Achieving Photon Number Resolution with Linearly Multiplexed Single-Photon Detectors

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Abstract. This work studies a photon-number resolving detector (PNRD) made by a linearly multiplexed single-photon niobium nitride detector (SPD) array integrated on a silicon nitride strip-loaded waveguide platform, fabricated on a lithium niobate on insulator (LNOI) substrate. Linearity allows the device to maintain the mathematical model for the fidelity of already existing spatially multiplexed SPDs, while significantly changing the detector's geometry. Integrating such a device on a LNOI platform allows to exploit the unique properties of lithium niobate, such as the high electro-optic effect. Additionally, niobium nitride SPDs are one of the best superconductor devices available nowadays, allowing for tunable, and overall high, detection efficiency and low dark counts rate, making them one of the best candidates for our platform.

Keywords: Integrated Photonics · Superconducting Nanowire Single Photon Detector · Photon-number Resolving Detector · Lithium Niobate on Insulator

1 Introduction

Photon-number-resolving detectors (PNRDs) are becoming pivotal for many integrated and quantum optics applications, such as photon-number measurements, quantum key distribution, LIDAR, and single-photon source calibration.

Nowadays, most PNRDs implementations rely on spatially multiplexed single-photon detectors [1] (SPDs): the incoming waveguide ends in a binary-tree structure which splits the input among 2^k branches and terminates in an array of high-efficiency SPDs.

Superconducting nanowire single-photon detectors (SNSPDs) are versatile devices able to combine the possibility of tuning the nanowire interaction with the waveguide while keeping a low level of dark counts [2]. Such technology is widely employed in

C. Di Natale et al. (Eds.): AISEM 2025, LNEE 1497, pp. 291–294, 2025.
https://doi.org/10.1007/978-3-032-08271-8_45

commercially-available spatially multiplexing PNRDs, but few works have been done to integrate PNRDs made of linearly multiplexed SNSPDs.

In this work [3], we propose a new linearly multiplexed PNRD architecture, replacing conventional binary-tree with a straight single waveguide. On top of the straight waveguide, an array of N niobium-nitride (NbN) SNSPDs is evanescently coupled. We derived the optimal length of each SPD, which is tuned to tailor the coupling strength to the desired value. This geometry preserves the analytic fidelity of spatial multiplexing devices while greatly simplifying the circuit layout and footprint. Such PNRD sits directly atop a silicon nitride (Si_3N_4 or SIN) strip-loaded waveguide on thin-film lithium niobate ($LiNbO_3$ or LN)-on-insulator (LNOI) substrate. This material stack let us exploit SIN's low propagation losses and well-established CMOS fabrication technology together with LN's electro-optic properties.

We also analyze different shapes of SNSPDs, impacting significantly both performance and fabrication feasibility. While, performance wise, the best nanowire shape would be the *wavy-wall* type, the choice changes once the fabrication constrains are considered. In this work we will analyze a process featuring the well-established meander structure.

2 Fidelity Scaling

In the binary-tree multiplexing, each SPD has an equal probability of collecting a single-photon due to the tree structure. To optimize the fidelity F of this system, that is the probability of correctly measuring the number of photons, each SPD must have $\eta = 100\%$ detection efficiency, which is the probability of coupling, absorbing and detecting a single-photon.

In the linear multiplexing, instead, to maintain for each SPD an equal probability to measure a single-photon it is necessary to modify the detection efficiency, by means of the coupling coefficient, of every SPD in the array. By performing combinatorial calculations, we obtained that, indexing the SPDs in the array with i ranging from N to 1, each detector's efficiency must satisfy $\eta_i = 1/i$.

Evaluating the fidelity of measuring m photons with N SPDS leads to the formula in Eq. (1),

$$F(m, N) = \Pr\big[\text{detected} = m|\text{incoming} = m\big] = m!\binom{N}{m}\frac{1}{N^m} \quad (1)$$

which is valid for the ideal case (waveguide is lossless, detector has unitary internal quantum efficiency and no dark counts), and it essentially represents the probability of distributing m photons in N SPDs with at most one photon per SPD.

