Three-Dimensional Laser Radar with APD Arrays*†

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ABSTRACT

M.I.T. Lincoln Laboratory is actively developing laser and detector technologies that make it possible to build a three-dimensional laser radar (3-D ladar) with several attractive features, including capture of an entire 3-D image on a single laser pulse, tens of thousands of pixels, few-centimeter range resolution, and small size, weight, and power requirements. The laser technology is based on diode-pumped solid-state microchip lasers that are passively *Q*-switched. The detector technology is based on Lincoln-built arrays of avalanche photodiodes (APD s) operating in the Geiger mode, with integrated timing circuitry for each pixel. The advantage of these technologies is that they offer the potential for small, compact, rugged, high-performance, systems which are critical for many applications.

INTRODUCTION

Lincoln Laboratory has an integrated program to develop technologies and address system issues relevant to 3-D laser radars. Technology development efforts include the development of silicon Geiger-mode APD arrays with associated timing circuitry, the development of InGaAs Geiger-mode APD arrays to expand the sensitivity of these devices to the short-wave IR, micro Nd:YAG laser development, and ladar prototype systems development. The ladar prototype systems we have developed or are developing include a 4 x 4 Geiger-mode APD brassboard system, which was developed and used to collect much of the 3-D data we have gathered to date, a 32 x 32 Geiger-mode system under development, and a ruggedized 32 x 32 Geiger-mode system, which will serve to prototype potential integrated-sytem applications. We also have ongoing efforts in data acquisition to study the phenomenology relevant to Geiger-mode 3-D laser radar and simulation efforts to model the performance of 3-D laser radar systems.

The following paper will elaborate on the existing Lincoln efforts dedicated to 3-D laser radar technologies and applications.

GEIGER-MODE INTEGRATED APD DETECTOR ARRAY DEVELOPMENT

An overview of the silicon Geiger-mode detector array configuration and development has been reported in earlier publications.[1-2] The basic configuration of the detector array is shown in Figure 1. The integrated focal plane consists of an array of Geiger-mode APD detectors epoxy bonded to a commensurate array of CMOS timing circuitry. Each hybrid pixel then contains a Geiger-mode APD and a timing circuit. The Geiger-mode APD can be thought of as a photodiode whose back bias voltage actually exceeds the level at which the detector will bread down. When photoelectrons are generated at the device junction due to the absorption of one or more signal photons (in practice, the devices have separate absorption and avalanche regions) they are accelerated in the electric field from the bias voltage. In the case of a "linear"-mode APD, the photoelectrons are accelerated enough to knock more electrons from the lattice and the total number of photoelectrons increases, resulting in gain. In a Geiger-mode device, the gain is so high that enough photoelectrons are generated to cause the device to breakdown and allow a large current to flow until any capacitance across the device is discharged. The advantage to this mode of operation is that variations in the gain from pixel to pixel or as a function of operating parameters or just due to statistical variations become irrelevant, since the device is driven

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far into saturation. The current pulse out of the device becomes very reproducible and can be used to trigger digital timing circuitry directly. Effectively, the device becomes sensitive to a single photon and the output is noiseless, except for fundamental shot noise. The saturation of the device from more than one photoelectron being generated in the absorption region can be addressed by limiting the signal level to an average of less than a photoelectron per laser pulse and looking statistically at the number of detections per number of laser pulses. This represents the most sensitive form of optical measurement in which every photon is counted.

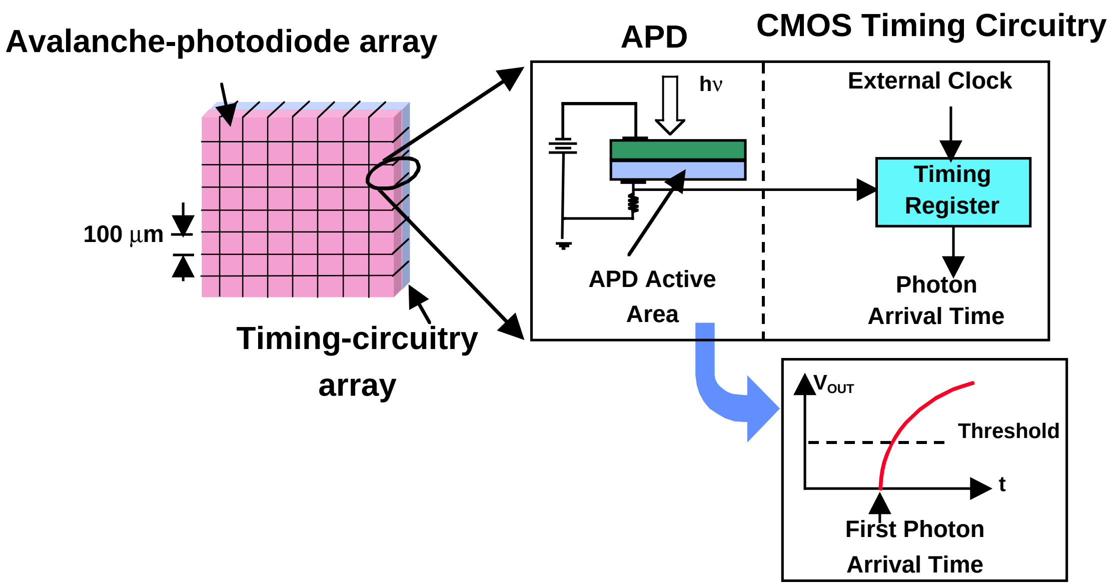

Figure 1: Geiger-mode APD arrays bonded to CMOS timing circuitry.

