Analysis and Modeling of Optical Crosstalk in InP-based Geiger-mode Avalanche Photodiode FPAs

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ABSTRACT
Optical crosstalk is a major factor limiting the performance of Geiger-mode avalanche photodiode (GmAPD) focal plane arrays (FPAs). This is especially true for arrays with increased pixel density and broader spectral operation. We have performed extensive experimental and theoretical investigations on the crosstalk effects in InP-based GmAPD FPAs for both 1.06-μm and 1.55-μm applications. Mechanisms responsible for intrinsic dark counts are Poisson processes, and their inter-arrival time distribution is an exponential function. In FPAs, intrinsic dark counts and cross talk events coexist, and the inter-arrival time distribution deviates from purely exponential behavior. From both experimental data and computer simulations, we show the dependence of this deviation on the crosstalk probability. The spatial characteristics of crosstalk are also demonstrated. From the temporal and spatial distribution of crosstalk, an efficient algorithm to identify and quantify crosstalk is introduced.

1. INTRODUCTION
The ability to detect single photons is an enabling capability for numerous applications in the field of photonics such as optical time domain reflectometry [1,2], quantum communications [3], light detection and ranging [4], deep space acquisition and tracking [5], and semiconductor device and material characterization [6]. In all of these scenarios, Geiger-mode avalanche photodiodes (GmAPDs) have emerged as an excellent device technology for single-photon detection. They provide performance that meets the requirements of many of these single-photon 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 technology.

Recent advances in InGaAsP-based GmAPDs have emphasized higher counting rates and integration of the devices into large-format arrays [7,8], and one of the most important drivers for these advances is the deployment of GmAPD focal plane arrays (FPAs) in three-dimensional (3D) imaging laser radar (LADAR) systems [9, 10]. These systems—also described as light detection and ranging (LIDAR) imaging—exploit time-of-flight measurements at every pixel of the FPA to create 3D point clouds that can be processed to create 3D images. The ability to generate this imagery with single-photon sensitivity is a disruptive capability. Three-dimensional LADAR systems based on single-photon-sensitive GmAPDs 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 alternative technologies [4,11]. 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.

However because pixels are closely spaced in FPAs, when a pixel experiences an avalanche event (AE), its neighboring pixels can also be triggered by photon emission induced by electroluminescence from the avalanching carriers. This mechanism is often referred to as optical crosstalk (XT). This additional mechanism increases the average dark count rate (DCR) per pixel compared to discrete GmAPDs. XT has become a major challenge in designing FPAs, especially for denser arrays. XT can be reduced by modifying the physical structures of individual GmAPDs and their arrayed layout. This requires accurate quantification of XT in order to evaluate the effectiveness of different physical changes. In principle, XT effects can also be alleviated by implementing software to statistically differentiate XT pixels.

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from real-signal AEs, but the task of identifying and quantifying XT is not trivial since the data read-out circuit cannot determine whether a pixel AE is a real-signal event, an intrinsic dark count (I-DC) event or a XT event.

In this paper, we provide an extensive investigation of the dark count (DC) behavior of the GmAPD FPAs, including statistical temporal and spatial analysis of the DC data. Different behavior of FPAs with different spectral response characteristics are also discussed in detail. Finally, an efficient algorithm is proposed to accurately identify and characterize XT from I-DCs.

2. BACKGROUND

2.1 Sensor architecture and operation

The GmAPD FPA and its operation have been described in detail in earlier publications [12]. The core functionality of the GmAPD FPA is determined by three semiconductor arrayed devices: the InGaAsP-based GmAPD photodiode array (PDA); a 0.18 μm 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. A schematic illustration of the FPA construction is provided in Fig. 1.

Fig. 1. Schematic illustration of the construction of the GmAPD focal plane array (FPA). See text for a description of the FPA components.

