Geiger-mode APD Camera System for Single Photon 3-D LADAR Imaging

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ABSTRACT
The unparalleled sensitivity of 3D LADAR imaging sensors based on single photon detection provides substantial benefits for imaging at long stand-off distances and minimizing laser pulse energy requirements. To obtain 3D LADAR images with single photon sensitivity, we have demonstrated focal plane arrays (FPAs) based on InGaAsP Geiger-mode avalanche photodiodes (GmAPDs) optimized for use at either 1.06 μm or 1.55 μm. These state-of-the-art FPAs exhibit excellent pixel-level performance and the capability for 100% pixel yield on a 32 x 32 format. To realize the full potential of these FPAs, we have recently developed an integrated camera system providing turnkey operation based on FPGA control. This system implementation enables the extremely high frame-rate capability of the GmAPD FPA, and frame rates in excess of 250 kHz (for 0.4 μs range gates) can be accommodated using an industry-standard CameraLink interface in full configuration. Real-time data streaming for continuous acquisition of 2 μs range gate point cloud data with 13-bit time-stamp resolution at 186 kHz frame rates has been established using multiple solid-state storage drives. Range gate durations spanning 4 ns to 10 μs provide broad operational flexibility. The camera also provides real-time signal processing in the form of multi-frame gray-scale contrast images and single-frame time-stamp storage drives, and automated bias control has been implemented to maintain a constant photon detection efficiency in the presence of ambient temperature changes. A comprehensive graphical user interface has been developed to provide complete control using a simple serial command set, and this command set supports highly flexible end-user customization.

Keywords: avalanche photodiodes, Geiger mode, single photon camera, photon counting, LADAR, 3-D imaging, focal plane arrays, InGaAsP

1. INTRODUCTION
The ability to generate true three-dimensional (3D) image data (i.e., angle-angle-range) provides dramatic advantages relative to two-dimensional (2D) imaging techniques. To extract details about objects in an imaged scene, traditional 2D intensity images require that object shapes be inferred from edge examination and complex image processing algorithms that generally involve assumptions about the object or scene that are not implicit in the image data. Three-dimensional data obtained by employing high-resolution LADAR range measurements at each pixel of the imager provide much higher resolution data than longer wavelength sensing techniques (e.g., radar) and results in far more accurate object recognition. The extension of the 3D imaging concept to detectors with single photon sensitivity [3] provides unparalleled sensitivity, with the capability for greatly accelerated 3D mapping rates and relaxed requirements on the launched power of optical pulses.

In previous work [4–6], we have presented the design and performance of 32 x 32 focal plane arrays (FPAs) based on 100-μm pixel pitch two-dimensional arrays of InGaAsP Geiger-mode avalanche photodiodes (GmAPDs). In this paper, we describe a turn-key 3D imaging camera system with single photon sensitivity based on these FPAs. FPGA and microprocessor control provides the camera head with significant on-board functionality and real-time signal processing. The camera head is integrated into a turn-key system based on a high-performance personal computer with...
a comprehensive graphical user interface (GUI). The GUI enables user control of all camera functions, including highly efficient data storage algorithms to facilitate continuous streaming data storage at frame rates up to ~200 kHz. The results presented in this paper are for cameras optimized for operation with 1.06 μm laser pulses, and comparable results have been obtained for systems delivered for operation at 1.5 μm, with a higher dark count rate being the primary tradeoff in providing longer wavelength detection.

After a brief overview of GmAPD-based FPA design in Section 2, we describe the camera-level integration of GmAPD FPAs in Sections 3. Section 4 contains a summary of the fundamental tradeoff between dark count rate (DCR) and photon detection efficiency (PDE) for a very low DCR camera. Characterization of inter-pixel crosstalk is presented in Section 5, the timing jitter performance of the camera system is outlined in Section 6, and we summarize our results in Section 7.

