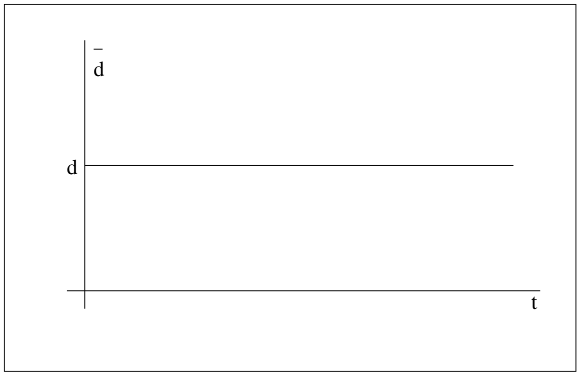

Figure 1: Dark rate (average number of dark events we expect at time t, where $t = 0$ is when the APD is powered) as a function of time. It is approximately uniform.

Crosstalk in Avalanche Photodiodes

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1 Theory

1.1 The phenomenon that is crosstalk

When an APD avalanches, it emits photons. I have no idea what the angular illumination pattern of an APD is, what colors it emits, or what intensity it emits. But, it is safe to assume that a photon created in element A may be able to find its way over to a neighboring element B and trigger an avalanche. We define a crosstalk event as an avalanche caused by a neighbor that fires.

I will often speak of “gates”. We often power the APDs for about 100 ns, and repeat this at 4 kHz. Each “gate” is each 100 ns period that the APDs are powered and ready to avalanche.

1.2 Dark Events

Even when it is not illuminated, the APD can avalanche from thermally excited electrons. Figure 1 shows the time dependance of the average dark rate of an APD. Since the dark rate is so small, the distribution is uniform in time. If the dark rate were high, the APD would often avalanche as soon as it was reverse-biased. Then, the dark rate would be peaked around $t = 0$. We call this first-photon biasing.

Poisson statistics tells us the probability of an APD avalanching from a dark electron in

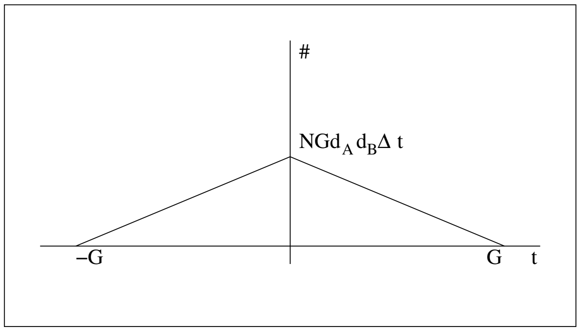


Figure 2: Distribution of double-dark events.

time Δt is

$$\int_{t_a}^{t_b} P_1(t) = \int_{t_a}^{t_b} \bar{d}(t)e^{-\bar{d}(t)} = de^{-d}\Delta t \approx d\Delta t$$

If we have two APD elements, A and B, the probability that both avalanche from a dark electron is given by

$$(d_A\Delta t)(d_B\Delta t)d_Ad_B\Delta t^2$$

Suppose the APDs are powered for a time G, and our timing resolution is Δt. For example, the APDs could be powered for 100 ns, and events that happen within 25 ps of each other are reported as occuring at the same time by our timer. The probability that both A and B register an event at the 'same time,' or within Δt of each other, is given by

$$\left(\text{Prob that A gets event at time} t \pm \frac{\Delta t}{2}\right)\left(\text{Prob that B gets event at time} t \pm \frac{\Delta t}{2}\right)(\text{Number of ways A and}$$

$$= (d_Ae^{-d_A}\Delta t)(d_Be^{-d_B}\Delta t)(\frac{G}{\Delta t}) \approx Gd_Ad_B\Delta t$$

We can ask how often both A and B register dark events in a single gate. Suppose we run many gates. We record data whenever A and B both avalanche from a dark event. Then we plot a histogram of the relative return times, $t_A - t_B$.This 'double-dark' distribution would be a convolution of A's and B's dark event distribution (Fig 2).

