Performance of superconducting nanowire single-photon detector with the fan coupling antenna array*

Wang Yu-Jue(王玉珏), Ding Tian(丁 天), Ma Hai-Qiang(马海强), and Jiao Rong-Zhen(焦荣珍)†

School of Science, Beijing University of Posts and Telecommunications, Beijing 100876, *China*

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The performance of superconducting nanowire single-photon detector (SNSPD) involving niobium nitride with the fan coupling antenna array is analyzed. The SNSPD has a high detection efficiency and counting rate. Hydrogen silsesquioxane and niobium nitride are filled in the gold grating deposited on the substrate in which the fan coupling antenna arrays are embedded. By changing the position of the fan coupling antenna array, the maximum area of optical intensity is obtained and the photon collection efficiency is increased by 26.5 times. The detection efficiency of SNSPD is improved without changing the detection speed. These parameters are important for designing a practical single-photon detector.

Keywords: surface plasmon polaritons, single-photon detector, nano-antenna array

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1. Introduction

A practical single-photon detector is one of the most important components in the fields of quantum information, optical quantum computing, and space-to-ground communication. In particular, the distribution length and secure key generation rate of a quantum key distribution system are constrained by the performance of single-photon detector. Superconducting nanowire single-photon detector (SNSPD) has been the focus of much recent work because of its broadband sensitivity to the wavelengths ranging from the visible to the near-infrared wavelengths, excellent timing resolution, high counting rate, and low dark-count rate.[1–6] However, it faces a problem in that detection efficiency and speed cannot be obtained at the same time. Many research groups have received the challenge of improving SNSPD operation.[7–10] It is well known that the use of a nano-antenna can greatly enhance the detection efficiency of single-photon detectors. The whole optical intensity on niobium nitride (NbN) area is 92 times more than that of single-slot without antennas.[11] However, the nanowire used in SNSPD is unlikely to be of a single-slot structure, which must have multiple single-slot structures. The number of the single-slot structures is proportional to the active area of the SNSPD, and is also related to the density of the nanowires.

In this paper, the performance of NbN meander SNSPD integrated with nano-antenna is analyzed by the finite element method (FEM). The unit of the structure is composed of fan coupling antennas at the collective port and a superconducting NbN nanowire with hydrogen silsesquioxane (HSQ) filled in the metal gap. It is observed that the collection efficiency will be greatly enhanced by the use of a fan coupling antenna array. In our simulation, we take into account both the detection efficiency and the speed of SNSPD. Our structure provides a new way to design the single-photon detector.

2. Calculation model

A sketch of the calculation unit is shown in Fig. 1. An infinite gold film with a gap array is deposited on the substrate (using the sapphire). A superconducting nanowire with the thickness 4.5 nm and the width $w = 80$ nm is sandwiched between the HSQ and the substrate. Fan coupling antennas are placed under the superconducting nanowire. Each part of the fan antenna is made up of a nanorod with the length of l_1 and the width w_1 and a semicircle with the radius of $l_2 + 0.5w_1$. At the end of the nanorod, there is a particle with a curvature radius of r and a width of w_1. The distance between the two parts of the fan antennas is g from end to end. The distance between the bottom and the center of the fan coupling antennas is h. The period of our structure is p and the width of the whole structure is 3 μm.

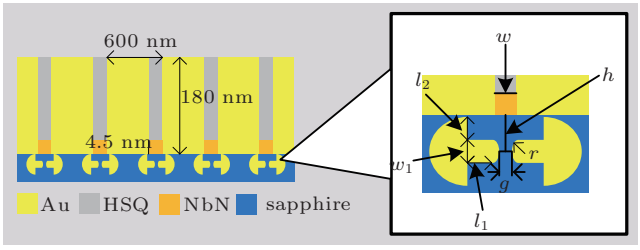


Fig. 1. (color online) Sketch of our structure unit.