Once the APD "fires", or breaks down due to the runaway avalanche process, a well-defined voltage pulse is generated that can directly toggle CMOS digital circuitry. As can be seen from Figure 1, each pixel of the APD array has an associated timing register. This is achieved by bonding the APD array to an array of CMOS timing circuitry. A block diagram of the timing circuit for each pixel is shown in Figure 2. The counter in the timing circuit consists of a 15-bit register with positive feedback. This configuration will count through a sequence of 2^{15}-1 psuedo-random numbers. Since the exact sequence is known, the random number can be decoded during readout with a simple lookup table to produce a count. The advantage to this type of counter is that it can be realized with a minimum of circuitry. Two effective bits of timing resolution are added by recording the clock state and a 90-degree phase-shifted version of the clock. Thus, 0.5-ns timing resolution can be achieved with a 500-MHz clock. The sequence of events for a 3-D measurement then involves sending out a laser pulse to flood-illuminate the field of view of the detector. A short time before the backscattered return from the target arrives at the receiver the pixel clocks are turned on by broadcasting a common clock to each of the pixel counters. As the photons arrive and cause the APD's to fire they latch and save the associated time as the count in the pixel timing register and the associated vernier bits. Finally, the digital values from each of the registers are read out in a serial fashion and the decoded time values are used to produce the 3-D image.

Figure 3 shows a slice through the middle of a pixel. The integration of the APD array with the CMOS timing circuitry is achieved by first thinning the APD array to about 15 microns and flipping the array over so it can be back illuminated. The thinned array, still at the wafer level, is then epoxy bonded to chips containing the, MOSIS produced, timing circuitry. Electrical connection is established between each APD and it's associated timing circuit by etching a "via" (angled) groove next to each APD, exposing a metal connection pad on the CMOS chip for each pixel. A surface metalization is then deposited that makes electrical contact with each APD and it's associated timing circuit.

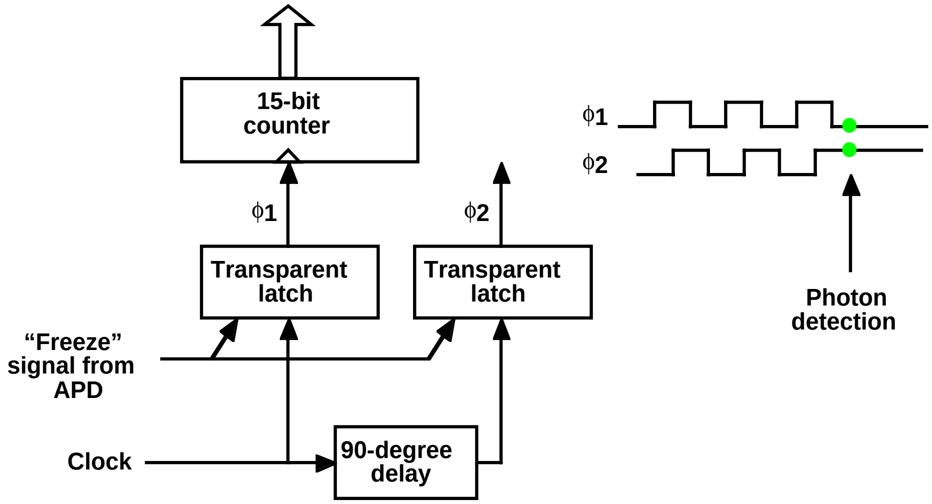

Figure 2: Pixel timing circuit.

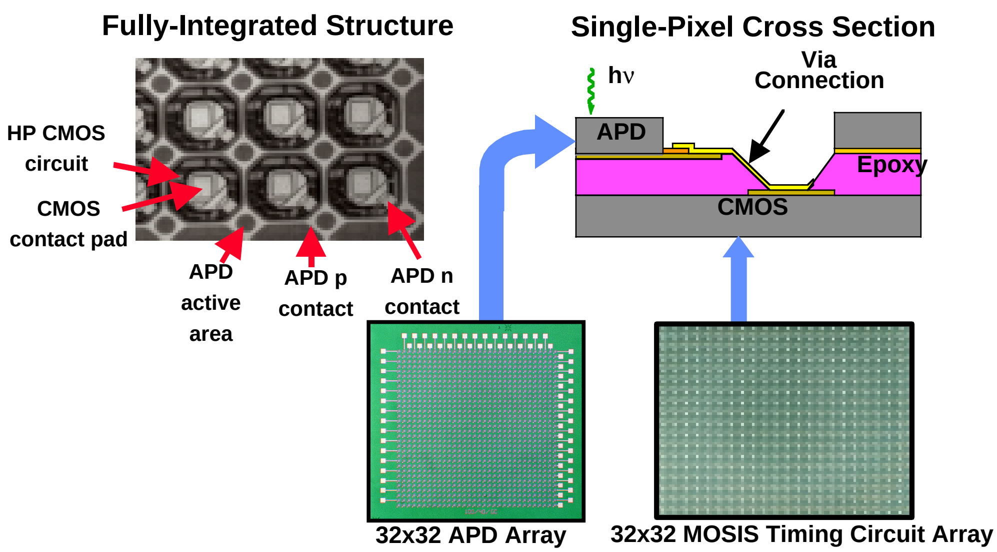

Figure 3: Geiger-mode APD array structure.

Lincoln Laboratory has been developing focal plane arrays with silicon APD arrays and CMOS timing circuitry for several years. Initially, 4 x 4 devices were developed and tested. These devices were wire bonded to 16 timing circuit elements situated around the perimeter of the array (Figure 4). More recently, fully-integrated 32 x 32 arrays have been developed, an example of which is shown in Figure 5. These devices have demonstrated functionality and are presently undergoing performance testing. A 32 x 32 array is due to be integrated into our "Gen-2" laser radar system, which will be described later in this paper.

