

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

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

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

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, afterpulsing, 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 \times lower than the measured 35%.

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

117 **Table 2: Mitigation strategies ranked by improvement.** 118

119 Strategy	120 Improved η	121 Improvement	122 Cost
123 Free-space detection	124 0.321	125 +883%	126 Medium
127 SNSPD upgrade	128 0.051	129 +55%	130 High
131 Improved alignment	132 0.034	133 +3.9%	134 Low
135 AR coatings	136 0.033	137 +2.4%	138 Medium
139 Fewer mirrors	140 0.033	141 +1.0%	142 Low

143 our conservative model. The Bayesian-inferred hidden loss factor is
 144 1.41 ± 0.15 , corresponding to an additional -1.50 dB of loss beyond
 145 our model.

146 3.4 Mitigation Strategies

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

151 4 CONCLUSION

152 Our analysis reveals that fiber NA mismatch is the dominant loss
 153 mechanism (9.3 dB), far exceeding all other sources combined. The
 154 fiber coupling stage alone reduces efficiency by a factor of $\sim 10\times$.
 155 The most effective mitigation is eliminating fiber coupling via free-
 156 space detection, which would recover 883% efficiency. For fiber-
 157 coupled systems, proper NA matching between the collection optics

158 and fiber is the critical optimization target. The hidden loss factor
 159 of 1.41 suggests additional minor losses from scattering, imperfect
 160 AR coatings, or detector non-idealities not captured in our baseline
 161 model.

162 4.1 Limitations and Ethical Considerations

163 This analysis uses a simplified optical model with estimated com-
 164 ponent specifications. Actual optical path may include additional
 165 elements or non-ideal effects (aberrations, scattering, polarization-
 166 dependent loss) not modeled here. The NA mismatch model as-
 167 sumes Gaussian beam profiles. No ethical concerns arise from this
 168 optical engineering analysis.

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