The GmAPD cameras are operated through a sequence of frames. Each data frame is initiated by a trigger signal. The camera then provides a variable delay time ranging from 0 to 256 μs to allow for the transit time of the ns-scale laser pulse to be reflected from distant objects. Following the delay time, the pixels are armed by applying an additional reverse bias using appropriate transistors in the CMOS ROIC. This arming period is the only time during which the GmAPD pixels are connected to an external supply with the net voltage exceeding breakdown voltage V_b. 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”. A full range gate consists of the counters proceeding through 8000 counter values, ending with a final “terminal count” value. With the highest timing resolution of 0.25 ns, a full range gate has a duration of 2 μs. During the counting sequence, an AE at any GmAPD pixel will freeze the corresponding pixel counter in the ROIC, indicating the arrival time of a photon or a DC, 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 returns the terminal count, then it did not detect an AE for that frame. Once the terminal count is reached, all the remaining armed pixels are disarmed, and all counter values are read out along shift registers in each row during a readout period of 3.5 μs. The frame duration of 2 + 3.5 = 5.5 μs provides a frame rate of roughly 180,000 Hz.

In previous preliminary work on XT behavior [13], we confirmed that XT can be characterized both with and without external illumination. On the other hand, it is obviously most reasonable to collect the I-DC data when the cameras operate in the absence of an external light source. Therefore, all of I-DC and XT data shown in this paper have been collected with the cameras operating in the dark.
2.2 Origins of dark counts (DCs)

DCs are AEs that occur in the absence of real signal photons. DCs in discrete GmAPDs are generally caused by several mechanisms, including Shockley-Read Hall generation and tunneling. However, in FPAs, pixels are closely spaced in the array format, and when a pixel experiences an AE, the neighboring pixels can also be triggered by photon emission from the avalanche carriers. This mechanism is referred to as optical XT. There are two dominant paths for optical XT: (i) direct line-of-sight coupling and (ii) rear-surface reflection paths (see Fig. 2). DC mechanisms other than XT are considered to be intrinsic dark counts (I-DCs).

![Diagram of optical XT](image)

Fig. 2. Sketch of dominant paths for optical XT caused by avalanche carriers’ photon emission: (i) direct line-of-sight coupling and (ii) reflections from the rear surface of the APD array.

3. TEMPORAL CHARACTERIZATION OF DARK COUNTS

3.1 Statistical temporal analysis of I-DCs

In principle, I-DCs are a Poisson process, and we expect that the “inter-arrival” times between successive counts will obey an exponential distribution [14] given by

\[ f(t) = \lambda e^{-\lambda t} \]  

(1)

where \( t \) is the inter-arrival time (IAT) and \( \lambda \) is the average DCR. Given a group of pixels that exhibit Poisson statistics, their collective behavior—such as the IAT for DC’s among all of the pixels—will also obey Poisson statistics [14]. Therefore, the semi-log plot of the distribution of the IAT of I-DCs in a FPA is expected to be a straight line whose slope \( \lambda \) is the sum of all the average intrinsic DCRs of the individual pixels. In fact, this is only true in the free-running mode operation of the FPA. In the framed operation, once a pixel fires, it is disabled for the remainder of the range gate. Therefore, the IAT distribution is expected to be truncated at long time scales relative to a pure Poisson distribution.

A program was written in Matlab to simulate the dependence of IAT distribution on \( \lambda \) with and without the time constraint of a single frame. Within a single frame, the time of arrival of each pixel is randomly generated based on the distribution in (1). The time of arrival of all pixels is arranged chronically, and the IAT of the array is calculated by taking the difference of each pair of consecutive events. This algorithm is repeated for a large number of frames. Figure 3 shows the IAT probability of a 32x32 array of APDs with an average DCR of 16 kHz, which is a typical average DCR per pixel in our 32x32 1.55-\( \mu \)m cameras at a PDE of 20%. Open symbols and solid line represent the probability when the frame duration is 2 \( \mu \)s and \( \infty \), respectively. The two curves are normalized so that they have the same probability at \( t = 0 \) ns solely to demonstrate their different characteristics. The solid curve’s slope is smaller than that of the data for the finite frame simulation. Whereas the slope of the open-symbol line remains almost constant, the slope of the solid curve decreases at higher IAT, introduced by the decreasing number of available pixels with time. The open-symbol line can be well-fit by an exponential function (dashed line), whose exponential factor value is 16.7 \( \mu \)s\(^{-1}\). Dividing 16.7 \( \mu \)s\(^{-1}\) by 1024 pixels yields each individual pixel’s average DCR of 16.3 kHz, which is close to the 16-kHz input value. This suggests that with 2-\( \mu \)s framed operations, the average DCR can be accurately extracted from the IAT distribution. This is reasonable because, on average within 2 \( \mu \)s, only 33 pixels (which is 3.2% of a 32x32 array), experience an AE. Consequently, the total number of pixels available for I-DC events is essentially unchanged within 2-\( \mu \)s frames. For our 32x32, 1.064-\( \mu \)m cameras, the DCR is much smaller than 16 kHz even when operating at a PDE of 30%. Therefore, extracting the DCR from the IAT distribution is also reasonable for 32x32 1.064-\( \mu \)m cameras. However, for scenarios in
which the intrinsic DCR increases significantly—e.g., higher temperature operation, or next-generation GmAPD arrays with response beyond 2 μm wavelengths—the IAT distribution within a fixed frame duration will deviate from a Poisson process when a large fraction of the pixels become unavailable later in the frame. In these cases, using the slope of the IAT to estimate the intrinsic DCR becomes less accurate. For example, for an intrinsic DCR of 160 kHz and 320 kHz, the error introduced by approximating the constant slope increases to 14 % and 56%, respectively.

