Metrological Characterization and Uncertainty Analysis of InGaAs/InP SPADs in Free-Running and Gated Operational Modes

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Single-photon avalanche diodes (SPADs) are pivotal for quantum communication and sensing [1], yet their performance is fundamentally shaped by the choice between free-running and gated operation. This work presents a comprehensive metrological characterization of a commercial InGaAs/InP IDQube SPAD module, directly comparing its key performance parameters in both operational modes. Reliable evaluation procedures are essential for verifying the performance of QKD optical systems and their key components [2]. We report quantitative measurements of the detection efficiency (DE), timing jitter, and afterpulsing probability, supported by complete uncertainty budgets for each parameter.

At a wavelength of 1550 nm, the measured DE for free-running operation was (15.0 ± 1.8)% (expanded uncertainty, k = 2). In gated mode, with a 50 ns detection window synchronized to 100 kHz laser pulses, the DE decreased to approximately (14.0 ± 2.2) % (k = 2). This reduction is primarily due to the finite gate width limiting the effective detection window compared to the continuous listening time in free-running mode. However, gated operation offers a superior signal-to-noise ratio by suppressing dark counts outside the gate window, reducing the rate from (985 ± 35) cps in free-running mode to (102 ± 8) cps [3].

Afterpulsing effects were characterized by analyzing inter-arrival time histograms of consecutive detection events. The afterpulsing probability was measured at approximately 3.2% for free-running mode (at 15% efficiency) and 1% for gated mode. Timing jitter analysis revealed a systematic decrease in jitter with increasing DE; at 35% DE, the jitter improved to 114 ps, as the higher internal electric field accelerates the avalanche buildup process.

A rigorous uncertainty analysis following the Guide to the Expression of Uncertainty in Measurement (GUM) [4] identified optical power calibration and optical attenuator accuracy as the dominant systematic uncertainty sources. This study establishes a robust metrological foundation for characterizing single-photon detectors, enabling precise performance prediction for applications such as Quantum Key Distribution (QKD) and quantum sensing.

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