Spectral Measurement of Breakdown Flashes in InGaAs Avalanche Photodiodes

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Abstract. Quantum key distribution (QKD) at telecom wavelengths (1260 nm ~ 1625 nm) has the potential for fast deployment using existing optical fibre infrastructure and telecom technologies. At these wavelengths, indium gallium arsenide (InGaAs) avalanche photodiodes (APDs) based detectors have to be used for photon detection. Similar to their silicon counterparts used at shorter wavelengths, they exhibit fluorescence from recombination of electron-hole pairs generated in the avalanche breakdown process. This "breakdown flash" may open side channels for attacks on QKD systems. Here, we characterize the breakdown flash from two commercial InGaAs single photon counting modules, and find a spectral distribution between 1000 nm and 1600 nm. We also show that with application of spectral filtering, this side channel can be greatly suppressed.

Keywords: Quantum Key Distribution, Avalanche Photodiodes (APDs), Breakdown Flash

1 Introduction

QKD implementations over optical fibres receive growing interest due to their potential for fast deployment over existing telecom fibre networks [1]. However, such implementations requires detection of single photons at telecom wavelength (1260 nm ~ 1625 nm). Avalanche photodiodes (APDs) based on Indium Gallium Arsenide (InGaAs) are the commonly used detectors for this wavelength range [2, 3, 4]. Despite their relatively high dark count rate as compared to their silicon counterparts, InGaAs APDs are able to detect single photons at telecom wavelengths with quantum efficiency up to 20% [4, 5].

While InGaAs APDs are widely used in telecom QKD implementations, certain unintended features of theirs may introduce side channels that can be exploited, enabling possible attacks on the system. It was reported previously that the silicon APDs emit florescence light during the avalanche breakdown process after the detection of a photon [6]. This light emission is due to the recombination of electrons and holes in the APD junction and has a spectra ranging from 700 nm to 1000 nm. Similar florescence is also observed in InGaAs APDs [7]. This fluorescence light (often referred to as 'breakdown flash') leads to potential eavesdropping attacks to the QKD system [6]. An eavesdropper may gain timing information of the detected photons by observing the breakdown flash leaked back to the optical channel. Thus other strategies must be in place to reduce or eliminate this side channel.

In this work we characterized the breakdown flash from two commercial InGaAs single-photon counting modules (ID220, ID Quantique). In doing so we obtained a lower bound for the breakdown flash probability. We also measured its spectral distribution and found that with spectral filtering, the number of detected breakdown flash events can be greatly suppressed.

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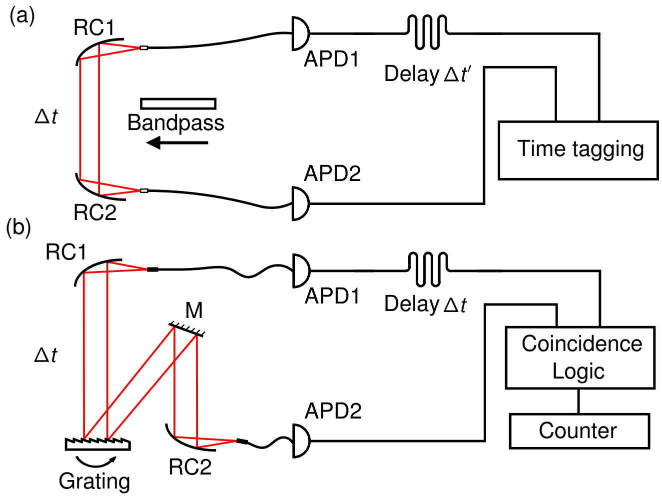

Figure 1: (a) Experimental setup for detecting the breakdown flash from two InGaAs APDs. (b) Experimental setup for measuring the spectral distribution of the breakdown flash.