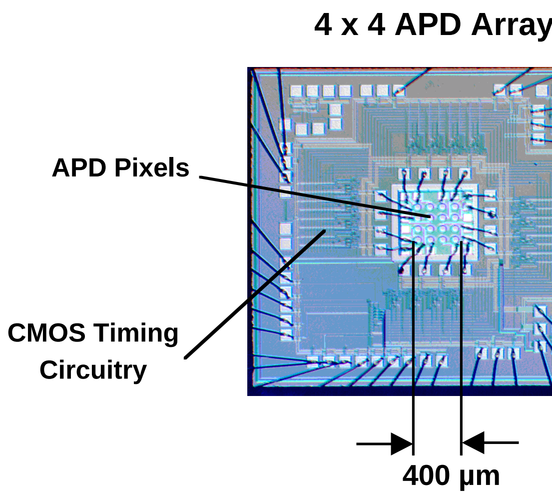

Figure 4: APD initial hybrid test structure.

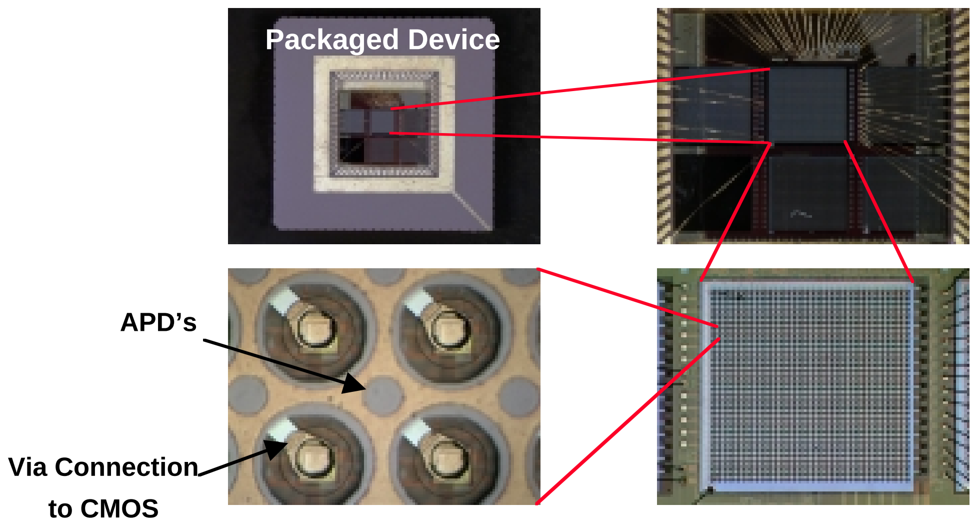

Figure 5: Fully integrated 32 x 32 array.

A simultaneous technology-development effort is underway at Lincoln to produce Geiger-mode APD arrays that are sensitive in the short-wave IR region. The material system being developed for this purpose is InGaAs. Initially, the devices were developed for sensitivity at a wavelength of 1.5 microns and single-element APD's with linear-mode gains greater than 50 at room temperature were fabricated (Figure 6). This development effort has since shifted to focus on Geiger-mode devices with high sensitivity at 1-micron wavelengths. Figure 7 shows a comparison of the structure of the 1.5 and 1-micron sensitive devices. As can be seen, the shorter-wavelength sensitive devices have a much simpler configuration and their development is expected to be more straightforward. The real advantage to the 1-micron sensitive devices, however, is in the fact that they are compatible with 1.06-micron Nd:YAG laser transmitters. Since these lasers are some of the most highly-developed and efficient short-pulse sources, having detectors optimized at their wavelength is paramount to minimizing the size and power requirements for many 3-D ladar applications. The eyesafety requirements can be easily met due to the high sensitivity of these detectors and high-PRF operation. Furthermore, the knowledge gained in the optimization of 1-µm-sensitive devices can also be applied to the fabrication of Geiger-mode 1.5-µm-sensitive devices. It is anticipated that 1-µm-sensitive APD's operating in the Geiger mode will be available in CY2001.

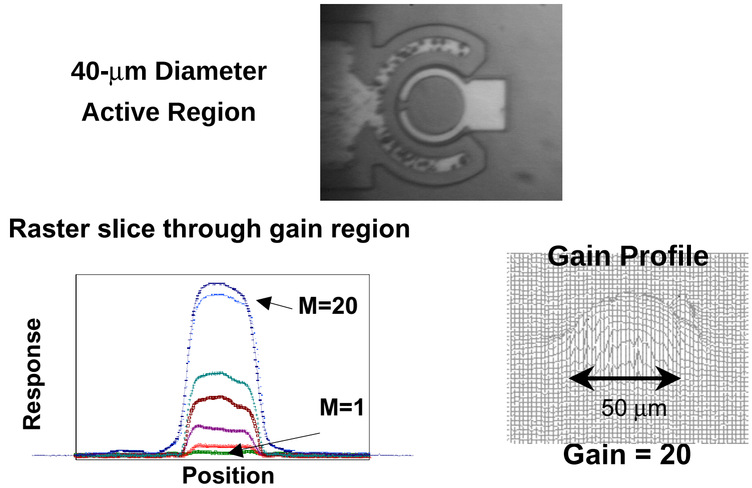

Figure 6: 1.5-µm-sensitive APD test results.

