

**Solutions for  
the Electronic  
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# ADVANCED IMAGING

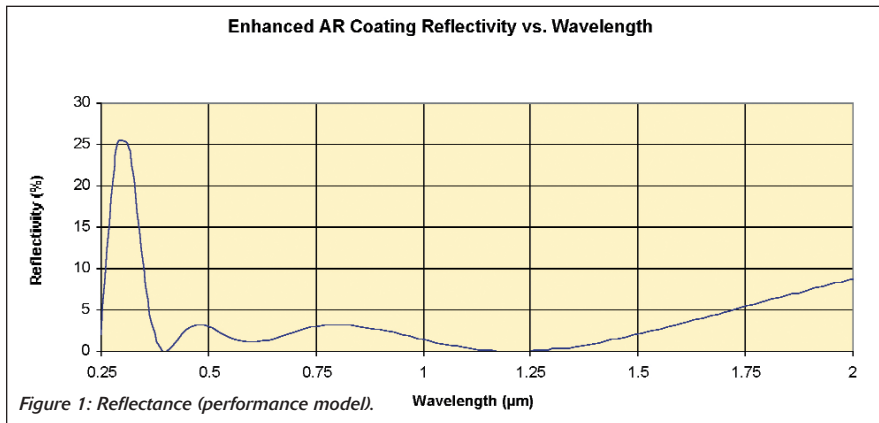
## **MULTI-SPECTRAL IMAGING BRIDGES PERFORMANCE GAP**

- *Semiconductor Technology Expands Markets*
- *Embedded Vision Products*
- *New Materials: Testing  
& Inspection Requirements*

# Broad-Spectrum Performance Via VisGaAs

New processing techniques have enabled both visible and near-IR imaging on a single detector.

by Ted Hoelter



A single photodetector that captures images in both the visible and near-infrared allows users to perform tasks that heretofore required two detectors. Similarly, the ability to design such detectors into a camera brings flexibility to applications in the 850 to 1700 nm range that previously dictated the use of two cameras.

## APPLICATIONS FOR INGAAS

FPA (Focal-Plane Arrays) based on indium gallium-arsenide (InGaAs) are used in a variety of commercial and military tasks, including various types of laser imaging, including characterization of the beam and imaging with NIR laser illumination. Others include imaging through paint for forensic

analysis, outdoor imaging using night glow and incorporation into spectroscopic instruments.

While other technologies span most of the NIR spectrum covered by standard InGaAs FPAs (900 to 1700 nm), most other technologies have drawbacks. For example, indium antimonide (InSb) can cover the same range with a high-performance sensor, but the material requires cryogenic cooling, resulting in a higher-cost, lower-reliability camera because of the sterling cooler. Short wavelength mercury cadmium tellurium, (HgCdTe), like InGaAs, does not require cryogenic cooling, but is more expensive because of limited availability of the detector material. Pyrometers can be used in many NIR applications, but they have

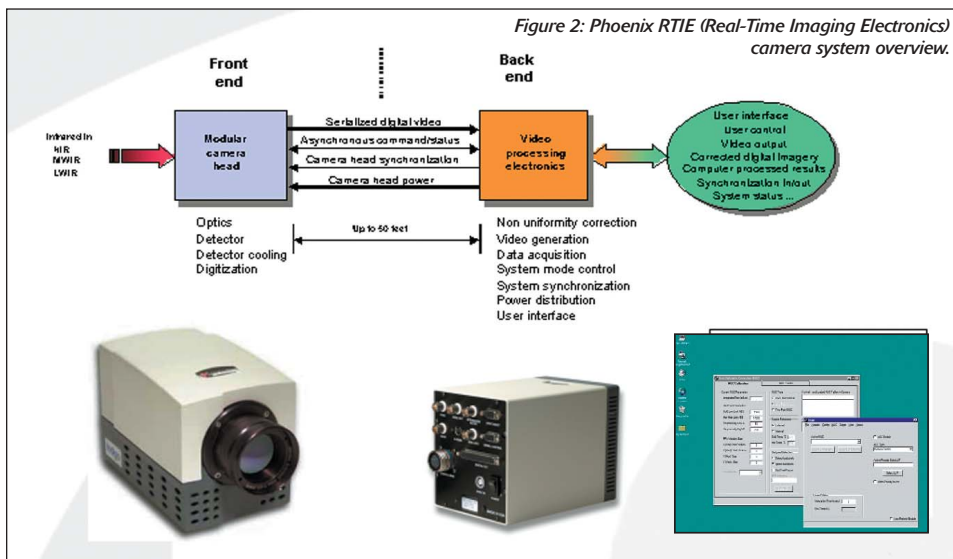
significantly reduced sensitivity compared to photon detectors.

