LA-UR- 02 - 1679

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# Advanced Laser Sensing Receiver Concepts Based On FPA Technology

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*Submitted to:*

SPIE 16th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls
1-5 April 2002
Orlando, FL

**Los Alamos**
NATIONAL LABORATORY

# Advanced laser sensing receiver concepts based on FPA technology

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## ABSTRACT

The ultimate performance of any remote sensor is ideally governed by the hardware signal-to-noise capability and allowed signal-averaging time. In real-world scenarios, this may not be realizable and the limiting factors may suggest the need for more advanced capabilities. Moving from passive to active remote sensors offers the advantage of control over the illumination source, the laser. Added capabilities may include polarization discrimination, instantaneous imaging, range resolution, simultaneous multi-spectral measurement, or coherent detection. However, most advanced detection technology has been engineered heavily towards the straightforward passive sensor requirements, measuring an integrated photon flux. The need for focal plane array technology designed specifically for laser sensing has been recognized for some time, but advances have only recently made the engineering possible. This paper will present a few concepts for laser sensing receiver architectures, the driving specifications behind those concepts, and test/modeling results of such designs.

## 1. INTRODUCTION

Since its development, the laser has found many applications, each requiring different hardware specifications. These specifications are driven by many factors including applicable wavelength, sensitivity requirements, and allowed system size to name a few. When designing a laser sensor, two main components to be considered are the laser and the receiver. This paper will address the receiver component by considering how advanced focal plane array (FPA) detectors have been used to improve performance over that achieved by standard single-element receivers.

Visible imagers have continued to be readily available and steadily improving with silicon CCD technology; however, more advanced high-speed imaging has required specialty readouts to be designed. Meanwhile, infrared applications have been growing at a slower pace in both number and complexity. While short-wave infrared (SWIR) applications have advanced array technology, both pixel size/number and readout speeds have typically lagged visible sensors, especially for the longer IR wavelengths. In general, each laser application has slightly different demands on hardware design, but laser sensing has some fundamental advantages that could be useful if receiver designs are pushed appropriately to capitalize on them.

This paper will begin with a discussion of basic detector array design, followed by two example laser applications/sensors. After this introductory information, a selection of detector array concepts will be described. The first concept is an integrating style readout array demonstrated in a 10x10, 50 μm pixel design[1]. This array is designed for low noise operation and is ideal for imaging a laser return signal and using multi-pixel signal averaging. The second array type comes out of the 3D Imaging (Flash) Ladar program sponsored by DARPA[2]. This design style is a single-shot, time-resolving approach to obtain range resolution in addition to the imaging information from the spatial array. The third concept, currently under development, is a pseudo-linear array for dispersive spectrometer-based laser receiver operation. The final design concept to be described is a heterodyne detection approach to be integrated in CMOS readout technology for array configurations.

## 2. ARRAY DETECTOR TECHNOLOGY

Array detector technology typically consists of three basic components, not including the typical control and data acquisition hardware. These are best described as a photon-to-electron conversion/absorption region, an interface (preamplifier) region, and a multiplexer readout circuit. A schematic is shown in Figure 1 to illustrate a typical infrared FPA design consisting of a detector array (HgCdTe), a silicon (CMOS) readout array, and the indium bump connections between the two. Within each unit cell (or pixel) an indium bump bond connects the absorbing detector pixel and the preamplifier. The preamplifier is the interface between the photoelectron output of the absorber pixel and the readout multiplexer. All three components factor into advancing the engineering limits in FPA designs for laser receiver requirements.

High-speed timing is an important issue, and limitation at times, for laser sensing. The FPA absorber material typically has a certain lifetime associated with photon absorption, carrier collection, and re-charging delay ('dead time'). The preamplifier design will have a temporal behavior determined by the desired operation qualities. For short pulse returns an integration time shorter than currently available may be desired. The readout multiplexer will also have significant timing limitations that may affect either pixel number, and thus spatial resolution/coverage, or frame rate, which may impact laser pulse repetition rate.