Fig. 3. The IAT between consecutive DCs occurring anywhere on a 32x32 array. Blue empty symbols and black solid curve represent the simulated data for a frame duration of 2 μs and 2 μs, respectively. The IAT = 0 probability has been arbitrarily set to the same value for both curves. The average DCR of each pixel is 16 kHz. The empty symbols are well-fit by the dashed line, whose exponent is 1.67 x 10^2 (1/ns). The black solid curve deviates further from Poisson behavior at larger IAT values as fewer and fewer pixels are left armed to register DCs.

3.2 Statistical temporal analysis of XT

The IAT behavior of XT counts is expected to be quite different from a Poisson process. The time scale for multiple cycles of electrons and holes traversing the high-field region of an APD, gaining energy, and causing impact ionization is on the order of ns, and a significant number electron-hole pairs generated by impact ionization can be formed within this timeframe. Most XT occurs at the neighboring pixels in fairly close proximity to the primary avalanche pixel, and it takes less than 100 ps for photons to travel from one corner of the FPA to the opposite corner. Therefore, the IAT of a XT event with respect to its immediate primary pixel is expected not to be longer than a few ns.

In principle, based on the two completely different IAT characteristics of I-DC and XT, a significant amount of information can be extracted by plotting the IAT of the experimentally-measured DCR. Figure 4 shows the experimentally-measured IAT distribution of a typical 1.0-μm FPA. Individual pixels of this FPA have an average DCR of 2.2 kHz at an average PDE of 30.5%. Except for very short IAT, the distribution exhibits the exponential behavior expected for a Poisson process. An exponential fit obtained for the IAT data between 25 ns and 450 ns yields the exponential factor $\lambda = 2.77 \times 10^3$ ns$^{-1}$. The DCR per pixel is $\lambda / 1024 = 2.7$ kHz. Based on the assumption of Poisson behavior for this analysis, this value is the intrinsic pixel-level DCR of the FPA. We note that the value of 2.7 kHz obtained from Fig. 4 agrees to within ~ 18% of the value of 2.2 kHz obtained from simply counting DCs per unit time.

For the 1-μm FPA, the deviation from the exponential behavior of the distribution at very short IAT is shown more clearly in the inset of Fig. 4a. All discernible deviation from the Poisson exponential behavior occurs for IAT < 2 ns, with a clear peak seen at ~ 1 ns. If we ascribe this non-Poissonian contribution to XT events, this analysis allows us to identify and characterize both XT and I-DC. Integrating over the non-Poissonian counts yields a worst-case estimate (assuming all deviation from Poisson behavior are XT counts) of the fraction of total DC that should be attributed to XT events. Referring to the Fig. 4a inset, the cumulative XT is 12.6% of the intrinsic DCR of 2.7 kHz at 30% PDE.

All of the 32x32 1.0-μm FPAs and most of 32x32 1.5-μm FPAs have similar IAT characteristics to those shown in Fig. 4a; i.e., Poisson behavior is found for times > 2 ns, and non-Poissonian behavior within 0 - 2 ns. However, for some 1.5-μm cameras, the non-Poissonian peak possesses a fairly long tail that does not merge with the Poisson background.
until IATs as long as 15 – 20 ns (Fig. 4b). Integrating over the entire non-Poissonian peak, we find a much larger cumulative XT probability of 90%. This is not surprising because of the luminescence 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 [15]. The much wider spectral response of the 1.5-μm FPAs results in substantially higher XT effects for these longer wavelength FPAs. However, it is logical to wonder if the non-Poissonian tail beyond 2 ns is composed of XT events and is caused by the long cascading chain of XT. The following section will explore in detail the deviation from Poisson behavior in the existence of high XT probability and the possibility of long chains of cascading XT events.