For an ideal SNSPD, another photon can be detected immediately after the detection of one photon. In practice, af-

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†Corresponding author. E-mail: rzjiao@bupt.edu.cn

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ter one detection, the superconducting state of SNSPD is destroyed. It will take some time for SNSPD to recover to its superconducting state, and during this period of time, SNSPD cannot detect other photons. We define the minimum interval time that the detector needs to distinguish two single photon signals as the reset time. The reset time τ of SNSPD is limited by large kinetic inductance of these nanowires:[12,13]

$$\tau \propto \frac{L_{\rm k}}{R}, \tag{1}$$

where R is the equivalent resistance of the circuit and $L_{\rm k}$ is the kinetic inductance of nanowire determined, as follows:[14]

$$L_{\rm k} = \frac{\mu_0 \lambda^2 l}{wd}, \tag{2}$$

where λ is the magnetic penetration depth, d is the film thickness, l is the length of nanowire, and w is the width of nanowire. From Eq. (2), it is easy to find that with longer nanowire the value of $L_{\rm k}$ is increased, which results in a longer reset time and means

$$V = \frac{\beta_v}{l}, \tag{3}$$

where V is detection rate while β_v is equation parameter. The observed field can be expressed using the reciprocity theorem as[15]

$$\boldsymbol{E}_{\rm d}(\omega) \cdot \boldsymbol{j}_{\rm rec} = \frac{-2{\rm i}}{\mu_0 \omega} \int_S \frac{\partial \boldsymbol{E}_{\rm rec}(\boldsymbol{R}, z, \omega)}{\partial z} \cdot \boldsymbol{E}_{{\rm exp}t}(\boldsymbol{R}, z, \omega) {\rm d}\boldsymbol{R}. \tag{4}$$

Here, $\boldsymbol{E}_{\rm d}$ is the observed electric field, $\boldsymbol{j}_{\rm rec}$ is the monochromatic current oscillating at frequency ω, $\boldsymbol{E}_{\rm rec}(\boldsymbol{r})$ is the reciprocal field, and $\boldsymbol{E}_{\rm expt}(\boldsymbol{r})$ is the experimental field. But a sparse meander will cause the decrease of detection efficiency with optical patch antenna array. We assume that a single photon is normally incident on the detection surface, and the probability of a received photons is:

$$p = \frac{S_{\rm wire}}{S_{\rm active}}, \tag{5}$$

where $S_{\rm wire}$ is the meander area while $S_{\rm active}$ is the active area of the detector. When the width of nanowire is fixed, a longer nanowire will have a higher detection efficiency. The detection efficiency is determined by the length of nanowire as

$$\eta = \beta_\eta l, \tag{6}$$

where β_η is the equation parameter. Equations (3) and (6) can explain why it is hard to find a tradeoff between counting rate and detection efficiency of SNSPD.

In order to cope with this defect, we use the fan coupling antenna array to improve the detection efficiency without reducing the device speed since the structure parameters of the nanowire are not changed.

3. Results and discussion

The active area of SNSPD is ideally supposed to be infinite. The pitch of the structure is 600 nm[16] while the thickness of the metal is 180 nm. The parameters of the fan coupling antennas are chosen as: $l_1 = 17$ nm, $l_2 = 33$ nm, $g = 10$ nm, $w_1 = 20$ nm, $h = 43$ nm, and $r = 30$ nm.[17] The optical indices are $n_{\rm NbN} = 5.23 + 5.82{\rm j}$, $n_{\rm sapphire} = 1.75$, $n_{\rm HSQ} = 1.39$, and $n_{\rm gold} = 0.55 + 11.5{\rm j}$[18] at 1550 nm. The TM mode light is incident, and the scattering boundary conditions are used in the simulations.

Figure 2(a) shows the optical intensity distribution, which is positively correlated to photon collection efficiency with optical patch antenna array. We find that the total optical intensity contained in the NbN meander SNSPD without optical patch antenna is 1.98×10^{-12} W.

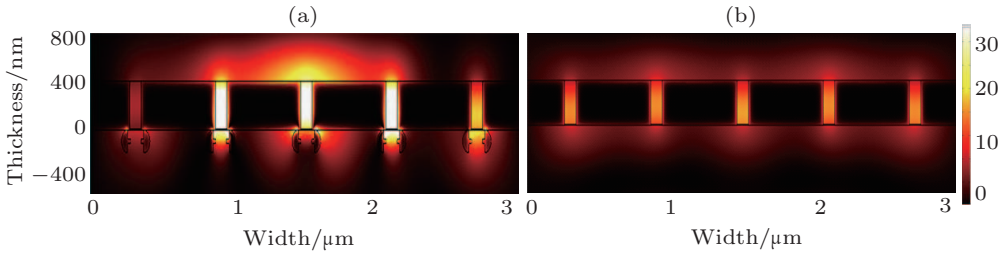


Fig. 2. (color online) Optical intensity distributions of 3-μm NbN meander SNSPD with optical patch antenna array (a) and without optical patch antenna array (b).