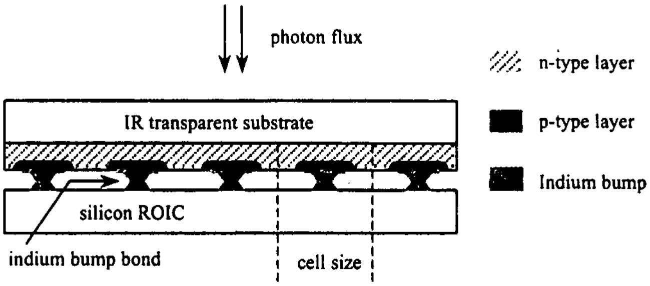


Figure 1. A schematic is shown to illustrate the three main components of a focal plane array: the detector material, the readout chip, and the connecting indium bump bonds. Each component contributes noise, at some level, to the measured signal.

Passive imaging sensors have been pushing the state-of-the-art array technology, with an emphasis on less cooling requirement and higher spatial resolution (smaller pixels and more of them). With the photon flux being limited in passive sensing applications, readout/preamplifier technology has been focused on lowering noise levels to increase sensitivity. Only in recent FPA design efforts have amplifier speeds been advanced with pulsed-laser detection in mind, shortening integration times to 50 nsec in one and sub-ns resolution in others. In Section 4 some demonstrated designs will be described, followed by one in development and another merely in the conceptual stage.

## 3. LASER REMOTE SENSING APPLICATIONS

Since the invention of the laser many applications have been found. For military sensing, one application that has continued to improve with technology is laser ranging. A laser pulse is transmitted to a target which scatters a photon 'echo' to be received back at the transceiver system. The time-of-flight is measured and translated directly to target range information. Previous system designs have incorporated scanners to raster the laser across a scene for an imaging capability. More recently array detector technology has been considered for imaging the scene; however, in this case the laser pulse must be spread across the field of view. By spreading the laser energy across the scene the energy per pixel is significantly reduced so both laser power and receiver sensitivity must be considered and improved if possible. Two examples of laser sensing will be described here to illustrate possible sensor architectures and applications. These systems are merely a selection of what has been demonstrated.

Technology developed at Los Alamos National Laboratory (LANL) in the mid-1990s demonstrated visible low-light level imaging with a photon-counting receiver and laser transmitter[3]. This system used a 655 nm, 83-ps pulse, with a peak power of 54 mW transmitted to the target. The receiver is a visible-sensitive (S-20) photocathode, with a microchannel plate stack followed by a crossed delay line anode structure with four outputs. Upon absorption of a return photon, the resultant single photoelectron is amplified by a ~$10^7$ gain in the MCP stack and the charge cloud is detected in the anode. The four outputs are measured and the correlated temporal data is translated into spatial (x,y) and range (z) information. This sensor has demonstrated sub-ns accuracy and few-cm range resolution. Laboratory experiments used a styrofoam block target with 'LANL' carved out of the surface, as shown in Figure 2a. The letters extended 5-cm from the styrofoam surface. Figure 2b shows a surface plot of the calculated topography from the measured range information. This type of demonstrated low-light level imaging lidar is of significant interest for military ranging and other applications. While currently limited to the visible spectral region due to the photocathode material, extension into the IR should be possible and would increase application.

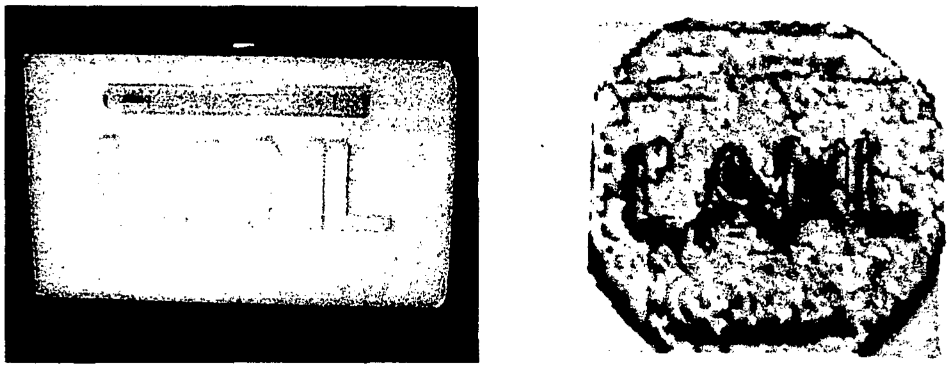


Figure 2. (a) The image on the left shows the styrofoam target, with the letters 5 cm tall. (b) On the right is a surface plot of the calculated topography based on the temporal measurements, directly related to range information.