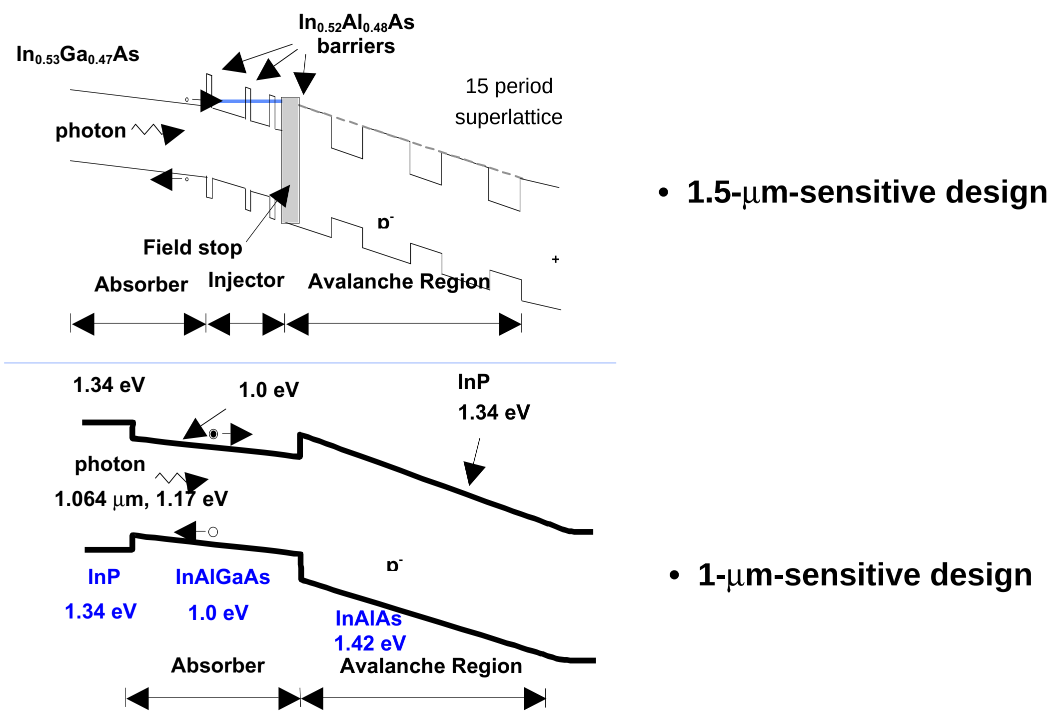

Figure 7: Comparison of InGaAs APD designs.

MICROCHIP LASER DEVELOPMENT

Lincoln Laboratory has developed and continues to develop state-of-the-art lasers that are highly compatible with ladar systems.[3] One of the most versatile of these devices is the so-called "µ-chip" laser (Figure 8). These devices are composed of diffusion-bonded pieces of Nd-doped YAG and Cr^{4+}-doped YAG. When the 808-nm radiation from a pump diode laser is directed into the end of the µ-chip laser, the Cr-doped YAG acts as a saturable absorber, causing the device to passively Q-switch. The truly novel aspect of these lasers lies in the fact that the cavity length, about 1 mm, is short enough to only support a single longitudinal laser mode under the gain bandwidth. This, when added to the fact the thermal lensing confines the modes transversely, causes the laser to automatically operate in a single longitudinal and transverse mode. Therefore, no external switching is required and the output pulse repetition frequency (PRF) of the laser can be controlled by modulating the pump radiation, for the laser to generate a near-diffraction-limited short-pulse output. Another ramification of the small size of the laser is that the output pulse width is typically less than 1 ns, which is optimal for high-range-resolution 3-D ladar applications.

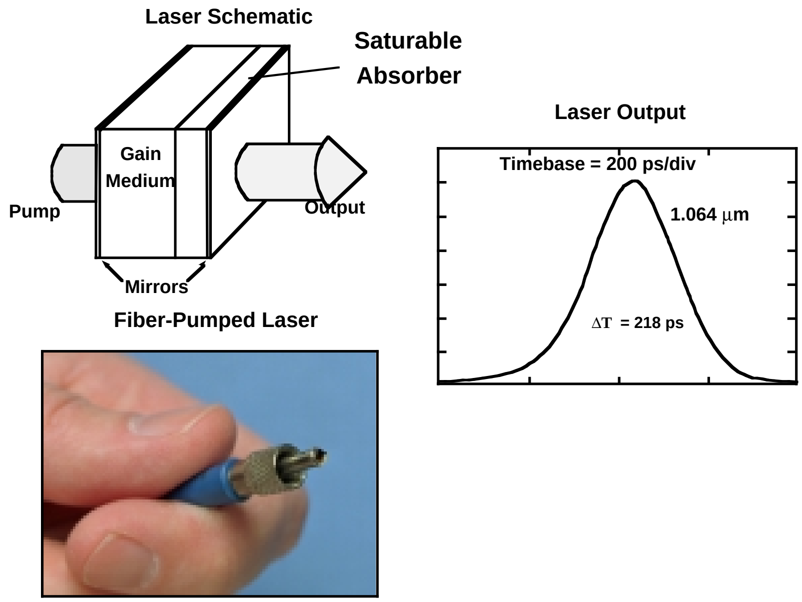

Figure 8: Miniature, passively-Q-switched, diode-pumped, solid-state laser.

Recent developments of the µ-chip laser have been aimed at increasing the per-pulse energy output. Laser systems with outputs in excess of 250 µJ at 1-kHz PRF's have been developed, which continue to produce sub-nanosecond (380-ps) pulses. Figure 9 shows an empirical relationship of the per-pulse energy output and PRF achievable with µ-chip lasers. Optimum photon-counting efficiencies would nominally require the laser to operate at very high PRF's. Under these conditions, the energy per pulse would be very small and master-oscillator power-amplifier, MOPA, configurations may be required. Under these circumstances, the µ-chip laser would serve as the master oscillator for the system. These laser configurations are presently under development at Lincoln Laboratory for integration into the Gen-2 32x32 3-D ladar system.