2. FOCAL PLANE ARRAY DESIGN CONCEPT

2.1 Geiger-mode avalanche photodiode (GmAPD) arrays

When an avalanche photodetector is biased above its breakdown voltage $V_b$, the creation of a single electrical carrier can induce a run-away avalanche that gives rise to a detectable macroscopic current. In this mode of operation, often referred to as Geiger mode, the detector is sensitive to the absorption of a single photon. (For this reason, these detectors are also often referred to as single photon avalanche diodes, or SPADs.) We have developed InGaAs/InP avalanche diode structures specifically for single photon detection in the wavelength range of 0.92 to 1.67 μm [7,8], and we have optimized this structure for shorter wavelength operation 1.06 μm by employing a quaternary InGaAsP absorber in place of the longer wavelength ternary InGaAs absorber. [9] We have described in detail the design, modeling, and characterization of discrete GmAPD devices employing both InGaAs and InGaAsP absorption regions in previous publications [7–11].

A schematic depiction of the GmAPD device structure is illustrated in Figure 1(a). For the FPAs integrated into our camera system, photon absorption occurs either in a quaternary InGaAsP layer ($E_g \approx 1.03$ eV) optimized for detection of single photons at 1.06 μm or a ternary InGaAs layer ($E_g \approx 0.75$ eV) optimized for detection of single photons at 1.55 μm. The absorption layer is spatially separated from a wider bandgap InP region ($E_g \approx 1.35$ eV) in which avalanche multiplication occurs. A primary goal of the design—the separate absorption and multiplication (SAM) region structure [12]—is to maintain low electric field in the narrower bandgap absorber (to avoid dark carriers due to tunneling) while maintaining sufficiently high electric field in the multiplication region (so that impact ionization leads to significant avalanche multiplication). The creation of a single electron-hole pair by photoexcitation in the absorber layer results in the injection of the hole into the high-field InP multiplication region in which impact ionization results in avalanche gain. With the GmAPD biased above $V_b$, the GmAPD detection process is inherently digital, and with appropriately designed detectors and threshold circuits, the detection process is noiseless.

To counteract the tendency for APD “edge breakdown” effects caused by enhanced electric field amplitudes at the edge of a cylindrical junction formed by a single dopant diffusion, we employ appropriate shaping of the diffused junction by using a pair of concentric dopant diffusions [13]. Figure 1(a) schematically illustrates the lowering of the electric field amplitude in the peripheral region of such an APD structure, and this design ensures that the gain profile across the center part of the active region is uniform and that the gain is reduced in the peripheral region. This lateral structure of our buried p-n junction design guarantees provides not only edge breakdown suppression, but also low perimeter leakage and high reliability. The active area of this planar geometry device [14] is determined by the patterning of a SiN dielectric passivation layer to create a diffusion mask for a subsequent diffusion of Zn dopant atoms to create a p'-InP region within the i-InP cap layer. For the 32 x 32 FPAs described in this paper, the optical active region diameter in each pixel is 34 μm.

2.2 CMOS Readout integrated circuit (ROIC) functionality

The basic functions of our 3D imaging FPA are performed by a custom CMOS readout integrated circuit (ROIC) mated to the GmAPD photodiode array (PDA) by indium bump hybridization. In the disarmed state, every pixel of the detector array is biased slightly below the breakdown voltage of the GmAPD using a single external low-noise voltage supply with voltages on the order of 70 to 80 V. Each imaging frame begins with the arming of all of the detector pixels.
by the ROIC, which applies an excess bias of up to \( \sim 4 \) V. The period during which the pixels remain armed is the “range gate”, which is typically on the order of a few microseconds. In a LADAR imaging system, the beginning of the range gate is synchronized (up to a fixed delay) with the launch of an optical pulse from which reflected photons will be detected. Every pixel contains a pseudorandom counter that provides detection timing information on a per-pixel basis. Upon asserting the master clock enable (MCE) signal, all pixel counters begin counting. Within each ROIC pixel, there is a threshold detection circuit that is triggered when an avalanche event occurs in the corresponding armed pixel of the photodiode array. When a detection occurs, an active quenching circuit removes the excess bias from the fired GmAPD pixel to disarm it, and the in-pixel counter is stopped so that the time of detection within the range gate is recorded. At the end of each range gate, pixels that do not sense an avalanche event record the terminal counter value, indicating that no event has occurred at that pixel. The frame readout then consists of scanning out all of the pixel counter values. This FPA architecture provides range resolution corresponding to the timing resolution of the pixel counters, whereas the intensity resolution is one bit per frame since each pixel returns only a single time-stamp value per frame. Intensity information is obtained by accumulating multiple frames.