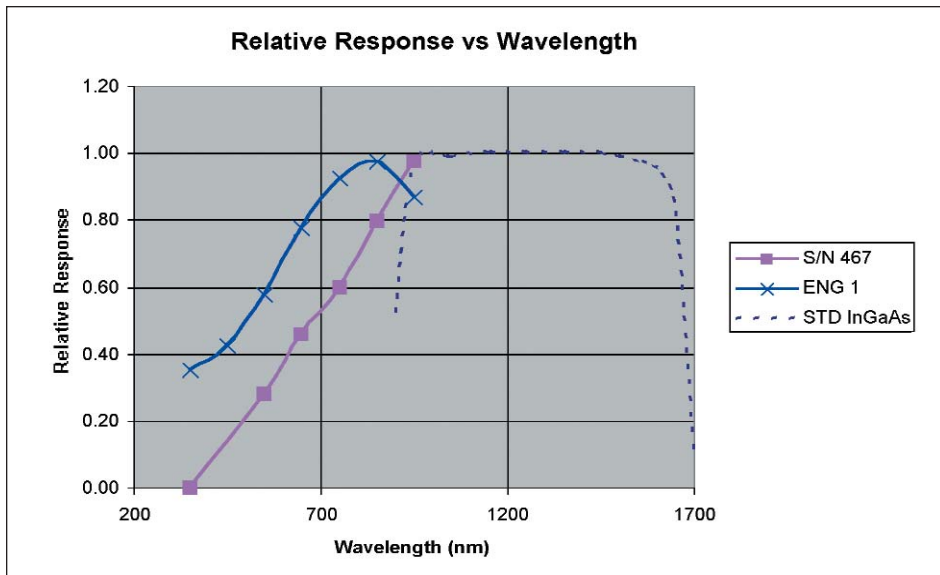
Some applications would benefit from enhancement of the spectral response of commercially available InGaAs FPAs and cameras. For example, standard InGaAs is not ideal if the application requires imaging 850 nm laser designators, along with other longer-wavelength NIR lasers. A second camera would be required to provide high-sensitivity imaging of the 850 nm laser.

In other instances, daylight NIR imaging provides an excellent high-contrast image, but will not accurately reflect a scene's visible information content because of differences in spectral reflectivity and absorptivity of objects in the scene. Painted-on numbers and letters, for example, may not be detectable with an NIR-only camera.

With these and other undiscovered applications in mind, a method for processing standard InGaAs detector material has been developed, enhancing the short-wavelength spectral response and extending the cut-on wavelength down to 400 nm. VisGaAs, a variation on standard InGaAs FPA detectors, uses special processing techniques to extend the spectral response of the detectors through the visible and into the ultraviolet. Test results show preliminary spectral response from 350 nm (ultraviolet) to 1700 nm (near-IR).

Many laser-based applications are found at 850 nm, and VisGaAs sensors can be used in those applications. Other candi-





AR coating to get meaningful spectral response data. An improved AR coating that spans the full spectral response from 400 to 1700 nm. Measurements with the new coating were unavailable at the time this article was written, but a performance model (Figure 1) allows the reflectance to be predicted.

FPA performance is closely tied to the performance of the ROIC used. The ISC9809 ROIC was originally designed for use with InGaAs detectors, but is also suited for VisGaAs detectors. The device is one of several ROICs that interface to the Phoenix camera, allowing the FPA to be integrated into a complete camera system.

