Integration of superconducting nanowire single-photon detectors in subwavelength-grating-structured waveguides

Regular paper

Alejandro Sánchez-Postigo[1,*], Connor Graham-Scott[1] and Carsten Schuck[1]

[1] Institute of Physics, University of Münster, Heisenbergstraße 11, 48149 Münster, Germany
[*] alejandro.sanchezpostigo@uni-muenster.de

Superconducting nanowire single-photon detectors (SNSPDs) offer leading measurement capabilities for quantum technology applications. Ultra-short waveguide-integrated SNSPDs embedded in optical cavities hold promise for simultaneously achieving high absorption efficiency and timing performance, but scattering loss dramatically reduce the detection efficiency. In this work, we explore the use of subwavelength grating metamaterials to mitigate such scattering loss.

Keywords: *SNSPD, waveguide, subwavelength grating metamaterial, SWG*

INTRODUCTION

Advances in key areas of photonic quantum technology such as quantum sensing, quantum key distribution and quantum information processing depend on the development of scalable, fast, and efficient methods to detect single photons [1]. Superconducting nanowire single-photon detectors (SNSPDs) have emerged as one of the most attractive single-photon detector technologies for quantum photonics [2]. SNSPDs comprise an electrically and optically accessible, ultra-thin (~5 nm), narrow (~100 nm) superconducting wire strip that is supplied with a bias current via two electrodes. When photons impinge on the SNSPD, they are absorbed and the superconducting state is supressed, which results in a voltage pulse that can be measured, thereby enabling photon counting. In conventional, standalone SNSPDs, the nanowire is arranged in a meander-like pattern, often embedded in a resonant structure that optimizes absorption of photons impinging under normal incidence from an optical fiber. SNSPDs have four important figures of merit: the detection efficiency, the dark count rate, the recovery time (τ_r), and the timing uncertainty or jitter (τ_{jitter}). Except for the dark count rate, which is mainly related to electrical noise and background radiation, the other performance metrics strongly depend on the geometry of the nanowire: The detection efficiency is limited by the area over which photons are allowed to interact with the nanowire. The detector speed is affected by the kinetic inductance of the nanowire, which increases with nanowire length, resulting in long recovery times. Finally, the jitter increases if the nanowire has bends where current crowding can occur and to a lesser extent with nanowire length.

For quantum optics experiments, photonic integrated circuits provide low loss and interferometric stability for single-photon manipulation. As illustrated in Fig. 1(a), in waveguide-integrated SNSPDs the superconducting nanowire is deposited on top of a dielectric waveguide, in the evanescent field of the guided mode, allowing for absorption along the direction of light propagation. By engineering the interaction length, conventional, U-shaped waveguide-integrated SNSPDs can provide absorption efficiencies higher than 90%, yet at the expense of reduced timing performance [2]. To enhance the latter, ultra-short, transversally oriented SNSPDs in optical cavities were realized, as depicted in Fig. 1(b) [3]. The dramatic reduction of the nanowire length yielded remarkable speed, $\tau_r \sim 500$ ps, and low jitter, $\tau_{\text{jitter}} = 32$ ps. Here, the light interacts with the nanowire in each of multiple round trips in the cavity, theoretically achieving a near-unity absorption efficiency despite short nanowire length. However, in practice, the absorption is strongly reduced due to scattering losses at the crossing between the waveguide and the slabs that support the nanowire, resulting in relatively low on-chip detection efficiencies near 30%.

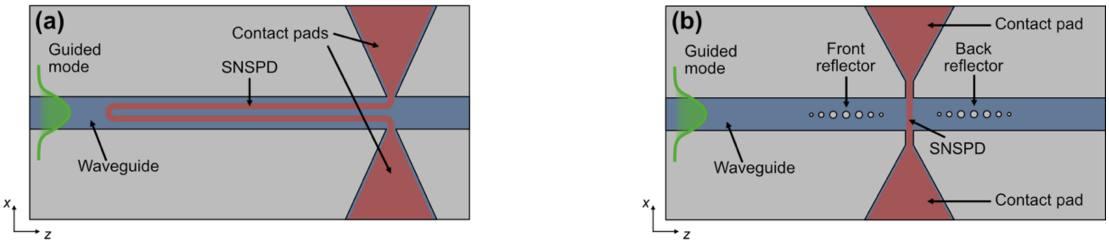

Fig. 1. (a) Conventional U-shaped waveguide-integrated SNSPD (top view). (b) Cavity-enhanced waveguide-integrated SNSPD proposed by Vetter et al. to increase speed and reduce jitter while keeping high absorption efficiency (top view) [3].

In this work, we show our preliminary work toward the goal of enhancing the on-chip detection efficiency of cavity-enhanced SNSPDs, integrated on silicon nitride waveguides for 1550-nm wavelength. This objective will be achieved by cladding the waveguide with a subwavelength grating metamaterial that suppresses scattering losses.