A different LANL remote sensing instrument, also developed during the mid-1990s, was a differential absorption lidar (DIAL) system used for both chemical absorption and surface reflectivity measurements. In a previous paper LANL investigators demonstrated the utility of a scanning $CO_2$ DIAL system in constructing vegetation maps for broad areas[4]. Although the scanning of a narrow lidar beam is a time-consuming process compared to imaging sensors, the detailed spectral characteristics in the reflectance information may be useful in many applications.

The lidar system for these measurements utilizes a pulsed $CO_2$ laser, acousto-optically tuned[5], operating at a 5 kHz pulse repetition/tuning rate. The wavelength is changed on every shot to a different $CO_2$ laser line, sweeping through both the 9.6 and 10.6 μm bands of $CO_2$ and providing 44 wavelengths. The 44-wavelength pattern is repeated to give a net frequency of 113 spectra per second. The receiver is a single-element, 8-12 μm sensitive HgCdTe detector. For target ranging, time traces of the return signal are collected with a digitizer and the peak of the return signal is recorded. Lidar images were obtained by sweeping the lidar line of sight across scenes with a rastered motion of a steering gimbal mirror. The typical data accumulation time employed was one second at each mirror location, giving a total of 256 seconds for a 16 by 16 grid of spatial points over a scene.

A visible image is shown in Figure 3a with the laser 'pixels' spectrally-clustered and overlapped. With the target reflectance and atmospheric absorption spectra mixed together in the lidar return signal, atmospheric contributions must be removed. This can be accomplished in an approximate fashion by subtraction of the mean spectrum of the entire image, with results shown in Figure 3b. Here it can be seen that different objects in the scene have slowly varying spectra with distinct slopes and amplitudes, as expected from known spectra of natural materials[6]. In addition to this spectral data, temporal measurements of the return pulse are translated into range information for 4D representation (x, y, range, spectral cluster). The imaging information obtained here using a single-element detector is beneficial yet time-consuming due to the rastering method. FPA receivers would speed up acquisition time.

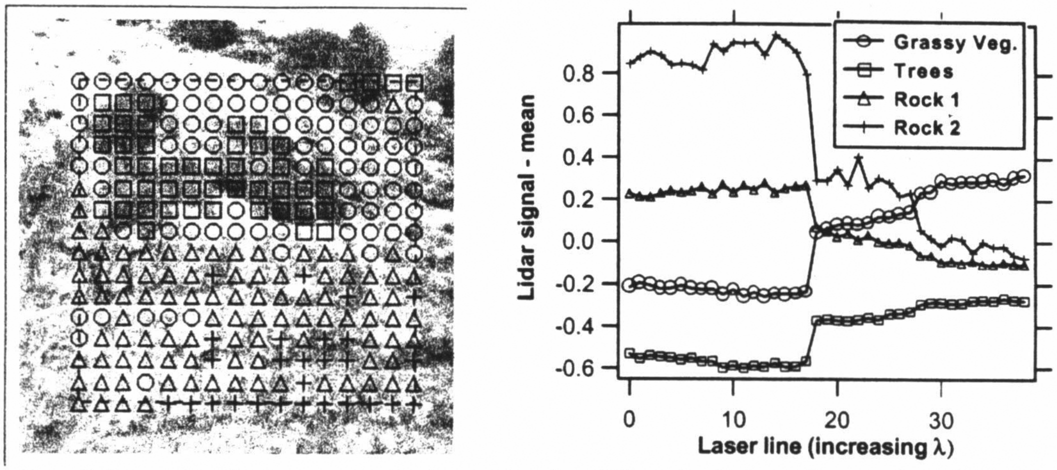


Figure 3. Laser return signals are spectrally clustered into four different descriptive markers. (a) In the left panel, the cluster information is overlayed on a visible image to show how trees differ from the two rock types and the grassy terrain. (b) The right panel shows the normalized terrain reflectance spectra to illustrate the difference in reflectance measured versus laser line (44 wavelengths). The abrupt shift near the center is due to a large wavelength gap between the 9.6 and 10.6 micron bands of the laser.