Complete camera-level performance was

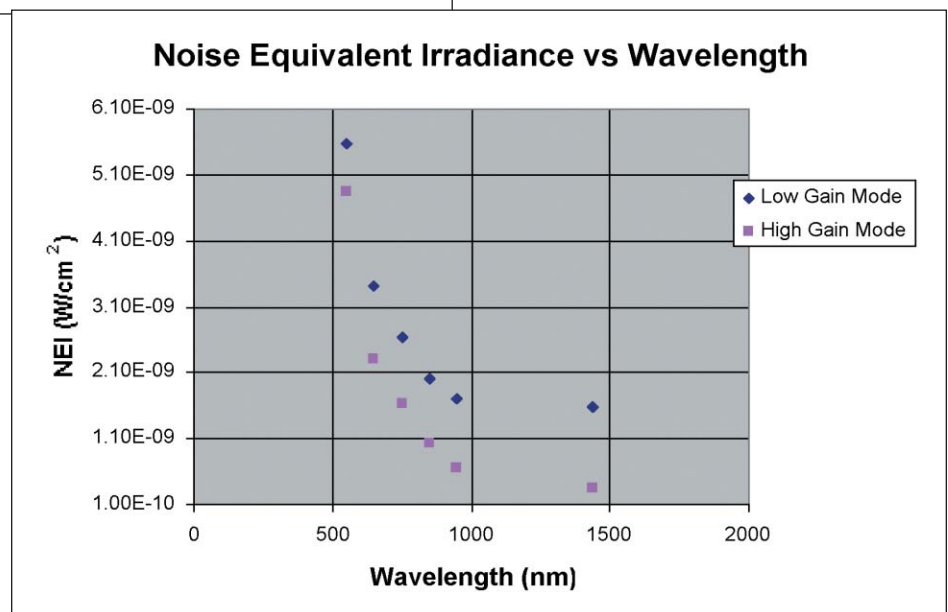
dates for VisGaAs include spectroscopy and other tasks that use two sensors to cover the region from the visible to 1700 nm; simultaneous imaging using ambient visible illumination and NIR laser illumination; and day-time visible/nighttime covert surveillance using illumination at wavelengths longer than is possible with today's light-intensification systems.

VisGaAs detectors use readily available InGaAs starting material. Precise details of the VisGaAs detector processing are proprietary, but the technology is complementary to the fabrication of InSb detectors. Developers continue to refine detector technology in an effort to improve short-wavelength response. The goal is to cover the region from 400 to 1700 nm.

### THEORY BECOMES PRACTICE

The Phoenix digital IR camera was chosen as the first platform to use the VisGaAs detectors, but other products are being evaluated as candidates for the technology as well. The Phoenix has a 14-bit extended dynamic range, snapshot exposure mode and a PC-based user interface via RS-232 link. The camera offers both 320 x 256 and 640 x 512-pixel FPA detectors. Detector cooling is via thermal electric stabilization, while video output includes NTSC, PAL, RS-170, S-video and 14-bit digital video.

Two different processing runs of VisGaAs detectors have been built into FPAs and integrated into camera systems. Measurements include spectral response, responsivity, uncorrected uniformity, sensitivity, pixel operability and corrected uniformity. The performance results were compared to standard InGaAs performance



on the same readout integrated circuit (ROIC), and were also assessed as to how they relate to performance requirements for imaging applications.

Die from VisGaAs detector material from the first two processing runs were hybridized with ISC9809 readout integrated circuits to form FPAs having a resolution of 320 x 256 pixels. The first processing run yielded one FPA designated ENG 1. The second processing run yielded two FPAs. This article focuses on results for ENG 1 and S/N 467; the latter is from the second run.

Standard InGaAs FPAs are typically finished with an anti-reflective (AR) coating to enhance quantum efficiency and to minimize image artifacts, which may result from excessive energy being reflected off the FPA surface. This AR coating, optimized for 900 to 1700 nm, has significant reflectance in the visible spectrum. Both VisGaAs FPAs were fabricated without an

