Conference materials
UDC 538.945
DOI: https://doi.org/10.18721/JPM.153.345

New design of a waveguide integrated photon number resolving superconducting detector with micron-wide strips

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Abstract. We report on the development of a design for a waveguide integrated photon number resolving superconducting detector with micron-wide strips. The detector is designed for a 1550-nm-wavelength single-mode waveguide. Using the planarization operation, it is possible to cover the waveguide and the entire area around it with a dielectric layer, producing a flat surface for the superconducting detector fabrication. The detector is formed in a shape of a straight line directly above the waveguide. The length and width of the superconducting detector are chosen to absorb maximum of the radiation from the waveguide. In the same superconductor layer, the Klopfenstein taper impedance transformer is designed as a non-uniform coplanar line. The use of impedance matching Klopfenstein tapers makes it possible to distinguish the resistances of several hot spots, that is, to distinguish the number of absorbed photons. The detector should absorb almost all radiation and be capable to distinguish up to 3 photons in an optical pulse.

Keywords: superconductivity, photon number resolving detector, integrated photonic, Klopfenstein taper

Funding: This study was funded by the Russian Science Foundation (RSF) grant No. 20-12-00287.

Citation: Dryazgov M. A., Korneeva Yu. P., Korneev A. A., New design of a waveguide integrated photon number resolving superconducting detector with micron-wide strips. St. Petersburg State Polytechnical University Journal. Physics and Mathematics, 15 (3.3) (2022) 230–234. DOI: https://doi.org/10.18721/JPM.153.345

Материалы конференции
УДК 538.945
DOI: https://doi.org/10.18721/JPM.153.345

Новый дизайн интегрированного на волновод детектора с разрешением числа фотонов на основе сверхпроводниковых полосок микронной ширины

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Аннотация. Мы сообщаем о разработке дизайна сверхпроводящего детектора с разрешением числа фотонов на основе полосок микронной ширины интегрированного на оптический волновод. Детектор помещается на волновод после операции планаризации диэлектрика. Разрешение числа фотонов достигается путем согласования импедансов коаксиальной линии и сопротивления детектора, зависящего от количества одновременно поглощенных фотонов. В качестве трансформатора импедансов мы предлагаем использовать сверхпроводящую копланарную линию переменной ширины в форме конуса Клопфенштейна.

Ключевые слова: сверхпроводимость, детектор с разрешением числа фотонов, интегральная фотоника, конус Клопфенштейна

Финансирование: Работа выполнена при поддержки Российского Научного Фонда грант № 20-12-00287.

Ссылка при цитировании: Дрязгов М. А., Корнеева Ю. П., Корнеев А. А. Новый дизайн интегрированного на волновод детектора с разрешением числа фотонов на основе сверхпроводниковых полосок микронной ширины // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2022. Т. 15. № 3.3. С. 230–234. DOI: https://doi.org/10.18721/JPM.153.345

Introduction

Superconducting Single Photon Detectors (SSPD) have proven to be excellent for detecting single photons [1] in quantum information applications. However, the challenges of quantum optics require detectors capable to resolve the number of photons [2]. Moreover, present development of quantum computers is directed towards integrated circuits [3]. All this suggests that superconducting photon-number resolving (PNR) detectors should be compatible with the integration on a photonic chip [4–6].

Traditionally, SSPDs are made as 100-nanometer-wide strips, which does not allow them to effectively absorb the radiation from the waveguide. This problem can be solved using micron-wide superconducting strips [7], planarized [8] and integrated with impedance matching Klopfenstein tapers [9].

The planarization makes it possible to cover the waveguide and the entire area around it with a dielectric layer, producing a flat surface for the superconductor deposition. Then a micron-wide superconducting strip can be placed above the waveguide, even if the strip is wider than the waveguide. The use of impedance matching Klopfenstein tapers makes it possible to distinguish the resistances of several hot spots, that is, to distinguish the number of absorbed photons.

We propose a new design of the PNR with a Klopfenstein taper on the waveguide and determine its parameters for manufacturing.

Waveguide and SSPD

The following parameters were chosen for modeling: the waveguide material is Si_3N_4 ($n = 1.9894$) surrounded by SiO_2 ($n = 1.444$) medium, waveguide width $w_{wg} = 1.68$ µm, waveguide height $d_{wg} = 0.5$ µm. Modeling in the COMSOL environment demonstrates that it will be a single-mode waveguide for a wavelength of $\lambda = 1550$ nm. A strip of NbN (with refraction index $n = 5.20685-5.82i$) 5 nm thick is placed above the waveguide. The ground contacts of the coplanar line are placed far enough away so as not to affect the absorption of radiation from the waveguide. The width of the superconducting strip w_{strip} and the thickness of the dielectric layer (d_{diel}) between the waveguide and superconductor are selected to ensure maximum radiation absorption (Fig. 1, *a*).