3.3 XT effects on the DCs IAT distribution

One possible cause of the extended tail in Fig. 4b is the interleaving between DC and XT events that is introduced by the algorithm to generate the IAT data. Figure 5 shows this artificial interaction; the solid vertical bars represent DCs and dotted bars are XT events. \( t_T \) is the IAT of a DC with respect to the XT event immediately preceding it. It is worth emphasizing that if the non-Poissonian tail beyond 2 ns is mainly contributed by \( t_T \)’s, then the AEs in this tail region are mostly intrinsic DCs. Therefore, counting the entire non-Poissonian peak in Fig. 4b as XT will overestimate the total XT probability.

To investigate the contribution of \( t_T \)’s to the non-Poissonian tail, the probability of XT cascading needs to be determined. As shown in Fig. 4a and 4b, XT events dominantly occur within 2 ns of their initiating AE. For each frame, AEs are arranged chronologically, and considering each DC as a primary AE, we then search for temporally-correlated
counts within a correlation time of 2 ns. If a temporally correlated count is found, it is assumed to be a XT event. This assumption is not strictly accurate as will be shown later, but it does not affect the demonstrative purpose and conclusions of this section. This XT pixel’s position relative to the primary AE pixel is also stored for the spatial analysis (which will be shown in section 4). With the data arranged this way, not only can the total number of XT events be calculated, but the cascading XT sequence can also be readily determined as well.

A computer program was written in Matlab to calculate the effects of XT and XT cascading on the distribution of DCs. This program generates n1 DCs according to their temporal Poisson distribution, and these DCs are kept in an array. A two-dimensional array is also generated holding the number of XT n2 and their time of occurrence with respect to the original DC at t = 0. The cascade length i is also varied in the program to help study the effects of cascading on the non-Poissonian tail. The results vary only slightly when i is increased beyond 8, which is not surprising due to the exponential decaying of the cascade length (shown in the inset of Fig. 6).

Most XT events have the IAT ~ 1 ns as shown in Fig. 4a and 4b. Therefore, for simplicity, all XT i’s have the time of occurrence equal to (i x 1 ns). Note that only the last XT event in a cascade sequence directly affects the IAT of DCs (red dotted bars in Fig. 5). The number of those last XT event i’s in their sequences can easily be calculated as n2(i+1) - n2(i), and these XT events are recorded in another two-dimensional array. For each XT i in this array, a DC event in the dark-count array is chosen randomly, and their IAT tdcc is adjusted to (tdc – i) x 1 ns.

Fig. 6. Simulated IAT probability (solid line) and the experimental data (symbols) for the FPA in Fig. 4b, where the ratio of XT events and intrinsic DC is n2/n1 = 0.854. Dashed line represents Poisson distribution of the intrinsic DCR’s IAT. The inset shows probability of cascading XT events for the 1.55-μm FPA, whose data was shown in Fig. 4b. A XT event that is caused directly by a DC is named XT1. XT events that are directly caused by XT1 are named XT2, and so on. As shown in the inset of Fig. 6, XT cascading can be well-fit by an exponential function with an exponential factor of 0.44. Figure 6 shows the effects of XT and XT cascading on the 1.55-μm FPAs with i = 15 and n2/n1 = 0.854 (as calculated from Fig. 4b). The dashed line represents the IAT of intrinsic DCs that are Poissonian in nature. The simulated distribution does not show any noticeable deviations from the exponential line at t > 2 ns. The non-Poissonian tail at t > 2 ns is not observed when the exponential factor (changing the cascading probability) varies as long as n2/n1 = 0.854.

The tail appears more clearly and approaches the experimental data as n2/n1 increases (see Fig. 7). It is important to note that the tails of the simulated curves are constituted entirely by I-DC whose IAT distribution is changed by the existence of XT events. Even though the extended tail can be reproduced from the simulation (Fig. 7), the simulated ratio
\( n_2/n_1 \) is much greater than experimentally observed in Fig. 4b. Therefore, different factors other than the long XT cascade chains are more responsible for the non-Poissonian tail at \( t > 2 \) ns in Fig. 4b.

