Performance of a superconducting single photon detector with nano-antenna*

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The performance of single-photon detectors can be enhanced by using nano-antenna. The characteristics of the superconducting nano-wire single-photon detector with cavity plus anti-reflect coating and specially designed nano-antenna is analysed. The photon collection efficiency of the detector is enhanced without damaging the detector's speed, thus getting rid of the dilemma of speed and efficiency. The characteristics of nano-antenna are discussed, such as the position and the effect of the active area, and the best result is given. The photon collection efficiency is increased by 92 times compared with that of existing detectors.

Keywords: quantum communication, superconducting single photon detector, nano-antenna

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1. Introduction

In the last few years, quantum information has been one of the hottest fields, and has attracted more and more attention.[1] A single-photon detector (SPD) is essential to some quantum communication protocols, for example BB84.[2] Although the development of new quantum information processing methods reduces the demand of the ideal single-photon,[3−6] the design of single-photon detectors with high speeds and efficiency is still very important.

A superconducting nano-wire single-photon detector (SNSPD) is a new kind of fast single-photon detector.[7] This kind of detector does not suffer from the after-pulse effect, although it may cause a self-heating problem, thus it strictly requires operating temperatures at 4 K or less. However SNSPD is facing a fatal problem, the device efficiency and speed are both determined by the kinetic inductance of the nano-wire, which means we must be at the expense of efficiency for speed, or speed for efficiency.[8] Recently, great efforts have been devoted to SNSPDs based on nanostructures, such as nano-antenna. In this paper we simulate a new kind of SNSPD that is a combination of a superconducting nano-wire and nano-antenna, which shows the potential to solve the problems discussed. The simulation results show that the nano-antenna greatly enhances the efficiency of the SNSPD, but hardly affects the detection speed.

2. Theory and simulation

2.1. Theory

An SNSPD usually works at a temperature just slightly below the critical temperature T_c, and the corresponding current in the nano-wire is I_c. When a photon hits the nano-wire, the energy will cause the temperature to rise at the very position, and turn the spot of the nano-wire into the normal state. If the current increases to a value beyond I_c, it in turn causes more regions to turn into the normal state until it changes the whole width of the nano-wire. So far, the most successful way is to fabricate a meander structure with an ultra thin NbN nano-wire. The active area scale is usually in the order of microns, but the meander structure can be dense or sparse, which is related to the length and kinetic inductance of the wire. The denser the NbN structure, the higher the efficiency will be. However, it also means that the nano-wire will be longer, thereby reducing the detection speed.[8] So, we integrate an SNSPD with a nano-antenna to enhance its performance in detecting a single photon.

According to Ref. [9], device efficiency is defined as the probability with which a photon hits the active area of the SNSPD and triggers a voltage pulse which can be detected and it is expressed as

$$\eta = p \times A \times \gamma, \tag{1}$$

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where p is the probability with which a single photon can hit the nano-wire; A is the probability with which a photon is absorbed when it hits the nano-wire; γ is the device efficiency which is related to the electric circuit, environment, etc. According to Ref. [10], the optical intensity of a particular area is related to the average number of existing photons in that area, which is bound up with the probability of a single photon hitting a certain area, which means,

$$p \propto \alpha, \tag{2}$$

where α is the optical intensity on the nano-wire. So, we can rewrite this formula as

$$\eta \propto \alpha \times A \times \gamma. \tag{3}$$

For simplicity, we assume that adding a nano-antenna does not affect the device efficiency, since we do not change the parameters mentioned above.

Device speed is determined by the reset time of the nano-wire. After absorbing a photon, the nano-wire cannot immediately detect another photon because the wire is in a normal state, and detection needs the nano-wire to work in a superconducting state.[11] Therefore, the device efficiency cannot be reset immediately. The reset time τ is defined as the recovery time of device efficiency. In our previous work, we usually considered τ to be the time that is needed to restore 90% of device efficiency, which means that the bias current recovers to 90%. The recovery time τ is expressed as

$$\tau = (L_{\mathrm{k}}/R)\ln[1/(1 - I_{90\%}/I_{\mathrm{B}})], \tag{4}$$

where L_{k} is the kinetic inductance, and it is determined by the length of the nano-wire; R is the resistance; I_{B} is the bias current, which is required to be slightly below the critical current I_{C}. In the whole process of our simulation, these parameters remain unchanged, so we can draw the conclusion that the reset time or the detection speed do not change.

