PHOTONICS Research

Design of a low-filling-factor and polarization-sensitive superconducting nanowire single photon detector with high detection efficiency

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We designed a low-filling-factor and polarization-sensitive superconducting nanowire single photon detector (SNSPD), which can achieve a high absorption efficiency and counting rate simultaneously. Numerical simulations show that high absorption efficiency can be achieved by low-filling-factor SNSPDs with a silicon slot and silver reflector. The absorptance of the NbN nanowire for a transverse magnetic (TM) wave at the wavelength of 1550 nm can be 84.4% when the filling factor is only 16.5%, and the corresponding polarization extinction ratio (PER) is 562.9; the absorptance of the NbN nanowire for a transverse electric (TE) wave can be 67.0% when the filling factor is only 11.7%, and the PER is 7.4.   © 2019 Chinese Laser Press

1. INTRODUCTION

Superconducting nanowire single photon detectors (SNSPDs) have various promising applications, including quantum optics experiments [1,2], quantum key distribution [3], satellite communication [4], single photon quantum imaging [5], and life sciences [6], due to their excellent performances such as high system detection efficiency (SDE) [7], high counting rate [8], broad spectral range (from visible to infrared wavelengths) [9], ultralow dark counting rate (DCR) [10], and low timing jitter [11]. Among these features, SDE is primarily important for the performance of SNSPDs. It is well known that the absorption efficiency is a vital point to achieve a high SDE and is related to the material of the superconducting nanowires and the structure of the SNSPDs [2]. To improve the absorption efficiency, many methods have been proposed such as SNSPDs integrated with an optical cavity [12], SNSPDs integrated with plasmonic structures [13], SNSPDs integrated with an optical nano-antenna [14], and the use of amorphous WSi as the superconducting material [7,15]. Using these methods, the incoming photons are strongly confined in the optical cavity, the electric field near the nanowires is enhanced, and the reflection and transmission of SNSPDs are decreased. Hence, high absorption efficiency can be achieved. However, all these devices suffer from an inevitable trade-off between the aim to maximize their absorption efficiency and the aim to maximize their counting rate, another important parameter that determines the detection speed of the SNSPD, because all these devices have a dense

meander nanowire in a large active area to absorb incident photons efficiently to improve the absorption efficiency and, hence, the practical detection efficiency. The counting rate is limited by the recovery time of the bias current, which is determined by the kinetic inductance of the nanowire [16,17], and the kinetic inductance is proportional to the length of the nanowire. Generally, the dense meander nanowire has a higher absorption efficiency than the sparse meander nanowire in the same active area; however, the counting rate is lower because of the larger kinetic inductance due to the longer nanowire. So, the performance of the conventional low-filling-factor SNSPDs needs to be enhanced. Here, the filling factor is defined as the nanowire width divided by the pitch of the nanowire.

Another system parameter of SNSPDs, the polarization sensitivity, has attracted the attention of many researchers in recent years, because understanding and utilizing polarization that is a primarily important property of light could greatly expand and enrich optical applications [18]. It is well-known that there is a strong dependence between the absorption efficiency and the polarization states of the incident light for SNSPDs, due to the dense periodic meander structures of the superconducting nanowires [19]. So, it is an advantage to fabricate detectors that are highly sensitive to the polarization of light. However, most previous research focused on designing polarization-insensitive SNSPDs [20,21]. With the development of SNSPDs and the increase of applications, it is important to consider whether these system parameters such as absorption efficiency, counting

rate, and polarization sensitivity can be achieved simultaneously when the performances of the devices are evaluated.

In this paper, we propose a method to solve the trade-off between absorption efficiency and counting rate by using the structure with silicon (Si) slots and a silver (Ag) reflector. Moreover, due to the meandered nanowire geometry structure, the SNSPD is also highly polarization sensitive. Numerical simulation results show that the absorption efficiency has a sharp increase and then a sharp decrease when the filling factor is in a special value range. Due to the sharp increase of the absorption efficiency, we design a low-filling-factor SNSPD that can achieve a high optical absorption efficiency, an increased counting rate, and high polarization sensitivity regardless of whether the incident photons are transverse magnetic (TM) polarized or transverse electric (TE) polarized.

