Statistical analysis of dark count rate in Geiger-mode APD FPAs

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ABSTRACT

We present a temporal statistical analysis of the array-level dark count behavior of Geiger-mode avalanche photodiode (GmAPD) focal plane arrays that distinguishes between Poissonian intrinsic dark count rate and non-Poissonian crosstalk counts by considering “inter-arrival” times between successive counts from the entire array. For 32 x 32 format sensors with 100 μm pixel pitch, we show the reduction of crosstalk for smaller active area sizes within the pixel. We also compare the inter-arrival time behavior for arrays with narrow band (900 – 1100 nm) and broad band (900 – 1600 nm) spectral response. We then consider a similar analysis of larger format 128 x 32 arrays. As a complement to the temporal analysis, we describe the results of a spatial analysis of crosstalk events. Finally, we propose a simple model for the impact of crosstalk events on the Poissonian statistics of intrinsic dark counts that provides a qualitative explanation for the results of the inter-arrival time analysis for arrays with varying degrees of crosstalk.

1. INTRODUCTION

The detection of single photons is an enabling capability for numerous photonics applications. In fields such as quantum communications and quantum information processing [1,2], it is the quantum mechanical properties of single photons that are exploited. More often, detection of single photons is essential when applications such as imaging and communications are pushed to their photon-starved limits [3,4,5]. For all of these scenarios, Geiger-mode avalanche photodiodes (GmAPDs) often emerge as a suitably capable device technology. They provide performance that meets the requirements of many of these applications, and they do so in a robust solid-state platform that is readily scalable to achieve a high degree of integration at a relatively low cost. Consequently, for the detection of single photons in the wavelength range from 0.9 μm to 1.6 μm, GmAPDs based on the InGaAsP material system have proven to be a preferred sensor choice.

Recent advances in InGaAsP-based GmAPDs have emphasized integration of the devices into large-format arrays [6,7], and one of the most important drivers for these advances is the use of GmAPD focal plane arrays (FPAs) in three-dimensional (3D) imaging laser radar (LADAR) systems [3,8]. Also described as light detection and ranging (LIDAR), the technique employed by these systems exploits time-of-flight measurements at every pixel of the FPA to create 3D images. The ability to generate such imagery with single-photon sensitivity is disruptive. Three-dimensional LADAR systems based on single-photon-sensitive GmAPDs, such as the Airborne Lidar Testbed (ALIRT) system fielded by MIT Lincoln Laboratory [9] and the High Altitude Lidar Operations Experiment (HALOE) deployed by Northrop Grumman [10], have demonstrated the capability to collect high-resolution 3D imagery from much higher altitudes and at rates at least an order of magnitude faster than competing technologies. For shorter distance applications, the single-photon sensitivity of these FPAs allows their implementation with much more modest laser sources, greatly reducing the size, weight, and power dissipation of the overall system.

In this paper, we first summarize the design and performance of cameras incorporating InGaAsP-based GmAPD FPAs [11,12], and we then provide a deeper investigation of the dark count behavior for a variety of these arrays based on a statistical temporal analysis of the dark count data first reported in [13]. Specifically, we distinguish between the Poissonian statistics of intrinsic dark counts and the non-Poissonian behavior arising from avalanche-mediated optical crosstalk. Using this analysis, we consider the impact on crosstalk of different size GmAPD active regions within the 100 μm pitch pixels of 32 x 32 format arrays, and we find that an area reduction of a factor of 3.6—from a 34 μm active diameter to an 18 μm active diameter—results in a crosstalk reduction by a factor of ~9. We also report the substantial increase in crosstalk for sensor arrays with broad spectral response (900 – 1600 nm) relative to those with narrow spectral response (900 – 1100 nm). We also compare the crosstalk of larger format 128 x 32 arrays with 50 μm pitch to

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that of the smaller, larger pitch 32 x 32 format sensors. After a brief discussion of a complementary spatial analysis of crosstalk behavior, we then propose a simple model for the impact of crosstalk events on the Poissonian statistics of intrinsic dark counts that provides a qualitative explanation for the results of the inter-arrival time analysis for arrays with varying degrees of crosstalk.