2 Detection of breakdown flash

The devices under test are two InGaAs APD based single-photon counting modules, APD1 and APD2 (ID220, ID Quantique, with fibre input). We utilize the setup shown in Fig. 1(a) where each counting module acts as both source and detector. To detect the breakdown flash events, APD1 and APD2 are optically coupled through freespace by a pair of reflective collimators (RC1 and RC2) with an overall transmission of ≈ 80% (including fibre losses). The effective optical path between the two APDs is about 9.6 m (9.5 m fibre +0.1 m free space) which corresponds to a photon traveling time of $\Delta t \approx 48$ ns between the two APDs.

The output signals from the two APDs are fed into two channels of an oscilloscope (Lecroy Waverunner 640

Zi), which is set to trigger when a signal is received from APD2. Once being triggered, the oscilloscope operates as a timestamping unit and records down the arrival time of any signal from APD1 starting from the time of the trigger event within the next 250 ns with a time resolution of 100 ps. An electrical delay of $\Delta t' \approx 56$ ns is applied to APD1.

The experimental setup is kept in dark, such that the breakdown flash events are only caused by dark counts in the APDs. A dark count is a thermally induced avalanche breakdown in the APD, hence it emits the same breakdown flash light as what would happen in a normal detection event [8]. We measured a dark count rate of 1.01×10^4 counts/s for APD1 and 5.55×10^3 counts/s for APD2.

When a dark count is detected in APD2 at $t = 0$ s, the oscilloscope is triggered. The dark count causes a breakdown flash that reaches APD1 after Δt. This generates a signal from APD1 which is delayed by $\Delta t'$. The signal is timestamped by the oscilloscope at $t = \Delta t + \Delta t'$. This indicates a breakdown flash emitted from APD2 and detected by APD1. Alternatively, a dark count detected in APD1 at $t = -\Delta t$ causes a breakdown flash that reaches APD2 at $t = 0$ and triggers the oscilloscope. Meanwhile, this dark count signal from APD1 reaches the oscilloscope and is recorded at $t = \Delta t' - \Delta t$ and this indicates a breakdown flash event from APD1 detected by APD2.

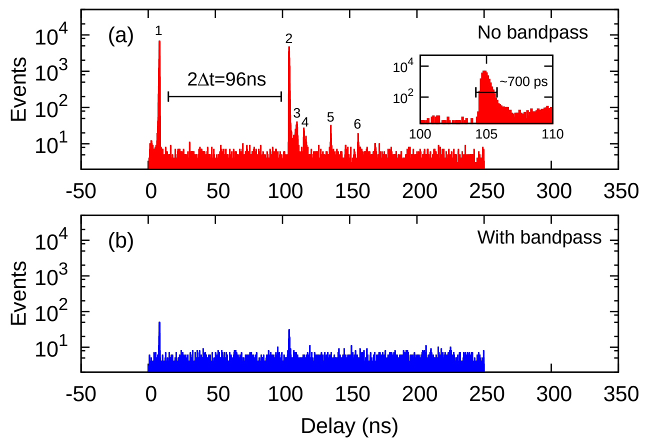

Figure 2: Histogram of the arrival times of signals from the APD1, with $t = 0$ instant being the oscilloscope triggered by a signal from APD2.

Fig. 2 (a) shows the histogram of the events timings recorded by the oscilloscope over an integration time of 10 minutes. Peak 1 (located at $t = \Delta t' - \Delta t \approx 8$ ns) and peak 2 (located at $t = \Delta t + \Delta t' \approx 104$ ns) corresponds to the cases where APD1(2) emits a breakdown flash detected by APD2(1). Each peak has a full width at half maximum (FWHM) of ~ 700 ps. The timing seperation between the two peaks is given by twice the travelling time Δt of the flash photons between the APDs. Peak 3 (located at $t \approx 110$ ns) is suspected to be afterpulsing signals of the APD. Peak 4, 5, and 6 are possibly due to the back reflection of photons at fibre joints as the time difference matches the length of the fibre patchcord we used in the setup. The measurement was repeated with a bandpass filter (Thorlabs FB1550-12, 1550 ± 6 nm). inserted between RC1 and RC2. The events timing histogram is shown in Fig.2, the number of breakdown flash events is suppressed by a factor of over 100.

