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Using Surface Plasmons to Enhance the Speed and Efficiency of Superconducting Nanowire Single-Photon Detectors

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Abstract: We report our design and fabrication of superconducting nanowire single-photon detectors integrated with gold plasmonic nanostructures, which can enhance the absorption of TM-polarized light, and can enlarge the effective area without sacrificing detector speed.

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Niobium nitride (NbN) superconducting nanowire single-photon detectors (SNSPDs) are an emerging, ultrasensitive photon counting technology which outperforms others at infrared wavelengths. Applications such as fiber-based quantum key distribution [1] have already been demonstrated. However, some other applications such as linear optical quantum computing require efficiency approaching 100%. Furthermore, there is inevitably a trade-off between coupling efficiency and the speed of the detector: coupling light into the detector requires a long meander to cover a large area, which will slow down the detector because its speed is limited by the kinetic inductance of the nanowire, proportional to the nanowire length. A multi-element approach [2] can solve this problem, but requires more complicated readout electronics. Thus, it is desirable to realize more efficient and faster single-element SNSPDs.

To make each individual detector more efficient and faster, we integrated SNSPDs with subwavelength gold gratings and cavities. The advantages of adding these gold plasmonic nanostructures are two-fold: firstly, the absorption of transverse-magnetic (TM)-polarized light can be enhanced to 96% according to our finite-element simulation; secondly, the effective area can be enlarged to facilitate its coupling with other optical systems without increasing the nanowire length. Therefore, the coupling-speed tradeoff can be reduced on the single-element level.

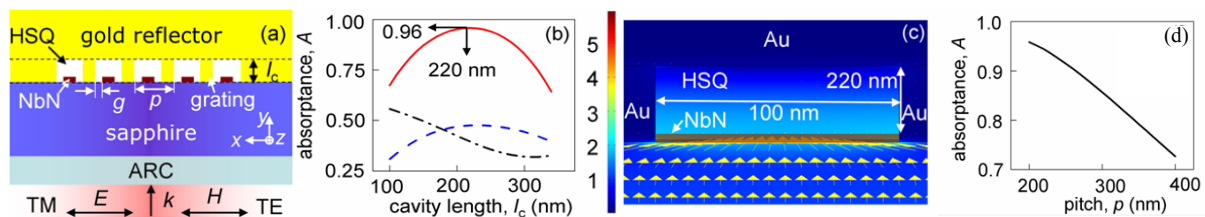


Fig. 1. A superconducting nanowire single-photon detector integrated with a gold grating and reflector: (a) device cross section (not to scale); (b) absorbance for TM-polarization as a function of cavity length, l_c (solid line, $p = 200$ nm), also compared with the detectors only integrated with a cavity (dashed line, $p = 200$ nm) or a grating (dash-dotted line, $p = 200$ nm); (c) the electrical field magnitude distribution (surface, with arbitrary units) and optical power flow (arrow) near the NbN nanowire, and note that the figure is not to scale; (d) absorbance for TM-polarization as a function of the pitch, p , by varying the width of the gold between adjacent NbN nanowires.

The device structure is schematically shown in Fig. 1 (a). Compared with the detector that our group demonstrated in the past [3], the key element added here is a gold sub-wavelength grating between adjacent NbN nanowires. This gold grating essentially behaves as a set of optical antennae because it can effectively collect TM-polarized incident photons as we will show below. For fabrication considerations, the gold grating layer is designed to connect with the gold reflector. On top of the NbN there is a 2-nm-thick layer of NbNO_x (not shown). The cavity length l_c is defined as the distance between the top surface of NbNO_x and the bottom surface of the reflector. Inside the cavity is hydrogen silsesquioxane (HSQ), commonly used as a resist for electron-beam lithography. The gap between the gold grating and the adjacent NbN is noted as g .

We performed finite-element optical simulation on this structure. The detector is illuminated from the bottom through the substrate, and the wavelength used throughout this paper is 1550 nm. For TM-polarization, the

absorptance peaks at $l_c = 220$ nm and the corresponding absorptance is 0.96 as shown in Fig. 1 (b). The absorptance of NbN with the cavity only and with the gold grating only was also obtained by simulation, shown as the dashed line and the dash-dotted line in Fig. 1(b), respectively. As a comparison, the largest absorptance with cavity only is $\sim 70\%$ when the light is TE-polarized.

The ability of the grating to collect the TM-polarized photons onto the NbN is shown in Fig. 1(c) by plotting the optical power flow (arrows): the photons are concentrated in the slot between the gold where the NbN is located. Essentially the gold grating acts as an array of metal-insulator-metal surface-plasmon waveguides, and such waveguides support modes with TM-polarization.

The effective active area of the detector can be enlarged by increasing the width of the gold structure without increasing the length of the NbN nanowire. Shown in Fig. 1(d), as the pitch increases from 200 nm to 400 nm by increasing the width of the gold grating between the NbN nanowires from 100 nm to 300 nm, while keeping other parameters unchanged, the absorptance is gradually reduced to 0.73. With sacrificing some absorptance, the total area of the detector is doubled, which makes coupling easier, which can increase the coupling efficiency.

We fabricated the detectors with an integrated gold grating and cavity. The process is simple and straightforward: the major difference with the process we used in the past [3] is that here, we used undiluted FOx-14 to yield much thicker resist about 230 nm. We demonstrated that direct e-beam writing on such thick HSQ with appropriate doses can yield uniform nanowire meander structure. After 100 second reactive ion etching with tetrafluoromethane, the rest thickness of HSQ was measured to be 200 nm. We spun ~ 1 μm S1813 photoresist and opened a window aligned with the devices. We evaporated 10 nm silicon oxide followed by 3 nm titanium and 330 nm gold, and did lift-off in N-Methyl-2-pyrrolidone at 90 °C. After liftoff, the devices with 100 nm wide NbN nanowire on 300 nm pitch are shown in Fig. 2 with the gold grating and cavity structure.

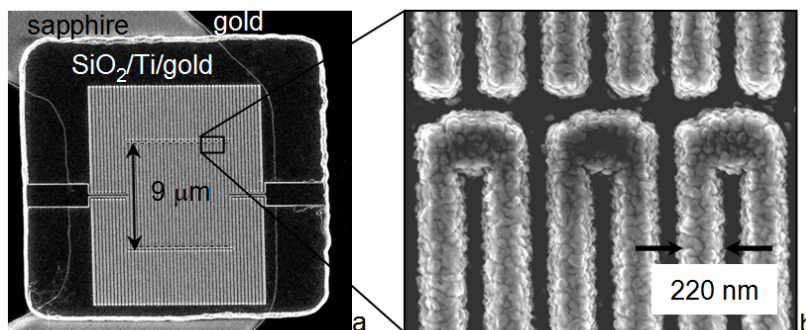


Fig. 2. Scanning electron microscopic images of a detector with integrated gold grating and cavity. The detector is 9- μm -by-9- μm in area, with 100-nm wide NbN nanowire meander and a pitch of 300 nm, and coated with 10-nm silicon oxide, 3-nm titanium and 330-nm gold.

In summary, we have designed and fabricated superconducting nanowire single-photon detectors integrated with gold gratings and cavities. According to our design, the absorption of TM-polarized incident light can be greatly enhanced, and the effective area of the detector can be enlarged without increasing the length of the nanowire. We believe that these detectors can work simultaneously with high system detection efficiency and high speed.

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