Realistic propagation loss ($\alpha_w < 0.3$ dB/cm) and nanowire absorption ($\alpha_c \approx 422$ dB/cm) modify the effective η_i via an exponential attenuation with intensity given by the ratio $r = \frac{\alpha_w}{\alpha_c}$, which enters a generalized fidelity formula reported in [3].

State-of-the-art SNSPD dark count rates ($\gamma \sim 30$ kHz over $\Delta t \approx 10$ ns) further modify F by the no-count Poisson multiplicative factor $e^{-\gamma L_{tot} \Delta t}$. Even in the worst case, F degrades by only a few percent compared to the lossless, zero-dark count scenario.

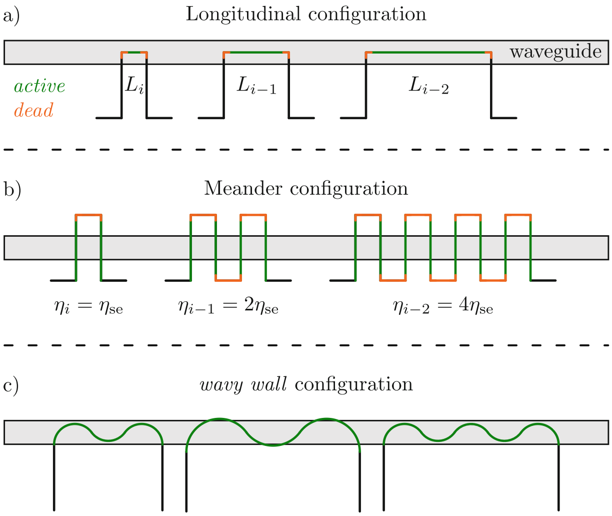

Fig. 1. Different configurations of SNSPDs on top of the waveguide. a) represents the longitudinal configuration, characterized by a variable-length and longitudinally centered nanowire. b) represents the meander configuration, characterized by being a multiple of the single-element unit SPD. c) represents the *wavy wall* configuration, characterized by nanowires with constant curvature for its length. Picture from [3].

3 Nanowire Arrangement and FEM Simulations

We compared three different nanowire layouts, as shown in Fig. (1), each with their pros and cons.

1. **Longitudinal**: the nanowire is parallel and centered on the waveguide; it allows continuous tuning of η_i by accordingly choosing the nanowire length, but prone to current crowding in 90 degrees bends.
2. **Meander**: transverse straight segments with wide U-turns away from the mode; discrete η_i as combination of single-element efficiency η_{se} but fabrication friendly.
3. **Wavy-wall**: uniform-curvature sinusoidal arcs centered on the waveguide; in principle allowing continuous η_i and no current-crowding issue but requires high resolution and fast lithography.

FEM simulations confirm that the meander layout achieves the target efficiency with negligible extra loss, while U-turn bends contribute with negligible factors if put sufficiently away from the mode (above 6 µm).

Other results obtained from FEM simulations are.

1. **Propagation stability**: Strip-loaded TE modes exhibit no lateral leakage ($\Delta n > 0$) and bend-loss critical radius $R_{crit} \approx 434$ µm, that is the radius from which radiative losses are no longer negligible.
2. **Unit absorption**: after 5 µm of transversal nanowire length the absorption saturates. Depending on the SIN thickness, comprised between 180 nm and 200 nm, η_{se} saturates to a value between 2.5% and 3.5%.

4 Conclusions and Future Perspectives

We have demonstrated a fully integrated, linearly multiplexed SNSPD array on SIN/LNOI platform, with analytic fidelity matching binary-tree spatial PNRDs and with robustness against waveguide losses and dark count rates. FEM-driven design suggests the meander geometry for balancing fabrication ease and performance.

Crucially, our linear architecture allows incremental addition of new SNSPD elements post-fabrication: adding a few SPDs at the beginning of the waveguide extends the dynamic range with little increment to the PNRD total length. The modularity and small footprint make this device readily integrable into larger LNOI-based quantum photonic circuits.

This work contributes to paving the way to compact, scalable, PNRDs for on-chip quantum state characterization, quantum communications and beyond.

References

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