2. OPTICAL ABSORPTION EFFICIENCY

The superconducting nanowire of a conventional SNSPD is normally fabricated in a meander pattern, which can be approximated as a periodic structure. The optical absorption efficiency (denoted by A) of the superconducting nanowire can be expressed as [22]

$$A = \frac{\int_{-w/2}^{w/2} \int_0^t w \, \text{Im}[\varepsilon]|E|^2 dxdy}{\int_{-p/2}^{p/2} \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} |E_0|^2 dx}, \quad (1)$$

where w and t are the width and thickness of the nanowire, respectively; p is the lateral pitch of the unit cell; E_0 is the electric field of the incident light; E is the electric field within the nanowire; ε is the dielectric constant of the nanowire; and ε_0 and μ_0 denote the permittivity and permeability of the background material, respectively. From Eq. (1), it is obvious that the electric field intensity inside the nanowire determines the absorption efficiency of the SNSPD. In order to investigate the relation between the absorption efficiency and other structure parameters, a commercially available numerical simulation software, i.e., FDTD Solutions (by Lumerical Inc.) is used. Figure 1 shows the simulated structure consisting of a Ag reflector, Si and hydrogen silsesquioxane (HSQ) slot, NbN
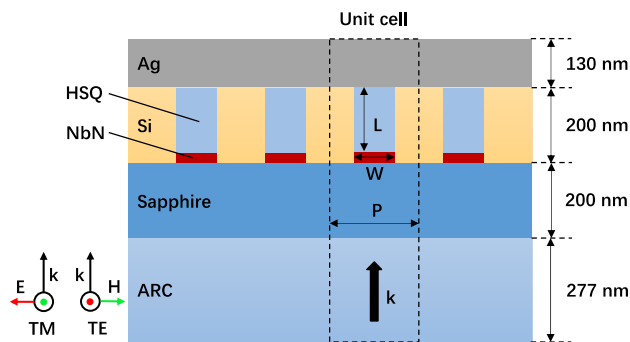
nanowire, sapphire substrate, and anti-reflection coating (ARC) from top to the bottom (the illumination side). The thicknesses of the NbN nanowire, Ag, Si, sapphire, and ARC layers are 4, 130, 200, 200, and 277 nm, respectively. In the simulation, complex refractive indices $n_{\text{Ag}} = 0.322 + i10.99$ [23], $n_{\text{Si}} = 3.628$ [23], $n_{\text{NbN}} = 4.905 + i4.293$ [23], $n_{\text{HSQ}} = 1.4$ [12], and $n_{\text{Sapphire}} = 1.74$ [12] were used. The region surrounded by the dashed line indicates the unit cell for the numerical simulation. The pitch of the unit cell, the length of the cavity, and the width of the nanowire are denoted by P, L, and W, respectively. The wavelength of incident light is 1550 nm. The TM wave was assumed to be polarized perpendicularly to the nanowire, and the TE wave was assumed to be polarized parallel to the nanowire, as shown in Fig. 1. HSQ was chosen as the ARC due to its low index of refraction at 1550 nm, and 277 nm of HSQ was required for the $\lambda/4$ ARC [12]. Periodic boundary conditions were used in the simulation, and edge effects of the meander nanowire were neglected.

This structure is similar to the structure of the SNSPDs adding a metal optical antenna [14]; however, because of the use of Si dielectric, which is a high refractive index material to compensate the dielectric mismatch between the NbN nanowire and the slot material [24], the performance of the SNSPDs is different. To demonstrate the superior performance of low-filling-factor SNSPDs, they are compared with conventional SNSPDs with a Ag optical antenna in the following discussion. The only difference is the slot material, while the other parts remain the same. First, we investigated the distribution of the electric field in the structure for the two different materials and two orthogonal polarization states.

