InGaAs NIR focal plane arrays for imaging and DWDM applications

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ABSTRACT

Indigo Systems Corporation has recently developed a line of high performance NIR devices and cameras based upon InGaAs detector arrays. The InGaAs detector arrays are fabricated at Indigo Systems Detector Operations facility and include 640x512 and 320x256 staring focal plane arrays which are utilized in three camera configurations ranging from the miniature alpha camera to the Merlin and Phoenix high performance cameras. The InGaAs detector arrays are very high performance devices with operability routinely exceeding 99.9%. In addition to the staring arrays for imaging applications, two varieties of linear arrays are also being produced at Indigo Systems Detector Operations including a 512 element and 1024 element devices. The linear arrays are intended for use in telecommunications for DWDM applications and are provided in industry standard packages for insertion into DWDM systems. All linear arrays require 100% perfect operability and this is routinely achieved.

Keywords: InGaAs, NIR, FPA

1. INTRODUCTION

Detector arrays based upon the alloy $In_{0.53}Ga_{0.47}As$ have spectral response from 0.9µm to 1.7µm. In recent years the demand for cameras and linear arrays sensitive to this spectral band has grown dramatically. Applications for cameras and linear arrays operating in the 0.9µm – 1.7µm spectral band include military, telecommunications and semiconductor manufacturing examples. Military uses include imaging eye-safe laser target designators, night vision, and camouflage detection. Semiconductor manufacturing applications include detection of failures in silicon microprocessors by detection of photoemission. Indigo's InGaAs cameras can be used for inspection of wafers and die, because many semiconductor wafers and die (such as silicon and gallium arsenide) are transparent at near-infrared wavelengths. For wafer and die inspection, cameras can be coupled to a microscope.

The greatest demand for $In_{0.53}Ga_{0.47}As$ based cameras and linear arrays has been in the telecommunications industry. For cameras some typical applications include beam profiling, dynamic imaging of routers and switches and detection of laser operation. For linear arrays typical applications include high performance channel and optical signal to noise ratio (OSNR) monitoring applications for dense wave division multiplexing (DWDM) systems.

Anyone who wants to "launch" laser light into an optical fiber or other device needs to precisely measure the beam's cross-sectional intensity profile. Indigo Systems cameras allow the user to shine a laser beam directly onto the sensor to image the shape of the beam cross section as shown in figure 1. Other applications include imaging the optical outputs of optical fiber ends, DEMUXs, amplifiers, routers and switchers, fiber gratings, add/drops, splitters, couplers and taps. Indigo's Phoenix cameras can produce freeze-frame images of rapidly changing or moving laser beams as with MEMS-based routers and switching fabric. Very high frame rates (up to 10,000 frames/second), shutter speeds as fast as 500 nanoseconds and external triggering capability allow the user to characterize system performance to a degree not possible with any other commercial infrared camera. Indigo's Merlin and Phoenix cameras can provide a rapid indication of the presence of laser light in the telecom wavebands, and can be calibrated by the user to serve as imaging power meters.