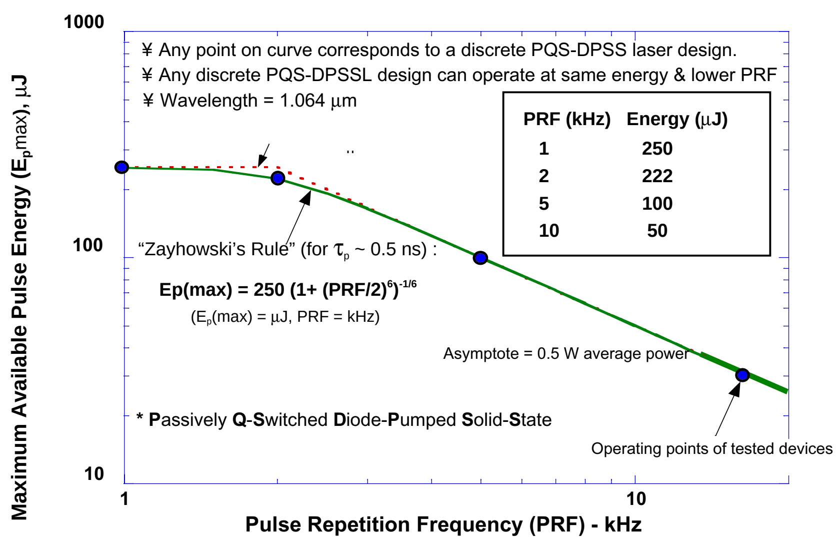

Figure 9: Microchip laser energy and PRF

LADAR DEVELOPMENT ACTIVITIES

Lincoln Laboratory has developed a prototype 3-D ladar using a 4x4 Geiger-mode APD array. This brassboard ladar system was developed to test the efficacy of photon counting for 3-D image generation and to collect 3-D images on a variety of targets for developing processing and display algorithms. A photograph of the optical head of the brassboard ladar system is shown in Figure 10. The transmit and receive optics of this system share a common 5-cm aperture and the field of view is directed across the target with a pair of single-axis scan mirrors. Since this device was developed before the 4x4 APD arrays, wire bonded to timing circuitry, were available, the brassboard ladar utilizes external timing circuitry to process the signals from the detector array. A block diagram of the 4x4 brassboard ladar is also shown in Figure 10. The transmit laser is one of the Lincoln µ-chip lasers, frequency doubled to 532 nm. This laser has a 1-kHz, 30-µJ, output and flood illuminates the 4x4 field of view with an adjustable divergence. A zoom lens on the receive optical train allows the pixel field of view to be varied between about 0.2 and 2 mrad. A pair of scan mirrors direct the field of view of the 4x4 array over a larger area in order to generate 32x32 or 128x128 imagery of targets. Many of the 3-D data presented later in this section were collected with this device.

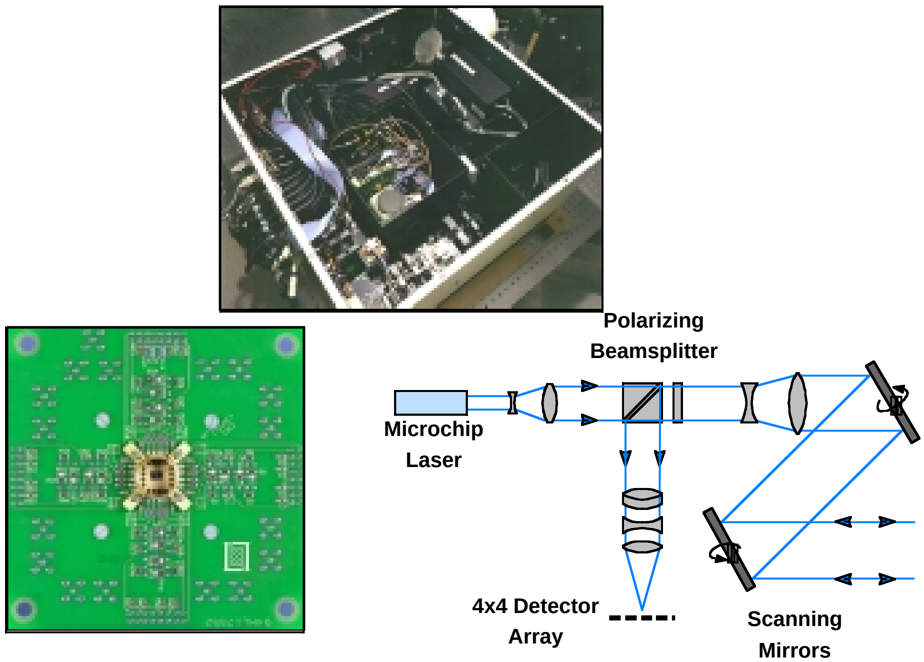

Figure 10: 3-D Ladar brassboard.

Development is currently proceeding on a "Gen-2" 3-D ladar that will incorporate a 32x32 fully-integrated APD array. A functional diagram of this device is shown in Figure 11. The operating wavelength of the Gen-2 ladar will initially be 800 nm. This was chosen to accommodate the sensitivity of the silicon APD's while not producing a visible laser beam. The laser being developed will consist of an amplified µ-chip laser which is frequency doubled to 532 nm and pumps a titanium-sapphire laser, tuned to operate at 800 nm (Figure 12). Initial laser performance specifications call for 8 - 10-kHz operation with 20-µJ per pulse output. The program plan calls for a subsequent upgrade of the laser output to 150 µJ per pulse with the addition of a larger amplifier.

The receive optics for the Gen-2 system are centered around a 10-cm parabolic/pair telescope which re-images the field into a following Matkutsov telescope. The receive optics design was motivated by the requirement to allow operation from 800 nm to a 1.5-micron wavelength with only minor refocus and a change in bandpass filter required. This will allow the upgrade of the system to 1.06-micron operation as the APD arrays sensitive at this wavelength become available. The collimated beam space between the two telescopes also offers a location for a narrow bandpass filter. The Gen-2 system will have a pixel field of view of 250 µrad and is designed to operate out to ranges of several kilometers. The system will be incorporated with a two-axis scan mirror developed by Left Hand Design, which will allow the acquisition of imagery over +/- 20-degree field angles.