There is a simple explanation for the appearance of this distribution. There are many ways for A and B register an event at the same time. They could both report an event at $t = 1$ ns, or they could both report an event at $t = 2$ ns, etc. Thus, there are $G/\Delta t$ ways that A and B can report an event at $t_A - t_B = 0$. However, there is only one way for element A to report an event G ns before element B does; $t_A = 0$ ns and $t_B = G$ ns. Hence, the pyramid shape of the distribution.

There is a more technical explanation for the shape of Figure 2. The rate that two APDs avalanche from dark events, $\bar{DD}(t)$ is the convolution of the dark rates for the two individual APDs to avalanche from a dark:

$$\bar{DD}(t) = \int \bar{d}_A(t)\bar{d}_B(t - t')dt'$$

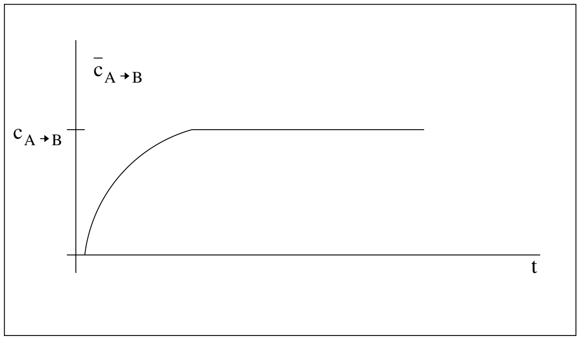


Figure 3: Crosstalk rate element A causing an avalanche in B. $t = 0$ is when element A fires.

Everything said is also true for any phenomenon that can cause the APD to avalanche at random times, provided the avalanche rate is small. **NUMBERS** How small? Small enough that the APD does not preferentially bias towards early events. Essentially, any phenomenon that produces an overall avalanche rate that is uniform (like that of Figure 2) will exhibit the characteristics described. In one experiment, we ran the APDs under dim room lights. The ambient light can cause the APD to randomly avalanche in the same way as themally excited electrons. The (dark + room) light avalanche rate is still low enough that it is not first photon biased by the APD.

1.3 Crosstalk

When an APD element avalanches, it produces photons. It is feasible that these photons could find their way to a nearby APD and cause it to avalanche. We call an avalanche in element B that is caused by an avalanche in element A a *crosstalk* event.

Crosstalk is a rare occurance. Let us assume the crosstalk rate is low enough that it is not first-photon biased. From the point of view of element B, crosstalk is just another random source of photons. Thus, the crosstalk rate as a function of time in element B would look uniform, like that of Figure 2, where $t = 0$ is when element A avalanches.

However, it takes about 200 ps for element A to fully avalanche. And, there may be some indirect path that the photon takes from element A to element B. So, it is impossible for element B to avalanche at the same time as element A. We have to modify our crosstalk rate to include a dip around $t = 0$. Figure 3 shows a more realisitc distribution for crosstalk rate.

So, Figure 3 tells us, given element A avalanches at $t = 0$, how many times per second neighboring element B would avalanche becuase of A. Since this rate is very low, the probability that B avalanches becuase A avalanched at t=0 is given by

$$\int_{t_a}^{t_b} P_1(t) = \int_{t_a}^{t_b} \bar{c}(t)e^{-\bar{c}(t)} \approx ce^{-c}\Delta t \approx c\Delta t$$

2 Early Experiments

We performed several experiments to learn about crosstalk. First, we looked at the number of times two neighboring APD elements avalanched under various conditions to determine if crosstalk occured. Then, under total darkness, we ran many gates through the elements and recorded the number of times both avalanched. Finally, we illuminated one element with our laser and recorded the number of times both avalanched.

2.1 Early Tests

We were initially unsure if crosstalk between APD elements even occured. Our first tests were simple tests to see if there was a measurable effect. The room lights were turned off. We focused a laser beam onto one APD element "A". The beam was attenuated by various amounts. A neighboring element "B" was also used. The APDs were reverse-biased by 27.8 V.

