

Abstract

The absorbance of SNSPDs' was improved by integrating (1) single ~quarter-wavelength HSQ-filled nano-optical cavity closed by a thin gold reflector (OC-SNSPD), and (2) nano-cavity-array consisting of vertical and horizontal closing gold segments (NCAI-SNSPD), into conventional periodic pattern of niobium-nitride (NbN) stripes. The optimal orientations were determined numerically by varying the polar and azimuthal illumination angles synchronously. It was shown that larger absorbance is achievable due to p-polarized illumination of NbN patterns in P-structure configuration in OC-SNSPD, while higher absorbance is achievable in S-structure arrangement in NCAI-SNSPD. The near-field study revealed that the highest absorbance observable at perpendicular incidence on P-structures in OC-SNSPD is due to the E-field concentration around NbN segments aligned at the nano-optical cavity and substrate interface. The peculiarity of NCAI-SNSPDs is that off-axis p-polarized light illumination results in almost polar-angle-independent perfect absorbance in S-structure arrangement, with shallow local maximum-minimum pair caused by TIR and surface plasmon excitation phenomena. Collective resonances in periodic arrays of plasmonic MIM nano-cavities ensure EM-field transportation to the NbN stripes effectively, capable of maximizing the absorbance in NCAI-SNSPD.

Introduction

- SNSPD [1, 2]
- OC-SNSPD [3, 4]
- NCAI-SNSPD [5, 6]
- illumination direction [7-10]

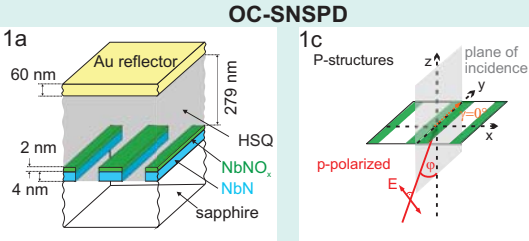


Fig. 1. Schematic drawings of the optical systems studied: 200 nm periodic pattern of 4 nm thick and 100 nm wide NbN stripes (a) arrayed below HSQ-filled nano-cavity having 279 nm length covered by a continuous 60 nm thick Au reflector; (b) integrated with MIM nano-cavity-array composed of 100 nm wide vertical and 60 nm thick horizontal gold segments. The two specific orientations studied in more details are: (c) P-structure configuration ($\gamma=0^\circ$), and (d) S-structure arrangement ($\gamma=90^\circ$).

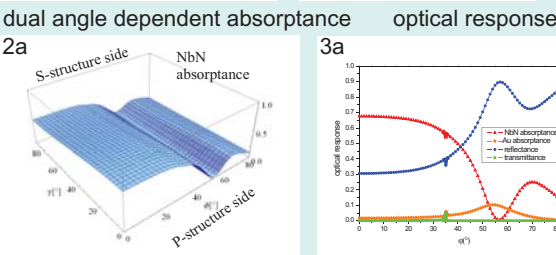


Fig. 2. Dual-angle-dependent absorbance due to p-polarized light illumination of NbN patterns (a) in OC-SNSPD, (b) in NCAI-SNSPD. The absorbance was determined by calculations performed over the $\gamma=[0-90^\circ]$ and $\varphi=[0-85^\circ]$ intervals, with $\Delta\gamma=\Delta\varphi=5^\circ$ resolution.

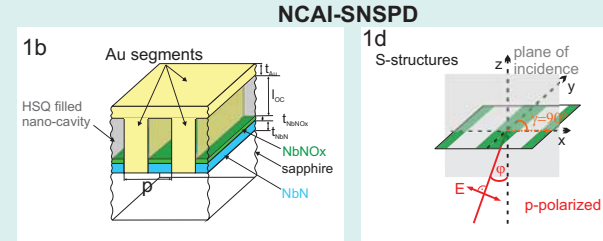


Fig. 3. Comparison of optical responses for the case of p-polarized light illumination of NbN patterns.