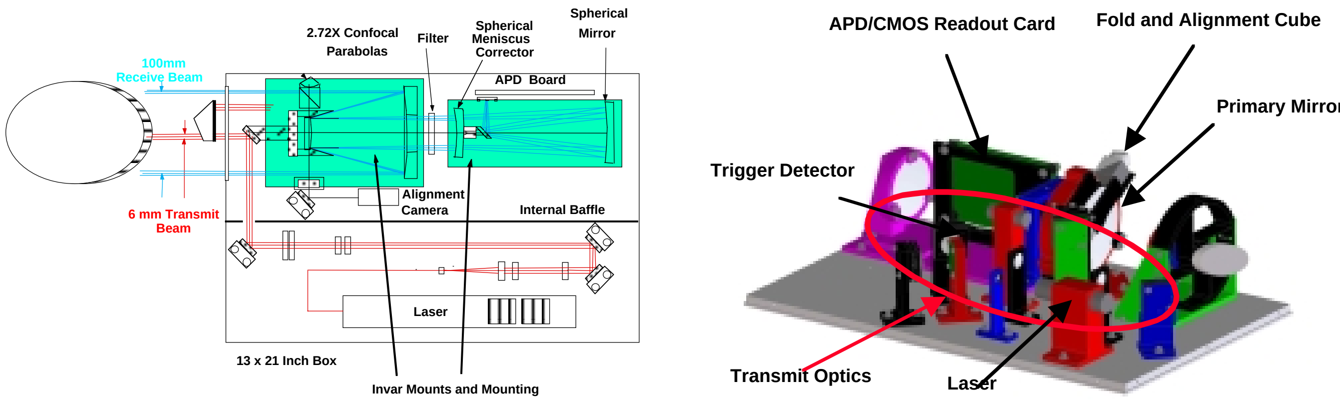

Figure 11: Gen-2 Ladar system.

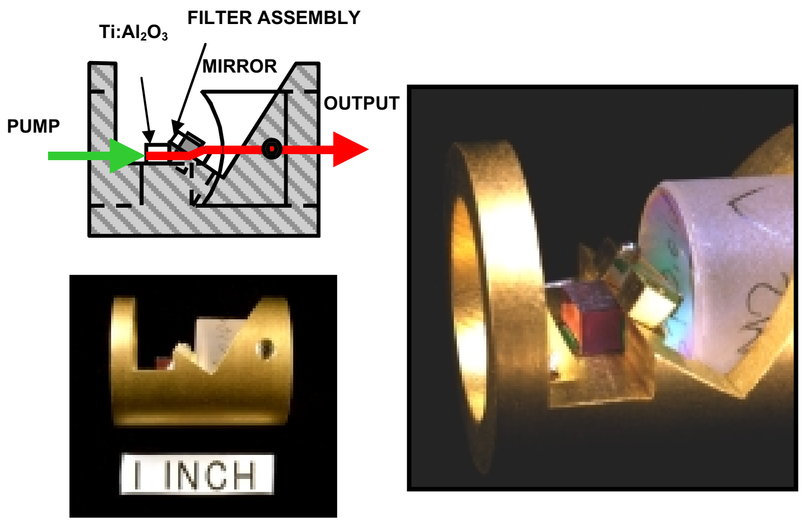

Figure 12: 800-nm Ti-Sapphire laser assembly.

The 32x32 APD receiver to be incorporated into the Gen-2 system has pixels on a 100-µm pitch with a 30-µm diameter active area for each. In order to concentrate the returned signal on the active area of each pixel, a 32x32 array of lenslets will be integrated onto the front of the array. These lenslets will be fabricated by a technique developed at Lincoln that utilizes mass transport of lithographically-generated GaAs. The advantage of this is the ability to precisely control the lenslet surface and generate relatively low F numbers (F/4 is required for the Gen-2 ladar). Another option would dispense with lenslets on the receiver and instead employ a holographic filter in the transmit laser chain, which would cause the transmit beam to be an array of spots whose divergences were matched to the active-area fields of view for each pixel. This technique will be utilized in the ruggedized ladar system (discussed below). The Gen-2 ladar is due to be operational by early Fall, 2001, and will be used in ground tests at the Eglin AFB shortly thereafter.

Besides the already-developed 4x4 brassboard system and the Gen-2 ladar under development, Lincoln Laboratory is also integrating a ruggedized version of the 32x32 APD array ladar. The goal of this effort is to develop the engineering expertise needed to ruggedize and miniaturize the various components of the ladar system. CAD drawings of the design for this system are shown in Figure 13. This system will use a silicon 32x32 APD array, without lenslets, as the receiver. The transmitter will be a frequency-doubled µ-chip laser (Figure 14) operating at 532 nm. The transmit beam for this ladar will be converted to an array of spots whose divergencies match the fields of view of the receiver pixels. This system will also incorporate a two-axis scan mirror fabricated by Left Hand design. Part of this development effort will be directed towards reducing the size and power requirements of the array readout electronics and the laser drive power supply. Although the size of this system is still greater than that required for many applications, its development represents a significant step forward in efforts to package these particular technologies and the lessons learned will be directly applicable to even more compact and rugged system designs.