WAVEGUIDE-INTEGRATED SNSPD ENHANCED BY SUBWAVELENGTH GRATING METAMATERIALS

Subwavelength grating (SWG) metamaterial waveguides are periodic structures with a period or pitch,

$$\Lambda < \frac{\lambda}{2n_{\mathrm{B}}}, \tag{1}$$

that frustrates all diffraction orders, where λ is the operating wavelength and n_{B} is the effective index of the supported mode. Then, as schematized in Fig. 2, the structure behaves as a homogeneous metamaterial. As a first approximation, an SWG structure formed by alternating materials with refractive indices n_1 and n_2 and a duty cycle DC = a/Λ (see Fig. 2) can be modelled, for the in-plane polarization, as an isotropic metamaterial with refractive index

$$n_{\parallel} = [\mathrm{DC} \cdot n_1^2 + (1 - \mathrm{DC}) \cdot n_2^2]^{\frac{1}{2}} \tag{2}$$

when the structure is periodic in the propagation direction (z), as in Fig. 2, and

$$n_{\perp} = [\mathrm{DC} \cdot n_1^{-2} + (1 - \mathrm{DC}) \cdot n_2^{-2}]^{-\frac{1}{2}} \tag{3}$$

when the structure is periodic in the transverse direction (x). Anisotropic models and more accurate, wavelength-dependent approximations for the equivalent refractive indices $n_{\parallel}$ and $n_{\perp}$ can be found in [4]. By judiciously choosing the pitch and duty cycle (DC = a/Λ), the refractive index, dispersion, and birefringence of the metamaterial can be tailored. This index-engineering property has led to photonic integrated devices with unprecedented performance, including fiber-chip couplers, optical antennas, Bragg filters, and polarization management structures [4].

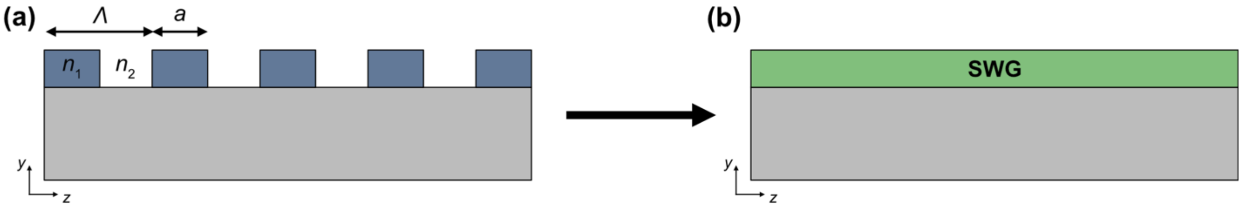

Fig. 2. (a) A periodic waveguide operating in the subwavelength regime, i.e., Λ satisfies Eq. (1). (b) The periodic waveguide behaves as an equivalent homogeneous metamaterial waveguide.

Here, we leverage the diffractionless nature of SWG waveguides to mitigate the scattering loss at the nanowire supports (slabs) in cavity-enhanced SNSPDs. A schematic representation of the proposed geometry is shown in Fig. 3(a). A waveguide core is assisted by a periodic lateral cladding with a pitch that meets Eq. (1). Consequently, light travels through the SWG-cladding waveguide as in a conventional waveguide with a metamaterial cladding [see Fig. 3(b)]. In this scenario, unlike in conventional SNSPDs [3], the crossings due to the nanowire supports are virtually invisible. Furthermore, the SWG-enhanced SNSPD can be smoothly embedded within an optical cavity just by increasing the pitch of the periodic waveguide to meet the Bragg condition (i.e., $\Lambda = 0.5\lambda/n_{\mathrm{B}}$) at the front and back parts of the structure. In addition, the absorption efficiency could be increased by placing more nanowires in parallel on the cladding strips, thereby forming a superconducting nanowire avalanche photodiode (SNAP).

To analyze the absorption efficiency of the proposed structure, we calculate the imaginary part of the effective index of the fundamental mode that is supported by the Si_3N_4 waveguide perturbed by the nanowire. Figure 4(a) illustrates the simulated structure, in which the lateral SWG cladding is replaced by a homogeneous isotropic metamaterial with an equivalent refractive index of 1.72, which corresponds to an SWG cladding with $n_1 = 2$ (Si_3N_4 strips), $n_2 = 1$ (air gaps), $\Lambda = 400$ nm, and DC = 50% [4]. For simulation purposes, the width of the lateral cladding is considered infinite. An NbTiN thin film is deposited on top of the structure, with complex refractive index 4.83 + j5.11 [5]. The nanowire is covered with an HSQ protective layer. The effective index of the mode, estimated using an FEM simulation [6], is 1.58 + j0.07, which corresponds with an absorption rate of 2.4 dB/µm. Assuming a nanowire width of 100 nm, this yields an absorption of 0.24 dB per nanowire, consistent with previous results [3].

