Methods to Optimize Plasmonic Structure Integrated Single-Photon Detector Designs

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Abstract

Introduction: Predesigned plasmonic structures are capable of enhancing optical phenomena, the key concept is tailoring the integrated devices' composition to engineer the spectral response and near-field distribution [1]. Our previous studies have shown that three-quarter-wavelength periodic plasmonic structures are capable of improving single-photon detection efficiency [2, 3]. Parametric sweep method in RF Module of COMSOL Multiphysics® software was used to determine the optimal orientations of different detectors, where coupling of localized and propagating modes makes possible to achieve large absorptance. The purpose of present study was to optimize plasmonic structure integrated superconducting nanowire single-photon detector (SNSPD) designs taking into account constraints, that ensure experimental realization.

Use of COMSOL Multiphysics: Integrated SNSPDs were designed, which consist of meandered absorbing niobium-nitride (NbN) patterns on silica substrate to ensure fabrication. Three designs were inspected (1) nano-cavity-array (NCAI-), (2) nano-cavity-deflector-array (NCDAI-) and (3) nano-cavity-double-deflector-array (NCDDAI-) integrated SNSPD (Figure 1). The integrated patterns' periodicity was set to the $P=792$ nm three-quarter-wavelength of SPPs propagating at gold-silica interface. The $w=100$ nm NbN stripes width and the $t=60$ nm closing gold reflector thickness was fixed. RF Module of COMSOL was applied to determine the optical response and near-field distribution in case of p-polarized 1550 nm light illumination of integrated SNSPD devices in conical mounting. In reference studies the length of the nano-cavities and deflectors was set to $h=220$ nm quarter-wavelength of MIM modes excitable in a single HSQ channel in gold. In optimization study the length of the HSQ filled gold cavities and of gold deflectors was optimized, while the double deflectors' length was kept equal to promote fabrication. The optimization was performed by applying Monte-Carlo and Nelder-Mead algorithms of COMSOL in two steps and by applying a special algorithm sequence. Finally the optimum illumination directions of different SNSPDs resulting in maximal NbN absorptance were determined by parametric sweeps.

Results: Comparative study of pre-set and partially optimized SNSPDs' optical responses has shown that the preferred orientations of these design types is very similar, however several percent NbN absorptance increase can be achieved in partially optimized systems (Fig. 2a-to-3a). The optimal azimuthal orientation of each devices is S-orientation ($\varphi=0°$ azimuthal angle). In NCAI-SNSPD the maximal absorptance is achieved at large tilting, however the maximum is

decreased from 73.7% to 65.6%, when the cavity length is optimized for perpendicular incidence. In NCDAI-SNSPD and NCDDAI-SNSPD the absorptance maxima appear at similar ~20° tilting and the achieved absorptance is increased from 78.2% and 86.8% to 79.7% and 89.9%, respectively, due to larger E-field enhancements attainable via cavities and deflectors with optimized length (Fig. 2b-d to Fig. 3b-d). The absorptance peaks are narrower in case of optimized cavity-deflector lengths, indicating that device optimizations have to be performed taking into account requirements of specific applications.

Conclusion: Optimization of integrated plasmonic structures' makes possible to achieve larger single-photon absorptance, already in case of large number of unvaried geometrical parameters determined by users and limits of fabrication. The most efficient optimization can be realized by a special algorithm sequence and monitoring changes in the band structure.

Reference

1. M. S. Tame, K. R. McEnery, S. K. Özdemir, J. Lee, S. A. Maier, M. S. Kim: Nature Physics 9 (2013): 329-340.

2. M. Csete, Á. Sipos, A. Szalai, G. Szabó: Optics Express, 20/15 (2012) 17067.

3. M. Csete, Á. Sipos, A. Szalai, G. Szekeres, F. Najafi, G. Szabó, K. K. Berggren: Scientific Reports 3 (2013): 2406.
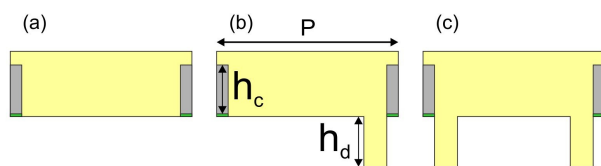
Figures used in the abstract

Figure 1: Fig. 1. Inspected plasmonic structure integrated single photon-detector designs (a) NCAI-SNSPD, (b) NCDAI-SNSPD, (c) NCDDAI-SNSPD.
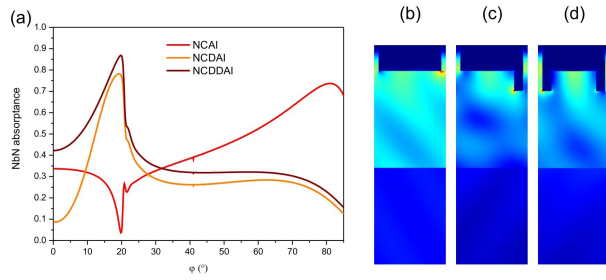
Figure 2: Fig. 2. (a) Achieved NbN absorptance as a function of polar angle in pre-set integrated systems (hc=220 nm, hd=220 nm). Normalized E-field distribution at the maxima in polar angle in pre-set (a) NCAI-SNSPD, (b) NCDAI-SNSPD, (c) NCDDAI-SNSPD.
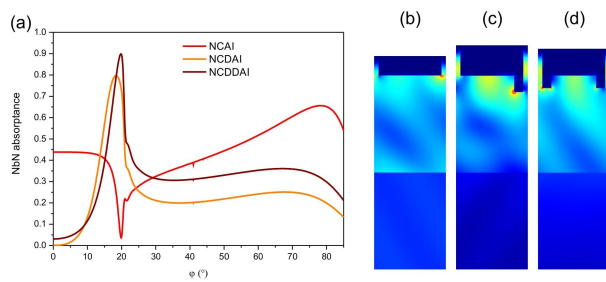

Figure 3: Fig. 3. (a) Achieved NbN absorptance as a function of polar angle in partially optimized integrated systems (hc=220 nm, hd=220 nm). Normalized E-field distribution at the maxima in polar angle in partially optimized (a) NCAI-SNSPD, (b) NCDAI-SNSPD, (c) NCDDAI-SNSPD.