The simulation results in the COMSOL environment are shown in Fig. 1, b. It is clearly visible that for maximum absorption, the thickness of the dielectric layer between the waveguide and superconductor should be as small as possible: for example, the absorption of 1.4 dB/µm is achieved for $d_{diel} = 0$ nm, and for $d_{diel} = 100$ nm the absorption is only 0.7 dB/µm. Absorption increases with increasing width of the superconducting strip. However, as shown in the inset in Fig. 1, b, for strips wider than 2 micrometers, the increase in absorption is extremely small and does not give any improvement.

Thus, it is necessary to place 2-µm-wide superconducting strip directly on the waveguide. Even

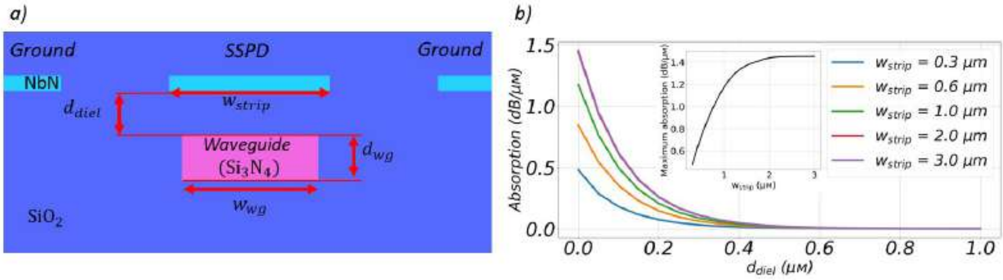

Fig. 1. A cross-section showing the waveguide with an SSPD on top (*a*). The dependence of the absorption on the thickness d_{diel} of the dielectric layer between the waveguide and SSPD (*b*). The red and purple curves (for w_{strip} = 2 and 3 μm) are indistinguishable due to the similar absorption values. In insert: dependence of the maximum absorption (at d_{diel} = 0) on the width of the superconducting strip

though the width of the superconducting strip is greater than the width of the waveguide, this is possible if the waveguide is covered with a thick dielectric layer and, using the planarization operation, the dielectric layer is removed along the upper boundary of the waveguide.

To achieve the maximum absorption of 1.4 dB/μm, the length lstrip of the superconducting strip required to absorb 99% of the radiation from the waveguide is 14 μm.

Klopfenstein taper

A normal domain with a resistance of about 1 kΩ is formed, when a photon is absorbed in a superconducting strip. Accordingly, when two or more photons are absorbed, the number of normal domains increases proportionally. However, the resistance of a different number of normal domains is indistinguishable against the coaxial line impedance of 50 Ω. To solve this problem impedance matching is necessary which will ensure distinguishing between resistances of normal domains, that is, the number of absorbed photons.

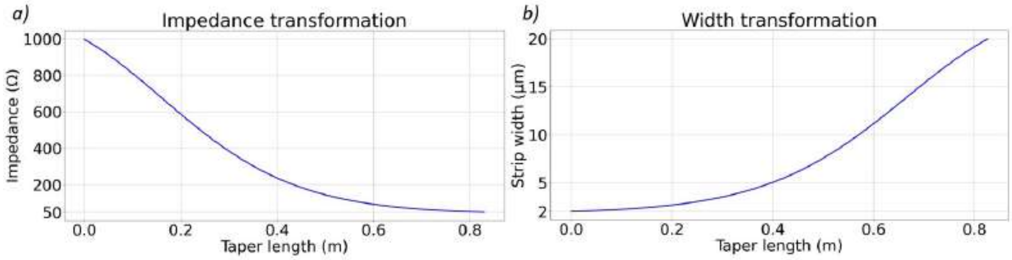

Fig. 2. Smooth transformation of impedance along the length of the co-planar line calculated using Klopfenstein's formulas (*a*). The width of the signal contact vs line length (*b*)

The matching of the impedances of the coaxial line and the normal domain is carried out using the Klopfenstein taper. First, determine the reflection coefficient without impedance matching according to formula:

$$\Gamma_0 = \frac{1}{2}\ln\frac{Z_0}{Z_l} \tag{1}$$

here Z_1 = 50 Ω is the characteristic impedance of the coaxial line, Z_0 = 1 kΩ is the resistance of the normal domain. Then Γ_0 = 1.5.