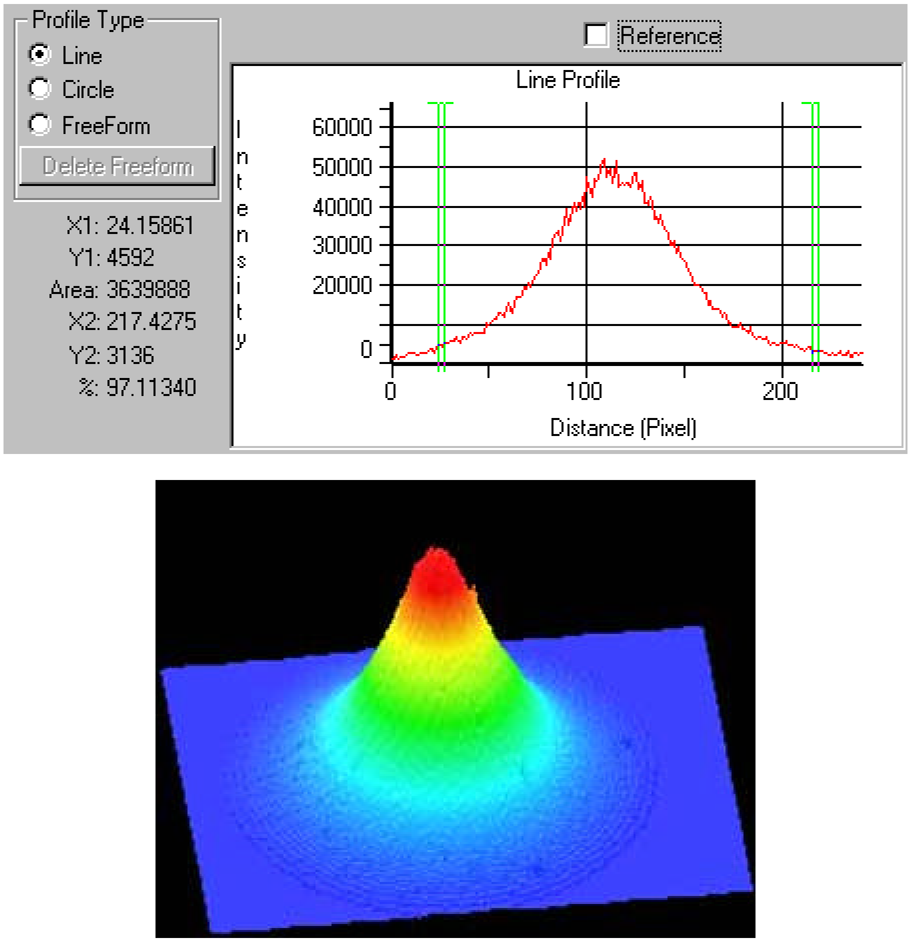

Figure 1: Output of an optical fiber at a wavelength of 1550 nm. This surface plot is updated dynamically, allowing the user to change beam focusing or adjust other parameters while seeing the result on the screen in real time.

2. InGaAs DETECTOR TECHNOLOGY AT INDIGO SYSTEMS

Indigo has developed the capability to fabricate InGaAs detector arrays in-house for all camera and linear array products offered. All detector arrays are of the backside illuminated structure and interconnected to the readout integrated circuit (ROIC) via indium bump interconnections as shown in figure 2.

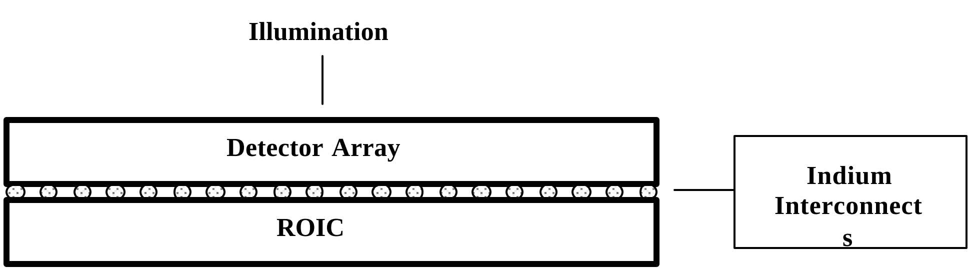

Figure 2: Physical construction of a backside illuminated indium bump bonded hybrid focal plane array.

The detectors are fabricated using a planar architecture as shown in figure 3. Starting material is 3” InP substrates doped n+. The InGaAs absorbing layer and the InP passivating layer are grown by MOCVD or by VPE and are also doped n-type. The composition of the absorbing layer is $In_{0.53}Ga_{0.47}As$ which is lattice matched to InP. Growing the lattice matched composition, $In_{0.53}Ga_{0.47}As$, avoids the introduction of mismatch dislocations with a consequent degradation of device performance. A further consequence of growing the lattice matched composition is that the detector spectral sensitivity extends no further than 1.7 µm. The first step in device fabrication is to provide the diffusion mask. Silicon nitride (Si_3N_4) is deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) as shown in figure 3-ii. A photoresist pattern is exposed and developed and through this pattern the diffusion vias are etched in the Si_3N_4 by Reactive Ion Etching (RIE). The individual photodetector pixels are then formed by zinc diffusion through the Si_3N_4 diffusion mask. The zinc diffusion is achieved in an open tube system from an elemental Zn source as shown in figure 3-iii. The next step is to deposit the n-type and p-type ohmic contacts. Each metal is deposited through a photoresist pattern and a liftoff process. In the case of the n-type contact, it is deposited over an area where the InP has been etched and steps up to a region where the InP was not etched. This two level structure for the n-type contact ensures that all the In bumps will be at the same height when deposited. Finally the In bumps are deposited and the backside of the detector array is anti-reflection coated.

