

# 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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**camino primitivo jakobsweg de** - Jan 30 2023

web camino primitivo jakobswegen fakten geheimtipp unter den jakobswegen 4 aller pilger wählen diesen weg 310 kilometer länge wegprofil schwer ideale reisezeit frühjahr bis herbst reisedauer 2 5 3 wochen der camino primitivo ist ein exot unter den jakobswegen

nordspanien jakobsweg camino primitivo mit tipps für - Apr 01 2023

web 16 90 preisangaben inkl ust abhängig von der lieferadresse kann die ust an der kasse variieren weitere informationen lieferung für 3 69 20 22 mai details lieferadresse wählen nur noch 10 auf lager menge in den einkaufswagen jetzt kaufen zahlung sichere transaktion versand buecher galerie ac verkäufer buecher galerie ac

*camino primitivo 2023 etappen höhenprofil reiseführer* - Sep 06 2023

web länge 321 kilometer etappen 13 15 etappen kürzere etappen möglich dauer 2 3 wochen zeit höhenprofil täglich bergauf

bergab ausdauer erforderlich unterkünfte gute infrastruktur herbergen und andere unterkünfte kosten ab 25 30 tag an  
abreise ausrüstung anreise flugzeug oder bahn und bus

**camino primitivo der älteste jakobsweg komoot** - Dec 29 2022

web der camino primitivo ist sehr anstrengend und anspruchsvoll er ist immer noch sehr ursprünglich geblieben und führt  
durch die faszinierende bergwelt in nordspanien dieser ursprünglich gebliebene jakobsweg beginnt in der alten königsstadt  
oviedo weitere informationen auf der webseite jakobsweg lebensweg

*wanderführer jakobsweg camino primitivo fernwanderweg* - Sep 25 2022

web wanderführer spanien jakobsweg camino primitivo fernwanderweg blick ins buch 16 90 inkl 7 mwst zzgl versandkosten  
artikelnummer 978 3 86686 482 5 schlagwörter kap finisterre pilgern 141 jakobsweg oviedo santiago de compostela pilgern  
in spanien raimund joos spanien camino camino primitivo santiago

spanien jakobsweg camino primitivo thalia - Oct 27 2022

web das buch beschreibt den verlauf des ca 310 km langen jakobsweg camino primitivo von oviedo bis santiago de  
compostela und den anschließenden weg zum kap finisterre 89 5 km der weg über die berge asturiens und galiciens gilt  
unter insidern als eine reizvolle Mischung aus pilgern und bergwandern