# 4. ASSORTED RECEIVER CONCEPTS

## 4.1. Small-format, low-noise imaging laser receiver (Fermionics Corp.)

The design and fabrication of a high-speed, low-noise FPA was carried out under a Department of Energy (DOE) Small Business Innovation Research (SBIR)[7] Grant to Fermionics Corp. (during FY99 and FY00). The ROIC design was subcontracted to Indigo Systems Corporation. Major program goals included sensitive LWIR detection, a 10x10 pixel array format with 50 μm pitch, a 100 kHz frame rate, a 100 ns integration time (or less), and less than 50 noise electrons. In this project, HgCdTe was selected as the detector material and the readout design was based on a capacitance transimpedance amplifier (CTIA). The Phase II project successfully delivered two long-wavelength infrared (LWIR) arrays and one mid-wavelength (MW) array.

The delivered MWIR array was operated while illuminating with a high-temperature cavity blackbody source. Operating parameters demonstrated up to a 160 kHz frame rate and as short as 60 ns integration time. First, noise levels were tested with the FPA covered by a cold-shield. Signal levels were measured as a function of integration time to determine dark current. Measured dark current was negligible for the MWIR array, with the readout noise dominating at a level of ~ 80 $e^-$. Then, with the cold-cap removed, the 1.6 mm aperture from the blackbody source was imaged onto the detector array with a 3:1 demagnification. The spot was scanned across the array for response, crosstalk, and uniformity measurements. One frame from these measurements is shown here in Figure 4, with a negative response scale (black is higher photon flux than white). The illuminated spot is centered on the 10x10 array to illustrate the distribution of a gaussian source across multiple pixels.

Laser remote sensing applications can be hard-pressed when trying to increase sensitivity; however, significant advances may be realized by applying new FPA technology. The MWIR (and LWIR) FPA designed here is of significant interest when considering imaging lidar. High-repetition rate pulsed-laser sensors typically rely on signal averaging to increase detection sensitivity by collecting multiple shots prior to any change in the target characteristics (atmosphere variation, surface temperature/motion, etc...). To ensure maximum signal collection, most sensors select a large, single-element detector, at the expense of increased dark current and background photon flux. Some applications may find an imaging array such as this demonstrated 10x10 FPA to be advantageous for selectively averaging only portions of the return laser signal. This type of operation may significantly improve laser sensing detection limits, even if simply due to the order-of-magnitude reduction in readout noise over typical wire-bonded elements.

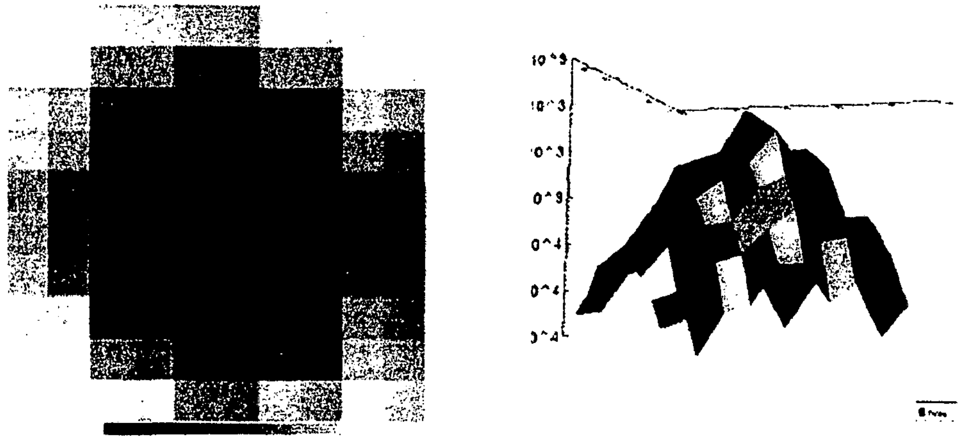


Figure 4. An image of the cavity blackbody aperture on the 10x10 FPA is shown on the left, black being high photon flux. This image, along with an associated surface plot on the right, is shown to illustrate the distribution of photon flux across multiple pixels.