2.2. Nano-structure simulation

It has been well shown that the nano-antenna and optical cavity together with an anti-reflection coating (ARC) can greatly enhance the performances of the single-photon resource and detector. Efforts are devoted to the fabrication of new nano-structures with better performances in detecting single-photons. Here, we demonstrate a new nano-wire integrated with a nano-antenna. The single-photon collection efficiency is enhanced by 92 times compared with that of the existing nano-structure.

In the first step, we simulate the simplest case, where there is no cavity structure, and an ARC or nano-structure is attached. The incident light impinges perpendicularly on an NbN nano-wire located in a slot which is surrounded by gold, and the structure is based on a sapphire substrate. Using the best parameters in Ref. [12], the NbN nano-wire is 4.5-nm thick and 80-nm wide, and the wavelength is 1550 nm. The optical indices of NbN, sapphire, hydrogen silsesquioxane (HSQ), and gold are 5.23+5.82j, 1.75, 1.39, and 0.55+11.5j respectively. In the simulations, we use Comsol software to simulate the optical intensity distribution under scattering boundary conditions. Figure 1 shows the optical intensity distribution, which is positively correlated to photon collection efficiency. The whole optical intensity in the NbN region is 2.15×10^{-14} W.

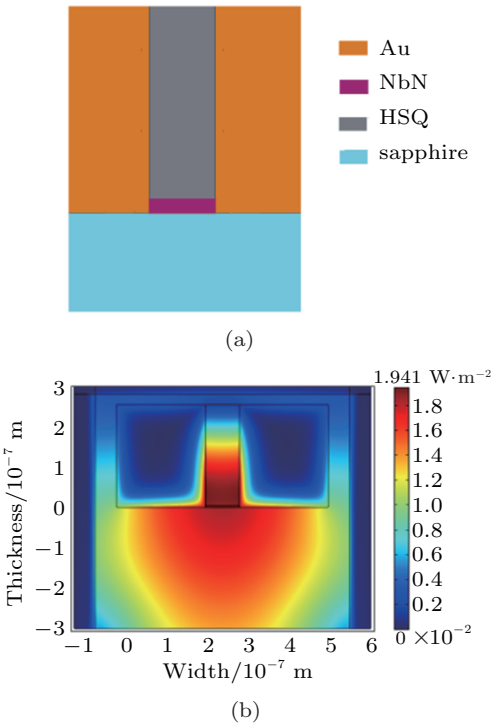


Fig. 1. (a) The schematic diagram of a single slot structure. The model consists of a gold–HSQ–gold slot on the top of a sapphire substrate and the NbN nanowire at the aperture of the waveguide. (b) A simulated optical intensity distribution of a single slot structure. We modified the display colours to illustrate the result.

In the second step, we simulate a single slot with an optical cavity and an ARC, and the results are shown in Fig. 2. The 277 nm of HSQ is required for

a $\lambda/4$ ARC, and the cavity thickness is 195 nm. The 1 nm of Ti and 120 nm of Au form a mirror for the optical cavity. The whole optical intensity in the NbN region is 1.62×10^{-13} W.

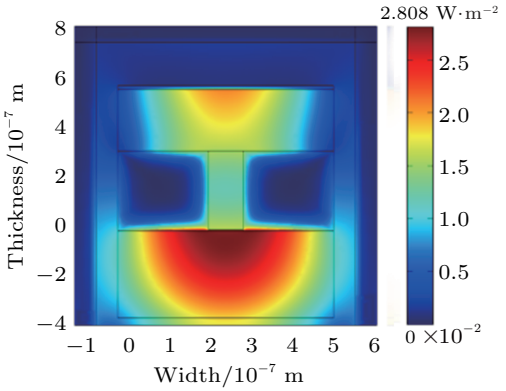


Fig. 2. Simulated optical intensity distribution of a single slot structure with a cavity and an ARC. We modified the display colours to illustrate the result.

In the third progress, we simulate a single slot with an optical cavity, ARC and a nano-antenna, which was demonstrated by Refs. [13] and [14]. Figure 3(a) shows the structure of the nano-antenna. We placed the antenna on both sides of the slot structure as shown in Fig. 3(b). The result is better than progress 2, as shown in Fig. 3(c).

To further study the antenna influence on photon collection efficiency, we place the antenna at different positions and examine the optical intensity on the NbN area. Firstly, we place the antenna on both sides of the NbN, in this case, the size of gap is the same as that of the NbN, then we measure the efficiency starting from $y = 0$ nm (see Fig. 3(b)). The results are shown in Table 1 and Fig. 4.

Then, we set $y = -30$ nm, and study how the optical intensity varies with a gap between the antenna and slot. We start from gap = 0 nm, and the results are demonstrated in Table 2 and Fig. 5.