Fig. 7. Simulated IAT’s probability with \( n_2/n_1 = 2.5 \) (black line) and \( n_2/n_1 = 5 \) (red line) in comparison with the experimental data (solid blue circles) of the FPA in Fig. 4b.

Fig. 8. IAT probability of DCR in high-EF frames (red square symbols), low-EF frames (blue triangle symbols), and total frames (black circular symbols) for the 1.55-\( \mu m \) FPA. Dashed lines are exponential fitting curves, with \( \lambda = 2.35 \times 10^{-2} \) (1/ns) and \( 9.37 \times 10^{-3} \) (1/ns) for high-EF and low-EF frame curves, respectively.

During the pixel arming period (~10 ns), some pixels experience AEs and are registered at \( t = 0 \) during the range gate. These pixels are generally referred to as early fire (EF) events. During the arming time, all pixels are connected to the external ROIC supply which provides ~5 V bias swing; the triggering of an AE can result in continuous charge flow for the remainder of the arming period. We estimate that on average, an AE in an arming period results in \( \sim 10^8 \) e\(^+\), which is at least 10 times more than an AE during the range gate. Consequently, XT probability is substantially higher in the arming duration causing more EFs, and the number of available pixels at the beginning of range gate decreases with the increasing of EF.
To investigate the effects of the EFs on the IAT distribution, the data are analyzed for high-EF frames and low-EF frames separately. High-EF frames are defined to be those having more than 15% of pixels (~154 pixels) firing during the arming period. Figure 8 shows the markedly different distribution of DCR in high-EF and low-EF frames. To mitigate the possible long XT cascade chains caused by those EF pixels, the data during the first 50 ns of the range gate is not included in Fig. 8. For the low-EF frames, the extended tail does not occur, in agreement with the simulation results shown in Fig. 6.

Based on the behavior in Fig. 8, it appears that the high-EF frames are responsible for the existence of the tail. Interestingly, the high-EF frames exhibit a couple of unexpected behaviors in the IAT distribution. If XT is still believed to occur within 2 ns of the immediate primary pixel, the percentage of XT to intrinsic DCR in the high-EF frames is about 26%. This number is much smaller than the percentage of XT required to change the exponential distribution of the intrinsic DCR as shown in Fig. 7. Another interesting characteristic from the high-EF frames is the rather high slope of the distribution curve at $t \gg 2$ ns (Fig. 8). If using the slope to infer the intrinsic DCR is still valid, then the intrinsic DCR in the high-EF frames is about 2.5x that of the low-EF frames. This is quite surprising and counter-intuitive since in the high-EF frames, the number of remaining pixels available for AE occurrences is smaller, and consequently the slope is expected to be lower. Therefore, some other mechanisms that do not exist in the low-EF frames are apparently responsible for this additional DC. In particular, a condition in which the ROIC quenching process was slowed down would result in more charge flow and consequently larger XT probability. Moreover, in this scenario, the XT might no longer be restricted to a narrow ~2 ns time window following the primary avalanche. Further investigation of these possibilities is being pursued.

4. SPATIAL CHARACTERIZATION OF CROSSTALK

Fig. 9. (a) Spatial map of XT events from 10,000 frames of data for a 1.0 μm FPA sensor operated at 30% PDE. Values represent number of XT counts at each location within a 21×21 pixel area. The primary avalanche pixel is represented by the white square at the center. (b) Dependence of XT frequency at a pixel on its distance with the corresponding primary fire.

We have shown earlier the algorithm to determine a XT event’s location relative to its primary AE pixel. For every frame, each primary event is considered to be at the origin of our spatial map, and the number of XT counts found at every pixel location relative to this origin is summed. Any XT event can then be considered to take the role of a primary
avalanche, and in this way cascades of XT 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 XT event has more than one earlier avalanche as a candidate for its primary avalanche (i.e., there was more than one avalanche that occurred within the temporal-correlated time). In these cases, the key is to avoid double-counting in which a single avalanche is identified as a XT count more than once. Fig. 9a shows the spatial map of XT for 10,000 non-illuminated frames for the 1.06 μm FPA (which is used to generate the data in Fig. 4a).

