

# Enhancing Photon-Number Resolution in Integrated Circuits via Mixed-Efficiency Detector Arrays

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**Abstract:** We introduce a photon-number-resolving detector combining fixed- and variable-efficiency single-photon detectors into a single linear array. This hybrid architecture overcomes standard fabrication constraints, significantly improving photon-counting fidelity for scalable integrated quantum applications.

Photon-number-resolving detectors (PNRDs) are fundamental components for emerging quantum photonics applications, ranging from photonic quantum computing to advanced quantum communication protocols [1,2].

Recent studies have shown that linearly multiplexing an array of single-photon detectors (SPDs) along a single waveguide significantly reduces the overall footprint of the PNRD architecture, thereby improving scalability and loss management [3]. Ideally, this linearly multiplexed scheme relies on the absorption efficiency of each detector following a  $1/i$  law. However, physical fabrication constraints in integrated platforms dictate a minimum feature size for the SPDs. This imposes a strict lower bound on the achievable detection efficiency, preventing the full optimization of the multiplexed configuration.

An alternative approach involves using a uniform array composed entirely of identical SPDs operating at this minimum fabricable efficiency to reduce multi-photon absorption events [4]. Unfortunately, to match the performance of multiplexed systems, uniform arrays must be excessively long.

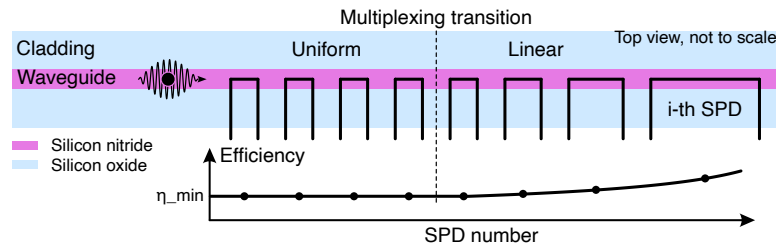


Fig. 1 The hybrid photon-number-resolving detector array, featuring both uniform and multiplexed detection sections.

To circumvent the limitations of both pure configurations, we propose a novel hybrid architecture that combines their distinct advantages. This mixed-efficiency device consists of an initial uniform section comprising  $N_U$  identical detectors (each fixed at the minimum efficiency  $\eta$ ), cascaded into a linearly multiplexed section of  $N_M$  detectors that follow the  $1/i$  law, as visible schematically in Fig. 1.

We evaluated the photon-number-resolution fidelity of this hybrid scheme against both standard multiplexed and uniform configurations, assuming a practical minimum fabricable efficiency of  $1/33$ .

At a representative working point of  $m = 5$  photons, a purely multiplexed array of 33 SPDs yields a fidelity of 72.77%. Conversely, an infinite uniform array defines the absolute theoretical upper bound at 85.57%. Our proposed hybrid configuration, 33 uniform SPDs followed by 33 multiplexed SPDs, achieves a fidelity of 83.76%. This demonstrates that the hybrid approach operates remarkably close to the asymptotic theoretical limit and substantially outperforms the purely multiplexed counterpart. By strategically placing a section of low-efficiency SPDs prior to a multiplexed array, we drastically improve the overall fidelity while strictly maintaining a finite, manufacturable footprint. This mixed-efficiency scheme offers a highly practical and scalable route for high-performance photon counting in integrated photonic circuits.

## Example References

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