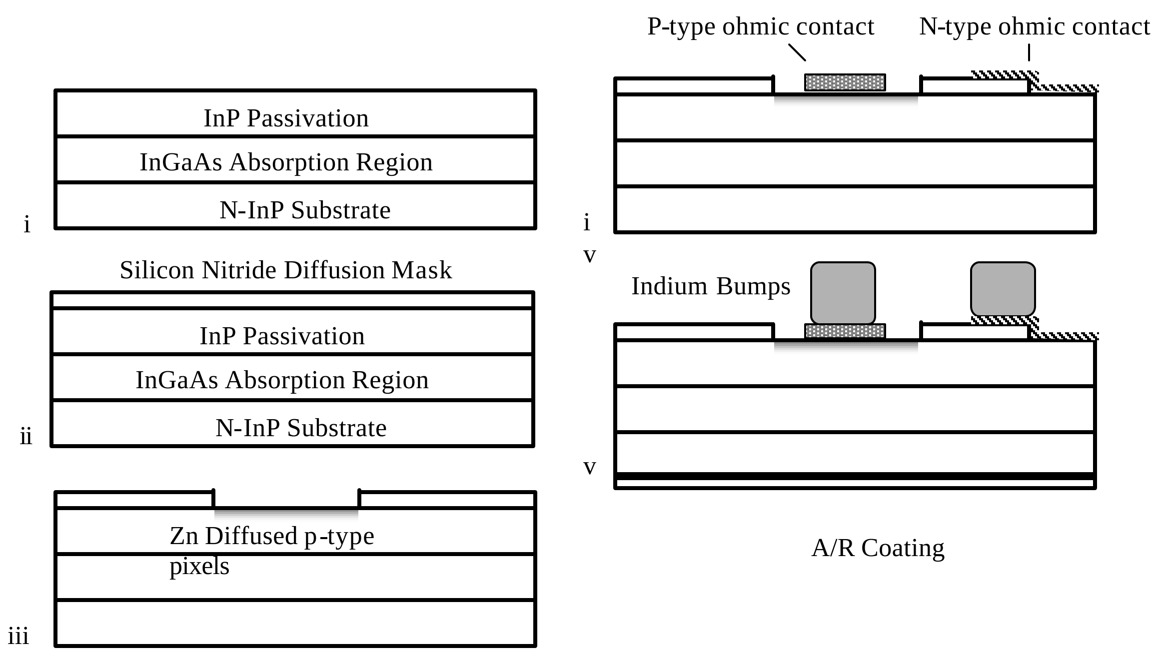

Figure 3: Fabrication sequence for InGaAs planar detector arrays.

3. FOCAL PLANE ARRAYS (FPA's)

3.1 320 x 256 staring focal plane array

The 320 x 256 InGaAs photodiode arrays produced at Indigo Systems are mated with Indigo's ISC9809 ROIC. The 320 x 256 element FPA is constructed with the pixels on a 30 µm pitch. This FPA will support a wide range of system requirements from very low background applications (nightglow) to daytime high illumination conditions. To accommodate the wide scene dynamic range requirements, two selectable integration capacitors are used to control the input circuit transimpedance gain. A 0.01pF integration capacitor is used for low noise and low flux levels down to 10^{-5} ft Lambert corresponding to approximately $2x10^{10}$ photons/cm^2/sec for 0.9µm to 1.7µm spectral band using f/1.5 optics assuming a 2856 Kelvin blackbody distribution. For higher flux levels, a 0.21pF integration capacitor can be selected thereby providing over a factor of 20 dynamic range. A capacitive feedback transimpedance amplifier (CTIA) provides a low noise detector interface circuit capable of operating at low input currents without frame-to-frame image lag. A sample and hold capacitor is also part of the input unit cell architecture which allows the FPA to be operated in full frame snapshot mode and provides the maximum integration time available. The integration time is electronically controlled (gated) by an external clock pulse and is adjustable from 0.5µsec to approximately the frame time of 33.3msec for 30 Hz operation. This provides an additional factor of 66,000 to the total system dynamic range. Additional features include programmable operating modes such as dynamic image transposition, dynamic windowing, selectable number of outputs, variable signal gain, input charge skimming and on-chip power adjustment. Performance specifications of the ISC9809G InGaAs FPA are summarized in table 1 below.