![Schematic cross-section of a planar-geometry diffused-junction GmAPD device structure illustrating the reduction of electric field amplitude at the edge of the device by tailoring of the diffusion profile to avoid edge breakdown effects.](image)

Figure 1. (a) Schematic cross-section of a planar-geometry diffused-junction GmAPD device structure illustrating the reduction of electric field amplitude at the edge of the device by tailoring of the diffusion profile to avoid edge breakdown effects. (b) Notional concept for a GmAPD focal plane array, consisting of the hybridized chip stack with readout integrated circuit (ROIC), Geiger-mode APD photodiode array (PDA), and microlens array (MLA) attached to a ceramic interposer for electrical signal routing and cooled by a thermoelectric cooler (TEC) in a hermetically sealed housing.

The ROIC incorporates an on-chip phase-locked loop (PLL) circuit to provide the clock for controlling all timing operations. The FPAs achieve 13-bit timing resolution using 11-bit pseudorandom counters with two additional vernier bits created by using a copy of the clock with a 90 degree phase shift [3]. At the end of each range gate, frame data is scanned out using a dedicated I/O port for each of the 32 rows in the 32 x 32 array format, and scan circuitry achieves the read-out of the 32 pixels in each row in \( \sim 3.4 \) μs. The range gate duration is user-selectable with any value between 4 ns and 10 μs. For a typical range gate duration of 2 μs, the full frame duration of \( \sim 5.4 \) μs corresponds to a frame rate of 186 kHz. For very short (i.e., ns-scale) range gates, the frame rate is determined entirely by the 3.4 μs readout time and is on the order of 300 kHz. In addition to the internally supplied clock, the FPA can be run with an external clock input for system synchronization. The ROIC design for this 32 x 32 format was carried out in 0.18 μm CMOS technology with circuit elements appropriately scaled to ensure forward compatibility with 50-μm pitch 32 x 128 ROICs used in larger format FPAs that we have described elsewhere [15].

### 2.3 Module design summary

The schematic illustration in Figure 1(b) shows the principal elements of the assembled FPA module. Following the hybridization of the GmAPD PDA to the CMOS ROIC, we align and attach a GaP microlens array (MLA) to the exposed back surface of the PDA to increase the FPA fill factor. We have developed a passive alignment technique employing matched alignment fiducials on the PDA and MLA that provides for micron-scale alignment of the MLA to the PDA active areas. A high-performance optical epoxy is used to attach the MLA to the PDA with relatively rapid curing, and the process has been confirmed to be robust with respect to elimination of possible shifting of the MLA position after alignment. Based on the characterization of FPA pixel-level photon detection efficiency before and after MLA attachment, the effective fill factor for broad illumination of the FPA is found to be \( \sim 75\% \).
Once the MLA has been attached to the PDA, the resulting chip stack of ROIC+PDA+MLA is attached to a ceramic interposer that facilitates electrical routing of signals from the ROIC to the package interconnection pins. The interposer is then placed on a two-stage thermoelectric cooler (TEC), which has been previously mounted to the ceramic housing along with a CuW heat sink. The ceramic housing includes a pin grid array with 175 pins for electrical connections, and a hermetically sealed lid with an anti-reflection coated sapphire window provides optical access to the sensor and provides reliable operation in harsh environments. The solid body cut-away diagram in Figure 2(a) shows a scale model of the assembled module, and the photograph in Figure 2(b) illustrates a fully assembled FPA module prior to lid attachment.

![Figure 2.](image)

**Figure 2.** (a) Solid body model of FPA module with cut-away showing, from bottom to top, CuW heatsink (gold), ceramic package (gray), thermoelectric cooler (white), interposer board (light blue), hybridized ROIC+PDA+MLA chip stack (dark blue), and package window (clear). (b) Detailed photograph of fully assembled FPA module (without lid) shows the 32 x 32 hybridized chip stack in the center of interposer board.