First, both elements A and B were powered for 190 ns, and the laser was turned on. This was repeated 19000 times at 1 kHz. Element A avalanched N_A times, and element B avalanched N_B times. There are three different effects that can cause element B to avalanche: darks, stray laser light, and crosstalk. Element B can avalanche from a thermal electron (dark event). Although the laser is focused on element A, some light may get to element B and cause it to avalanche. And ann avalanche in A may trigger an avalanche in B (crosstalk).

Next, only element B was powered on. Again, the gate width was 190 ns and it was repeated 19000 times at 1 kHz. Element B avalanched M_B times. Now there are only two effects that can cause an avalanche in B: darks and stray laser light.

So, the number of avalanches in B that were due to crosstalk from A is simply $N_B - M_B$. For 19000 gates, this number was typically $280 - 120 = 150$. The number did very from test to test, and varied when the laser attenuation was varied.

2.2 Experiment 1: Dark + Crosstalk

We ran our system with all the room lights off, and the laser turned off. Two neighboring APD elements, J15 and J11, were powered for 190 ns. This was repeated at 4 kHz, 900 million times. The APD elements were powered with 28.1 V.

Whenever both APD elements avalanched within the same gate, we recorded the relative avalanche times, as reported by our Time to Digital Converter (TDC). The TDC has a span of 100ns, which is divided up into 4096 bins (12 bits). Thus, each TDC bin is 25 ps wide. We threw away events whose TDC time was outside the range (100,3900). Thus, we only looked at events within a 3799 bin = 95 ns window. The TDC uses the APD's avalanche as a start signal, and has a common stop signal from our command module. Thus, we effectively only looked at avalanches that happen in the last 95 ns of the 190 ns gate.

There are three possible mechanisms for element A and B to avalanche within the same gate.

One way A and B can avalanche in the same gate is if they both happen to avalanche from thermal electrons. Both A and B happen to avalanche from a "dark" event. For a moment, let's say that A and B can only avalanche from dark events. Whenever A and B avalanche, we record the relative time between the two avalanches, $t_A - t_B$. We do this many times, and make a histogram.

Figure 2 shows what we expect this histogram to look like. In our case, there are 3799 ways that A and B can report a dark event at the same time. But there is only one way that element A can report an event 3799 bins before element B, and vice versa. Hence the pyramid shape of the distribution.

If we assume the average dark rates are uniform in time (like Figure 1), we can calculate the peak of the distribution, at $t_A - t_B = 0$. Let G be the length the APDs are powered and we are recording avalanches from them. Here, G = 3799*25 ps = 95 ns. Let Δt be the width of one bin in our timer (25 ps here). Let N be the number of times we power the APDs, the number of gates. Finally, let d_A and d_B be the dark rates of element A and element B. In other words, d_A is the number of dark events that element A would report per second, on average, if APDs could report more than one avalanche. So, $\bar{d}_A(t) = \text{const} = d_A$. The peak of the double-dark distribution is given by

$$N\frac{G}{\Delta t}\left(d_A \Delta t\right)\left(d_B \Delta t\right) = NG\Delta t d_A d_B$$

$(d_A \Delta t)$ is the probability that A reports a dark event at t_0, and $(d_B \Delta t)$ is the probability that A reports a dark event at t_0. And $\frac{G}{\Delta t}$ is the number of ways A and B can report the same time; the number of t_0's there are.

Elements A and B can both avalanche in the same gate if A avalanches from a dark event, and the avalanche in A causes an avalanche in B. In other words, A avalanches and crosstalks to B. Whenever B avalanches becuase of crosstalk from A, we can record the relative time between the two avalanches, $t_A - t_B$. Since A avalanched first from a dark event, $t_A - t_B < 0$.