Parameter	**Performance**
Array Configuration	320 (H) by 256 (V)
Pixel Pitch	30µm x 30µm
Well Capacity Cint = 0.01pF Cint = 0.21pF	 175K Electrons 3.5M Electrons
Input Current Range Minimum Maximum	 <1fA >1µA
Operating Temperature	Room Temperature to , 80 Kelvin
Total Readout Noise Room Temperature	High Gain Mode Low Gain Mode ~ 50 electrons ~475 electrons
Number of Outputs	Selectable 1, 2, or 4
Maximum Frame Rate (Full Frame) One Output Two Outputs Four Outputs	 110 FPS 200 FPS 350 FPS
Power Dissipation Minimum (One Output) Nominal (One Output, 10 MHz Output Pixel Rate) Maximum (Four Outputs, 10 MHz Output Pixel Rate)	 < 15 mW < 75 mW < 159 mW
Output Voltage Swing	2.7 V
Non-Linearity	< 0.1 %
Integration Time Minimum Maximum	 0.5 µsec (0.25 µsec at 80 Kelvin Operating Temperature) ~ Frame Period
Quantum Efficiency	> 90% 0.9µm – 1.7µm
Uncorrected Non-Uniformity	<5%, 3.5% typical
Operability	>99.5%, 99.99% typical

Table 1: Performance of the Indigo ISC9809G 320 x 256 focal plane array.

3.2 640 x 512 staring focal plane array

The 640 x 512 InGaAs photodiode arrays produced at Indigo Systems are mated with Indigo's ISC0002 ROIC. The 640 x 512 element FPA is constructed with the pixels on a 25 µm pitch. This FPA is the "big brother" to the ISC9809G with all of the same operating features. As with the smaller FPA, the ISC0002G supports a wide range of system requirements from very low background applications (nightglow) to daytime high illumination conditions. To accommodate the wide scene dynamic range requirements, two selectable integration capacitors are used to control the input circuit transimpedance gain. A 0.005pF integration capacitor is used for low noise and low flux levels. For higher flux levels, a 0.13pF integration capacitor can be selected thereby providing over a factor of 26 dynamic range. A capacitive feedback transimpedance amplifier (CTIA) provides a low noise detector interface circuit capable of operating at low input currents without frame-to-frame image lag. A sample and hold capacitor is also part of the input unit cell architecture which allows the FPA to be operated in full frame snapshot mode and provides the maximum integration time available. The integration time is electronically controlled (gated) by an external clock pulse and is adjustable from 2.0µsec to approximately the frame time of 33.3msec for 30 Hz operation. This provides an additional factor of over 16,000 to the total system dynamic range. Additional features include programmable operating modes such as dynamic image transposition, dynamic windowing, selectable number of outputs, variable signal gain, input charge skimming and on-chip power adjustment. Performance specifications of the ISC0002G InGaAs FPA are summarized in table 2 below.

Parameter	**Performance**
Array Configuration	640 (H) by 512 (V)
Pixel Pitch	25µm x 25µm
Well Capacity Cint = 0.005pF Cint = 0.13pF	 84K Electrons 2.2M Electrons
Input Current Range Minimum Maximum	 <1fA >1µA
Operating Temperature	Room Temperature to , 80 Kelvin
Total Readout Noise Room Temperature	High Gain Mode Low Gain Mode ~ 50 Electrons ~400 Electrons
Number of Outputs	Selectable 1, 2, or 4
Output Voltage Swing	2.7V
Non-Linearity	< 0.1 %
Integration Time Minimum Maximum	 2.0µsec ~ Frame Period
Quantum Efficiency	> 90% 0.9µm – 1.7µm
Uncorrected Non-Uniformity	<5%, 3.5% typical
Operability	>99.5%

Table 2: Performance of the Indigo ISC0002G 640 x 5126 focal plane array.