### 3. GEIGER-MODE APD CAMERA SYSTEM INTEGRATION

To deploy the FPA described in the previous section, we have designed a fully integrated camera-level system for turn-key operation. The modular camera head (see Figure 3) consists of three boards: (i) an FPA board contains the FPA sensor and provides for its power and temperature regulation; (ii) an FPGA board contains an FPGA and microcontroller that provide extensive on-board functionality through firmware programming; and (iii) an interface board provides an industry-standard CameraLink interface to the system computer, power regulation, and external clock and trigger inputs. The camera head requires only a single DC source between 12 and 36 V, from which all required biases and power levels are generated internally.

The APD array temperature is controlled by an internal temperature control module, which provides programmable set-point and temperature monitoring functions. The camera has real-time monitoring of operating conditions such as ambient and FPA-level temperature, and in the event that temperature conditions change (e.g., a rise in ambient temperature), the camera automatically adjusts temperature set-points and FPA bias levels to maintain a fixed sensitivity (i.e., photon detection efficiency) based on factory calibrations. Camera head cooling options include fan-based convective cooling capable of maintaining a GmAPD array operating temperature of \( \sim 248 \) K and fluid-based cooling capable of establishing a GmAPD array temperature of \( 233 \) K or lower. Fan-based cooling assumes an ambient temperature of \( \sim 298 \) K and is limited by the ability of the TEC to maintain a temperature differential \( \Delta T \sim 50 – 55 \) K. Fluid-based cooling can sustain a much lower target array operating temperature in the presence of elevated ambient temperatures.

The camera clock signal can be supplied by an internal oscillator or by an external source to support synchronization of the camera with the rest of the imaging system. A master clock division function enables different range gate durations, with an associated difference in the pixel time bin resolution of the 13-bit in-pixel counters. Using the master clock division feature, the maximum duration of the 13-bit range gates can be set at 2, 4, 8, or 10 μs, while range gates can...
also be set as short as 4 ns by using fewer time bins per gate. In the 2 μs range gate setting, each of the $2^{13}$ time bins has a duration of 0.25 ns, and for longer range gate settings, the time bins are proportionally longer. When using the internal oscillator as the master clock, the camera supports a free-run mode where image data is collected continuously at a programmable frame rate.

The camera FPGA captures the FPA pixel counter data in real time on 32 parallel lines at a data rate of 125 Mb/s/line. Data are buffered and decoded in the FPGA to produce processed frame data in the form of linear time-of-flight values. Data are transferred to the computer using the CameraLink interface, and depending on the desired acquisition frame rate, the interface may be configured for “base”, “medium” or “full” transfer format modes in accordance with the definitions of the CameraLink standard. In addition to the 32 x 32 pixel timestamp data, every data frame includes a 64 byte header row with extensive operational status and monitoring information, as well as a summary of FPGA-based real-time sensor diagnostics and signal processing such angle-angle frame-averaged contrast images and coarse-binned timing histograms on a per-frame basis. The number of frames to be averaged for each contrast image is user-selectable (up to 32,768), and the number of bins to be used for histograms of the time-stamp data in each frame is user-selectable at any power of 2 between 8 and 1024. The header information then indicates frame type (e.g., raw time-stamp data or frame-averaged contrast image data) as well as the coarse-grained time bin corresponding to the mode of the timing histogram along with the number of pixel counts in this mode.

The camera system includes a high-performance computer with a comprehensive graphical user interface (GUI) that provides complete camera control (see Figure 4) using a simple serial command set transferred via the camera control channel of the CameraLink interface. The GUI software has been streamlined to support data transfer to multiple harddisk or solid-state drives in RAID 0 configuration at frame rates in excess of 180 kframe/s. With 2 bytes per pixel...
and 32 x 33 pixels per frame (which includes the header row with each frame), the maximum frame rate of 186 kframe/s (assuming 13-bit range gates with a 2 µs duration) generates a data stream of 393 MB/s. High-performance data storage algorithms enable continuous streaming of this data to 480 GB of solid-state drive memory, allowing for continuous data acquisition for 20 minutes. The existing system configuration can be easily expanded to 2 TB of storage to provide 80 minutes of continuous acquisition at the full frame rate.

