Optimized Illumination Directions of Single-photon Detectors Integrated with Different Plasmonic Structures

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Abstract

The near-field enhancement accompanying plasmon excitation on noble metal structures is widely applied in recent science and technology. The fulfillment of double resonance condition, i.e. when localized and propagating plasmonic modes are excited simultaneously on periodic arrays of resonant plasmonic objects, enables to enhance different optical phenomena [1]. Our previous studies have proven that illumination of different superconducting nanowire single-photon detectors (SNSPDs) at optimum directions results in significant absorption enhancement [2, 3]. The purpose of present study was the design of novel SNSPDs integrated with plasmonic structures having potential to exploit double resonance phenomena. The optimum illumination directions of different SNSPD designs were determined by COMSOL. Absorption of niobium-nitride (NbN) stripes with parameters according to conventional SNSPDs was studied in two different periodicity regions having potential to realize absorptance maximization (p=220 nm) and parallel electrical optimization (3p=660 nm). Both NbN patterns were integrated with (1) single ~quarter-wavelength dielectric-filled nano-optical cavity closed by a thin gold reflector (OC-SNSPD) (Figure 1a & 2a), (2) nano-cavity-array closed by vertical and horizontal gold segments (NCAI-SNSPD) (Figure 1b & 2b), and (3) nano-cavity-deflector-array consisting of longer vertical segments with proper periodicity (NCDAI-SNSPD) (Figure 1c & 2c). Port boundary condition was applied to define illumination by p-polarized light in conical mounting and periodic boundary conditions were set at the vertical sides of models consisting of three/one unit cells of 220/660 nm periodic integrated patterns. Both polar and azimuthal angles were swept with 5° steps in dual-angle studies, and then the polar angle was tuned with 1° and 0.05° resolutions in entire [0°-90°] region and around maxima at optimum azimuthal orientations. Finally, the time evolution of the E-field distribution was studied. The comparative study of the optical responses and near-field patterns indicated that the optimum orientation fundamentally depends on the detector design. The optimum illumination direction of OC-SNSPDs is perpendicular incidence onto NbN stripes in P- orientation (0° azimuthal angle), when the gold reflector ensures E-field concentration around NbN segments aligned at the bottom of nano-optical cavity (Figure 1-4/a). Improved absorptance is achievable in S-orientation (90° azimuthal angle) of NCAI-SNSPDs and NCDAI-SNSPDs, due to excitation of localized plasmonic modes in arrays of MIM nano-cavities (Figure 1-4/b, c). In short-periodic NCAI-SNSPD the almost polar-angle-independent perfect absorptance is slightly perturbed by total internal reflection and propagating surface plasmon excitation (Fig. 1b & 3b). In long-periodic NCAI-SNSPD the enhanced reflectance precludes the possibility of absorptance maximization, since the

surface waves propagating below the nano-cavity-array result only in local absorptance maxima (Figure 2b & 4b). The advantage of deflectors with proper periodicity is enhanced absorptance at small polar angles in both NCDAI-SNSPDs, and the appearance of large absorptance maximum in long-periodic NCDAI-SNSPD (Figure 1-4/c). This is due to appropriate deflection of plasmonic modes propagating below the NbN stripes. The orientation of NCDAI-SNSPD at polar angle corresponding to double resonance condition is capable of compensating three times lower fill-factors due to E-field confinement via plasmonic modes excited in cavities above and propagating below NbN stripes (Figure 2c & 4c).

Reference

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2. M. Csete, Á. Sipos, F. Najafi, X. Hu, and K. K. Berggren, "Numerical method to optimize the polar-azimuthal orientation of infrared superconducting-nanowire single-photon detectors," Appl. Opt. 50/29 5949-5956 (2011).
3. M. Csete, Á. Sipos, A. Szalai, G. Szabó: "Impact of polar-azimuthal illumination angles on efficiency of nano-cavity-array integrated single-photon detectors", Optics Express, 20/15 (2012) 17067.

Figures used in the abstract

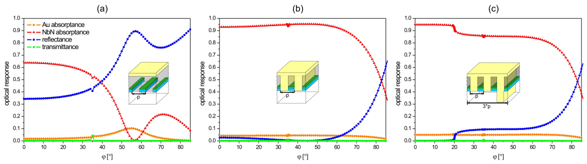

Figure 1: Optical responses of short-periodic designs as a function of polar angle: (a) OC-SNSPD, (b) NCAI-SNSPD, (c) NCDAI-SNSPD.

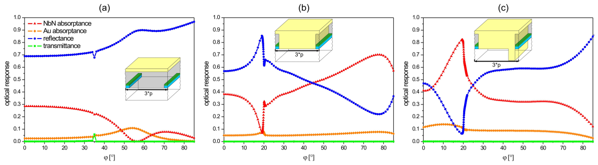

Figure 2: Optical responses of long-periodic designs as a function of polar angle: (a) OC-SNSPD, (b) NCAI-SNSPD, (c) NCDAI-SNSPD.

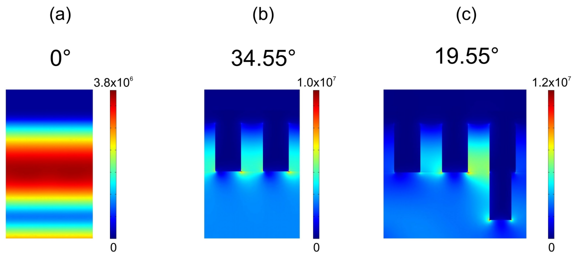

Figure 3: Near-field distribution in short-periodic designs at (a) global maximum in OC-SNSPD, (b) local maximum in NCAI-SNSPD, (c) inflection point in NCDAI-SNSPD.

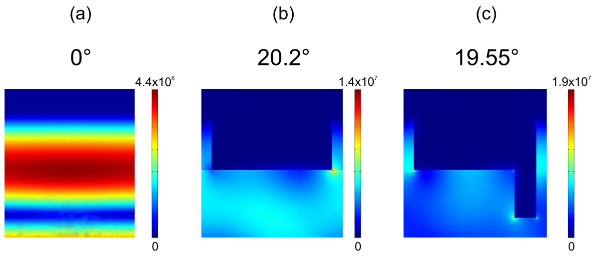

Figure 4: Near-field distribution in long-periodic designs at (a) global maximum in OC-SNSPD, (b) local maximum in NCAI-SNSPD, (c) global maximum in NCDAI-SNSPD.