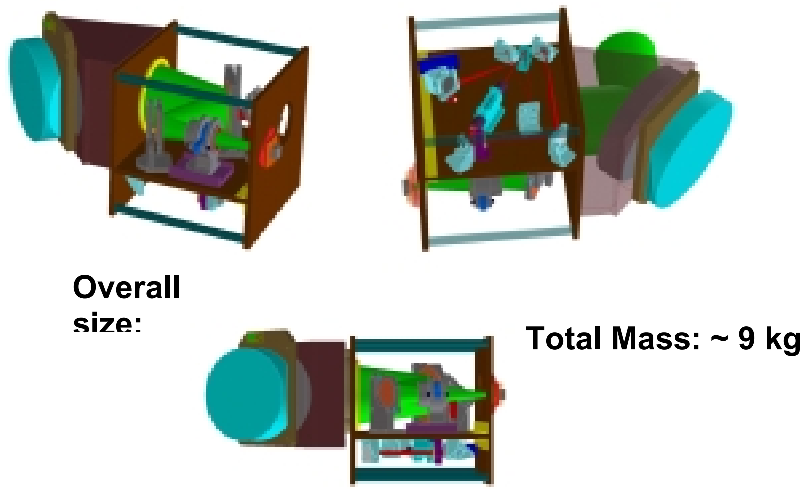

Figure 13: Compact / ruggedized laser radar.

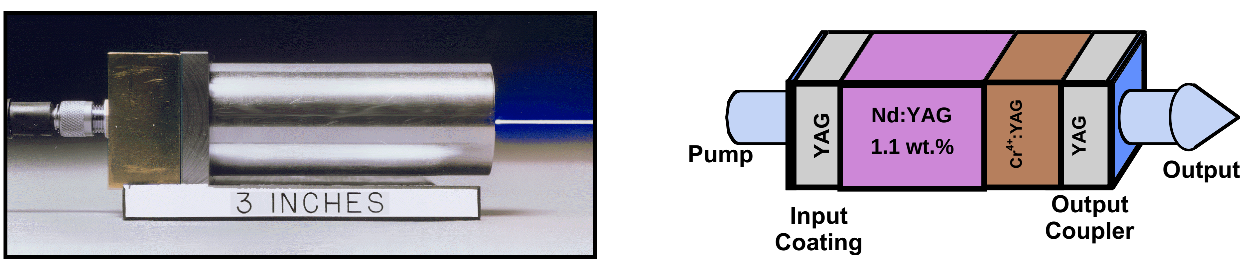

Figure 14: High-power micro-chip laser configuration.

DATA COLLECTION AND SIMULATION EFFORTS

Lincoln Laboratory has ongoing efforts to both collect and simulate 3-D ladar data from photon-counting systems. The data collection efforts to date have primarily employed the 4x4 brassboard system described in the previous section. This system has collected data on a variety of targets in our indoor 80-m test range at Lincoln Laboratory, at a 500-m range at the Lincoln Firepond facility, at the Lincoln Laboratory Flight Facility, and at San Diego harbor. We are continuing to collect image data with this ladar and have plans for future fieldings of this system. The data collected with this system has served to baseline our simulations and to develop visualization tools for interpreting the 3-D data. We have also employed our brassboard ladar to make simultaneous measurements with passive IR cameras to investigate techniques for fusing IR and 3-D data.[4]

Some of the most relevant data, from a tactical-applications perspective, collected to date was gathered at the Lincoln Firepond facility. This is located approximately 40 miles north-west of the main Laboratory in Westford, Mass. A photograph of the Firepond 500-m test range is shown in Figure 15. In these measurements a Lincoln low-light-level

CCD camera was placed side-by-side with the brassboard ladar. Both the CCD and the APD sensors produced 128x128 images which were matched in field of view and the CCD camera could image a target that was actively illuminated. An example of two actively-illuminated images collected with the CCD camera are shown in Figure 16. These images are produced by averaging 200 frames where each has an average signal level of 105 and 1.7 photoelectrons/pixel, respectively. In the higher signal image a truck is clearly visible, but what is not visible is that there is another truck behind a camouflage net on the other side of the image. In the lower-signal image neither truck is clearly visible. These are to be compared with a 3-D image collected by the 4x4 brassboard system collected at the same time. In this case the average signal level per pixel over the 200 frames is only 0.4 photoelectrons. As the rotated version of the image demonstrates, not only is the truck out in the open clearly identifiable, but the truck behind the camouflage net can also be clearly identified. This measurement not only demonstrates the power of 3-D imaging for looking through obscurants, but also demonstrates the utility of photon counting, which enables these measurements to be made at very low signal levels.

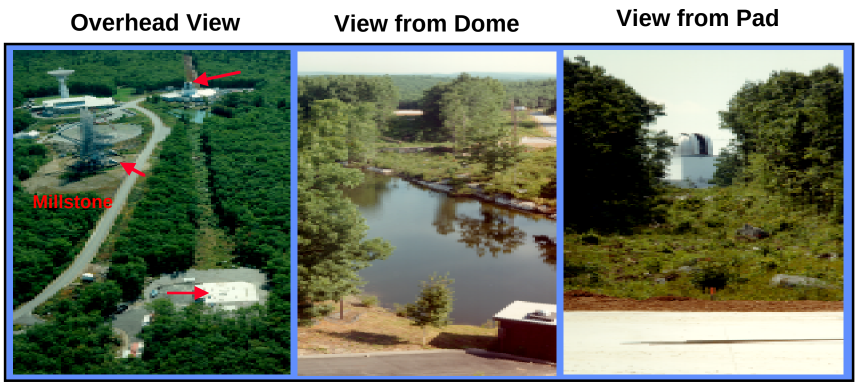

Figure 15: Firepond 500-m test range.

