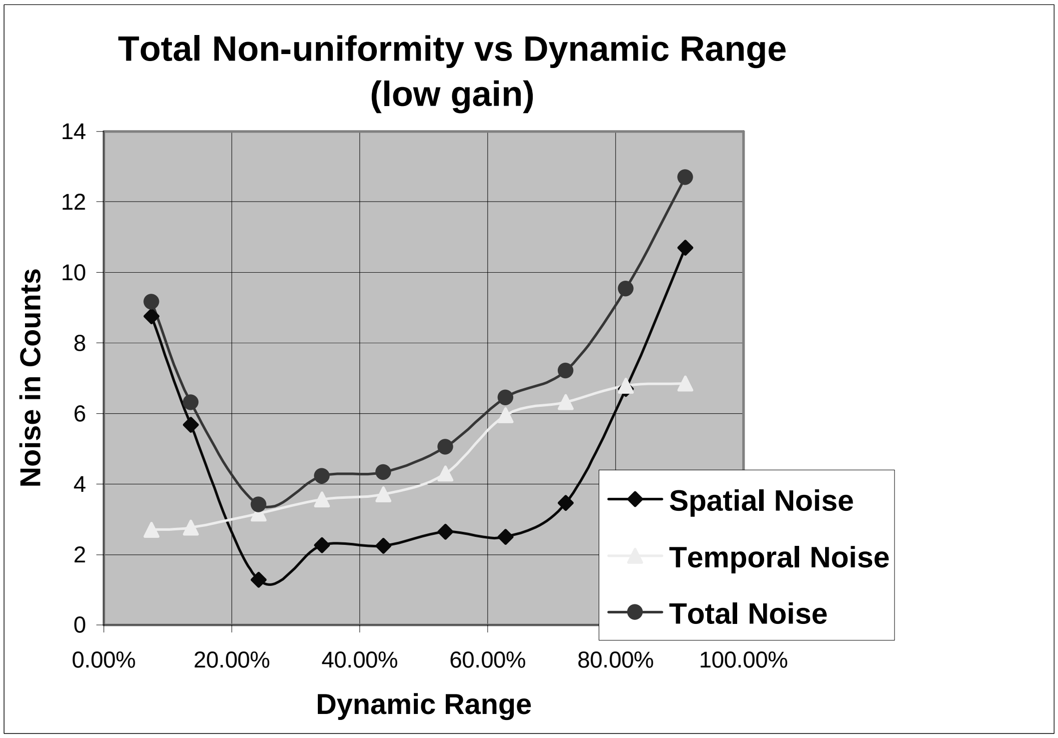

Figure 9: Non-uniformity in low gain mode

2.6 Imagery

2.6.1 Indoor imagery

Images of indoor and outdoor scenes were acquired to demonstrate camera capabilities such as simultaneous acquisition of imagery with NIR and visible content and to show typical image generation capability in an attempt to associate image quality with measurements such as corrected uniformity. Figures 10 and 11 are indoor pictures taken under low illumination levels. Figure 10 was generated with a VisGaAs FPA. It shows a computer screen with Internet Explorer open to the Google search engine web site a plastic container of filled with water and soldering iron beginning to heat up (approximately 200 Celsius). Figure 11 shows the same monitor and plastic water bottle imaged with a standard InGaAs FPA. Without the visible imaging capability the monitor only appears to glow a uniform intensity. This is from the fluorescent back light that has a NIR component. Also apparent in figure 11 is that the water is less transparent. This is to be expected since water strongly absorbs NIR at several wavelengths between 900 and 1700 nm.

Because the imagery on the computer monitor is entirely comprised of visible light components, the VisGaAs FPA clearly demonstrates visible light imaging capabilities. The detection of the low temperature soldering iron also demonstrates excellent NIR sensitivity. While silicon CCD cameras are also capable of imaging hot objects, their relatively short cut-off wavelength results in 4 orders of magnitude more signal for NIR cameras using InGaAs sensors.

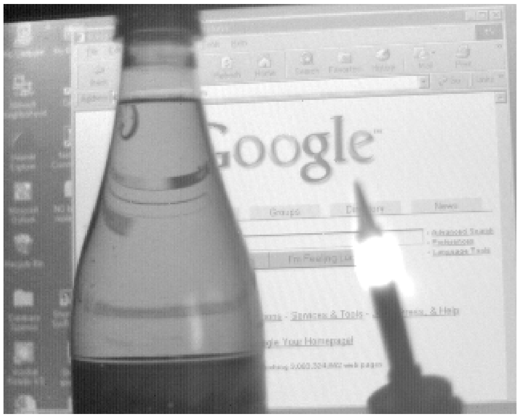

Figure 10: VisGaAs FPA S/N 467

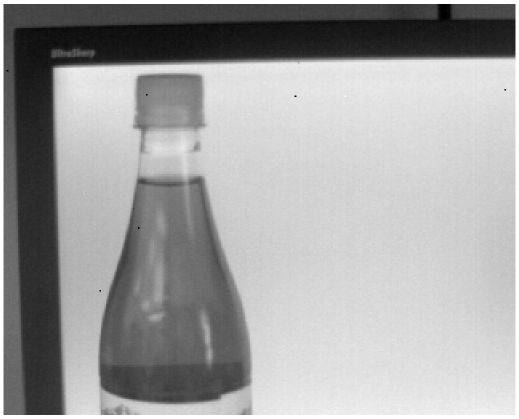

Figure 11: standard InGaAs FPA

It is also apparent from figure 10 that the NIR energy from soldering iron is out of focus. This is the result of inadequate color correction across spectral range from visible to NIR with the lens used to collect this imagery. The lens used to collect these images is a visible lens that also has high NIR transmission. It works well as either a visible-only lens or a NIR-only but can't function well when performing simultaneous imaging of both spectral regions. Further work is anticipated to find a lens better optimized for simultaneous visible/NIR imaging.

2.6.2 Outdoor imagery

Imagery of outdoor high contrast scenes were taken to demonstrate the excellent corrected uniformity across high dynamic range scenes that was measured in section 2.5. Figure 12 was taken with FPA S/N 467 operating in low gain mode with an integration time of 16 ms and an f/8 lens aperture setting.

3. CONCLUSIONS

VisGaAs FPAs have been demonstrated to show the following characteristics: enhanced short wavelength spectral response, responsivity and sensitivity characteristics comparable to standard InGaAs, and excellent corrected uniformity across a broad part of the sensor's dynamic range. More work is anticipated in the areas of enhanced AR coating, lens optimization. Further enhancement of the short wavelength response may also be realized as processing parameters are refined.

Figure 12: VisGaAs outdoor imagery, FPA S/N 467

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