4. DARK COUNT RATE AND PHOTON DETECTION EFFICIENCY PERFORMANCE

The most fundamental tradeoff in the operation of GmAPDs is that between the dark count rate (DCR) and photon detection efficiency (PDE). Operation at higher excess bias beyond the breakdown voltage results in higher PDE but also increases DCR. Optimal operating conditions can vary significantly with application. [7] In 3D LADAR imaging, daytime operation is usually accompanied by significant solar background, in which case it is generally advantageous to operate at higher PDE as long as DCR does not exceed the solar background count rate. In contrast, nighttime operation can benefit from lower PDE operation to provide lower DCR.

In previous work, we have demonstrated ideal 32 x 32 format sensors with 100% pixel operability for GmAPD FPAs optimized for either 1064 nm or 1550 nm. For instance, in [6] we presented results for a 1064 nm FPA that exhibited an average DCR of 14 kHz at an average PDE of 39% and an operating temperature of -20 °C, with every one of the 1024 pixels in the array having DCR < 20 kHz. We have also demonstrated similar high-quality 32 x 32 FPAs with ternary InGaAs absorbers for use at wavelengths as long as 1620 nm with 100% pixel operability [6].

For the camera described in this paper, we have achieved considerably lower DCR performance for 1064 nm operation—by at least a factor of 6—at a similar PDE and the same operating temperature. The wafer maps in Figure 5 illustrate the DCR and PDE for every pixel of the sensor. These maps report average values per pixel for measurements of 25,000 frames. For array-level PDE characterization, a collimated diode laser source was used to provide broad illumination with uniform optical intensity across the array exhibiting no more than ±5% variation. Optical pulses with a pulse width of ~50 – 75 ps and an optical density of 0.1 photons per pixel area (i.e., 100 µm × 100 µm) were synchronized to arrive at any desired time within the range gate, and data were collected for a single pulse arrival per frame. PDE values were collected using the grayscale contrast image functionality described above in Section 3 and were confirmed to be independent of the pulse arrival time within the frame as well as of the frame rate. For an average PDE of 37.2%, the average DCR is 2.0 kHz at -20 °C, and all pixels have DCR < 3.4 kHz.
Aside from 16 unconnected pixels in the upper left corner of the array, this array exhibits excellent uniformity. As shown in the accompanying histograms in Figure 6, the DCR distribution has an rms deviation of 0.4 kHz, the PDE distribution has an rms deviation of 2.8%, and both distributions have an approximately Gaussian shape. Modest systematic variations showing a slight reduction in both DCR and PDE around the perimeter of the array (refer to the maps in Figure 5) are due to a process-related increase in the breakdown voltage at the edges of the array. Another view of the DCR vs. PDE uniformity of these arrays is provided by plotting the dependence of DCR on PDE for a random selection of pixels across the array, as shown in Figure 7. Regardless of position on the FPA, pixels show consistent DCR vs. PDE behavior, as expected based on the rms variations of 0.4 kHz for DCR and 2.8% for PDE found for the histograms.

**Figure 6.** Histograms of (a) dark count rate and (b) photon detection efficiency for 32 x 32 pixel maps illustrated in Figure 5. Unconnected pixels in the upper left of the array have been left out of the distributions.

**Figure 7.** Dependence of DCR on PDE for a random sample of pixels from the 32 x 32 FPA with performance maps and histograms illustrated in Figure 5 and Figure 6, respectively. Regardless of position on the FPA, pixels show consistent DCR vs. PDE behavior, as expected based on the rms variations of 0.4 kHz for DCR and 2.8% for PDE found for the histograms.
5. CROSSTALK CHARACTERIZATION

When avalanches occur in a GmAPD, the acceleration of electrical charges in the high-field avalanche region can result in the emission of photons. This hot carrier luminescence effect creates only a small number of photons—on the order of one photon for every $10^5$ to $10^6$ carriers—but because the pixels of a GmAPD array are sensitive to single photons, even a small number of emitted photons can lead to measurable optical crosstalk effects if these photons are detected at neighboring pixels. The first design imperative for minimizing crosstalk is to limit avalanche events to a relatively small number of carriers since fewer avalanche carriers will emit fewer photons due to luminescence. Accomplishing this goal relies on minimizing parasitic capacitances that are discharged with each avalanche event and pixel-level circuit design in the ROIC that limits current flow associated with detection events. A second strategy that can be employed for crosstalk reduction is the incorporation of structures within the array design that prevent emitted photons from reaching neighboring pixels. One approach to such a strategy is to fabricate etched trenches between neighboring pixels of these GmAPD PDAs, as described in [4].