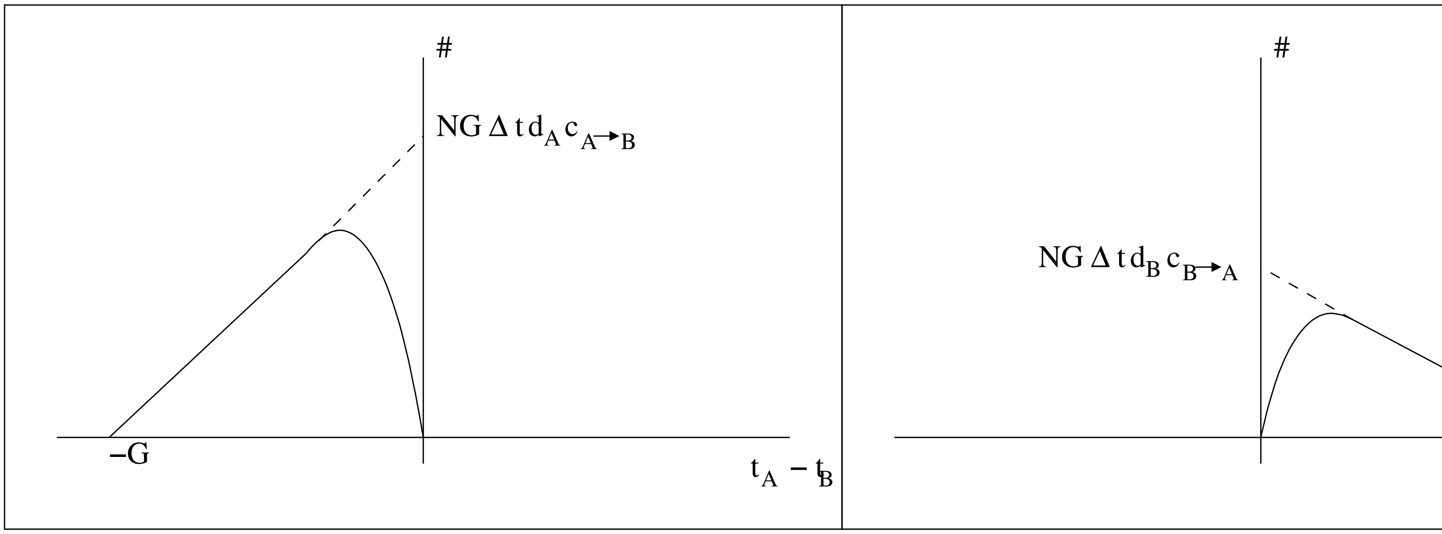
Again, let us assume that the average dark rates are uniform in time; $\bar{d}_A(t) = \text{const} = d_A$. Let us also assume for now that the crosstalk rate of B is also uniform in time; $\bar{c}_{A\to B}(t) = \text{const} = c_{B\to A}$. Again, we can draw a histogram of relative avalanche times, $t_A - t_B$. Since both the dark and crosstalk rates are constant, the distribution will look like half of a triangle. There are 3799 ways for A and B to avalanche at the same time, 1 way for B to avalanche from crosstalk 3799 bins after A. Sine we are looking at crosstalk from A to B, there is no way for B to avalanche earlier than A.

We can calculate the peak of the distribution at $t_A - t_B = 0$. It is given by

$$N\frac{G}{\Delta t}\left(d_A \Delta t\right)\left(c_{A\to B} \Delta t\right) = NG\Delta t d_A c_{A\to B}$$

So, $(d_A \Delta t)$ is the probability that A reports a dark event at t_0, and $(c_{A\to B} \Delta t)$ is the probability that B reports a crosstalk event at t_0. And $\frac{G}{\Delta t}$ is the number of ways A and B can report the same time; the number of t_0's there are.