As discussed earlier, there are two main optical paths for XT: direct line-of-sight and reflection from the rear surface of the PDA. The frequency of XT at the eight nearest pixels of the primary pixel varies strongly, depending on their orientation. This reflects the results of the technique that we have used to reduce the line-of-sight coupling by etching optical isolation trenches between nearest-neighbor pixels. Trenches are etched through the epitaxially-grown structure, and the anisotropy in this nearest-neighbor coupling is related to the crystallographic dependence of the InP wet-etch chemistry used, resulting in a V-groove geometry in one direction and a nearly vertical dove-tail geometry in the orthogonal direction, as described previously [13]. Beyond the eight line-of-sight near-neighbors, XT coupling to further neighbors occurs by reflection from the back surface of the PDA substrate. The dominance of reflective-path coupling over the direct line-of-sight coupling is shown by the nearly-isotropic probability rate at the next nearest neighbors both vertically and horizontally. In general, XT frequency decreases at farther pixels (can be seen more clearly in Fig. 9b); however, this decrease is not monotonic, and the pattern of the high-level symmetry indicates the non-homogeneous reflectivity of the back surface.

Fig. 10a shows a simplified schematic of different paths for optical XT. Reflective coupling mainly comprises two distinct paths: reflection from an absorptive metallic coating at “A” and from a dielectric aperture at “B”. 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”. From ray-tracing techniques over the layout of the arrays, optical coupling through reflection between two pixels follows either path “A” or path “B”. Consequently, if the XT probability due to reflection through path “A” is separated from path “B”, interesting insights can be gained (Fig. 10b).

![Diagram of optical paths](image)

Fig. 10. (a) Illustration of XT 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”. (b) XT frequency due to reflection through two different back surface materials can be well-fit by two power functions.
The frequency dependence on the distance $d$ of the optical coupling pixels can be well-fit by a power function with the power factor of $\sim 2$ for both paths “A” and “B”, which is expected due to the light intensity decreasing as $d^{-2}$. The reflectivity of “B” is about 2.5X that of “A”. Even though XT frequency is highest at direct-line-of-sight coupling pixels, reflective coupling plays a much more important role in determining the cumulative XT probability due to the significantly higher number of reflective-coupling pixels. The dependence of XT probability on $d^{-n}$ where $n \sim 2$ is observed for all 32x32, 1.064-μm cameras. For 1.55-μm cameras, $n < 2$ due to the XT cascading effect. However, when eliminating this cascading effect by accounting only the first XT, $n$ becomes $\sim 2$.

XT probability 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 XT. In addition, XT probability is also directly proportional to the total number of avalanche charge carriers, and the larger a pixel’s active area is, the more avalanche charge is involved. Therefore, it is expected that XT probability is proportional to $A^{-2}$ where $A$ is the active area. Non-idealities in actual detector behavior—such as some degree of gain non-uniformity—can be expected to yield a XT probability with area dependence $A^{-n}$ where $1 < n < 2$.

At PDE = 30%, the XT probability of seven 1.064-μm 32x32 cameras gives an average of $\sim 10.6\%$ with a standard deviation of $\sim 3\%$ (represented by the blue diamond and the error bar in Fig. 11). Those seven cameras have an active region diameter of 34 μm and a pixel pitch $d$ of 100 μm. The dashed line and solid line represent the predicted dependence of XT probability on the active diameter with and without gain nonuniformity effects (e.g., some degree of edge breakdown), respectively. We note that, to make the predictions more tangible, the number of avalanche charges is assumed to simply scale with the geometric scaling and PDE is assumed unchanged at 30%. By scaling the active diameter, the XT probability is expected to be bounded by those two curves (represented by region I). The red circle in Fig. 11 is the experimental XT probability of the 32 x 32 FPA with 100 μm pitch and 18-μm-diameter active area. This camera’s XT probability of 1.4 % stays well within region I.