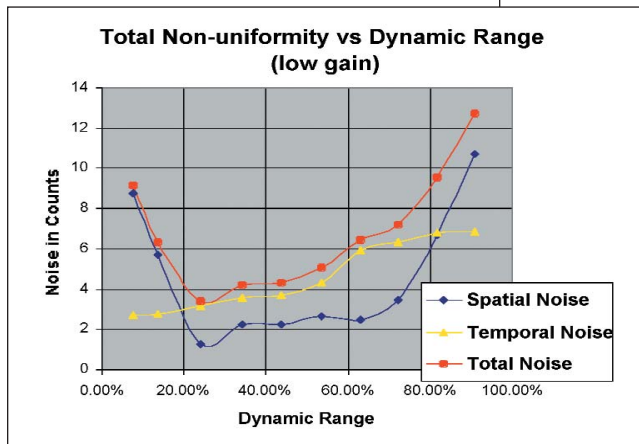
obtained and compared to commercial Phoenix InGaAs systems by integrating the VisGaAs FPA into a Phoenix camera head (front end) and configuring the camera to operate with a Phoenix Real Time Imaging Electronics (RTIE, or back end) video-processing unit (see Figure 2). No modifications were required to the FPA package or the Phoenix camera head because the relevant FPA mechanical dimensions are the same between InGaAs and VisGaAs FPAs.

The Phoenix camera head comprises an FPA package, power supply and digitizer electronics in a sealed, ruggedized housing. The FPA package is vacuum-evacuated and houses the FPA on a thermoelectric cooler for temperature stabilization and isolation from the external environment. The digitizer electronics provide all necessary clocks and biases to the FPA, performing A-to-D conversion of the FPA output.

The Phoenix RTIE receives digitized output from the camera head and performs digital signal processing on the uncorrected signal, as shown in Figure 2. The first step is the application of a non-uniformity correction (NUC) to each pixel in the data stream in real-time. Immediately after NUC, any bad pixels in the image are replaced, allowing analog and digital video to have both NUC- and bad-pixel replacement applied. These functions can be user-disabled/enabled independently on either the analog or digital video output. The digital output was used for data acquisition.

### SPECTRAL RESPONSE

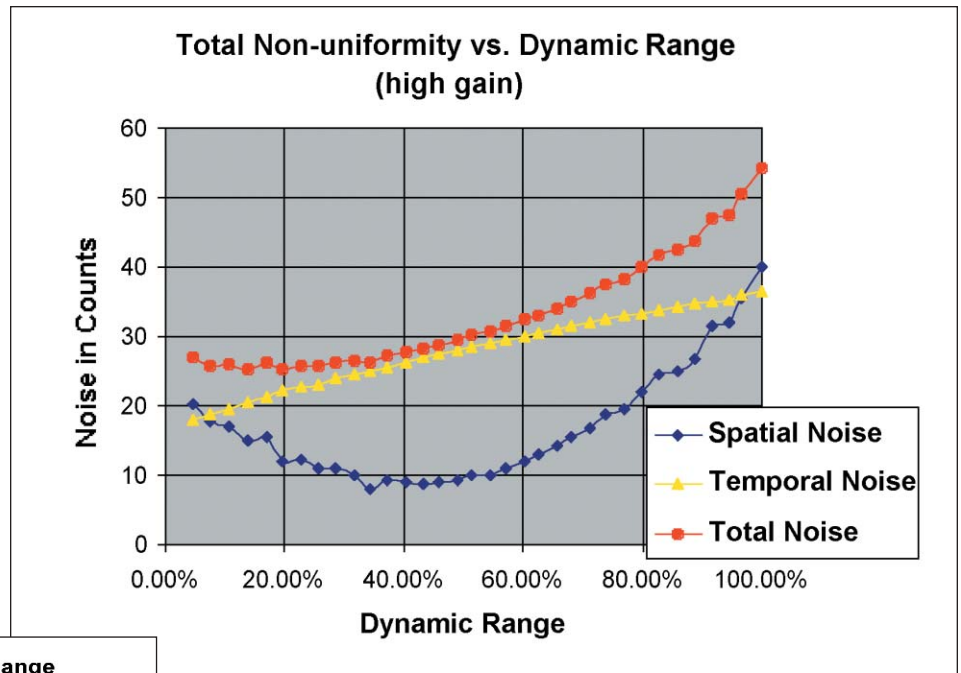
Spectral response was measured for FPAs ENG1 and S/N 467. Broadband signals of



sufficient intensity were delivered to the narrow band-pass spectral filters to obtain signals at distinct wavelengths across the UV, visible and NIR bands. The FPA window is made of BK-7 glass, with a broadband anti-reflective coating on both sides. Measurement of the window indicated it would not interfere with spectral response measurements.

