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Review

Single-Photon Detectors for Quantum Integrated Photonics

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Abstract: Single-photon detectors have gained significant attention recently, driven by advancements in quantum information technology. Applications such as quantum key distribution, quantum cryptography, and quantum computation demand the ability to detect individual quanta of light and distinguish between single-photon states and multi-photon states, particularly when operating within waveguide systems. Although single-photon detector fabrication has been established for some time, integrating detectors with waveguides using new materials with suitable structural and electronic properties, especially at telecommunication wavelengths, creates more compact source-line-detector systems. This review explores the state of the art of single-photon detector research and examines the potential breakthroughs offered by novel low-dimensional materials in this field.

Keywords: quantum information; integrated photonics; single-photon detectors

1. Introduction

Since the 1980s, significant advancements have been made in understanding how quantum mechanics can be applied to solve practical problems, such as developing a computer that operates based on quantum principles. In recent years, efforts have been focused on creating quantum information and computation platforms that are compatible with digital and telecommunications technologies without requiring a cryogenic environment. The current state of research in quantum integrated photonics is reviewed in Ref. [1], highlighting the most widely used integrated photonic platforms and summarizing key achievements and results from the past decade. Integrated photonics on Silicon-On-Insulator (SOI) substrates has become a well-established field of research with significant impact, particularly in quantum computing. Despite the potential to create highly complex circuits using this technology, the foundation remains a set of fundamental "building blocks" that are combined to form intricate designs. Ref. [2] provides a comprehensive review of the current state of integrated photonic building blocks, focusing specifically on passive elements. It explores the fundamental principles and design methodologies that are essential for constructing these components and advancing the field further. In [3], one can find the latest endeavors in hybrid photonic platforms leveraging the combination of integrated silicon photonic platforms and nanoscale materials, allowing for the unlocking of increased device efficiency and compact form factors. Moreover, the review provides insights into future developments and the evolving landscape of hybrid integrated photonic nanomaterial platforms. The quest for reliable and integrable single-photon sources (popular approaches include spanning cold atoms and ions [4], quantum dots [5,6], isolated molecules [7], color centers in the solid state [8]), and single-photon detectors (SPD) is at the center of the research efforts in the field.

A photon is defined as the elementary excitation of a single mode of the quantized electromagnetic field [9]. This fundamental particle exhibits characteristics of both particles and waves, serving as a discrete quantum of electromagnetic radiation. Photons are characterized by their frequency, with a single photon in a specific mode having an energy equal to Planck's constant (h) multiplied by the frequency (ν) of that mode. Despite their often-described monochromatic nature, practical applications involve "single-photon states" that can be mathematically described as superpositions of monochromatic photon modes, allowing for considerations of their localization in time and space. These particles