We then evaluate the probability of detecting a breakdown flash event by measuring the absolute rate of detected breakdown flash events. In this measurement, we use a coincidence stage instead of an oscilloscope and the electrical delay on APD1 is adjusted to match the photon traveling time of Δt between the two detectors. For flash events emitted by APD1 and detected by APD2, the dark count signal from APD1 and the breakdown flash signal from APD2 thus arrive at the coincidence stage within a coincidence window of ~ 500 ps. This is counted as a coincidence event and it indicates a breakdown flash emitted from APD1 is detected by APD2. The number of breakdown flash events emitted by APD2 is measured in the same manner, except that the same electrical delay is applied to APD2.

For each configuration, we continuously measure the number of coincidences for 1 hour. We counted 79.4 ± 2.9 events/s from APD1 to APD2 and 58.4 ± 3.1 events/s from APD2 to APD1. Divided by the dark count rate of the emitting ADPs, this yields a $0.78\% \pm 0.03\%$ probability of detecting a breakdown flash from a dark count in APD1, and a $1.05\% \pm 0.07\%$ probability of detecting a breakdown flash from a dark count in APD2.

3 Spectral distribution of breakdown flash

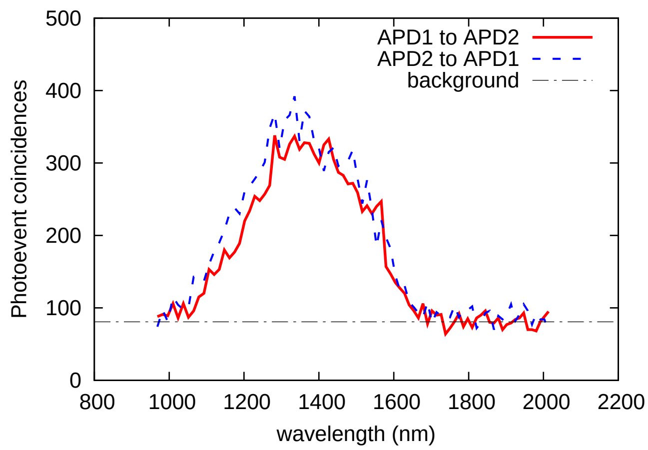

Figure 3: Spectral distribution of breakdown flash. The spectra ranges from 1000 nm to 1600 nm and peaks at about 1300 nm.

We next measure the spectral distribution of the breakdown flash with the setup shown in Fig. 1 (b). A monochromator consisting of a reflective grating (600 lines/mm, blazed at 1.25 μm) and a pair of reflective collimators (RC1 and RC2), is inserted in the optical path between the two APDs. The grating is rotated to select the transmission wavelength between them. To obtain a lower bound for the spectral resolution of the monochromator, we measure the spectrum of light from a 1310 nm single mode diode laser and found the full width at half maximum (FWHM) of the spectral distribution to be 3.3 nm. The collection efficiency of the first-order diffraction of the same 1310 nm light into the RCs is $\approx 89\%$.

We scanned over a range from 1000 nm to 2000 nm and at each point, we perform the same coincidence measurements as those mentioned in the previous section but with an integration time of 30 minutes. The results are shown in Fig. 3. We observe coincidence events over a wide range from 1000 nm to 1600 nm. The number of events reaches its maximum at about 1300 nm. These results are not corrected for the transmission efficiency of the monochromator and the detection efficiencies of the two APDs. The spectra cut off at wavelengths where the detector efficiency becomes negligible [9], hence the actual spectra of the breakdown flash are possibly wider than what we observed in Fig. 3.

4 Conclusion

We characterized the breakdown flash from two commerical InGaAs single-photon counting modules (ID220 from ID Quantique) using a coincidence measurement. We obtained a lower bound for the breakdown flash probability to be on the order of 1%. We also measured its spectral distribution with a grating monochromator. The observed breakdown flash is spectrally distributed between 1000 nm and 1600 nm with its peak at about 1300 nm. We also show that with spectral filtering, the number of detected breakdown flash events can be greatly suppressed.

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