Figure 2 shows the electric field intensity for the Ag-HSQ-Ag slot and Si-HSQ-Si slot when the incident light is TM polarized. The electric field intensity in the Si slot is higher than that in the Ag slot, especially, in the region where the NbN nanowires are placed. The same result for the TE waves can be obtained from Fig. 3. A high electric field intensity in the nanowire corresponds to a high absorption efficiency of the SNSPD. It is worth noting that the optimum pitches of the unit cell are different for TM and TE incident waves when the absorption efficiencies achieve the maximum, which can be illustrated by
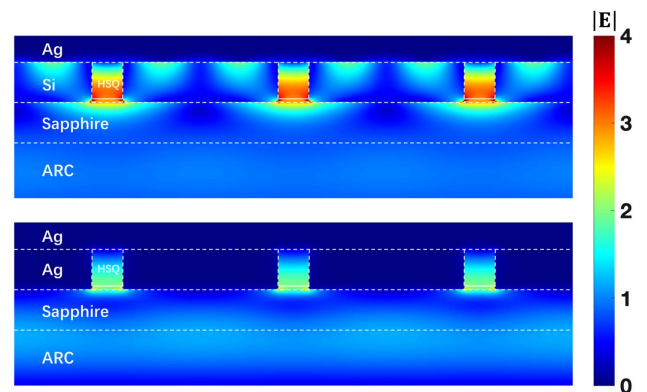

Fig. 1. Schematic of the stack structure of the SNSPD with a Si slot and Ag reflector. The region surrounded by the dashed line indicates the unit cell for the numerical simulation. The pitch of the unit cell, the length of the cavity, and the width of the nanowire are denoted by P, L, and W, respectively. The direction of the incident light is shown by the black arrow, and the polarization directions of TM and TE waves are marked.

Fig. 2. Distributions of the electric field intensity in the Si-HSQ-Si slot (picture above) and that in the Ag-HSQ-Ag slot (picture below). The incident light is TM polarized, the pitch is 486 nm, and the width of the nanowire is 80 nm.
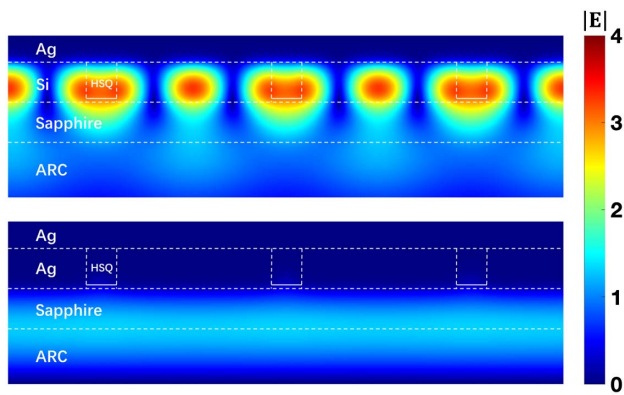
Fig. 3. Distributions of the electric field intensity in the Si-HSQ-Si slot (picture above) and that in the Ag-HSQ-Ag slot (picture below). The incident light is TE polarized, the pitch is 682 nm, and the width of the nanowire is 80 nm.

