Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

Detection efficiency characterization for free-space single-photon detectors: Measurement facility and wavelength-dependence investigation

Cite as: Appl. Phys. Lett. **125**, 221108 (2024); doi: 10.1063/5.0226170
Submitted: 29 June 2024 · Accepted: 13 November 2024 ·
Published Online: 27 November 2024

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Note: This paper is part of the APL Special Collection on Advances in Quantum Metrology.
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ABSTRACT

In this paper, we present an experimental apparatus for the measurement of the detection efficiency of free-space single-photon detectors based on the substitution method. We extend the analysis to account for the wavelength dependence introduced by the transmissivity of the optical window in front of the detector's active area. Our method involves measuring the detector's response at different wavelengths and comparing it to a calibrated reference detector. This allows us to accurately quantify the efficiency variations due to the optical window's transmissivity. The results provide a comprehensive understanding of the wavelength-dependent efficiency, which is crucial for optimizing the performance of single-photon detectors in various applications, including quantum communication and photonics research. This characterization technique offers a significant advancement in the precision and reliability of single-photon detection efficiency measurements.

The detection of single photons represents a crucial stage in a variety of scientific and technological applications, including quantum communication,[1–3] quantum computing,[4–6] quantum imaging,[7] and quantum sensing[8–11] with photons. Accurate photon detection is essential for ensuring the reliability and precision of these applications. Consequently, the calibration of the detection efficiency of single-photon detectors (SPDs) is of paramount importance.[12–22] Such an efficiency is defined[23] as the probability of a SPD producing a measurable signal in response to one incident photon, depending on the wavelength and detection rate, with specific wavelength and count rate specifications.

However, unlike detectors calibrated using classical radiometric techniques, there is currently no established standard for calibrating the detection efficiency of SPDs based on the measured counts. This lack of standardization presents a significant challenge, as it may hinder the ability to ensure reliable calibration by different labs, leading to incompatible calibration results even if formally traceable to the International System of Units (SI), because of the exploitation of incorrect (as non-standardized) measurement models. For this reason, a pilot study[24] has recently been initiated among various national metrology institutes (NMIs) worldwide to attempt to define a characterization standard for free-space silicon single-photon avalanche diodes (Si-SPADs) detecting photons with a wavelength of 850 nm. This collaborative effort aims to establish a unified and precise methodology for assessing the performance and detection efficiency of these detectors, thereby providing a reliable benchmark for scientific research and technological applications that depend on accurate single-photon detection.

Si-SPADs are SPDs operating in Geiger mode.[25–28] They are widely exploited due to their high detection efficiency in the visible range (up to 80% for wavelengths around 650 nm), their low dark count rate (tens of counts per second), and their short dead time and jitter (typically tens of nanoseconds and hundreds of picoseconds, respectively). They can be exploited for a broad wavelength interval, spanning from approximately 400 nm to 1000 nm. In particular, they find huge application for free-space Quantum Key Distribution (QKD),[29] wherein the employed wavelength is often around 850 nm, because of the transmissivity of the atmosphere just considering the