2. SENSOR ARCHITECTURE AND OPERATION

2.1 Focal plane array design

The core functionality of the GmAPD FPA is determined by three semiconductor arrayed devices: the InGaAsP-based GmAPD photodiode array (PDA); a 0.18 \( \mu \)m CMOS readout integrated circuit (ROIC); and a GaP microlens array (MLA). The PDA pixels are connected to their corresponding ROIC pixels by indium-bump flip-chip hybridization. The MLA is then aligned and attached to the substrate side of the rear-illuminated PDA to maintain a high optical fill factor of \( \sim 75\% \) for optical coupling to the active region in each PDA pixel. The ROIC I/O channels are wirebonded to a ceramic interposer which facilitates routing of electrical signals to appropriate pins of a pin grid array in the hermetic housing assembly. An integrated thermoelectric cooler maintains a temperature differential of 50°C to 55°C relative to the ambient temperature of the housing: for a typical 25°C ambient, the FPA operates at about -25°C to -30°C. A schematic illustration of the FPA construction is provided at left in Figure 1, and photographs of an assembled FPA are show at center and at right in the figure.

The GmAPD devices in each pixel of the PDA are based on a buried p-n junction fabricated using a zinc dopant diffusion process that provides highly uniform and reliable pixels in large scale arrays. PDAs optimized for operation using source lasers with an output wavelength near 1 \( \mu \)m employ an InGaAsP absorber region that results in spectral response over the wavelength range from 900 nm to 1100 nm. PDAs intended for use with longer-wavelength sources near 1.5 \( \mu \)m make use of an InGaAs absorber region that results in wider spectral response from 900 nm to 1600 nm. In previous publications, we have described the design of these GmAPD devices [6,14] and their incorporation into array formats [11,15].

2.2 Camera-level integration

The GmAPD FPA has been integrated into a modular camera head with three principal electronic boards. The FPA board supports the FPA sensor itself, and it has circuitry that controls FPA power and temperature regulation. The FPGA board contains an Altera FPGA and a microcontroller that provide extensive on-board functionality through firmware programming. In addition to facilitating operation of the ROIC, the FPGA also collects and formats raw data from the ROIC for transfer off of the camera head. This data transfer is executed by the interface board using an industry-standard CameraLink protocol, and this board also manages external power regulation and external clock and trigger inputs. Through a CameraLink interface, the camera head communicates with the system computer that controls all camera functions through comprehensive graphical user interface software. Beyond camera control, this software also provides for real-time data storage to solid-state drives in RAID0 configuration, accommodating data rates in excess of 4 Gb/s at the maximum camera frame rate of 182,000 Hz.
2.3 Sequence of framed operation

Each data frame of the GmAPD cameras described in this paper is initiated by an internal or external trigger signal. Triggering the sensor brings the reverse voltage of the GmAPDs above $V_b$ by an excess bias $V_e$ and corresponds to charging up the capacitance of each GmAPD to $V_c = V_b - V_d + 5 \text{ V}$. Once the pixel arming sequence is complete, linear-feedback shift register pseudorandom counters in all the pixels are enabled to begin timing during the “range gate”. The counters have 13-bit resolution, and a full range gate consists of the counters proceeding through 8000 counter values. During the counting sequence, an avalanche at any GmAPD pixel will freeze the corresponding pixel counter in the ROIC, indicating the arrival time of a photon or a dark count, and the pixel is then disarmed by actively quenching the bias voltage of that pixel below $V_b$. A pixel records only one time-stamp value per frame. At the end of a frame, if a pixel did not detect an avalanche event, then it returns the terminal count of the in-pixel count. By adjusting the ROIC clock frequency, we can vary the time duration associated with each counter increment from 0.25 ns to 1.25 ns. Given 8000 of these “time-bins” in each range gate, the total range gate duration can be varied from 2 $\mu$s to 10 $\mu$s. The sequential combination of a 2 $\mu$s range gate followed by a 3.5 $\mu$s read-out time provides the maximum frame rate of 182 kHz.

2.4 FPA performance attributes

The GmAPD FPA exhibits a number of critical performance attributes. The probability of successfully detecting a single photon when it arrives at one of the FPA pixels is referred to as the photon detection efficiency (PDE) of that pixel. In all of the PDE data presented in this paper, we provide camera-level PDE values which include all optical losses associated with elements in the optical path, including the ~75% fill factor of the microlens array.

There is also a finite probability of false counts being triggered in the absence of photon arrivals, giving rise to an effective dark count rate (DCR). The measured dark counts actually include counts originating from several mechanisms. The generation of dark carriers by thermal excitation or trap-assisted tunneling dictates the intrinsic DCR. Additionally, during any avalanche event, the resulting charge flow can give rise to photon emission, likely due to intraband relaxation of hot carriers crossing the diode p-n junction [16], and the photons emitted by this hot-carrier luminescence effect can initiate correlated avalanches at other array pixels. These “crosstalk” counts can be initiated by avalanches associated with photon detections or dark counts, and they therefore are present in any array-level raw data collected for PDE or DCR. One of the benefits of the dark count analysis described below is the unambiguous extraction of the crosstalk contribution to DCR based on a statistical analysis of the temporal attributes of array-level DCR data.