Fig. 4. Then, we consider the relation between the optical absorption efficiency and the pitch. The structure parameters in Fig. 1 were chosen, and the nanowire width was fixed to 80 nm when the value of the pitch was constantly increased in the simulation. Figure 4 shows the calculated absorption efficiency dependence of the pitch for different slot materials, Si and Ag. Two representative polarization states (TM polarized and TE polarized) of the incident light were selected for comparison. In principle, the absorption efficiency of the nanowire in the Ag slot is decreasing slowly with the increase of pitch for both TM and TE waves. The absorption efficiency is very low for TE waves due to the polarization sensitivity of the SNSPD [19]. For the Ag slot, the absorption efficiency will decrease with the filling factor increasing. When the pitch exceeds 380 nm, the absorption efficiency is lower than 60%. This is why the performance of the conventional low-filling-factor SNSPDs is poor. However, the absorption efficiency for the Si slot has a sharp decrease, compared with the Ag slot, with the filling factor reducing, has a sharp increase after the value is close to 0, and then is up to the maximum value when the pitch is in a special value range. According to our simulation, the
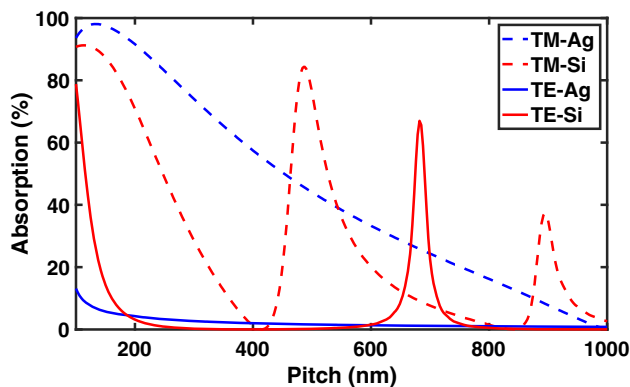
absorption efficiency of the NbN nanowire in the Si slot for TM waves is 84.4% when the pitch was 486 nm (16.5% filling factor); the absorption efficiency of the NbN nanowire in the Si slot for TE waves is 67.0% when the pitch was 682 nm (11.7% filling factor). When the pitch of the unit cell changed, the distribution of the electric field would be changed because Si, a high-index dielectric, was applied as the slot material. It has a strong transmission of light at the wavelength of 1550 nm compared to Ag. When the value of the pitch reaches a special range, the absorption efficiency has a sharp increase due to the electric field intensity in the region of the nanowire being greatly enhanced. It is different from the non-resonant collection effect when Ag was used as the slot material [14]. So, the absorption efficiency has a sharp increase for both TM and TE waves when the pitch is changed. This special situation can be used to design a low-filling-factor SNSPD with high absorption efficiency.

In order to achieve the optimal absorption efficiency, the resonant optical cavity effect needs to be considered. Because the pitch to achieve high absorption efficiency in TM mode and TE mode has already been calculated, the pitch was fixed to 486 nm for TM-polarized incident light and 682 nm for TE-polarized incident light, and the width of the nanowire is fixed to 80 nm. Figure 5 shows the calculated optical absorption efficiency dependence on the cavity length, which is defined as the vertical distance between the NbN nanowire interface and the Ag reflector. When Ag was chosen as the slot material, each Ag-HSQ-Ag slot and the Ag reflector form a cavity, eliminating optical transmission and reducing reflection, and thus the incident photons are strongly absorbed by the NbN nanowire. The absorption efficiency oscillates with the cavity length, demonstrating the cavity effect, for the TM waves [14]. The absorption efficiency maintains a very low level for the TE waves, with the cavity length changed, because of the polarization sensitivity issue. Similarly, when Si was chosen as the slot material, each Si-HSQ-Si slot and the Ag reflector also form a cavity. Due to the Si material, which compensates the dielectric mismatch between the NbN nanowire and the cavity and has a strong optical transmission of light at the wavelength
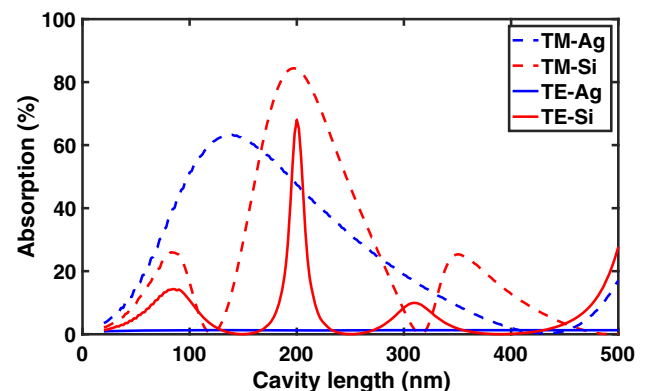

Fig. 4. Simulated pitch dependence of the optical absorptance in the nanowire. The dashed blue, solid blue, dashed red, and solid red lines represent the Ag-HSQ-Ag slot with TM incident waves, Ag-HSQ-Ag slot with TE incident waves, Si-HSQ-Si slot with TM incident waves, and Si-HSQ-Si slot with TE incident waves.

