

# 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  $\mu$ m. 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 98% [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 aforementioned applications [16].

The overall system detection efficiency ( $\eta_{\text{sys}}$ ) 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]:  $\eta_{\text{sys}} = \eta_{\text{coup}} \times \eta_{\text{abs}} \times \eta_{\text{int}}$ .

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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