Another performance attribute—and potential contributor to dark counts—is the afterpulsing effect [17] caused by the trapping of charges resulting from one avalanche and the occurrence of correlated dark counts a short time later due to the subsequent detrapping of these charges. Afterpulsing can be mitigated by imposing a sufficiently long “hold-off” time following an avalanche event to allow detrapping of substantially all of the trapped charges prior to re-arming a GmAPD. Under typical GmAPD operating conditions (e.g., 3 V excess bias and an FPA temperature of 248 K), afterpulsing effects can be significant for hold-off times of less than ~1 $\mu$s, but hold-off times longer than this are adequate to reduce afterpulsing to inconsequential levels, as found by some of the present authors for discrete GmAPDs [17] as well as by Frechette et al. for GmAPD arrays operated with asynchronous ROICs [18]. Although afterpulsing constitutes a non-Poissonian contribution to dark counts when it is present, for the FPAs described in this paper, the GmAPDs are always disarmed during the 3.5 $\mu$s readout time of our framed ROIC operation. This readout period acts as a hold-off time that mitigates any afterpulsing effects, and so we ignore them in the temporal statistical analysis that follows below.

3. DARK COUNT RATE VS. PHOTON DETECTION EFFICIENCY TRADE-OFF

The most fundamental tradeoff in the operation of GmAPDs is that between DCR and PDE. Higher PDE can be obtained by operating the detector at a larger excess bias, but only at the expense of consequently higher DCR. Both parameters are proportional to the avalanche probability $P_a$, which increases with larger excess bias, and so to first order PDE and DCR will increase by the same proportional amount as the excess bias is raised. To the extent that the DCR includes electric field-mediated mechanisms—primarily trap-assisted tunneling effects [19]—the DCR will exhibit a larger rate of increase with excess bias than that of the PDE.
The PDE performance of a 32 × 32 format GmAPD camera can be summarized by plotting a spatial map of PDE values obtained for all 1024 pixels, as shown in Figure 2(a) for an FPA sensor with 900 nm to 1100 nm spectral response and 34 μm diameter active regions. Pixel-level PDE values are obtained by averaging 10,000 frames of data. During each frame, the array is illuminated by a short laser pulse of ~150 ps duration that is collimated and calibrated to provide a mean photon number of μ = 0.1 photon per pixel area. PDE for each pixel is determined by the number of counts observed and scaling for μ. The measured dark counts are subtracted from the illuminated measurements to obtain PDE values, but these PDE values do include crosstalk counts, which are quantified in the next section. The data presented in the figure are obtained at an excess bias corresponding to a mean DCR of 2.2 kHz (see below) and an FPA temperature of 248 K. The corresponding distribution of PDE values is described by the histogram in Figure 2(b), for which the mean PDE is 30.5% and the standard deviation σ(PDE) is 4.0%.

![Figure 2](http://example.com/figure2.png)

**Figure 2.** Photon detection efficiency performance for 32x32 GmAPD camera operating at 1.06 μm.

Under the operating conditions used to obtain the PDE performance map in Figure 2, we demonstrate the DCR performance for the same camera in the absence of illumination with the map of DCR values of all pixels of the FPA in Figure 3(a). These data are obtained from 10,000 frames of data with the camera operating at an average PDE of 30.5% and at an FPA temperature of 248 K. Each frame had a duration of 2 μs, and the DCR was computed by dividing the...
Spatial variations in pixel-level PDE and DCR across the FPA are generally dominated by systematic variations in the breakdown voltage $V_b$ of the GmAPDs in each pixel. Because the same disarm voltage $V_d$ and 5 V CMOS bias voltage swing are applied to all pixels in the array, any variation in $V_b$ will result in a corresponding variation in excess bias $V_e$. A lower $V_e$ will lead to lower values for both PDE and DCR, and inspection of the performance maps in Figure 2 and Figure 3 indicates that there is some systematic reduction in both of these parameters near the edges of the arrays, particularly the lower edge. This is the result of slight differences in fabrication processes for pixels along the edges of the GmAPD PDA. We also observe systematic, fairly monotonic gradients in performance over longer length scales encompassing full arrays, and these originate from gradients in the properties of the epitaxial wafers used to fabricate the GmAPD PDAs. For the metal-organic chemical vapor deposition processes used to grow these wafers, variations in key structural attributes such as epitaxial layer thickness and doping concentration are fairly radial, as evidenced by wafer-level characterization techniques such as Fourier transform infrared (FTIR) spectroscopy and photoluminescence, and these longer-scale performance variations can be correlated to the underlying wafer properties [20].