### 4.2. 3-D laser ranging technology (DARPA 3-D Flash Ladar Program)

The DARPA 3-D Flash Ladar Program[2] has awarded several contracts to develop single-pulse, imaging laser range detection sensors. The main emphasis of these efforts has been to develop detector array technology that meets the requirements to have both spatial imaging (2-D arrays) and range resolution (sub-ns detector gating). Significant challenges exist in developing such FPA devices, topped by:

- a single laser pulse illuminating a large field-of-view requires a **high-sensitivity detection material** to record what could be a single photon return per pixel
- high-resolution range information may require **~100 ps timing resolution** for useful spatial discrimination

This program has equal challenge in improving detection material/mechanisms and electronic readout speeds/jitter. Amongst the awarded contracts, several different approaches to confront these challenges have been considered that are of significant interest. Avalanche photodiode (APD) arrays have been considered and are operable at the desired short-wavelength IR (1.5 μm and extendable to 5 μm)[8]. HgCdTe and InGaAs PIN photodiode arrays are being considered for eventual multi-color operation[9]. In addition, image tubes are being used in one approach where a photocathode and microchannel plate make up the absorption/gain region, which is then interfaced with a readout array[10]. These projects, working on different hardware approaches, are all addressing the same goal of high-speed, 3-D laser imaging at long range.

The Raytheon Electronic Systems effort, building off previous experience, has developed APD arrays in a small (10x10) format that have reasonable gain and low-noise performance. The readout design allows for multiple return detection, with each pixel triggered independently by the rising edge of a return pulse. In addition to the standard threshold crossing detection, intensity information is also recorded. This FPA effort is extending to larger format arrays and field demonstrations are planned in 2002.

Rockwell Science Center development has built off the PIN photodiode detection technology, with an emphasis on improved readout technology rather than designed gain in the absorbing material, as in APD structures. The readout is designed for 30 $e^-$ noise levels with multiple sampling of the echo laser return for accurate shape characterization and range retrieval. One significant advantage in this project is the interest in extending the detector materials to multi-wavelength (two-color) or even passive imaging hybridized with the active (laser) return detection.

Finally, Advanced Scientific Concepts has been working on the application of image tube technology combined with advanced readout arrays. This approach relies on a photocathode material to absorb a photon and emit an electron. A microchannel plate then amplifies the photoelectron and a readout array then detects the resulting charge cloud and processes the echo laser return signal for a range determination. The main concern in this approach is the extension of photocathode materials into the infrared (1.5 μm and beyond).

These programs, entering a phase of field-test campaigns sometime this year, should demonstrate significant advances in FPA technology for application to laser sensing.

### 4.3. Dispersive spectrometer based DIAL receiver design (Princeton Scientific Instruments)

Advanced remote spectral sensing technology is being driven by the need for more accurate measurements of spectra, with one method being DIAL. In DIAL, at least two wavelengths are transmitted. The return signals measured are compared spectrally to look at the difference in absorption on the two wavelengths. The LANL sensor introduced earlier consists of 44 $CO_2$ laser wavelengths being transmitted in series, repeating the spectral series at a rate of ~100Hz (5 kHz tuning/pulse repetition frequency - prf). The measured return signals give a spectrum to be analyzed for species detection, either from chemical absorption or surface reflectivity. LANL experience in DIAL has driven design, for increased sensitivity by signal averaging, toward pulse repetition frequencies on the order of 100 kHz for 50 wavelengths of operation. With this design parameter, the selected receiver concept was based on a dispersive spectrometer. The main elements in this decision were:

- low-noise operation of FPA readout technology ($< 100\ e^-$ ROIC noise)
- thermal infrared operation requires tunable narrow filter ($1\ cm^{-1}$ wide, tunable over $200\ cm^{-1}$)
- 100 kHz frame rate operation (based on expected laser prf)
- filtering technology at 100 kHz non-existent
- electronic tuning; FPA + grating spectrometer ⇒ electronic selection of wavelength measured

The design and fabrication of an FPA for application in an advanced DIAL sensor was recently begun by Princeton Scientific Instruments under a DOE SBIR project[11]. The recent Phase II effort has begun to finalize parameters and fabricate test assemblies, prior to fabrication of a full prototype array. The CMOS concept that appeared to afford the best possibilities was to provide each IR detector with its own wide bandwidth transimpedance preamplifier. This concept is illustrated in the schematic shown in Figure 5.

The individual amplifiers are addressed by a multiplexer circuit that connects selected amplifiers to a Track and Hold input to an analog to digital converter (A/D). The amplifier will be configured to integrate the detector photoelectron current during the interval of the returning laser pulse in a DIAL instrument system. The integrator would be reset just before the expected return pulse and the integrator output would be sampled at ~100 ns intervals over a period that would straddle the return. This would provide samples of the background signal as well as capture the laser pulse related signal. The laser lines and their sequence for a given observation period would be translated by the DIAL system into a sequence of focal plane pixel addresses, based on previous calibration of the spectrograph. Based on this a priori information, specific pixels would be energized and addressed by the multiplexing circuit in ~10 microsecond intervals. In some cases having simultaneous measurements of several wavelengths may be possible and desired to minimize fluctuations in pertinent spectral channels. This FPA based receiver technology may be compatible with such a design.

### 4.4. Heterodyne imaging array concept (LANL proposed effort)

Optical heterodyne detection has been predicted to offer significant improvement in capability over demonstrated direct-detection receivers, especially in long-range remote sensing applications where signal returns are weak compared to noise levels inherent to typical detector designs. With appropriate care, practical receiver designs have been demonstrated to meet these expected improvements; however, additional capabilities other than mere photon sensitivity (**amplitude measurement**) have also been identified. For example, optically mixing or heterodyning a reference and signal irradiance has been realized as a method of **frequency encoding** a desired signal, allowing a means of filtering to