Compared with the structure without the antenna array shown in Fig. 2(b), we can easily see that there is a great enhancement of the intensity in each of all the gaps of the structure with the antenna array. Fan coupling antennas have the ability to enhance the incident intensity due to the gap between the two semicircle and the nanorods.[19] They can also localize the intensity in the gap. Surface plasmon polaritons (SPPs) are first generated at the incident end and go through the gap. They are then re-excited by the fan coupling antennas and are reflected back to the gap. Hence, there are more SPPs in the

gaps with the fan coupling antennas than without the antennas.

To better study the influence of antennas on the photon collection efficiency, we change the positions of the antennas and examine the optical intensity in the NbN area. The relation of active area optical intensity with the changing of h (or g) is obtained in Fig. 3. In Fig. 3(a), the optical intensity decreases as h increases, on the condition that the width of the gap is fixed and the SPP collection of the gap is also fixed. There is strong electromagnetic field located in the fan coupling antenna and the field is reflected back to the gap. The shorter distance between the bottom of the gap and the antenna is easy to make more SPPs back to the gap. Hence, the optical intensity is large with small h.

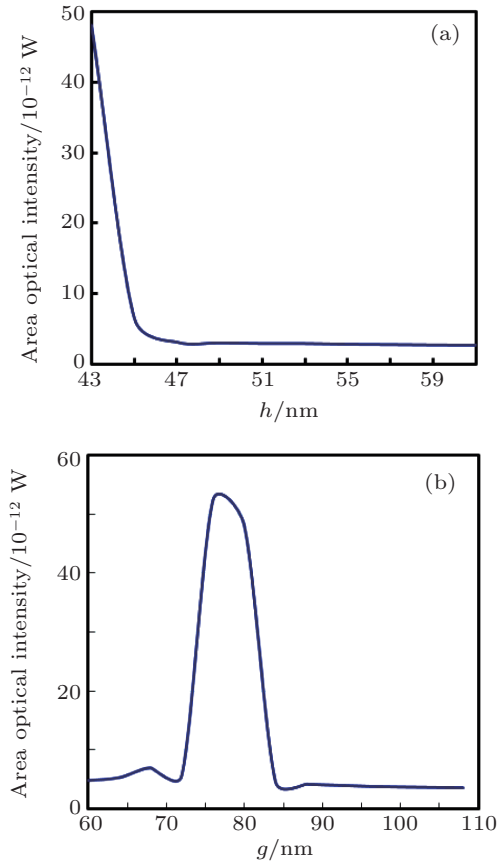


Fig. 3. (color online) Variations of area optical intensity with h (a) and g (b).

In Fig. 3(b), the variation of area optical intensity with g is shown on the condition that h equals 43 nm. There is a best position to make the intensity largest in the gap. The distance between the two parts of the fan antennas is a little smaller than w to achieve a largest intensity. The fan coupling antennas gain much more SPPs and they send these SPPs back to the gap. If g is larger than w, the fan coupling antennas have a longer gap and the ability to locate SPPs is weakened. If g is smaller than w, SPPs are first reflected back by the antennas and then located in the antenna. As a result, the number of SPPs is reduced and the area optical intensity is reduced.

In Fig. 3, the best position is obtained on the condition that h equals 43 nm and g equals 76 nm, where the whole optical intensity in the NbN region is about 5.24×10^{-11} W after the antennas have been added. Therefore, the collection efficiency is enhanced 26.5 times. Although the collection efficiency gained in our structure is 3.4 times less than that in a single-slot structure,[11] the gain is also obvious. The decrease happens because of the mutual interference between the periodical structure.

4. Conclusion

The performance of SNSPD involving niobium nitride with the fan coupling antenna array that has high detection efficiency and counting rate is analyzed. By using the fan coupling antenna array, we demonstrate that the photon collection efficiency is enhanced 26.5 times for NbN meander SNSPD with a length of 3 μm, which represents a higher detection efficiency. Furthermore, since the structure parameters of nanowire do not change, the reset time will also not change. Thus, the detection efficiency of SNSPD is enhanced without changing the detection speed of the device.

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