4. STATISTICAL TEMPORAL ANALYSIS OF DCR AND CROSSTALK EXTRACTION

4.1 Statistic model of dark counts

In the previous section, we presented a basic description in Figure 3 of the DCR behavior of the GmAPD FPAs based on the number of frames for which each pixel exhibits a dark count. In this section, we show that we can extract a great deal more information about the measured dark counts by considering their timing information. In principle, dark counts possess the following attributes of a Poisson process [21]: (i) they are memoryless—i.e., counts from non-overlapping time intervals are mutually independent; (ii) for sufficiently small time intervals, the probability of a count is proportional to the duration of the time interval, and (iii) for sufficiently small time intervals, the probability of more than one count in this interval is negligible. Assuming that dark count occurrences are Poissonian in nature, we expect that the “inter-arrival” times between successive counts will obey an exponential distribution [21] given by

$$f(t) = \frac{\lambda e^{-\lambda t}}{C}$$

where $t$ is the inter-arrival time, $\lambda$ is the average dark count rate, and the normalization constant $C$ is the total number of counts and guarantees that $\int_0^\infty f(t) dt = 1$ where the integration is performed over all $t$ from 0 to $\infty$. This normalization can also be generalized to any sub-section of the measured data for $T_1 \leq t \leq T_2$ by ensuring that

$$\int_{T_1}^{T_2} f(t) dt = e^{T_2} - e^{T_1}$$

where $C$ is now the number of counts in this sub-section.

Given a group of pixels that exhibit Poisson statistics, their collective behavior—such as the inter-arrival times for dark counts among all of the pixels—will also obey Poisson statistics [21]. Noting this fact, we analyze dark count inter-arrival times from the entire array. We also consider all pixels of the array to be an ensemble of identical devices, and this assumption is reasonable as long as the standard deviation of the pixel-level DCR distribution is fairly small compared to the mean; for the data in Figure 3, $\sigma(DCR)/DCR \sim 0.18$.

It is important to note that the accuracy of the DCR values obtained in the previous section—based on counting the number of frames for which each pixel exhibits a dark count—depends on the fact that, for each pixel, the probability of a dark count within a single 2 $\mu$s frame is sufficiently low. Each pixel can detect only a single avalanche event per frame, and if there were a significant probability of multiple dark counts per frame, all but the first dark count would be missed. However, for the average DCR of 2.2 kHz in Figure 3, the average time between counts is 455 $\mu$s, and the Poisson probability of more than one dark count [21] during a 2 $\mu$s range gate is $< 0.001\%$. The probability of more than one dark count per 2 $\mu$s range gate exceeds 1% only for DCR $> 75$ kHz.

4.2 Temporal analysis of InGaAsP/InP (1.0 $\mu$m) 32 x 32 FPAs

We proceed with a statistical analysis of the DCR data from 10,000 frames as follows. From each frame, we order the dark counts collected from all of the pixels according to their timestamp values, and the elapsed time between each pair of successive dark counts provides us with a set of inter-arrival times for that frame. The distribution of all inter-arrival
times obtained from all frames is then plotted on a semi-log scale as in Figure 4(a). The timing resolution of the plot is 0.25 ns—i.e., each plotted point corresponds to a 0.25 ns interval—as dictated by the time bin resolution of the time stamp counters in the FPA. The timing resolution of the plot is 0.25 ns—i.e., each plotted point corresponds to a 0.25 ns interval—as dictated by the time bin resolution of the time stamp counters in the FPA. Except for very short inter-arrival times, the distribution exhibits the exponential behavior expected of a Poisson process. An exponential fit according to Eq. (1) was obtained for the inter-arrival time data between 25 ns and 450 ns, with appropriate normalization provided by Eq. (2). Ideally, this fit should yield identical values for the pre-factor and exponent, and the values found—$2.64 \times 10^{-3}$ and $2.77 \times 10^{-3}$, respectively—agree to within 5%. Taking their average as a best estimate for $\lambda$, and noting that this is the dark count rate per nanosecond, we rescale to dark counts per second to obtain an array-level dark count rate of $~2.7 \times 10^6$ Hz. Considering that this rate is for all 1024 pixels of the array, the DCR per pixel of $\lambda/1024$ is $2.6$ kHz. Based on the assumption of Poissonian behavior for this analysis, this value is the intrinsic pixel-level DCR of the FPA. We note that the value of 2.2 kHz obtained from Figure 3 agrees to within $\sim$15%.