Fig. 5. Simulated cavity length dependence of the optical absorptance in the nanowire. The dashed blue, solid blue, dashed red, and solid red lines represent the Ag-HSQ-Ag slot with TM incident waves, Ag-HSQ-Ag slot with TE incident waves, Si-HSQ-Si slot with TM incident waves, and Si-HSQ-Si slot with TE incident waves.

of 1550 nm, the electric field in the Si slot is enhanced and is even higher than that in the Ag slot. The absorption efficiency is maximum as the cavity length is about 200 nm for both TM and TE waves. With the optimum cavity length, the maximum absorption efficiency of the nanowire in the Si slot is higher than that in the Ag slot for both TM and TE waves. It is obvious from the amplitudes of change that the absorption efficiency for TE-polarized photons is more sensitive than that for TM-polarized photons as the cavity length changed.

To investigate the correlation between the pitch and cavity length when Si was used as the slot material, Fig. 6 shows the calculated optical absorption efficiency dependence on the pitch when the cavity lengths are different. For TM waves, the optimum pitch is slightly reduced, and the maximum absorption efficiency is slightly decreased when the cavity length is increased. For TE waves, the optimum pitch is greatly reduced, and the maximum absorption efficiency is slightly increased when the cavity length is increased. It shows that the change of cavity length can affect the optimum pitch for both TM and TE waves, and nanowire is more sensitive to parallel-polarized photons than perpendicular-polarized photons [22]. Considering the errors in realistic fabrication, we also investigated the absorption efficiency dependence on the width of the nanowire. Figure 7 shows that when the width deviates from 80 nm, the absorption efficiency changes slowly for TM waves, but decreases sharply for TE waves. So our design is less sensitive to fabrication tolerance in terms of nanowire width when the incident light is TM polarized than when it is TE polarized. It is the same conclusion for the fabrication tolerances in terms of pitch and cavity length shown in Figs. 4 and 5.
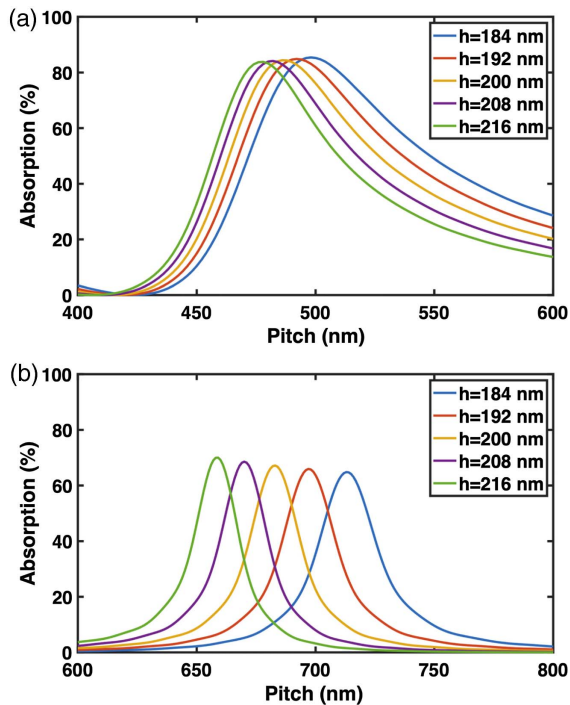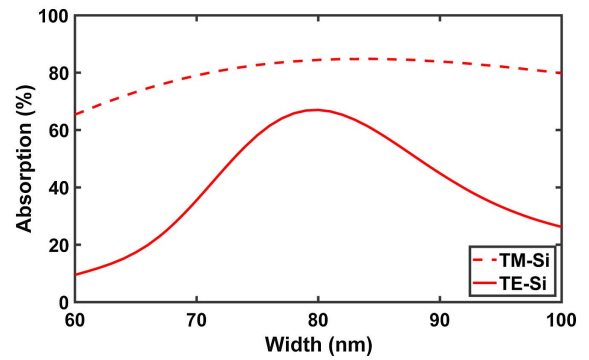
Fig. 7. Simulated nanowire width dependence of the optical absorptance in the nanowire. The cavity length is fixed to 200 nm. For TM waves, the pitch is 486 nm. For TE waves, the pitch is 682 nm.

