低噪声大光敏面 InGaAs 近红外单光子探测器

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摘要：随着单光子探测技术在激光雷达和量子信息领域的应用日渐深入，单光子探测器的研制也受到了研究人员的更多关注。研制了基于国产单光子半导体雪崩二极管（Single-Photon Avalanche Diode, SPAD）的低噪声大光敏面铟镓砷（InGaAs）近红外单光子探测器。该 SPAD 有效光敏面直径为 50 μm，为了同时保证大光敏面下的低暗计数水平和低死时间，采用了在真空腔体内进行深制冷和主动淬灭的方案，研制了低功耗的高速主动淬灭电路并使其在腔内与 SPAD 芯片直接互联，降低暗计数的同时提高了 SPAD 的淬灭和恢复速度。针对腔内淬灭电路及 5 级热电制冷片(Thermo-electric cooler, TEC)的发热问题，着重考虑了探测器的散热结构设计。结果表明，所研制的探测器在 1550 nm 波长的最大可用探测效率约为 26%，最低制冷温度为 201 K；在 203 K、探测效率为 8%、最短死时间 40 ns 时，后脉冲概率为 11.7%，暗计数率为 1.3 kHz。上述结果表明，这一低噪声计数、大光敏面的通信波段近红外单光子探测器适用于对性能和环境空间要求更严苛的应用场合。

关键词：单光子雪崩二极管；单光子探测；近红外；深制冷；大光敏面

Low-noise InGaAs near-infrared single-photon detector with large photosensitive surface

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Abstract： With the increasing application of single-photon detection technology in the field of lidar and quantum information, the development of single-photon detectors has attracted more and

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more attention by researchers. In this paper, a low-noise InGaAs near-infrared single-photon detector with large photosensitive surface based on domestic SPAD is developed. The diameter of the effective photosensitive surface of the SPAD is 50 μm. In order to reduce the low dark count under the large photosensitive surface, the scheme of applying both deep cooling and active quenching in the vacuum chamber is adopted, and a high-speed active quenching circuit with low power consumption is developed. It can be directly interconnected with the SPAD chip in the chamber, which can reduce the dark count, simultaneously improve the quenching and recovery speed of the SPAD. In purpose to solve the heating problem of the quenching circuit in the chamber and the 5-stage TEC, the design of the heat dissipation structure of the detector is emphatically considered. The results show that the maximum usable detection efficiency of the detector is about 26% at 1550 nm, and the lowest cooling temperature is 201 K. At 203 K, when the detection efficiency is 8% and the shortest dead time is 40 ns, the afterpulse probability is 11.7 %, meanwhile the dark count rate is 1.3 kHz. The above results show that this low-noise count communication-band near-infrared single-photon detector with large photosensitive surface is suitable for applications with more stringent requirements on performance and environmental space.

Keywords：single-photon avalanche diode; single-photon detection; near infrared; deep cooling; large photosensitive surface

1 引言

随着单光子探测技术在远距离激光雷达、量子信息等领域的不断深入应用[1]，其中的单光子探测器（Single photon detector, SPD）是不可或缺的核心器件[2]。由于单光子探测器的性能与其工作模式和设置参数紧密相关，研究针对不同场景下不同应用领域的单光子探测器的参数优化具有重要意义。

在近红外波段，目前主流的单光子探测技术包括基于InGaAs阴极的光电倍增管（Photomultiplier Tube, PMT）、半导体单光子雪崩二极管（Single-Photon Avalanche Diode, SPAD）、基于光子上转换技术以及超导纳米线单光子探测器(Superconducting Nanowire Single Photon detector, SNSPD)等[3]。PMT技术具有光敏面大、响应快、成本低等特点[4]，但是多数PMT仅对可见光响应，对近红外特别是1550 nm响应的PMT制冷设备体积庞大，探测