Taking the maximum permissible reflection coefficient Γ_m = 0.1, the constant A, which is responsible for a smooth change in the impedance, can be found by (2):

$$A = \cosh^{-1}(\Gamma_0 / \Gamma_m) \tag{2}$$

Then A = 3.4. The length of the Klopfenstein taper is found by formula:

$$L = \frac{Ac}{2\pi f_{\min}\sqrt{\varepsilon}} \tag{3}$$

here $c = 3 \cdot 10^8$ m/s is the speed of light in the vacuum, ε = 3.9 is the absolute permittivity of the

SiO$_2$, f_{min} = 100 MHz is the minimum frequency of the transmitted signal. Then L = 83.4 cm.

To achieve a smooth change in the impedance, formula (4) is used:

$$\varphi(x, A) = \int_0^x \frac{I_1(A\sqrt{1-y^2}}{A\sqrt{1-y^2}} dy, |x| \le 1 \tag{4}$$

here $I_1(x)$ is the modified Bessel function of the 1st order.

Finally, the change in impedance according to the Klopfenstein formula (5) is shown in Fig. 2, *a*.

$$\ln Z(z) = \frac{1}{2} \ln Z_0 Z_l + \frac{A^2}{\cosh A} \Gamma_0 \varphi\left(\frac{2z}{L} - 1, A\right), 0 \le z \le L \tag{5}$$

Impedance matching is performed by using nonuniform transmission line with varying a coplanar line impedance. A smooth change in the width of the superconducting strip (Fig. 2, *b*) acting as a signal contact from 2 μm to 20 μm with a constant gap width of 20 μm over L = 83 cm will provide a smooth change in impedance according to the Klopfenstein formula.

Now it becomes possible to distinguish the resistance of one normal domain from two, three or more. That is, to distinguish the number of photons in an optical pulse.

Design concept

We suggest photonic integrated circuit which has transmission lines with ground-signal-ground (GSG) probing pad which matched to the RF probe impedance of 50 Ω. The Klopfenstein taper is used for matching between SSPD and GSC probing pad. On a SiO$_2$ dielectric substrate there is a silicon nitride (Si$_3$N$_4$) waveguide. The waveguide is covered with a dielectric layer (SiO$_2$) with subsequent planarization, which will allow placing a detector on top with impedance matching transformer in the form of a Klopfenstein taper. The detector is made in the form of a straight 2-μm-wide strip of NbN 14 μm long. After all, the structure is covered with a dielectric layer to prevent radiation scattering (Fig. 3).

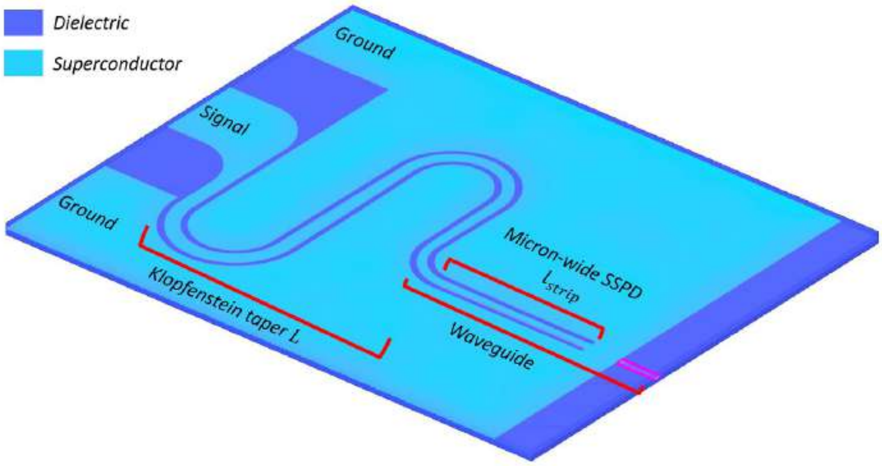

Fig. 3. The design concept of the PNR-SSPD with a Klopfenstein taper integrated on the optical waveguide (not to scale)

The described detector absorbs 99% of the radiation from the optical waveguide and is able to distinguish up to three photons in an optical pulse due to impedance matching.

Conclusion

We have proposed a design for a waveguide integrated PNR superconducting detector with micron-wide strips connected to Klopfenstein taper. The optimal parameters were calculated for absorbing 99% of the radiation and matching the impedance of the coaxial line and the superconductor in the normal state: w_{strip} = 2 μm, l_{strip} = 14 μm, w_{wg} = 1.68 μm, d_{wg} = 0.5 μm, L = 83.4 cm.

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Received 14.07.2022. Approved after reviewing 14.07.2022. Accepted 18.07.2022.