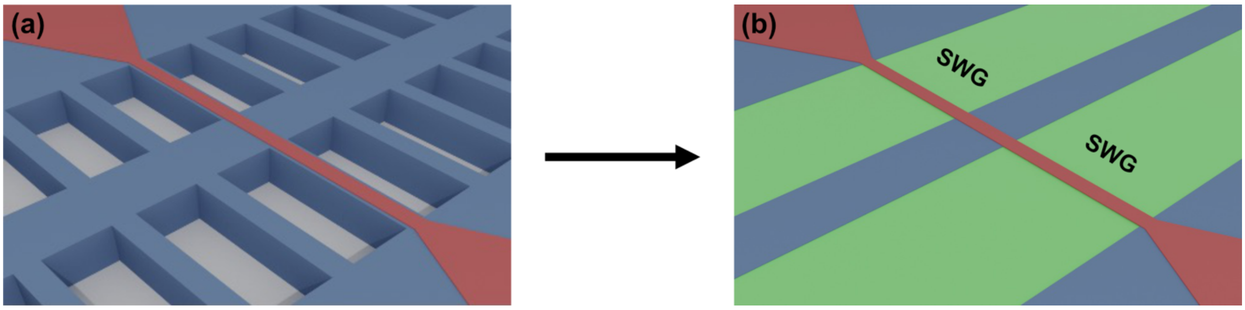

Fig. 3. (a) Proposed SWG-cladding-enhanced waveguide-integrated SNSPD. (b) Equivalent homogeneous metamaterial model for the proposed SWG-cladding-enhanced waveguide-integrated SNSPD.

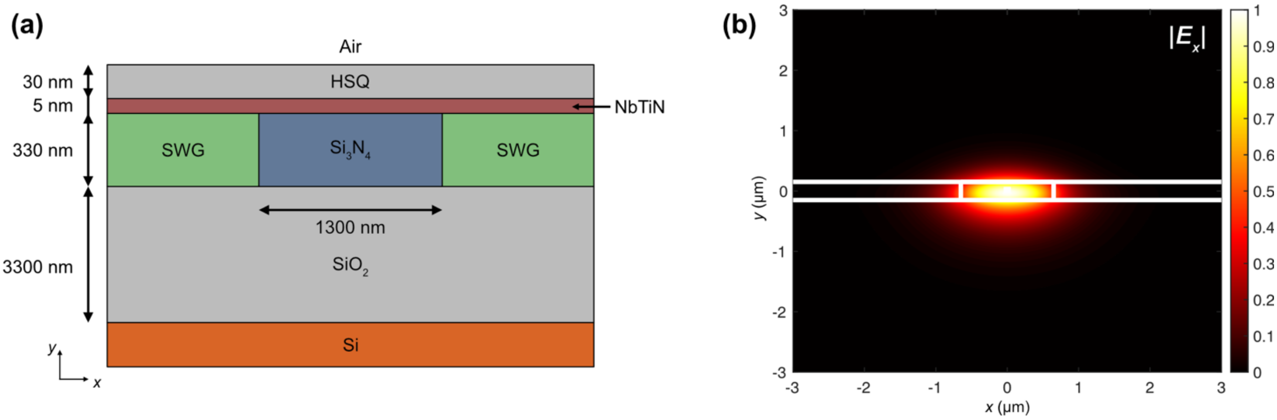

Fig. 4. (a) Schematic representation, not to scale, of the waveguide-integrated superconducting nanowire substituting the SWG lateral cladding with an equivalent metamaterial (front view). (b) Amplitude profile of the TE-polarized fundamental mode supported by the structure in (a) at a wavelength of 1550 nm.

CONCLUSION

In this work, we present our first attempts toward the implementation of a new waveguide-integrated SNSPD concept that has the potential to optimize the absorption efficiency while exhibiting outstanding timing performance. By taking benefit from the non-diffractive and non-reflective nature of subwavelength gratings, minimum scattering losses are expected, in contrast to reported cavity-enhanced SNSPDs that are not based on subwavelength metamaterials. First simulations show an absorption per nanowire of 0.2–0.3 dB, which is comparable to other state-of-the-art devices and provides good insight for the implementation of the proposed SWG-enhanced SNSPDs.

Acknowledgements: Marie Skłodowska-Curie Actions Postdoctoral Fellowship (ESSENS, 101064466). Funded by the European Union. We acknowledge support from the Horizon 2020 Framework Programme (SURQUID, 899824); Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. The European Union cannot be held responsible for them.

References

[1] J. O'Brien et al., *Photonic quantum technologies*, Nature Photonics, vol. 3, pp. 687-695, 2009.
[2] S. Ferrari et al., *Waveguide-integrated superconducting nanowire single-photon detectors*, Nanophotonics, vol. 7, no. 11, pp. 1725-1758, 2018.
[3] A. Vetter et al., *Cavity-enhanced and ultrafast superconducting single-photon detectors*, Nano Letters, vol. 16, no. 11, pp. 7085–7092, 2017.
[4] J. M. Luque-González et al., *A review of silicon subwavelength gratings: building break-through devices with anisotropic metamaterials*, Nanophotonics, vol. 10, no. 11, pp. 2765-2797 (2021).
[5] Supplementary material of M. A. Wolff et al., *Broadband waveguide-integrated superconducting single-photon detectors with high system detection efficiency*, Applied Physics Letters, vol. 118, no. 15, p. 154004, 2021.
[6] FemSIM – https://www.synopsys.com/photonic-solutions/rsoft-photonic-device-tools/passive-device-femsim.html