We now consider the deviation of the distribution in Figure 4 from exponential behavior at very short inter-arrival times; this behavior is shown more clearly in the inset of the figure. All discernible deviation from the Poisson exponential behavior occurs for inter-arrival times < 2 ns, with a clear peak seen at $\sim$1 ns. If we ascribe this non-Poissonian contribution to crosstalk events, this analysis gives us significant insight into crosstalk behavior. For instance, these data suggest that the most frequent delay between a primary avalanche and its correlated crosstalk event is 0.75–1 ns. Much short delays of < 0.25 ns—i.e., a crosstalk count occurring within the same time bin as the primary count—are much less likely, as are longer delays of > 2 ns. Moreover, we can integrate over the non-Poissonian counts to find a worst-case estimate (assuming all deviation from Poisson behavior is from crosstalk counts) of the fraction of total dark counts that should be attributed to crosstalk events. Again referring to the Figure 4 inset, the cumulative crosstalk is 12.6% of the intrinsic dark count rate of 2.6 kHz at 30% PDE. Note that this includes all non-Poisson temporally correlated events, without regard for their spatial separation, which will be treated in the next section.

The probability for a crosstalk event to occur is directly related to the likelihood that a photon emitted by an avalanching pixel is optically coupled to the active region of a neighboring pixel. From this geometric perspective, it follows that FPAs with smaller active regions in each pixel should exhibit less crosstalk. We confirmed this expectation by performing the statistical temporal analysis just described on DCR data obtained from a 32 x 32 FPA with 100 µm pitch and 18 µm diameter active regions in each pixel to obtain the distribution in Figure 4(b). These data—particularly the inset—show that in comparison to the data in Figure 4(a) for an FPA with 34 µm diameter active regions, the crosstalk is greatly reduced. Integration of the total non-Poissonian portion of this distribution gives a total cumulative...
crosstalk of just 1.4%. This is a striking result given that it represents a factor of ~9 reduction in crosstalk relative to the FPA with 34 μm diameter devices even though the ratio of device areas is only 3.6. Inspection of the non-Poissonian peaks in the short inter-arrival time distributions in the two insets in Figure 4 qualitatively illustrates this nearly order-of-magnitude reduction in crosstalk based on the relative heights of the peaks at ~1 ns in these plots. This result suggests that a more detailed geometric model incorporating factors beyond the device area ratio will be required to obtain a quantitative explanation of these measurements.

4.3 Temporal analysis of InGaAs/InP (1.5 μm) 32 x 32 FPAs

The operation of GmAPDs at longer wavelengths near 1.5 μm requires a detector structure with an InGaAs absorber. The narrower bandgap of this material, relative to InGaAsP used for detection of wavelengths near 1.0 μm, dictates that higher thermal dark carrier generation rates will lead to higher DCR under comparable operating conditions for temperature and bias. Additionally, other device design considerations tend to favor the use of thinner absorption regions for 1.5 μm, resulting in lower PDE at a given excess bias. We have reported reasonably extensive results for the DCR vs. PDE behavior of GmAPDs at 1.5 μm for discrete devices [6] as well as arrays [11]. However, the much wider spectral response of the 1.5 μm GmAPD FPAs has implications regarding their crosstalk behavior. In a study of crosstalk effects in 1.06 μm GmAPD FPAs, Younger et al. [22] reported measurements of the breakdown spectrum due to avalanches in the InP multiplication region, with a peak in the spectrum centered near the InP band edge and a broad blackbody component extending to at least 1.7 μm. Because an InGaAs absorber detects photons over this entire spectral band, one finds substantially higher crosstalk effects for these longer wavelength FPAs.

In Figure 5 we present results for a 1.5 μm FPA obtained from the same statistical analysis described in the previous sub-section. Once again, the inter-arrival time histogram is accurately fit by the expected Poisson exponential behavior in (1), and there is close agreement between the values of the prefactor and the exponent in this fit. From these fit values, we compute an intrinsic (Poisson) dark count rate of 9.2 kHz. This value is less than half of the 22 kHz DCR found by simply counting all dark counts (which includes crosstalk) for the corresponding operating conditions of 20% PDE and 253 K.

![Figure 5](image)

**Figure 5.** Statistical analysis of the inter-arrival times for dark counts from a 32 x 32 GmAPD array with an InGaAs absorber for ~1.5 μm detection with 34 μm diameter active regions. Excess bias corresponds to 20% PDE. Inset: details of data between 0 to 30 ns.

![Figure 6](image)

**Figure 6.** Statistical analysis of the inter-arrival times for all dark counts from a 128 x 32 GmAPD array with an InGaAsP absorber for ~1 μm detection. Excess bias corresponds to 30% PDE. The inset shows details of data between 0 to 40 ns.