By optimizing the pitch, cavity length, and nanowire width, a low-filling-factor SNSPD with a high absorption efficiency can be obtained, and the simulation can also provide some guidance for realistic fabrication. Next, its performance of the counting rate and the polarization sensitivity will be considered.

3. COUNTING RATE AND POLARIZATION SENSITIVITY

Kinetic inductance determines the counting rate of the SNSPDs [17]. The kinetic inductance of the nanowire can be expressed as

$$L_k = \mu_0 \lambda^2 l/S, \tag{2}$$

where μ_0 is the vacuum permeability, λ is the penetration depth, l is the nanowire length, and S is the cross-section area of the nanowire. The reset time τ, which is defined as the time needed for device efficiency, after a detection event recovers up to 90% of the device efficiency if there was no detection. From L_k, we can obtain τ, which is also defined as the time needed for the current to recover from 0 to $I_{90\%}$ by

$$\tau = \frac{L_k}{R} \ln\left[1\left/\left(1 - \frac{I_{90\%}}{I_b}\right)\right.\right], \tag{3}$$

where I_b is the bias current, $I_{90\%}$ is the current when the device efficiency is 90% of the device efficiency at I_b, and $R = 50\ \Omega$. In the following analysis, we assumed that $I_b = 0.95 I_c$, where I_c is the critical current of the superconducting nanowire, and $I_{90\%} = 0.9 I_c$ [14]. After our simulation, Fig. 4 shows that the absorption efficiency of the 16.5%-filling-factor SNSPD is as high as that of the conventional 33.6%-filling-factor SNSPD with the Ag slot for TM incident light. It is assumed that two kinds of devices have active areas of the same size and NbN nanowires of the same width. After being calculated, the length of the 16.5%-filling-factor nanowire is about 50.3% of the length of the 33.6%-filling-factor nanowire, with the same result for L_k. So, it can be roughly estimated that the reset time of the 16.5%-filling-factor SNSPD is 50.3% of that of the conventional 33.6%-filling-factor SNSPD. This is just an approximate calculation, and there are many other factors to consider in practice. For the TE incident light, the 11.7%-filling-factor SNSPD has about 67% absorption efficiency, which is much higher than that of the conventional

Fig. 6. Simulated pitch dependence of the optical absorptance in the nanowire when the cavity lengths are different, and the nanowire width is fixed to 80 nm. (a) The incident light is TM polarized. (b) The incident light is TE polarized.

SNSPD regardless of any filling factor. It indicates that our proposed SNSPD can achieve the improved counting rate and have a better performance in the high-speed detection situations.

When the Si material was chosen to compensate the dielectric mismatch between the nanowire and the cavity, the polarization sensitivity of the SNSPD is greatly reduced [21]. In order to recover the high polarization sensitivity of the SNSPD, we utilized the meandered nanowire geometry structure. Due to the Si-HSQ-Si slot structure, the polarization sensitivity of the SNSPD is greatly improved. Figure 8 shows the simulated polarization related to the absorption efficiency and the corresponding polarization extinction ratio (PER) for the SNSPD. The angle is defined as the angle between the polarization direction and the direction perpendicular to the nanowire. Figure 8(a) shows that the PER is about 562.9, and the corresponding maximal absorption efficiency is 84.4% when the pitch is 486 nm. Here, the PER is defined as the absorption efficiency ratio of the TM to TE wave. It is also obtained that the PER is about 7.4, and the corresponding maximal absorption efficiency is 67.0% when the pitch is 682 nm from Fig. 8(b). The difference is the PER, which is defined as the absorption efficiency ratio of the TE to TM wave here. The shape of curves is like a peanut, further demonstrating the high polarization sensitivity of the SNSPD. In order to further investigate the relationship between the PER and structural parameters, especially considering the realistic fabrication errors, the PER related to the pitch when the nanowire widths are different was discussed. Figure 9(a) shows that the optimum pitch is reduced slowly, but the maximum of the PER is increased sharply when the nanowire width is reduced for TM waves. As shown in Fig. 9(b), for TE waves, the optimum pitch is reduced sharply, and the maximum of the PER is increased slowly and is more sensitive to the changes of pitch. It is worth noting that when the PER is maximum, the absorption efficiency is not the optimum, because the PER is a ratio. When the nanowire width is reduced, the PER can achieve a higher value, but the absorption efficiency is reduced at the same time. So, it has a trade-off between the absorption efficiency and the PER in our design, but the PER is already very large when the absorption efficiency is the optimum.
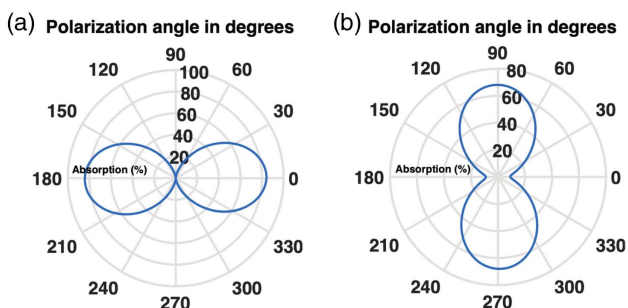