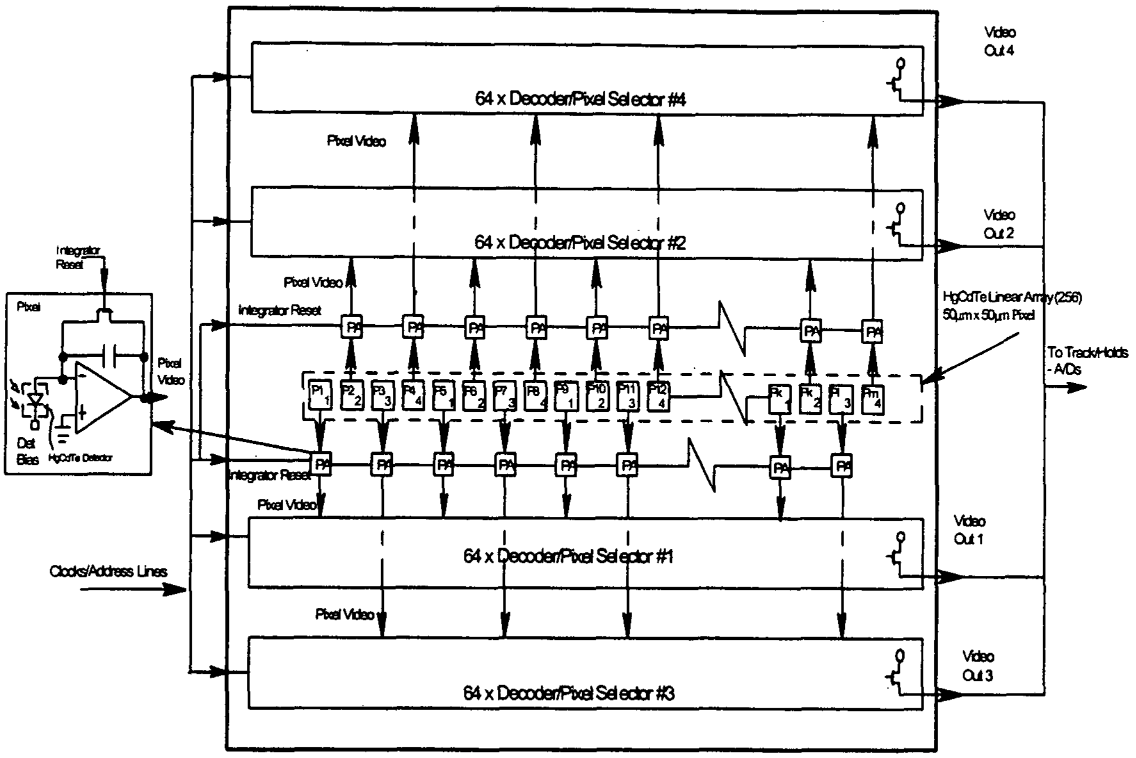
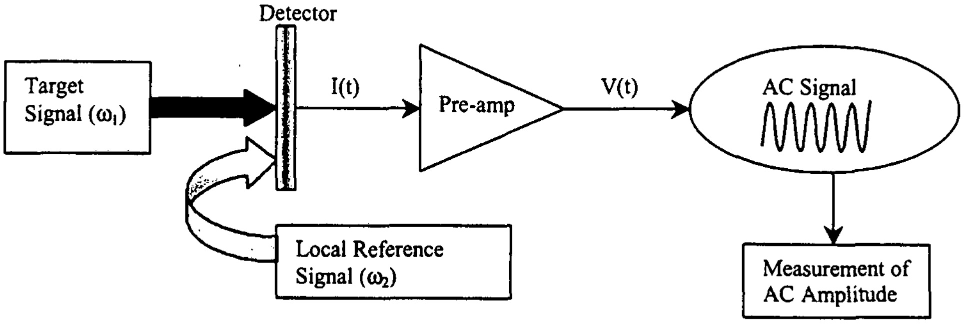


Figure 5. A schematic drawing of the basic focal plane configuration employing a single row of 50 µm pitch detectors, read out by two ROIC, one on each side of the detector array. Each IR detector has its own current transimpedance amplifier (CTIA) configured as an integrator that is reset just prior to arrival of the laser return pulse.

reduce background variability. Measured frequency information also allows direct measurement of wind speeds or even remote vibration measurement. When array technology is applied, **phase information** is used to maintain correlation between pixels for amplitude summation and signal averaging. In addition, for passive radiance measurements, a local oscillator source has been shown to be useful in spectrally filtering without the need to propagate a laser source over long ranges. Generally speaking, heterodyne detection offers increased capability, and complexity, through the amplitude, frequency, and phase information involved.

Heterodyne receivers have until recently been limited to single- or few-element detector designs due to the complexity inherent to measuring a beat frequency, phase, and amplitude. With each interrogation time, an entire waveform output from the detector is measured, stored, and post-processed later for analysis. By scanning the field-of-view, single-element heterodyne systems have demonstrated an imaging capability. However, while this method is time and data intensive the benefits are limited in application. In addition, single element receivers are restricted in performance due to coherence length and phase distortion across the detection surface. For some time now there has been a recognized need for multi-pixel array receivers[12], whether it be for true spatial imaging or simply independent phase registration and amplitude summing for speckle mitigation. The need for real-time (snapshot mode), array-based heterodyne detectors has been clear, but only recent developments in silicon CMOS processing (following advances of the computer industry) have made possible the concept of adding more complex capabilities to the underlying readout structures for focal plane array (FPA) devices.