This discrepancy in DCR determination can be understood upon closer examination of the non-Poisson behavior at short inter-arrival times exhibited in the inset to Figure 5. Just as found for the 1.0 μm FPA in the Figure 3 inset, the inter-arrival time distribution for the 1.5 μm FPA peaks sharply at 0.75 – 1.0 ns. However, unlike the shorter wavelength FPA, the non-Poisson peak associated with crosstalk counts possesses a fairly long tail that does not merge with the Poisson background until inter-arrival times as long as 15 – 20 ns. Integrating over the total number of
crosstalk events indicated by the non-Poisson peak, we find a much larger cumulative crosstalk probability of \( \sim 90\% \). The combination of these crosstalk counts with the 9.2 kHz intrinsic DCR would yield an apparent DCR of 17.5 kHz, in reasonable agreement with the 22 kHz found from simply counting all dark events. We will discuss the relationship of the long tail in the non-Poissonian behavior to the presence of high crosstalk probabilities in the context of our description of a physical model for crosstalk later in the paper.

### 4.4 Temporal analysis of InGaAsP/InP (1.0 \( \mu \text{m} \)) 128 x 32 FPAs

A final example of the impact of array geometry on crosstalk is provided by analyzing crosstalk data obtained from an InGaAsP/InP FPA for 1.0 \( \mu \text{m} \) photon detection with a larger 128 x 32 format and a smaller 50 \( \mu \text{m} \) pixel pitch. The active regions in these smaller pixels have 18 \( \mu \text{m} \) diameters, so the ratio of pixel pitch to active diameter is nearly identical to that of the 32 x 32 array used to obtain the data in Figure 4(a)—i.e., 100 \( \mu \text{m} \) pitch and 34 \( \mu \text{m} \) active diameter. However, this smaller pitch, larger format FPA exhibits considerably larger cumulative crosstalk of 34\% (vs. 12.6\% for the 32 x 32 FPA), as illustrated in Figure 6, and as in the case of the higher crosstalk FPA in Figure 5, this inter-arrival time distribution also contains a notable non-Poissonian “tail” for inter-arrival times as long as \( \sim 30 \text{ ns} \). Although a detailed geometric analysis is needed to quantitatively explain these results, we believe that the factor of \( \sim 3 \) increase in crosstalk for smaller pitch (given similar pitch-to-active diameter ratios) is primary due to the smaller pixel spacing. It should also be considered that the 128 x 32 format array has four times as many pixels. Although we expect contributions of further pixels to drop off by \( \sim 1/R^2 \) where \( R \) is the distance between the avalanching pixel and a distant crosstalk pixel, these further neighbors are included in the temporal analysis which considers all dark counts, regardless of spatial distribution.

### 5. SPATIAL DISTRIBUTION OF CROSSTALK

The temporal analysis of the GmAPD FPA dark count data in the previous section provides valuable information concerning the intrinsic DCR and crosstalk characteristics. However, while this statistical analysis is quite powerful, it is does not yield information pertaining to the spatial distribution of crosstalk events. Therefore, in this section, we describe the complementary analysis of spatial correlations of dark counts occurring within short temporal separations to infer the spatial characteristics of crosstalk behavior.

For our spatial analysis, we again rely on dark count data by considering each dark count to be a primary avalanche and then look for any subsequent dark counts that occur a short time later. It is instructive to review the dark count statistical analysis in the previous section to guide our choice of a relevant time duration over which dark counts can be considered to be temporally correlated. In particular, the insets to Figure 4 for 32 x 32 InGaAsP/InP (1 \( \mu \text{m} \)) FPAs suggests that non-Poissonian behavior associated with crosstalk is dominant for only \( \sim 2 \) ns. Given the possibility of subtle correlations that persist for longer inter-arrival times, we have used \( T_c = 10 \text{ ns} \) as a conservative choice of correlation timeframe \( T_c \) during which counts are considered to be temporally correlated and are associated with crosstalk events. According to this reasoning, we generate a spatial map of crosstalk probabilities by considering each dark count as a primary avalanche and then searching for temporally correlated counts within correlation time \( T_c \). If a temporally correlated count is found, it is assumed to be a crosstalk event, and its position relative to the primary avalanche pixel is noted. Every primary event is considered to be at the origin of our spatial map, and the number of crosstalk counts found at every pixel location relative to this origin is summed. Any crosstalk event can then be considered to take the role of a primary avalanche, and in this way cascades of crosstalk events may be identified. We note that any procedure for assigning spatial correlations such as the one just described may have an inherent ambiguity in certain cases in which a crosstalk event has more than one earlier avalanche as a candidate for its primary avalanche (i.e., there was more than one avalanche that occurred with a temporal separation less than \( T_c \)). In these cases, the key is to avoid double-counting in which a single avalanche is identified as a crosstalk count more than once.