The quantitative assessment of crosstalk behavior in the GmAPD camera consists of the identification of avalanche events that are temporally and spatially correlated. Because our sensor provides precise timestamp data for each avalanche event, it is straightforward to analyze frame data for temporal correlations. For each pixel of the array at which an avalanche occurred—let us call the timestamp and position of this primary avalanche $T_0$ and $(X_0,Y_0)$, respectively—we search all other pixels in the vicinity of $(X_0,Y_0)$ for avalanches that have occurred in the time interval $\Delta T$ following $T_0$. We have found that the probability of correlated avalanches for $\Delta T > 10$ ns is negligible. There is also the probability that uncorrelated dark counts could be mistaken for correlated crosstalk events, but for operating conditions with DCR values of 10 kHz, the probability of a dark count at any given pixel within a particular 10 ns interval is only $10^{-3}$.

In the past, we have applied this crosstalk evaluation method using two approaches. In the first case, we rely on the DCR data and look for correlations within the dark count data. Although dark counts at any given pixel are very infrequent, if we can assume that the crosstalk behavior at all locations in the array is identical, then a statistical summary based on all dark count primary avalanches, regardless of pixel location, from a sufficiently large number of frames will provide a good assessment of the crosstalk. In the second case, we illuminate a single pixel with a single photon per frame and then look for correlated crosstalk events related to this optically induced primary avalanche. We have confirmed that we obtain identical results for both approaches. [4] Although the use of dark count data requires more computationally intensive analysis, the acquisition of the raw data is more straightforward. The results presented in this section were obtained using dark count data from 10,000 frames.

![Figure 8](image.png)

**Figure 8.** (a) Crosstalk probability per pixel vs. distance from primary avalanche for 32 x 32 GmAPD camera at PDE = 30%. (b) Cumulative crosstalk probability for a given number of crosstalk events occurring within a 9 x 9 pixel area surrounding the primary avalanche pixel.

Using the dark count analysis just described, we illustrate in Figure 8(a) the dependence of the crosstalk probability per pixel on the distance between the primary (dark count induced) avalanche and the correlated crosstalk avalanche in units of the pixel pitch (i.e., 100 μm). For instance, the data point for a distance of 1 pixel corresponds to the four nearest
neighbors (up, down, right, and left), and the data point for a distance of ~1.4 pixels corresponds to next-nearest neighbors in the four diagonal directions. Results are presented for a PDE value of 30%. The patterns observed in this plot have been found to be a reproducible signature [4–6] dictated by the geometric structure of our GmAPD PDAs.

The definition of appropriate metrics for quantifying crosstalk in GmAPD imagers is not straightforward. We can easily compute the probability of a crosstalk event for any given neighboring pixel with a specific geometric relationship to the primary avalanche pixel, as in Figure 8, but it is not clear how relevant this is for end users with particular application objectives. Younger, et al., at MIT Lincoln Laboratory provide a useful discussion [16] of crosstalk quantification and system-applicable figures of merit, and they propose that the probability $P(n>1)$ of correlated crosstalk avalanches occurring at more than one nearby pixel is a useful figure of merit since the occurrence of just a single crosstalk event is often tolerable for system designers, whereas two or more events can cause significant performance degradation. In Figure 8(b), we report the related probability $P(n)$ that exactly $n$ correlated crosstalk events occur, and from these data, we find that the probability $P(n>1)$ of more than one crosstalk event occurring is less than 2%. If we sum all of the points in the figure to arrive at the total crosstalk probability $P_{\text{tot}}$ which includes contributions for all $n$, we find $P_{\text{tot}} = 11.6\%$. Additionally, we can use the same data to calculate an expectation value $E(n)$ for the average number of crosstalk events per detection event, and we find $E(n) = 0.14$.