Now, in reality, it is impossible for A to instantaneously cause B to avalanche via crosstalk. At the very least, it takes 200 ps for the avalanche in A to fill the entire element. So, we



(a) (b)

Figure 4: (a)Distribution of relative return times, where A avalanches from a dark event, and B avalanches becuase of A via crosstalk. (b)Distribution of relative return times, where B avalanches from a dark event, and A avalanches becuase of A via crosstalk.

should not expect B to avalanche via crosstalk at the exact same time as A avalanches. In other words, the crosstalk rate is not constant in time. It dips to zero at $t = 0$, as shown in Figure 3. Figure 4a shows a more realistic crosstalk distribution for $t_A - t_B$.

Finally, elements A and B can both avalanche in the same gate if B avalanches from a dark event, and the avalanche in B causes an avalanche in A. Since B avalanched first from a dark event, $t_A - t_B > 0$. Figure 4b shows the crosstalk distribution for $t_A - t_B$. Notice that the "crosstalk from A to B" distribution is not necessarily a mirror image of the "crosstalk from B to A" distribution. This is because it is possible that $d_A \neq d_B$ and $c_{A\to B} \neq c_{B\to A}$.

In summary, there are three ways elements A and B can crosstalk in the same gate. Both A and B can avalanch from thermal electrons (dark events). A can avalanche from a thermal electron, and causes an avalanch in B (crosstalk from A to B). B can avalanche from a thermal electron, and causes an avalanch in A (crosstalk from B to A). All three effects add together to create the distribution seen in Figure 5. At $t_A - t_B = 0$, we expect to see a minimum of

$$NG\Delta t d_A d_B$$

If crosstalk was instantaneous, the peaks at $t_A - t_B = 0$ would be

$$NG\Delta t d_A d_B + NG\Delta t d_A c_{A\to B}$$

and

$$NG\Delta t d_A d_B + NG\Delta t d_B c_{B\to A}$$

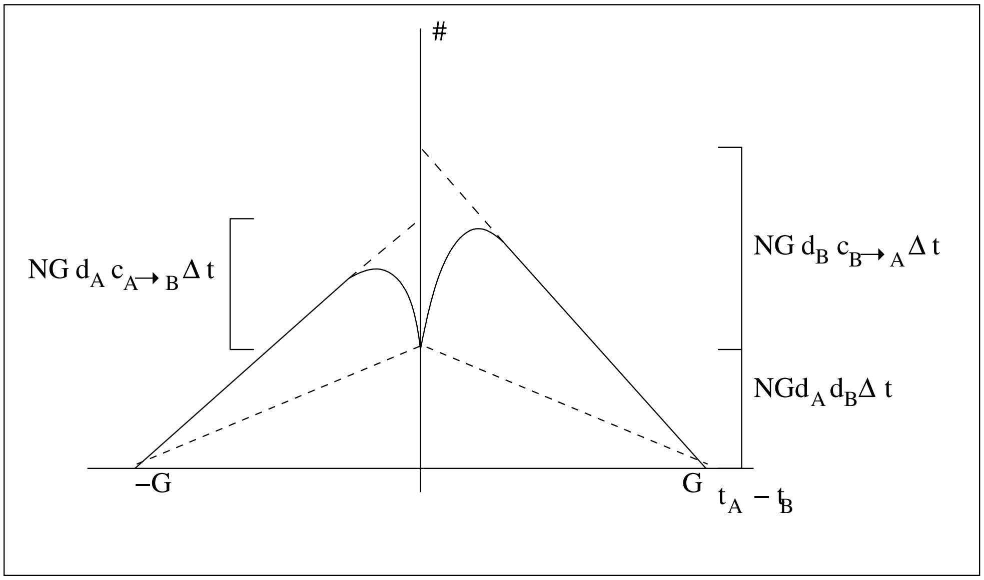


Figure 5: (a)Distribution of relative return times, where A avalanches from a dark event, and B avalanches becuase of A via crosstalk. (b)Distribution of relative return times, where B avalanches from a dark event, and A avalanches becuase of A via crosstalk.