For a given number of dark frames (e.g., 10,000), we find every dark count in each frame and use the correlations just described to create a spatial map of how many times a crosstalk event occurred at a given pixel location relative to the primary avalanche. This procedure can be used for arbitrarily large distances bounded only by the size of the array. We exhibit a 21 \( \times \) 21 map in Figure 7 for the 1 \( \mu \text{m} \) FPA used to generate the data in Figure 4(a). Although line-of-sight coupling of photons to adjacent neighboring pixels is reduced by etching optical isolation trenches between them, the crosstalk between these near-neighbor pixels is still dominant. Beyond the eight line-of-sight near-neighbors, crosstalk coupling to further neighbors occurs by reflection from the back surface of the PDA substrate, as shown schematically at the right side of Figure 7. Such reflections have been reduced by depositing an absorptive metallic film over as much of the PDA back surface as possible. However, it is necessary to have dielectric anti-reflection coatings (ARCs) within
apertures placed directly above each pixel to facilitate coupling of light collected from each microlens in the MLA to its corresponding PDA pixel active region. For large angles of incidence, these ARCs give rise to high reflectance and define symmetry points for significant reflections to further neighbor pixels. These reflection characteristics are illustrated schematically in the figure and explain the high-level symmetry seen in the spatial crosstalk map.

Figure 7. LEFT: Spatial map of crosstalk events from 10,000 frames of data for 1.0 μm FPA sensor 261 operated at 30% PDE. Values represent number of crosstalk counts at each location within a 21 × 21 pixel area. The primary avalanche pixel is represented by the white square at the center. Structure in the map is discussed in the text.. RIGHT: Illustration of crosstalk photon propagation explaining structure in spatial map. From a primary avalanche at pixel “1”, line-of-sight coupling from “1” to “2” is reduced by etched isolation trenches. Reflective coupling from “1” to “4” is reduced by an absorptive metallic coating at “A”. The requirement for a dielectric aperture at “B” to allow signal photons (incident from top of figure) to reach pixel “3” promotes relatively high reflection from “1” to “5”.

6. MODELING OF INTER-ARRIVAL TIME DISTRIBUTION WITH CROSSTALK

In order to obtain a better understanding of the underlying behavior exhibited in the temporal analysis of crosstalk, we have considered the impact of crosstalk counts on the inherent Poissonian dark count distribution. Our goal is to understand specific features of the measured data, particularly the origin of the considerable non-Poissonian “tail” in the inter-arrival time distributions found for the higher crosstalk data presented in Figure 5 and Figure 6. We first consider the occurrence of random dark counts according to a Poisson process with time increments Δt and inter-arrival times T,

\[ T \sim \text{Poisson}(\lambda) \]

as illustrated in Figure 8(a). A Poisson process is memoryless and exhibits the properties described in the figure caption in the limit of \( \Delta t \to 0 \). We then consider the introduction of crosstalk counts, which are interleaved between intrinsic dark counts as shown in Figure 8(b) and which follow their respective primary avalanches by an average time \( T_c \).

Inspection of this model readily shows that the crosstalk counts segment an intrinsic dark count inter-arrival time \( T \) into two segments \( T_c \) and \( T' \), with \( T = T_c + T' \). \( T_c \) is the inter-arrival time between a primary avalanche and a temporally correlated crosstalk event, while \( T' \) is the inter-arrival time between the crosstalk event and the next intrinsic dark count. The overall inter-arrival time distribution is modified by the addition of a large number of events at \( T_c \)—one for each crosstalk avalanche—and the associated replacement of \( T \) by \( T' = T - T_c \). In the experimental data presented in the previous section, the inter-arrival time peaks seen in the insets of all figures clearly establishes that \( T_c \sim 1 \) ns.

This model has been used to calculate the effects of crosstalk on the dark count inter-arrival time distribution, including the possibility of “cascades” of crosstalks in which one crosstalk event acts as the primary avalanche which triggers another crosstalk count. Our simulation generates \( n_i \) dark counts according to a temporal Poisson distribution and tracks the number of crosstalk events \( i \) and their time of occurrence with respect to a primary dark count at \( t = 0 \). In this calculation, \( i \) represents the cascade length. The results vary only slightly when \( i \) is increased beyond 8 because the
probability of longer cascades turns out to decay exponentially with cascade length. The total number of crosstalk events $n_2$ is calculated by counting the total number of avalanche events in excess of the expected Poisson distribution from $t = 0$ to $2$ ns. Because our empirical results show that the dominant inter-arrival time for crosstalk events is $\sim 1$ ns, for simplicity we assume that a cascade of $i$ crosstalk events has a time of occurrence equal to $i \times 1$ ns. Note that only the last crosstalk event in a cascade sequence directly affects the inter-arrival time to the next intrinsic dark count—i.e., reducing $T$ to $T'$ as illustrated in Figure 8(b). For the case of a cascade of $i$ crosstalk events, the inter-arrival time $T'$ is reduced to $(T - i \times 1$ ns).

