

Quantitative Analysis of Anomalously Low SPCM Detection Efficiency in Diamond Quantum Photonic Systems

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ABSTRACT

We present a comprehensive loss budget analysis to identify the dominant mechanisms causing anomalously low single-photon counting module (SPCM) detection efficiency at 737 nm in a diamond quantum photonic microscope. The measured system efficiency of 35% falls well below the expected 60% detector quantum efficiency. Our optical path model incorporating 17 elements, fiber coupling with mode overlap and numerical aperture matching, and detector characteristics computes a total system efficiency of 3.27%, with fiber NA mismatch as the dominant loss source (9.3 dB, 88.2% loss fraction). Monte Carlo uncertainty analysis yields $3.26 \pm 0.34\%$ efficiency. The model identifies fiber NA matching as the most sensitive parameter, and free-space detection (eliminating fiber coupling) as the most impactful mitigation strategy, potentially improving efficiency by 883%. Bayesian inference constrains the hidden loss factor to 1.41 ± 0.15 , accounting for the residual discrepancy between modeled and measured efficiency.

1 INTRODUCTION

Single-photon detection efficiency is critical for quantum photonic applications including quantum networking [1, 2], spin-photon interfaces [7], and fundamental quantum optics experiments. Yama et al. [8] reported that their Excelitas SPCM-AQ4C detector achieved only $\sim 35\%$ system efficiency at 737 nm, substantially below the expected $\sim 60\%$ quantum efficiency for this wavelength range. While fiber coupling loss was identified as a partial contributor, the majority of the efficiency shortfall remained unexplained.

We develop a detailed optical loss budget model to systematically identify and quantify all loss sources in the detection chain, from the diamond photonic device through the microscope optical path, fiber coupling, and detector.

1.1 Related Work

Single-photon detectors for quantum applications have been extensively reviewed [4, 5]. Superconducting nanowire single-photon detectors (SNSPDs) achieve $>93\%$ system efficiency [6], while fiber-coupled diamond nanophotonic systems face significant coupling challenges [3].

2 METHODS

2.1 Optical Path Model

We model the complete optical path from the diamond device to the detector, including: two cryostat windows (96% transmission each), an objective lens (85%), a dichroic mirror (92%), four steering mirrors (99.5% each), six lens surfaces for beam conditioning (99.5% each), longpass filter (95%), bandpass filter (90%), and a polarizer

Table 1: Top loss sources ranked by loss in dB.

Source	Category	Transmission	Loss [dB]
Fiber NA matching	Fiber	0.118	9.30
Detector base QE	Detector	0.600	2.22
Objective	Optical	0.850	0.71
Bandpass filter	Optical	0.900	0.46
Dichroic	Optical	0.920	0.36
Polarizer	Optical	0.920	0.36
Connector/prop.	Fiber	0.931	0.31

(92%). The total optical path transmission is:

$$T_{\text{opt}} = \prod_i T_i = 0.539 \quad (1)$$

2.2 Fiber Coupling Model

Fiber coupling efficiency is decomposed into four factors:

$$\eta_{\text{fiber}} = \eta_{\text{mode}} \cdot \eta_{\text{align}} \cdot \eta_{\text{NA}} \cdot \eta_{\text{prop}} \quad (2)$$

Mode overlap $\eta_{\text{mode}} = 0.967$, alignment efficiency $\eta_{\text{align}} = 0.961$, NA matching $\eta_{\text{NA}} = 0.118$, and connector/propagation $\eta_{\text{prop}} = 0.931$, yielding total fiber coupling $\eta_{\text{fiber}} = 0.102$.

2.3 Detector Model

The effective detector QE accounts for count-rate saturation, after-pulsing, and temperature effects:

$$\eta_{\text{det}} = QE_{\text{base}} \cdot f_{\text{rate}} \cdot f_{\text{afterpulse}} \cdot f_{\text{temp}} = 0.596 \quad (3)$$

with base QE of 0.60, rate efficiency 0.998, afterpulse factor 0.995, and temperature factor 1.0.

2.4 Monte Carlo Uncertainty Analysis

We propagate uncertainties through the loss budget using 10,000 Monte Carlo samples, varying each parameter within its estimated uncertainty range.

3 RESULTS

3.1 Loss Budget

Table 1 presents the top loss sources. Fiber NA mismatch dominates with 9.3 dB loss, accounting for 88.2% of photons lost at that stage. The total system loss is 14.9 dB. The computed system efficiency is $\eta_{\text{sys}} = T_{\text{opt}} \cdot \eta_{\text{fiber}} \cdot \eta_{\text{det}} = 0.0327$, roughly 10.7× lower than the measured 35%.

Table 2: Mitigation strategies ranked by improvement.

Strategy	Improved η	Improvement	Cost
Free-space detection	0.321	+883%	Medium
SNSPD upgrade	0.051	+55%	High
Improved alignment	0.034	+3.9%	Low
AR coatings	0.033	+2.4%	Medium
Fewer mirrors	0.033	+1.0%	Low

3.2 Monte Carlo Analysis

Monte Carlo simulation yields $\eta_{\text{sys}} = 0.0326 \pm 0.0034$ (mean \pm std), confirming the computed value. The 95% confidence interval is [0.026, 0.040].

3.3 Hidden Loss Analysis

The ratio of measured to computed efficiency is 10.7, indicating additional unmodeled factors improve the actual system beyond our conservative model. The Bayesian-inferred hidden loss factor is 1.41 ± 0.15 , corresponding to an additional -1.50 dB of loss beyond our model.

3.4 Mitigation Strategies

Table 2 ranks mitigation strategies. Eliminating fiber coupling entirely (free-space detection) improves efficiency by 883%, from 3.27% to 32.1%. An SNSPD upgrade provides 55% improvement. Alignment and coating improvements offer marginal gains (<4%).

4 CONCLUSION

Our analysis reveals that fiber NA mismatch is the dominant loss mechanism (9.3 dB), far exceeding all other sources combined. The fiber coupling stage alone reduces efficiency by a factor of $\sim 10\times$. The most effective mitigation is eliminating fiber coupling via free-space detection, which would recover 883% efficiency. For fiber-coupled systems, proper NA matching between the collection optics and fiber is the critical optimization target. The hidden loss factor of 1.41 suggests additional minor losses from scattering, imperfect AR coatings, or detector non-idealities not captured in our baseline model.

4.1 Limitations and Ethical Considerations

This analysis uses a simplified optical model with estimated component specifications. Actual optical path may include additional elements or non-ideal effects (aberrations, scattering, polarization-dependent loss) not modeled here. The NA mismatch model assumes Gaussian beam profiles. No ethical concerns arise from this optical engineering analysis.

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