Figure 3 shows the normalized spectral response versus wavelength of FPAs ENG 1 and S/N 467. A plot of the spectral response of standard InGaAs is also provided on the same chart for reference. Data markers on each plot indicate the wavelengths where data was taken. Because InGaAs FPAs are photon detectors, the non-normalized response data was measured in units of quantum efficiency: electrons per photon.

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 because of a lack of longer-wavelength narrow band-pass filters. ENG 1 showed



relatively better short-wavelength response than S/N 467 and was able to image wavelengths as short as 350 nm. Both sensors showed no response at 250 nm.

### RESPONSIVITY AND SENSITIVITY

An important aspect of the responsivity measure-

ment is that it provides a first indication of total FPA operability by screening for pixels with low to no responsivity. A typical requirement for operability is that a pixel have responsivity of at least 50% of the mean responsivity. Using this definition, approximately 0.2% of the pixels were classified as inoperable (*i.e.*, 99.8% were operable) for FPA S/N 467. This value exceeds the present operability specification of 99.5% for standard InGaAs FPAs, indicating the VisGaAs process does not negatively impact operability.

Sensitivity is a critical performance parameter for FPAs and camera systems. It defines the camera's ability 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 set of conditions. NEI was measured as a function of wavelength for FPA S/N 467, using the filters described above.

Figure 4 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 a broadband 1276 to 1605 nm filter. This same filter is used for production testing of standard InGaAs FPAs. The values at 1445 nm of  $1.6E-9$  W/cm<sup>2</sup> and  $3.5E-10$  W/cm<sup>2</sup> meet the published specification for standard InGaAs FPAs, indicating that excellent NIR sensitivity is retained. Future FPAs fabricated with enhanced AR coating will exhibit improved NEI at all wavelengths. The 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 at shorter wavelengths. 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.

### CORRECTED UNIFORMITY

While mean per-pixel sensitivity is a crucial aspect of camera performance, the sensitivity is useful only if the camera also has excellent uniformity. Uniformity is usually measured by calculating the standard deviation in pixel output across the FPA when viewing a uniform source. If an 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). Because temporal noise variations place a limit on frame-to-frame uniformity, it is useful to plot fixed-pattern noise together with temporal noise across a sensor's dynamic range. If the fixed-pattern noise value is less than the temporal noise value, the non-uniformity correction is usually considered to be sufficient for most imaging applications. A value for total noise can also be found 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.

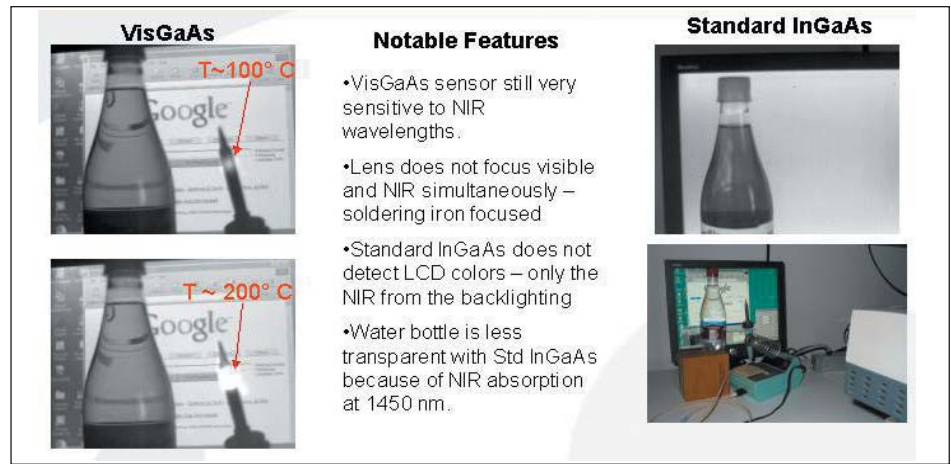


Figure 7: An LCD monitor demonstrating visible capabilities, taken indoors, under low-light conditions, generated with a VisGaAs focal plane array (left) and with a standard InGaAs focal plane array (right).