### 6. TIMING JITTER CHARACTERIZATION

In a LADAR system, the accuracy with which the range of an object can be determined is limited by the uncertainty in the measurement of the roundtrip time-of-flight between the sensor and the object. The contribution of the imaging sensor to the total uncertainty, commonly referred to as the timing jitter, is an important characteristic of the camera performance. For optical pulses that nominally arrive at the sensor at precisely the same time within successive range gates, pixels with perfect timing characteristics will always register a count in the same time bin (i.e., with the same timestamp). However, finite timing jitter can cause counts to occur in different time bins.

To characterize the camera timing jitter, we used broad-area illumination of the entire sensor with a short (sub-ns) optical pulse at a fixed time within the range gate. The data reported below was taken for pulse arrivals after an elapsed time of 1 μs within a 2 μs range gate. We confirmed that identical jitter results were obtained for pulse arrivals very early and very late in the gate (e.g., 0.1 μs and 1.9 μs, respectively). Moreover, we have also verified that the counting throughout the range gate duration is highly linear (to within the 5 ps uncertainty of the reference instrument used in this measurement), as expected based on the use of a phase-locked loop as the on-chip clock source in the ROIC (see Section 2.2 above). The optical flux density within the short optical pulse was calibrated to provide a given average number of photons per pixel area per pulse.

We carried out jitter measurements in the limit of low flux density, with an average of $\eta = 0.1$ photons per pixel per pulse, as well as at higher average flux density of $\eta = 10$ photons per pixel per pulse. Given the Poisson nature of our attenuated diode laser source, in the $\eta = 0.1$ measurements, the probability of having two photons incident on the same pixel from a single pulse is less than 1%. Additionally, the precise arrival time of a single photon is probabilistically distributed consistent with the envelope of the attenuated optical pulse. Conversely, for multi-photon pulses with $\eta = 10$, there is a higher probability that an avalanche is triggered by a photon arriving earlier in the pulse envelope, and the overall detection probability is dramatically increased: for example, with the sensor operating at a single photon detection efficiency of 30%, the probability of a detection event at any given pixel with $\eta = 10$ Poisson pulses is 95%. The occurrence of lower measured jitter in the case of multi-photon $\eta = 10$ pulses would indicate that the variability in photon arrival time for the low photon number ($\eta = 0.1$) case plays a role in the overall determination of the timing jitter. However, as shown below, we find essentially equivalent timing jitter results for the $\eta = 0.1$ and $\eta = 10$ cases.

We first characterized the “intra-frame” timing jitter by assessing the timing consistency among all the pixels of the camera within a single frame. Figure 9 illustrates typical count distributions for the (a) $\eta = 0.1$ low flux density and (b) $\eta = 10$ high flux density just described. For both cases, the vast majority of the counts occur in the neighboring time bins 4004 and 4005, where each time bin corresponds to 250 ps. The count distributions are consistent with a Gaussian distribution with an rms deviation of ~175 ps in both cases, as illustrated by the fits in the figure.

It is important to note that this jitter measurement includes all system-level contributions to the timing jitter, including time bin quantization and the finite laser pulse width. We can attempt to calculate the impact of time bin quantization by considering that the rms deviation of a photon arriving at any time within the time bin is $250/\sqrt{12}$ ps ~ 72 ps. The
quadrature subtraction of this value from the total measured rms jitter is only a rough estimate since the “rectangular” shape of the time bin is highly non-Gaussian, but this estimate suggests that timing jitter due to quantization error is reasonably small relative to the overall measured value of ~175 ps. The finite laser pulse width constitutes a jitter contribution similar to time bin quantization (i.e., ~ 50 – 75 ps) and is thus small compared with the total measured jitter. Therefore, it is probable that the intra-frame jitter of ~175 ps is dominated by the timing variation among the camera pixels themselves.

We then characterized the “inter-frame” jitter by measuring the timing consistency over many frames. Although the data reported includes measurements for all 1024 pixels of the array, we have confirmed that a histogram obtained from the data of just a single pixel across multiple frames (e.g., 10,000 frames for the η = 0.1 measurement) has an essentially identical distribution. For the multi-photon case of η = 10, the number of counts is sufficiently large that data from a modest number of frames (e.g., 50) provides good statistical information. Figure 10 illustrates these inter-frame jitter results for the low and high flux density limits.

