

# Design of broadband high-efficiency superconducting-nanowire single photon detectors

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**Abstract:** In this paper several designs to maximize the absorption efficiency of superconducting-nanowire single-photon detectors are investigated. Using a simple optical cavity consisting of a gold mirror and a SiO<sub>2</sub> layer, the absorption efficiency can be boosted to over 97%; this result is confirmed experimentally by the realization of an NbTiN-based detector having an overall system detection efficiency of 85% at 1.31 μm. Calculations show that by sandwiching the nanowire between two dielectric Bragg reflectors, unity absorption (>99.9%) could be reached at the peak wavelength for optimized structures. To achieve broadband high efficiency, a different approach is considered: a waveguide-coupled detector. The calculations performed in this work show that, by correctly dimensioning the waveguide and the nanowire, polarization-insensitive detectors absorbing more than 95% of the injected photons over a wavelength range of several hundred nm can be designed. We propose a detector design making use of GaN/AlN waveguides, since these materials allow lattice-matched epitaxial deposition of Nb(Ti)N films and are transparent on a very wide wavelength range.

## 1. Introduction

Highly efficient detection of single photons is of capital importance not only for advanced quantum optics experiments but, increasingly, for many emerging industrial applications [1, 2]. Single-photon detectors (SPDs) are used today in many fields, such as quantum key distribution [3, 4], time-of-flight depth ranging applications such as the Lidar [5, 6], space-to-ground optical communication [7], singlet oxygen detection for medical applications [8], and integrated circuit testing [9, 10].

In recent years, superconducting-nanowire single-photon detectors (SNSPDs) have undergone rapid development, and they now outperform single-photon avalanche diodes (SPADs) [11, 12], especially in the infrared spectral range. Very high efficiencies, up to 93% [13–15] have been demonstrated with SNSPDs at telecom wavelength, which, combined with the very high detector speeds, make SNSPDs the ideal candidate for many of the above-mentioned applications [16].

The overall system detection efficiency ( $\eta_{\text{tot}}$ ) of a SNSPD can be seen as the product of three contributions: the coupling efficiency ( $\eta_{\text{coup}}$ ), the absorption efficiency ( $\eta_{\text{abs}}$ ) and the internal efficiency ( $\eta_{\text{int}}$ ) [1]:  $\eta_{\text{tot}} = \eta_{\text{coup}} \cdot \eta_{\text{abs}} \cdot \eta_{\text{int}}$ .

The coupling efficiency  $\eta_{\text{coup}}$  is the probability that a photon travelling in the optical fiber carrying the signal is coupled to the detector. The absorption efficiency  $\eta_{\text{abs}}$  provides a measure of the probability, for a photon impinging on the detector, to be actually absorbed by it rather than transmitted or reflected. Finally, the internal efficiency  $\eta_{\text{int}}$  is the probability of registering a voltage pulse at the nanowire leads when a photon is absorbed. This latter parameter depends on the choice and quality of the superconducting material (reported values reach > 90% for Nb(Ti)N [17], and close to 100% for WSi [13]), and its optimization will not be discussed in this paper.

The coupling efficiency,  $\eta_{\text{coup}}$ , is usually boosted by folding the detecting nanowire in a tightly packed meandering structure, covering a circular area several microns in diameter. It is then possible to efficiently couple the light output from a fiber to the center of the nanowire meander with a self-aligning method, achieving coupling efficiencies close to unity, [18].

Achieving high absorption efficiency is often difficult in SNSPDs. Since the light is usually coupled vertically to the thin (4–8 nm) nanowire, only a small fraction of it is absorbed. Several techniques have been developed to enhance  $\eta_{\text{abs}}$ . In

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*Photon Counting* Nikolay Britun,Anton Nikiforov,2018-03-21 Photon counting is a unified name for the techniques using single photon detection for accumulative measurements of the light flux normally occurring under extremely low light conditions Nowadays this approach can be applied to the wide variety of the radiation wavelengths starting from X ray and deep ultraviolet transitions and ending with far infrared part of the spectrum As a special tribute to the photon counting the studies of cosmic microwave background radiation in astronomy the experiments with muon detection and the large scale fundamental experiments on the nature of matter should be noted The book provides readers with an overview on the fundamentals and state of the art applications of photon counting technique in the applied science and everyday life

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