Fig. 3a. P-structure configuration ($\gamma=0^\circ$) in OC-SNSPD (grating-waveguide configuration [14]). The results of 0.05° resolution FEM calculations in $[34^\circ, 36^\circ]$ and (b) $[25^\circ, 36^\circ]$ intervals are merged into the graphs originating from computation performed with $\Delta\varphi=1^\circ$ resolution in $[0^\circ, 85^\circ]$ region.

Fig. 3b. S-structure arrangement ($\gamma=90^\circ$) in NCAI-SNSPD (coupled nano-cavity-array configuration [15]). The results of 0.05° resolution FEM calculations in $[25^\circ, 36^\circ]$ intervals are merged into the graphs originating from computation performed with $\Delta\varphi=1^\circ$ resolution in $[0^\circ, 85^\circ]$ region.

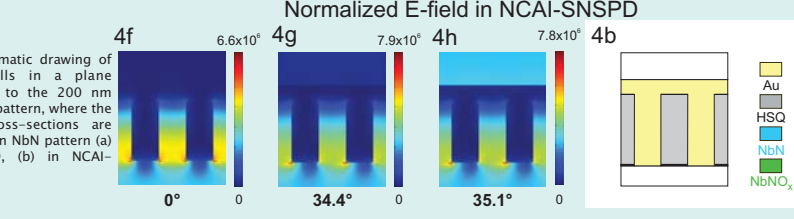
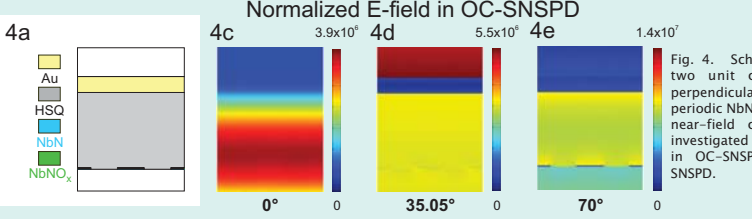


Fig. 4. The normalized E-field distribution due to p-polarized light illumination of OC-SNSPD in P-structure configuration indicates (c) E-field antinode at perpendicular incidence due to the gold reflector, (d) plasmon-related field enhancement above the reflector at 35.05° , (e) evanescent field enhancement at NbN-sapphire and below Au-HSQ interfaces at 70° .

Fig. 4. The normalized E-field distribution due to p-polarized light illumination of NCAI-SNSPD in S-structure arrangement indicates E-field confinement at the entrance of the HSQ cavities (f) with symmetrical intensity distribution at perpendicular incidence, (g) with asymmetrical distribution but maximal intensity value at 34.4° , (h) slightly decreased intensity caused by propagating plasmonic modes above the reflector at 35.1° .

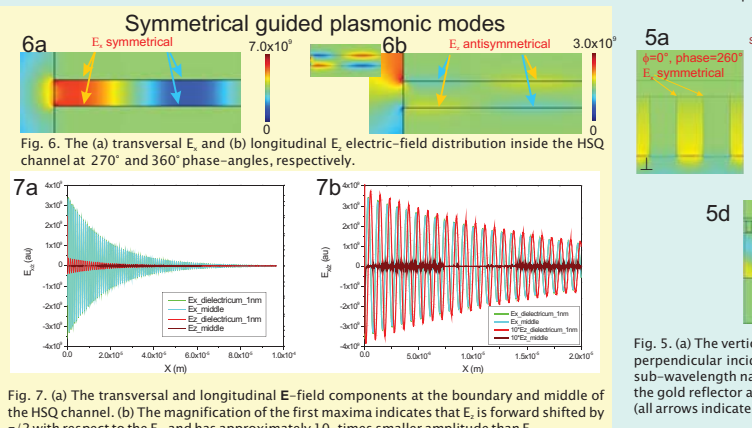


Fig. 6. The (a) transversal E_x and (b) longitudinal E_z electric-field distribution inside the HSQ channel at 270° and 360° phase-angles, respectively. (7a) The transversal and longitudinal E-field components at the boundary and middle of the HSQ channel. (7b) The magnification of the first maxima indicates that E_x is forward shifted by $\pi/2$ with respect to the E_z , and has approximately 10-times smaller amplitude than E_z .