3.3 512, & 1024 linear arrays

Both the 512 element and the 1024 element linear detector array are mated with Indigo's full custom ISC0007 ROIC. Unlike other large InGaAs linear arrays in which each detector element is wire bonded to the readout circuit, Indigo's ISC0007-GS FPA is constructed by indium bump bonding the detector array to the readout circuit thereby eliminating 512 or 1024 potentially unreliable wire bonds. To further the integrity of the hybridized device, the hybrid gap between the detector and readout is backfilled with a strong epoxy guaranteeing that the detector will never delaminate from the readout circuit. In the 512 mode, each pixel is 500 µm in length on a 25 µm pitch. In the 1024 mode each pixel is 500 µm in length on a 12.5µm pitch.

The ISC0007-GS linear InGaAs focal plane array (FPA) is designed for the demanding and highly specialized requirements of telecommunications optical monitoring. This FPA is supplied in an industry standard package which is hermetically sealed, backfilled and temperature stabilized, figure 4. This device is sensitive to optical radiation in the range from 900-1700 nm, compatible with S,C and L band laser applications.

Figure 4: Indigo's ISC0007-GS 512 and 1024 element packaged linear array for DWDM applications

This makes it ideally suited for high performance channel and optical signal to noise ratio (OSNR) monitoring applications for dense wave division multiplexing (DWDM) systems. The simple user interface provides system integrators with the highest performance power monitoring device without a complex system integration task. Another unique feature of the ISC0007-GS FPA is Indigo's proprietary µ-bias circuit which biases each detector at precisely zero volts. With the detectors thus biased, the detector dark current is no longer a function of temperature and the FPA exhibits performance stability over a broad temperature range. All ISC0007-GS focal planes exhibit 100% pixel operability. The performance of the ISC0007-GS is summarized in table 3 below.

Parameter	**Performance**
Array Configuration	512 x 1, 1024 x 1
Pixel Pitch	500µm x 25µm, 500µm x 12.5µm
Detector Bias	Proprietary µ-bias circuit
Quantum Efficiency	> 90% 900 – 1700 nm
Pixel Operability	100%
Operating Temperature Range	-20 C - +70 C
Number of Outputs	Selectable 1, 2, or 4
Output Voltage Swing	2.7V
Non-Linearity	< 2 %
Maximum Pixel Output Rate	2.5 MHz
Interface	4 clocks only
Scan Direction	Bidirectional

Table 3: Performance of Indigo's ISC0007-GS linear FPA.

4. CAMERAS

4.1 Alpha™ NIR miniature InGaAs camera

Alpha™ NIR is a compact, lightweight sensor head that employs a 320 x 256 Indium Gallium Arsenide (InGaAs) focal plane array (FPA). InGaAs detectors are highly sensitive to energy in the near-infrared (NIR) and shortwave-infrared (SWIR) wavebands from 900 to 1700 nanometers, well beyond the range of silicon CCD cameras.

Alpha NIR is ideally suited for detection of telecommunication laser radiation, particularly in the S, C, and L DWDM wavebands. Uses include: laser beam profiling; silicon wafer characterization; fiber alignment and inspection; and optical component measurement and analysis. Unlike lead-oxysulfide vidicons, InGaAs detectors are highly resistant to damage from intense lasers, allowing direct illumination onto the focal plane for beam profiling. Exposure times can be set from 1 microsecond up to 1 millisecond, providing a very wide dynamic range. This range allows users to measure all aspects of a laser beam profile from the peak to the outer fringes without attenuating the laser signal.

The small size, light weight and low power consumption of the Alpha NIR sensor head makes it ideal for integration into automated production or inspection lines that require machine vision in the 900-1700nm waveband; for example, a VCSEL inspection system that measures beam parameters such as shape and power.