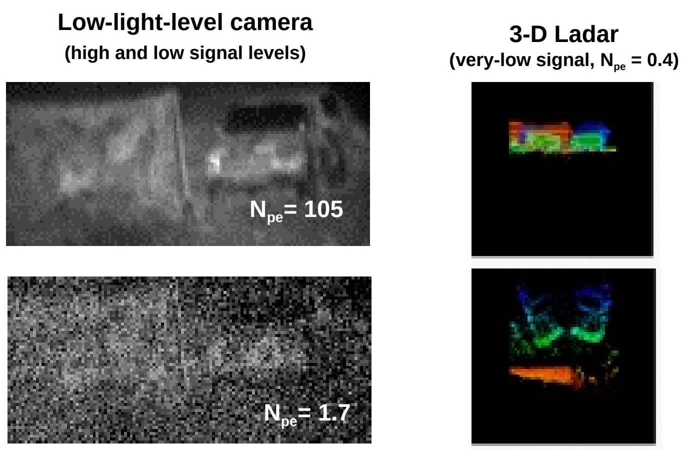

Figure 16: Comparison of actively-illuminated intensity and 3-D images of a pair of SUV's, one behind a camouflage net. N_{pe} is the average number of photoelectrons for each image over 200 processed frames.

Another comparison of a CCD image, in this case sunlight illuminated, with a 3-D image is shown in Figure 17. In this case the CCD image, which was collected as an average of 200 frames with 300 photoelectrons/pixel/frame, displays only one truck but the fact that another truck sits behind the tree line on the left is obscured. The corresponding 3-D image, using only an average of 0.3 photoelectrons/pixel over 200 frames, clearly shows the truck in the open and the truck behind the tree line when the image is rotated in software and redisplayed. Again, the utility of photon-counting 3-D imaging is shown. Also shown is the usefulness of rotating 3-D images for the perception of targets in clutter.

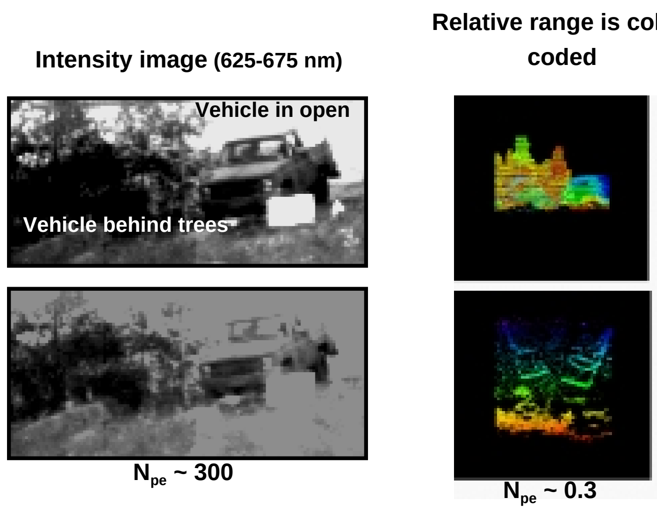

Figure 17. Comparison of intensity and 3-D images of a pair of SUV's, one behind a line of trees. N_{pe} is the average number of photoelectrons for each image over 200 processed frames.

Along with measurements, there is an ongoing Lincoln effort to simulate the performance of photon-counting ladar systems. An example of some of the simulation results are shown in Figure 18, which shows the simulated return from a forested scene from an airborne platform looking down. In this case, the average return per laser pulse is 0.05 photons with 4000 pulses averaged. The lower right image shows the data processed for the returns through the trees and in this case a second tank can be distinguished. These ongoing simulation efforts will eventually include more realistic models of foliage and camouflage obscurants.

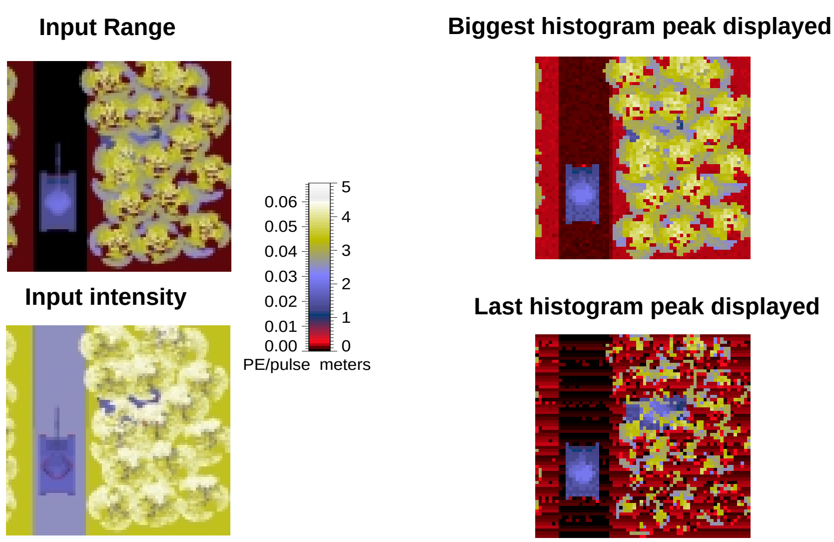

Figure 18: Simulation with trees (N_{pe} = 0.05, 4000 pixels, 30-cm pixel size).

SUMMARY

This paper has presented an overview of the ongoing efforts at Lincoln Laboratory for 3-D laser radar technology development. These efforts are composed of detector and laser transmitter technology development, ladar prototype development, 3-D image data collection, and ladar system performance simulation. The detectors under development are arrays of single-photon-sensitive Geiger-mode APD's. These are bonded to digital CMOS readout circuitry to provide direct digitial output from the detector chip of the 3-D images. The laser transmitter technology under development is primarily based on passively Q-switched microchip lasers, which can produce high-PRF, short pulses with excellent beam quality. The ladar prototype development includes an already-existing 4x4 brassboard as well as a testbed and a ruggedized system utilizing 32x32 APD arrays. Data collection efforts have proceeded to date with the 4x4 brassboard system and have demonstrated the efficacy of photon counting to produce high-quality 3-D imagery of targets behind obscurants with extremely low signal levels. Simulation efforts are also proceeding with the goal of producing simulated data under a variety of circumstances to aid in the development and optimization of processing algorithms.

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