Coherent detection of signal irradiance requires a detector bandwidth large enough to measure the beat frequency created by the difference between the reference and signal frequencies. This signal is filtered for a specific frequency and measured to determine the desired laser signal. Rather than outputting the ac signal from each detector pixel, requiring intensive post-processing, a proposed pre-amplifier design will filter and measure the heterodyne signal on-chip and output simple dc voltages corresponding to frequency and amplitude of the beat signal. Integrated signal detection and processing will allow for simplified control and acquisition electronics, which will lead to real-time display and feedback. Figure 6 shows a simple illustration of the laser local reference and signal return fields co-incident on the detector focal plane, followed by the electronic processing and output. The measured signal has a time dependent term whose intermediate frequency (i.f.) assists in filtering, for enhanced signal-to-noise detection. The i.f. is the heterodyne signal required, with the actual frequency proportional to the target motion and the amplitude proportional to the return intensity.



$$E = E_1 Cos(\omega_1 t) + E_2 Cos(\omega_2 t) \qquad signal \propto \left[\frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1 E_2 \cos(\omega_1 - \omega_2)t\right]$$

Figure 6. The pre-amplifier stage is designed to filter the signal for a desired bandpass center frequency, $\omega_1 - \omega_2$. The reference signal is shifted in frequency relative to the signal return. By tuning $\omega_2$, when a Doppler-shifted return $\omega_1$ is such that $(\omega_2 - \omega_1)$ is within the amplifier bandpass, the target signal has an AC amplitude that is measured. Therefore, both frequency shift (velocity of the target) and magnitude is measured. Range information is measured by using a pulsed laser source and gated measurements of the array. The target velocity is measured by varying the reference frequency on each frame, looking for maximum AC amplitude.

As an example, consider a pre-amp with a bandpass filter centered at 1 MHz. Using a 20 μs laser pulse, the return signal is measured during the gate time for the desired range and the 1 MHz signal offers ~20 periods of oscillation to measure an average amplitude. For this range location, the signal amplitude is recorded as a dc voltage output. A set of frames can be measured to cover various ranges to seek targets of interest within the field of view. Velocities are measured by varying the reference and/or transmitted frequency such that the target Doppler shift gives a maximum signal at the 1 MHz bandpass. Depending on the electronics bandwidth, the velocity is measured by noting the applied frequency shifts on the reference and transmitted laser that give maximum signal amplitude vs. frequency.

The example operation described here seems to be low risk with straightforward application. However, more advanced readout designs may be possible that could actually measure the dominant frequency component of the heterodyne signal. In addition, a tunable bandpass filter would move the control from the laser source to the detector electronics. Other concepts include 1) a differential measurement to distinguish high frequency shift targets from pseudo-stationary (low-frequency) targets and 2) a full fourier transform to determine all frequency components per pixel.

There are many detailed variations to this concept due to the capabilities and complexities involved. These variable application/design points must be considered, but inevitably some form of this concept will be demonstrated soon in fully-developed CMOS FPA designs extendable to large format. This detector technology will most likely significantly extend laser remote sensing applications even further.

## 5. CONCLUSION

In this paper we have discussed focal plane array technology and how it can be applied to enhance laser sensor performance. While significant advances continue to be made in passive camera designs, the speed and sensitivity demanded by laser remote sensing applications will require specialized design parameters. Past technological advances have enabled better performance, as described in the two LANL sensors; however, further design improvements are needed. Some applicable concepts were described being worked on under DOE SBIR, DARPA, or other funding. High-speed imaging FPAs are being realized now, along with specialized linear arrays, and heterodyne detection arrays. As these laser receiver designs improve, so will the sensor performance.

## ACKNOWLEDGEMENT

This work was performed under the auspices of the U.S. Department of Energy by Los Alamos National Laboratory under contract W-7405-Eng-36.

The authors would like to thank Cheng Ho, Joe Tiee, and C. Robert Quick of LANL for their helpful discussions and technical guidance in relation to the systems and concepts described here.

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[11] The work described in this section is part of an on-going DOE SBIR grant #DE FG02-00ER83080, with Phase II started Oct. 2001, building off an initial Phase I effort. This project is being monitored by LANL staff (P.L. Jacobson).

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