The Alpha NIR sensor head is designed for use with National Instruments'™ digital image acquisition (IMAQ) board. Indigo provides software and hardware in the form of a LabVIEW virtual instrument, a digital interface cable and an IMAQ board. The virtual instrument enables bi-directional remote serial camera control, including exposure time setting, invert/revert, gain state, and other sensor parameters.

The system allows the user to acquire and display 12-bit digital image data, change sensor head settings, calibrate the sensor head, and analyze the acquired data. Analysis tools include: regions of interest; line profiles; and spot meters. Non-uniformity compensation and bad pixel replacement are also supported through software. The Alpha™ NIR camera is shown in figure 5 and the performance specifications in table 4.

Figure 5: Miniature Alpha™ NIR camera

Detector	InGaAs	Array Format	320(H) x 256(V)
Pixel size	30µm x 30µm	Optical Fill Factor	<90%
Spectral Response	900 – 1700 nanometers	Thermal Stabilization	Thermoelectric
Window Material	BK7 Glass	f number	Set by Lens
Optical Interface	C-Mount	Lens Focal Length	25 mm 50mm
Digital Data	Real-time, 12 bit, Parallel	Frame Rate	30 Hz
Exposure Time	25 µsec – 16.6 msec	Total Dynamic Range	69dB
Linear Dynamic Range	66dB	Sensitivity NEI	$<1x10^{10}$ Ph/cm^2/sec
Operability	>99.5%	Damage Threshold	> 1W/cm^2
Time to Initial Image	30 sec @ 25C Ambiant	Power Dissipation	4.5W Max, 3W typical
Power Input	6VDC	Serial Commands	RS-232 Protocol
Dimensions H x W x L	2.1 x 2.5 x 3.7 inch	Weight	350 grams
Volume	320 cm^2		

Table 4: Specifications of Indigo's Alpha^{TM} NIR InGaAs Camera

4.2 Merlin NIR InGaAs camera

The Merlin®-NIR shown in figure 6 is a high-performance NIR infrared (NIR) camera system, based upon the ISC9809 Focal Plane Array, using uncooled Indium Gallium Arsenide (InGaAs) detectors. InGaAs is the best detector material available for sensing energy in the 0.9 to 1.7 micron waveband. The focal plane array (FPA) size is 320 x 256, with 30 x 30 micron pixels.

Figure 6: Indigo's Merlin®-NIR 320 x 256 InGaAs based camera.

The Merlin®-NIR is a fully integrated infrared camera that supports up to 25 memory locations for storage of pixel correction coefficients and camera setup parameters. A removable button panel provides remote control of the most-used camera functions, with on-screen display of camera menu items. The camera is also remote-controllable via a PC-based graphical interface application running under Windows NT through the RS-232 port. Merlin-NIR is designed for use with C-mount lenses. Several lens options are available.

Indigo offers two versions of the Merlin®-NIR IR camera: **Radiometric and Imaging** as summarized below in table5. Both camera types provide 12-bit digital data, as well as analog video in either NTSC or (optional) PAL format. The complete performance specifications of the Merlin®-NIR are summarized in table 6.

Merlin®-NIR Radiometric	**Merlin®-NIR Imaging**
Merlin®-NIR Radiometric cameras are factory-calibrated to provide temperature information for each pixel in the array with an accuracy of 2 degrees or 2%. Radiometric cameras feature movable cross-hairs, or spotmeters, that provide real-time temperature values on the video display. Temperature information from images can be acquired and analyzed using ThermaGRAM®, an easy-to-use yet extremely powerful digital data collection and report generation accessory.	The Imaging version of the Merlin®-NIR camera furnishes a thermal video image display, whereby a 12-bit value, or digital count, is calculated for each pixel based on the correction coefficients and user's setup specified by the user. For users that prefer digital pixel values, Indigo offers Talon®, a data capture accessory that acquires images at up to 60 frames per second for analysis and processing. Talon® is optimized to provide full-speed acquisition with no missing frames.

Table5: Comparison of the radiometric and imaging versions of Merlin®-NIR camera.