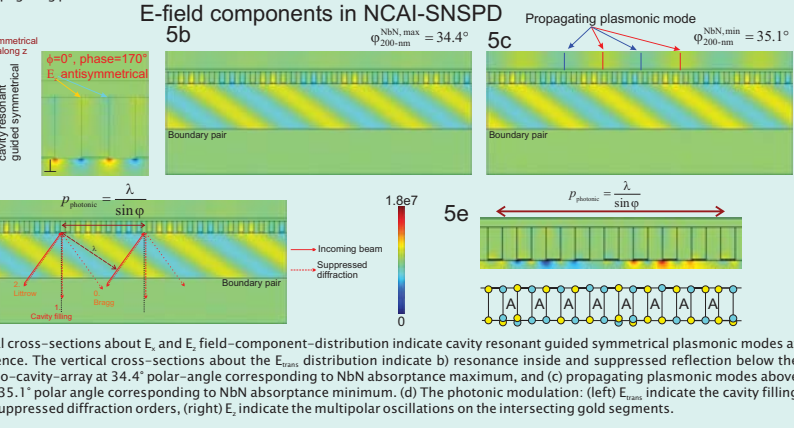


Fig. 5. (a) The vertical cross-sections about E_x and E_z field-component-distribution indicate cavity resonant guided symmetrical plasmonic modes at perpendicular incidence. The vertical cross-sections about the $E_{z,mid}$ distribution indicate (b) resonance inside and suppressed reflection below the sub-wavelength nano-cavity-array at 34.4° polar-angle corresponding to NbN absorbance maximum, and (c) propagating plasmonic modes above the gold reflector at 35.1° polar angle corresponding to NbN absorbance minimum. (d) The photonic modulation: (left) $E_{z,mid}$ indicate the cavity filling (all arrows indicate suppressed diffraction orders, (right) E_x indicate the multipolar oscillations on the intersecting gold segments.

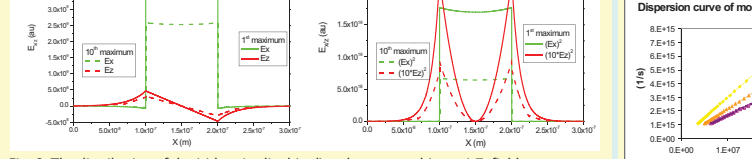


Fig. 8. The distribution of the (a) longitudinal (red) and transversal (green) E-field components, and the intensity of the (b) transversal (green) and longitudinal (red) E-field components, when the latter is rescaled according to Equation (2) to estimate the contribution of plasmonic modes. Symmetrical (long range) plasmonic modes in each MIM channel [17].

the plasma frequency in gold: $\omega_{pl}^{gold} = \sqrt{\frac{ne^2}{m\epsilon_0}} = 1.21479 \cdot 10^{15} \frac{1}{s}$

ratio between the two E-field components [16]: $\frac{E_{transversal}}{E_{longitudinal}} = \frac{E_x}{E_z} = \sqrt{\frac{\omega_{pl}^2 - \omega^2}{\epsilon_0 \cdot \omega^2}} = 10.206$

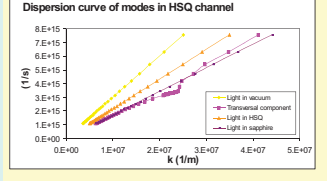


Fig. 9. The dispersion relation of the transversal E_x component at the middle of the channel in comparison to the light line in different media.

Methods

- illumination by $\lambda=1550$ nm p-polarized light from sapphire substrate side,
- illumination directions in conical mounting specified by φ polar and γ azimuthal angles [11]
- OC-SNSPD: single ~quarter-wavelength dielectric (HSQ) cavity with horizontal closing gold segment [12]
- NCAI-SNSPD: MIM array composed of ~quarter-wavelength HSQ cavities closed by vertical and horizontal gold segments [13]
- single infinite 10 μ m long and 100 nm wide HSQ channel aligning between two semi-infinite gold media

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