Fig. 9. Simulated PER dependence on the pitch when the nanowire widths are different, and the cavity length is fixed to 200 nm. (a) The incident light is TM polarized. (b) The incident light is TE polarized.

4. CONCLUSIONS

In conclusion, we have proposed a low-filling-factor SNSPD, which can achieve a high absorption efficiency, high counting rate, and high polarization sensitivity simultaneously. By numerical simulation and analysis, we found that a high absorption efficiency can be achieved even for the low-filling-factor SNSPD for both TM and TE waves by utilizing the Si-HSQ-Si slot and Ag reflector and setting the pitch of the unit cell in a special value range. Due to the meandered nanowire geometry structure, the SNSPD also has a high sensitivity to the polarization of the incident light. For TM waves, the SNSPD with a 16.5% filling factor shows a high absorption efficiency of 84.4% and PER of 562.9. For TE waves, the SNSPD with a 11.7% filling factor shows a high absorption efficiency of 67.0% and PER of 7.4. The value of the PER can be larger, as long as the absorption efficiency is sacrificed. The absorption efficiency and polarization sensitivity have strong dependence on the pitch of the unit cell. The low-filling-factor SNSPDs also have a high counting rate and a better performance in the high-speed detection situation. Our design in this paper provides a strategy to achieve high absorption efficiency, high counting rate, and high polarization sensitivity SNSPDs, which can be applied in a wide range of fields.

Fig. 8. Simulated polarization dependence of the absorption efficiency in the polar coordinate system. The angle is defined as the angle between the polarization direction and the direction perpendicular to the nanowire. The cavity length is 200 nm, and the nanowire width is 80 nm. (a) The pitch is 682 nm. (b) The pitch is 486 nm.
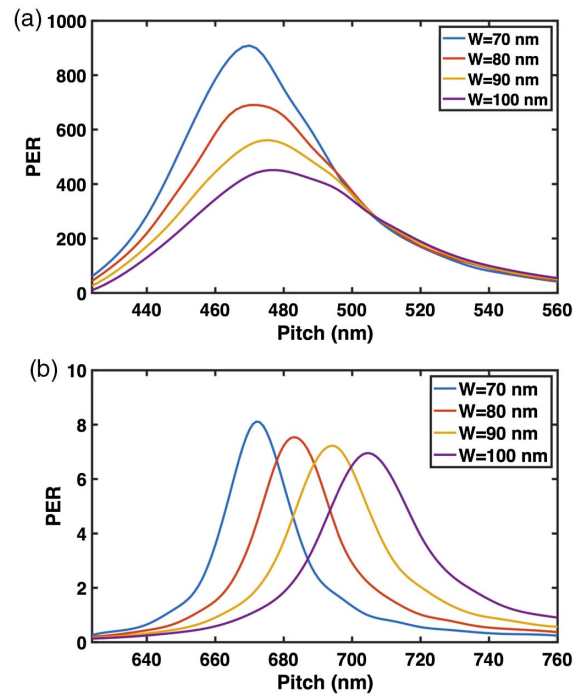
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