![Diagram](image)

**Figure 8.** (a) Illustration of events occurring according to a Poisson process: for $\Delta t \rightarrow 0$, events are independent (i.e., memoryless), the probability of an event is proportional to $\Delta t$, and only a single event occurs within $\Delta t$. Successive events are separated by inter-arrival time $T$. (b) The occurrence of a crosstalk count causes a particular Poisson inter-arrival time $T$ to be segmented into the crosstalk delay time $T_c$ and the remaining interval $T'$ until the next dark count.

In Figure 9, we show the simulated impact of crosstalk and crosstalk cascading on dark count inter-arrival times for short time intervals up to 20 ns. In Figure 9(a), the crosstalk probability $n_2/n_1$ has been set to be 0.126 to facilitate direction comparison with the experimental data presented in Figure 4(a), and the height and shape of the simulated inter-arrival time peak at $\sim 1$ ns agree well with the measurements. In an attempt to reproduce the emergence of the non-Poissonian tail observed for larger cumulative crosstalk values in Figure 5 and Figure 6, we repeated the simulation for larger values of $n_2/n_1$. For a much larger assumed value of $n_2/n_1 = 2.5$, Figure 9(b) does show the emergence of a tail above the Poissonian dark count background for inter-arrival times extending to at least 5 ns. This behavior is reminiscent of the tails seen in Figure 5 and Figure 6, but it is far smaller than the measured data, which was obtained for significantly lower values of $n_2/n_1$. Further investigation is on-going to gain an understanding of this quantitative discrepancy.

![Graphs](image)

**Figure 9.** Results of simulated inter-arrival time distributions for short time intervals up to 20 ns for cumulative crosstalk probabilities of (a) $n_2/n_1 = 0.126$ and (b) $n_2/n_1 = 2.5$. The solid line is the intrinsic Poissonian dark count background.
7. DISCUSSION

The temporal statistical analysis reviewed in this paper provides an extremely useful method for distinguishing between intrinsic dark count rate and crosstalk events. In the 1.0 μm FPAs, for which the crosstalk is relatively low, the non-Poissonian inter-arrival time behavior that we have ascribed to crosstalk events is limited to very short inter-arrival times of less than 2 ns, with a strong peak at 0.75 – 1 ns. It is likely that this timescale simply reflects the avalanche build-up and quench decay, and this explanation is supported by previous modeling of avalanche timescales [22,6]. It is not surprising that the 1.5 μm FPA results exhibit that same exact peak behavior since both GmAPD device structures employ the same InP multiplication region. However, the much longer tail found for the longer wavelength detector array can be attributed to the wider spectral response leading to elevated crosstalk probabilities and consequent cascades of crosstalk events. Concerning how much crosstalk can be tolerated, this will depend on the algorithms used for data analysis. Certainly, impressive imagery has been obtained using 1.0 μm FPAs with performance comparable to those described here [9,10]. Moreover, notwithstanding the much higher crosstalk observed for the 1.5 μm FPAs, these sensors have already proven to yield excellent field-trial results [23].

Reducing the size of the GmAPD active region within each pixel provides significant reduction in crosstalk and will simultaneously improve numerous other GmAPD performance metrics such as DCR, afterpulsing, and radiation tolerance [24]. Future work will include a more detailed geometric crosstalk model to explain the dramatic crosstalk reduction reported in sub-section 4.2 for reduced active regions. Additionally, the migration to smaller pitch and larger format arrays will demand smaller active area sizes based on simple geometric considerations as well as the fact that crosstalk effects will be exacerbated considerably as GmAPD pixels are scaled to smaller pitch, as described in subsection 4.4 relative to the results on 128 x 32 FPAs with 50 μm pitch. Finally, while active size reduction provides substantial benefits, these come at the expense of more challenging optical coupling.

The Poisson statistics of GmAPD dark counts and the associated exponentially distributed interarrival times have been described previously [25,26]. In this study, we have made use of these statistics to perform a temporal statistical analysis for dark counts from the entire array that is useful for distinguishing between intrinsic dark counts and crosstalk counts. The application of this analysis to other situations in which both Poisson and non-Poisson processes co-exist has been equally fruitful, as in the extraction of afterpulsing counts—which will have non-Poissonian statistics—from intrinsic dark counts using the same statistical analysis of inter-arrival times [27].

REFERENCES