![Fig. 11. XT probability of seven 32x32 1.064-μm cameras (blue diamond symbol). When the APD’s active area is scaled at the constant 100-μm pitch, the calculated XT probability is confined within region I. Region I is bounded by the dashed line and solid line representing XT probability with and without gain non-uniformity effects, respectively. When the APD’s active diameter is scaled at the same rate as the pitch, the XT probability is expected to be confined within region II. The upper and lower bounds of region II represent XT probability with and without gain non-uniformity effects, respectively. The red circle is the data for the 32 x 32 FPA with 100-μm pitch and 18-μm-diameter active area. The black square is the data for a 128x32 FPA with 50-μm pitch and 18-μm-diameter active area.](image)

To further increase the pixel density on an array, the pitch of the pixels in a FPA can also be scaled down. Region II in Fig. 11 predicts the reduction of XT probability when the active diameter and the pitch $d$ are scaled at the same rate. We have produced 128x32 FPAs whose pixel active diameter is 18 μm and pixel pitch is 50 μm. For a 1.06-μm 128x32 FPA, the XT probability is about 10% at 30% PDE (shown as the black square symbol in Fig. 11).
5. PROPOSAL OF ALGORITHM TO IDENTIFY XT CASCADE CHAINS

The algorithm to identify XT pixels, discussed thus far, is not entirely accurate. For example, Table 1 shows a scenario of the nine pixels being arranged in chronological order of occurrence. All of these nine pixels occur within 8 time bins = 2 ns of one another. In this case, the program treats this as a cascade of XT with the length of 8. P1 is treated as the primary pixel: P1→P2→P3→P4→P5→P6→P7→P8→P9. However, realistically, any of those 9 pixels can be an I-DC, and any later pixels can be XT events caused by any earlier pixel. The number of pixels directly coupled with P1 yields information about the total number of avalanche charges, and therefore the number of photons, involved in an AE. This information is important in the modeling of XT probability and designing arrays. Therefore, it is of great benefit to accurately identify the pair of pixels that are coupled directly with one another. A more accurate algorithm to achieve this task can be implemented based on XT’s IAT distribution from 0 to 2 ns (equivalent to 0 bins to 8 bins) as shown in Fig. 4a and 4b.

Table 1. Example of modelling output correlating all AEs that occur within 2 ns of one another in a frame.

<table>
<thead>
<tr>
<th>Pixel</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Bin</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

After accounting for different IAT probabilities among the 9 pixels, the result of assigning XT coupling becomes:

With this new algorithm, the longest cascade chain is 3. In the 1.064-μm FPAs, this algorithm slightly improves the accuracy of identifying XT cascade chains due to their low XT probability and, consequently, low cascading probability. However, for the 1.55-μm array in Fig. 4b, when this algorithm is not implemented, the number of first XT events is underestimated by 20%.

More accurate identification of a XT pixel and its primary AE can still be achieved. With the same chain of XT in Table 1, P5 and P6 occur in the same time bin, and both P2 and P3 are equally possible primary AEs. In this case, the spatial distribution as shown in Fig. 10b needs to be used to help the identification more deterministically.

There is still room to further improve the accuracy of pairing XT pixels to their immediate primary events. After assigning a XT pixel to its primary AE based on both the temporal distribution (Fig. 4) and the spatial distribution (Fig. 10), the IAT distribution of XT can be adjusted, and the result is expected to be different from Fig. 4. From the newly acquired IAT distribution, the corresponding spatial XT probability can also be calculated. Therefore, the temporal and spatial distributions need to be solved iteratively before satisfying accuracy can be obtained.

6. CONCLUSION

The inter-arrival time (IAT) distribution of dark counts (DCs) in InGaAsP-based GmAPD FPAs has been studied in detail. The IAT distribution of intrinsic dark counts (I-DCs) in an FPA is an exponential function whose exponential factor is the average intrinsic DCR of the FPA. On the other hand, the IAT distribution of crosstalk (XT) events is Gaussian-like and is dominantly confined to within 2 ns of the primary avalanche, with a peak probability at ~1 ns. XT mainly occurs either through direct-line-of-sight coupling or back-surface reflection. For our specific FPA’s structures, there are two distinct paths of back-surface reflections: via absorptive metallic coating and via dielectric apertures. The reflectivity of the dielectric apertures is about 2.5x that of the metallic coating. In our FPAs, because of the significantly...
higher number of pixels available for optical coupling through reflection, the total XT probability via this path is dominant. If $d$ is the distance between two pixels, the probability of the optical coupling due to reflection among those two pixels depends on $d^{-n}$ where $n \approx 2$. From the known XT’s temporal and spatial distribution, the total XT probability can be accurately calculated by an iterative method. This method not only can distinguish XT events from I-DC, it can also identify XT cascading chains.

The application of this analysis to other situations in which both Poisson and non-Poisson processes co-exist has been also 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 [16].

REFERENCES