As with the intra-frame jitter measurement, the inter-frame jitter data include all system-level jitter contributions. For the inter-frame jitter measurement, aside from the finite pulse width of the laser (~50 – 75 ps), there is a significant
additional jitter related to variation in the precise arrival time of the laser pulse, which was at least 150 ps for our measurement set-up. Taking the measured rms deviation from Figure 10 to be ~385 ps, if we use a quadrature subtraction of the laser pulse arrival time deviation and time bin quantization, the inherent inter-frame timing jitter of the camera is ~350 ps. Since other frame-to-frame system-level jitter contributions have not been considered, this is a worst-case estimate for the camera. We also suspect that the “flattening” of the Gaussian shape apparent in the measured results may be related to the frame-to-frame variation of the laser pulse arrival time, but this effect requires further investigation for a detailed explanation.

It is interesting to note that in both the intra-frame (Figure 9) and inter-frame (Figure 10) measurements, the data for the low flux density ($\eta = 0.1$) cases exhibits a trailing tail in the distribution for times later than the mean arrival time. The counts in these tails are caused by crosstalk events that occur within a few ns of the mean pulse arrival time, as discussed in the previous section. For the case of very low mean photon number (e.g., $\eta = 0.1$), most pixels remain untriggered after the pulse arrival and are still armed for the detection of crosstalk photons. If we integrate the total counts in this tail (e.g., for time bin 4009 and higher), the calculated total cumulative crosstalk is 9.5%, in reasonable agreement with the value of 11.6% reported above with reference to Figure 8(b). In contrast, for fairly large mean photon numbers (i.e., $\eta = 10$) per pixel, almost all pixels fire when the multi-photon pulses arrive, and so there are very few armed pixels available to detect crosstalk photons. This explains the lack of crosstalk-induced tails in the $\eta = 10$ data in Figure 9(b) and Figure 10(b).

Finally, as an alternative to estimating rms timing jitter by fitting the measured data with Gaussian distributions, one can simply perform a numerical calculation of the rms timing jitter directly from the acquired data (i.e., without the assumption of a Gaussian fit or any other functional form). In this case, one should exclude the low-level crosstalk tail just described from this calculation. We have confirmed that such numerical calculations give very good agreement with the Gaussian fits illustrated in Figure 9 and Figure 10 to within about 5%.

7. CONCLUSIONS

In this paper, we have described the features and performance of an integrated camera system based on Geiger-mode APD focal plane arrays with single photon sensitivity that functions as the sensor engine for 3-D LADAR imaging systems. The high level of integration realized for this sensor dramatically simplifies immediate use of the camera and provides substantial flexibility for numerous application needs. The flexibility of FPGA control in the camera head has allowed us to integrate on-board control of significant real-time functionality, such as grayscale contrast imagery collected over a user-specified number of frames and distance histograms on a per-frame basis. Moreover, high-performance data storage algorithms have been developed to provide continuous streaming of real-time image point cloud data for the full frame rate of 186 kHz with 2 $\mu$s range gates to solid-state drives within the system.

The results presented in this paper demonstrate the capability to provide extremely low DCR of 2 kHz for PDE of nearly 40% at 1064 nm. Additionally, this average pixel performance has been achieved with exceptionally high uniformity across the focal plane, with all operable pixels exhibiting <3.4 kHz DCR and an rms variation in the PDE of 2.8%. Cumulative crosstalk from all crosstalk events is generally between 10% and 15%, with less than 2% occurrence of more than one crosstalk event and a crosstalk expectation value of ~0.15. Timing jitter has been characterized for both intra-frame and inter-frame characteristics, and rms values of ~175 ps and ~350 ps have been determined for these two parameters, respectively.

Extension of this camera platform to larger format 32 x 128 sensors with 50 $\mu$m pitch is in progress. Attention to forward capability of both FPA-level sub-components and the system-level electronics, firmware, and software will allow for the efficient realization of these next generation sensors in the near future.

REFERENCES