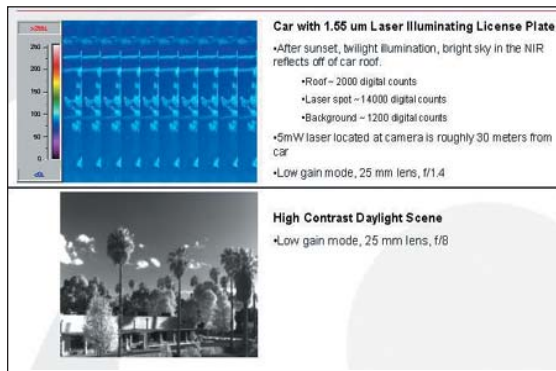


Figure 8: Imagery of outdoor high-contrast scenes demonstrates corrected uniformity across high-dynamic-range scenes.

Figures 5 and 6 are plots of uniformity as a function of dynamic range in high- and low-gain modes, respectively. In the case of high-gain operation, the temporal noise exceeds spatial noise across nearly the entire range of the FPA, indicating that an excellent non-uniformity correction can be achieved with VisGaAs FPAs. In the case of low-gain mode operation, the temporal noise exceeds the spatial noise from 20% in the dynamic range to 80% in the dynamic range. While not as good as high-gain mode, this performance is similar to standard InGaAs, and again indicates that VisGaAs FPA uniformity meets the requirements of a high-performance camera system.

Images of indoor and outdoor scenes were acquired to demonstrate camera performance, 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.

## IMAGING RESULTS

Figure 7 contains indoor pictures taken under low illumination levels. Those on the left were generated with a VisGaAs FPA

and show a computer screen with Internet Explorer open to the Google search engine, a plastic container filled with water and a soldering iron beginning to heat up (approximately 200° C). The right shows the same monitor and plastic water bottle imaged with a standard InGaAs FPA. Without visible imaging, the monitor appears to glow with a uniform intensity. This results from its fluorescent back light, which has an NIR component. Note that the water is less transparent on the right. This occurs because water strongly absorbs NIR at several wavelengths between 900 nm and 1700 nm.

Because the imagery on the computer monitor is comprised entirely of visible-light components, the VisGaAs FPA clearly demonstrates visible-light imaging. Detection of the low-temperature soldering iron also demonstrates excellent NIR sensitivity. While silicon CCD cameras can also image hot objects, their relatively short cut-off wavelength results in four orders of magnitude more signal at 200° C for NIR cameras using InGaAs sensors.

It is evident from Figure 7 that the NIR energy from the soldering iron is out of focus. This results from inadequate color correction across the range from visible to NIR based on the lens used to collect this imagery. That visible lens also has high NIR transmission. It works well as either a visible-only or an NIR-only lens, but cannot function well when performing simultaneous imaging of both spectral regions. An optimized VisGaAs lens has been designed, and is currently in fabrication with, an expected delivery date of late August.

Imagery of outdoor high-contrast scenes (Figure 8) demonstrate the corrected uniformity across high-dynamic-range scenes measured in an earlier section of this article. Figure 8 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.

## LOOKING FORWARD

VisGaAs FPAs demonstrate 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 planned, including characterization of FPAs with an enhanced AR coating and a performance evaluation of the optimized lens. Further enhancement of the short-wavelength response may also be realized as processing parameters are refined. ♦

(Photos: Indigo Systems)

Theodore R. Hoelter is Systems Engineering Director at Indigo Systems Corporation. His experience includes engineering and commercial testing of infrared focal plane arrays and readout integrated circuits, applications and systems engineering for IR imaging products and projects. Mr. Hoelter has written or co-authored papers on subjects including IR FPA testing, QWIP FPA and camera performance, microbolometer camera development and infrared scene simulation. In 1990, Mr. Hoelter received his B.S. degree in Physics from the University of California at Santa Barbara. He can be reached via Aileen Wrench of Indigo Systems at [awrench@indigosystems.com](mailto:awrench@indigosystems.com).