Detector Type	InGaAs	Detector Spectral Range	0.9 – 1.7 μm
Array Format	320(H) x 256(V)	Display Format	320(H) x 256(V)
Detector Pixel Size	30μm x 30 μm	Operating Temperature	291 Kelvin
Startup Time	< 2 minutes @ 30C	Integration Type	Snapshot Mode
Frame Rate	60, 30 or 15 FPS NTSC 50, 25 or 12 FPA PAL	Size H x W x L	4.0" x 4.5" x 8.0"
Weight	<3.5 lbs.	Video Output	NTSC (PAL optional), S video
NEI	<1E10 ph/cm^2/s low gain <5E9 ph/cm^2/s high gain	System Noise Level	<2 LSB
Corrected Uniformity	<0.1%	Operability	>99.5

Table 6: Performance specification of Indigo's Merlin®-NIR camera.

4.3 Phoenix NIR InGaAs camera

Indigo's Phoenix™ digital infrared camera line features 14-bit extended dynamic range, snapshot exposure mode, high frame rate capability, and excellent resolution within a small, rugged package, figure 7. Phoenix is a modular system consisting of a camera head, and a choice of two video signal processing electronics back ends, the Real-Time Imaging Electronics (RTIE) or Digital Acquisition System (DAS). This camera is ideal for any infrared commercial, industrial, scientific, or military use when flexibility and unequaled performance is vital.

Figure 7: Indigo's Phoenix™ digital infrared camera.

The Phoenix camera heads are available with either the ISC9809G 320 x 256 InGaAs FPA or the ISC0002G 640 x 512 format InGaAs FPA. All sensor types support windowing to allow high speed readout of sub-arrays. The same compact housing is used for each type of camera head, regardless of detector type or size. Designed for severe environments, the camera head offers both conductive and convective cooling for operation over wide ranges of temperature and altitude. As with Indigo's Merlin® infrared cameras, a common electrical, software, and user interface is provided within the Phoenix line. Indigo offers optics for Phoenix cameras ranging from microscopes to telescopes. The Phoenix-Near uses standard C-mount lenses.

The Real-Time Imaging Electronics (RTIE) is a dedicated electronics subsystem that provides both analog and digital video, at data rates up to 12.2 megapixels per second. The RTIE furnishes real-time pixel gain and offset corrections, and generates NTSC video (PAL optional), as well as S-Video. Phoenix employs a "split" architecture configuration under which the camera head is separated from the electronics by either a 10 or 50-foot interface cable. Camera control software is provided on a CD-ROM. The camera architecture supports field installation of software updates. Features supported include: windowing capability to allow frame rates greater than 23 kHz and 13 kHz for mid and large format FPAs, respectively; built-in programmable trigger delays; preprogrammed acquisition sequences to support event profiling; and a variety of synchronization modes to synchronize the camera to external events. The 14-bit digital data is available from the RTIE for transfer to a frame grab board via a 37-pin D-sub connector. Compatible with the RTIE, Indigo offers Talon® Ultra a digital image acquisition and analysis system, consisting of a digital frame grab board, 10-foot interface cable, and all software required for image acquisition and analysis. These components are configured and delivered in a Pentium™ III class computer. The Talon® software is based on a licensed version of Image Pro® 4.0 software with custom extensions. This software provides a full range of utilities for processing, measurement, analysis, and image output. It is ideally suited for any research professional – using Indigo's Phoenix™ IR cameras – to capture, study, manipulate, and store images and data.

The Digital Acquisition System (DAS) electronics is a Pentium™ III-based system that includes a proprietary camera interface/sync processor board capable of handling data rates up to a maximum of 40 megapixels per second. Post acquisition non-uniformity compensation is performed within the DAS. The DAS can store at least 10 seconds of full bandwidth data from the Phoenix camera head.

To aid in aiming and focusing the camera, the DAS provides a psuedo-real-time video display in a VGA window. User interface software is factory-installed. Camera architecture supports field installation of software updates. The Phoenix system's "split" architecture configuration also allows for the same 10 or 50-foot separation between camera head and DAS electronics. Synchronization modes, windowing capabilities and triggering features of the RTIE are common to the DAS system. One key difference between RTIE and DAS systems is a provision for two additional video channels in the DAS. This enables DAS electronics to capitalize on and extract the maximum performance capabilities of the FPA. Frame rates of 38 kHz and 22 kHz are supported for mid and large format FPAs respectively.