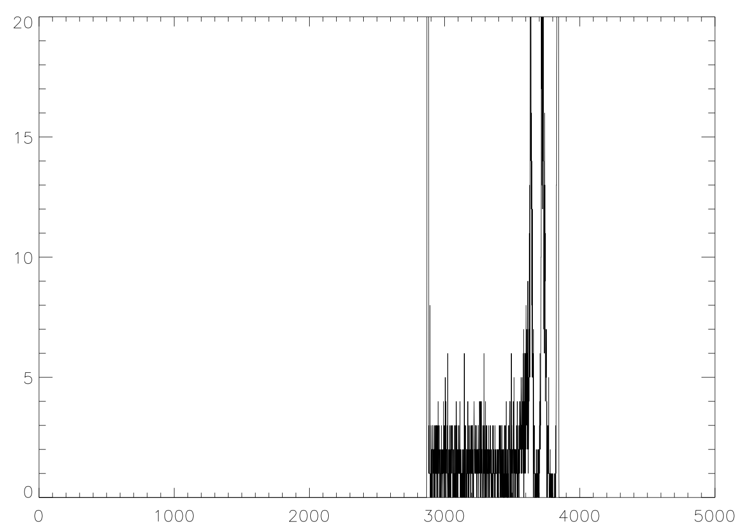


Figure 6: (a)Distribution of relative return times, where A avalanches from a dark event, and B avalanches becuase of A via crosstalk. (b)Distribution of relative return times, where B avalanches from a dark event, and A avalanches becuase of A via crosstalk.

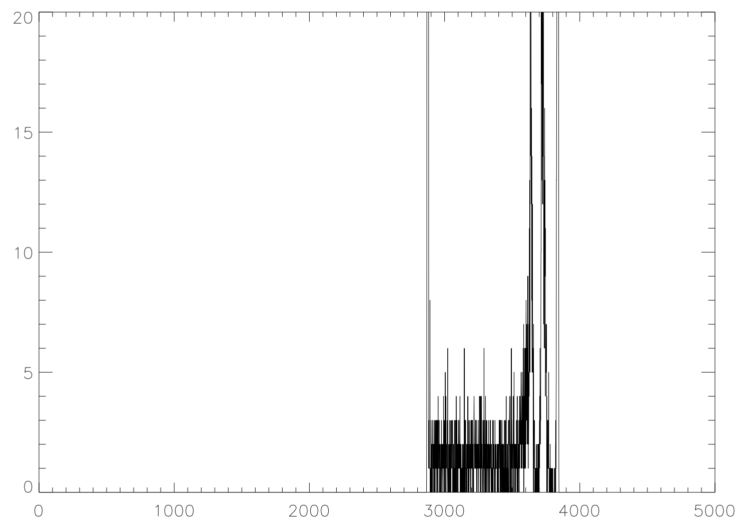


Figure 7: Distribution of relative return times.

Figure **??**

The number of avalanches in element A caused by crosstalk is approximately

$$N(\text{Probability B gets a dark event})(\text{Probability A gets crosstalk when B gets a dark event}) = N(d_B G)(c_B$$

The dark rate for each element is simply given by

$$d_A = \frac{(\#\text{ of gates that A reported an event})}{NG}$$

It is true that some of those events will be from crosstalk, but it is a very small amount since $d_A \gg d_B c_{B\to A} G$.

We can then determine $c_{A\to B}$ and $c_{B\to A}$ from fitting a line to the linear part of the distibution.

2.3 Experiment 2: Dark + Ambient Light + Crosstalk

2.4 Experiment 3: Dark + Laser Light + Crosstalk

2.5 Experiment 4: Dark + Crosstalk: 400ns

3 Crosstalk rate vs APD Bias Voltage

4 Crosstalk rate vs APD separation distance

5 Does crosstalk rate depend on where APD is illuminated?

6 Dark rate of various APD elements

7 Breakdown Voltage of various APD elements

8 Photon sensitivity of various APD elements

9 Conclusions

9.1 Electronic Supression