Table 1. Enhancement of photon collection efficiency with antenna position in the y direction.

y/nm	0	−5	−10	−15	−20	−25	−30	−35	−40
$O/10^{-13}$ W	2.20	3.98	5.21	7.24	10.5	45.2	111	1.10	44.6

Table 2. Enhancement of photon collection efficiency with antenna gap size.

Gap/nm	0	2	4	6	8	10
$\alpha/10^{-11}$ W	1.11	1.49	1.30	1.01	7.80	6.12

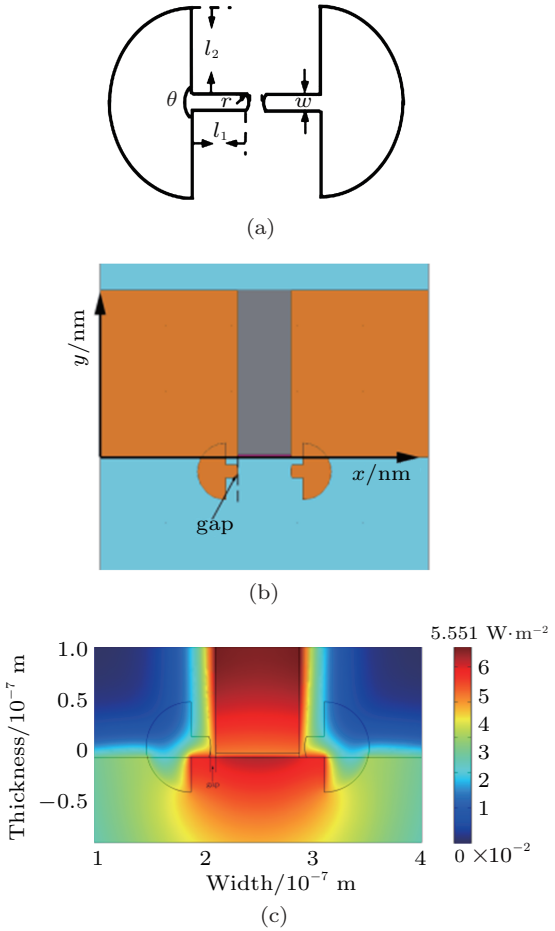


Fig. 3. (a) The structure of the nano-antenna, where l_1, l_2, r, g, w are 17 nm, 33 nm, 30 nm, and 20 nm, respectively, and r is the radius of curvature of the edge. (b) The scheme of the structure with an antenna used in a single slot. (c) Simulated optical intensity distribution of a single slot structure with a nano-antenna.

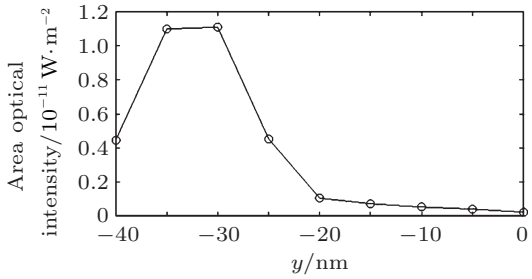


Fig. 4. Variation of photon collection efficiency with antenna position in the y direction.

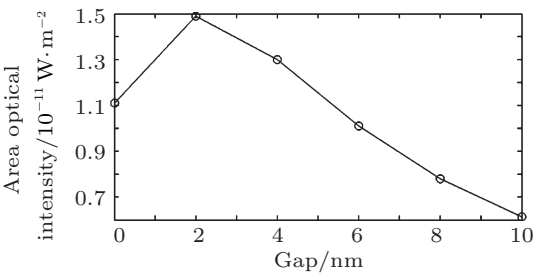


Fig. 5. Variation of photon collection efficiency with antenna gap size.

The best position is gap = 2 nm, y = 30 nm, where the whole optical energy on the NbN area is 92 times that of the single slot without a nano-antenna.

3. Conclusion

We introduced a new kind of nano-antenna to enhance the detection efficiency of the SNSPD with an ARC and an optical cavity. We used Comsol software to simulate our design. In the simulation, we focus on the photon collection efficiency of an SNSPD working in the TM mode, 1550 nm. We start a single structure and investigate how the antenna influences the photon collection of the nano-wire, and the best result is obtained when gap = 2 nm and y = 30 nm. The obtained photon collection efficiency is 92 times that of the existing SNSPD. The results definitely lead to a better detection efficiency. On the other hand, the detection speed of SNSPD does not decrease, because the kinetic inductance is not involved. Thus we get rid of the dilemma of efficiency or speed.

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