

# 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

# Design Of Broadband High Efficiency Superconducting

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*Scientific and Technical Aerospace Reports*, 1995      **Index to IEEE Publications** Institute of Electrical and Electronics Engineers, 1995 Issues for 1973 cover the entire IEEE technical literature      **Electrical & Electronics Abstracts**, 1997  
**Handbook of Superconductivity** David A. Cardwell, David C. Larbalestier, Aleksander Braginski, 2022-07-05 This is the last of three volumes of the extensively revised and updated second edition of the Handbook of Superconductivity The past twenty years have seen rapid progress in superconducting materials which exhibit one of the most remarkable physical states of matter ever to be discovered Superconductivity brings quantum mechanics to the scale of the everyday world Viable applications of superconductors rely fundamentally on an understanding of these intriguing phenomena and the availability of a range of materials with bespoke properties to meet practical needs While the first volume covers fundamentals and various classes of materials the second addresses processing of these into various shapes and configurations needed for applications and ends with chapters on refrigeration methods necessary to attain the superconducting state and the desired performance This third volume starts with a wide range of methods permitting one to characterize both the materials and

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