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

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IDEA:

- Integration of plasmonic structures (reflectors, NCA, NCDA into SNSPDs)
- Optimization of the geometry and illumination direction
- Optical responses, near-field distribution FEM

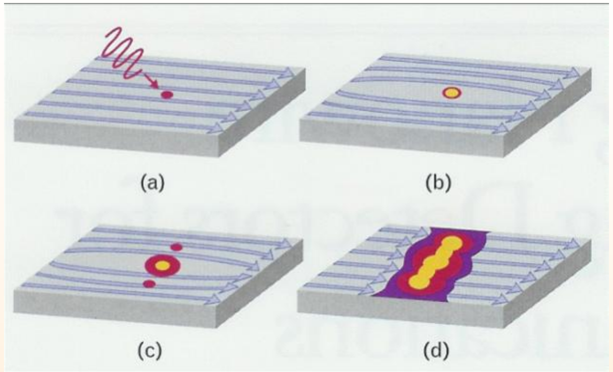
Mária Csete

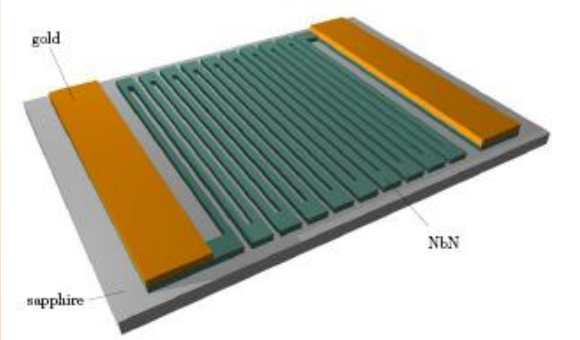
COMSOL conference Boston, 2012

Excerpt from the Proceedings of the 2012 COMSOL Conference in Boston

Superconducting Nanowire Single Photon Detectors (SNSPD)

- SNSPD
  - Application areas
    - IR photon counting
    - Quantum cryptography
    - Ultra-long range communication
  - Standard structure
    - 200 nm boustrophedonic pattern of
      4 nm thick NbN stripes with 50 % fill-factor
      2 nm thick $NbNO_x$
- SNSPD detection efficiency limited
  - Losses
    - Reflection
    - Transmission
    - Absorption by non-active elements
  - Optimization
    - NbN absorptance maximization



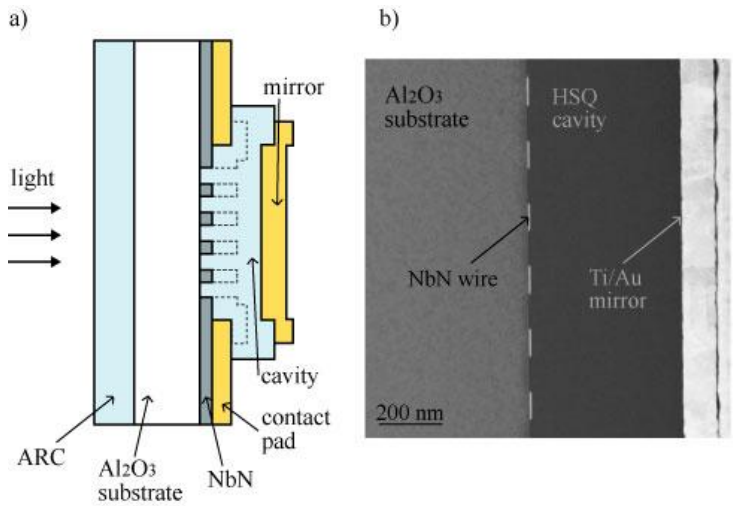


- Detection efficiency $DE = P_R \cdot A$
  - Optical optimization
    - Absorptance maximization: A
  - Electrical optimization
    - Probability of measurable electronic signal: P_R

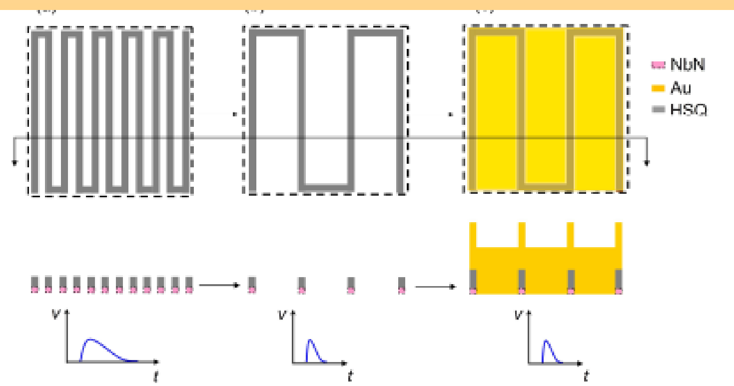
Gol'tsman, G. N., Okunev, O., Chulkova, G., Lipatov, A., Semenov, A., Smirnov, K., Voronov, B. M., Dzardanov, A., Williams, C., and Sobolewski, R., „*Picosecond superconducting single-photon optical detector*" Appl. Phys. Lett. **79(6)** 705-708 (2001).

First approach: device design optimization

- Integrated **optical cavity**
  - HSQ-filled dielectric cavity
  - Anti-Reflection-Coating: 120 nm Au film
  - *DE*=57 % at 1550 nm

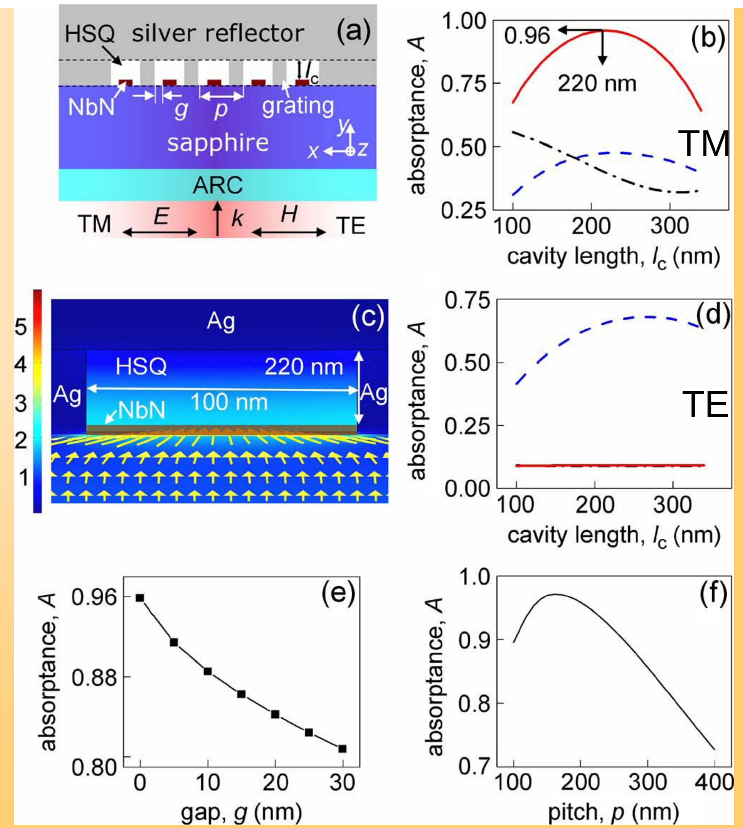


- K.M. Rosfjord et all: Opt. Express Vol. **14/2**, 527-534 (2006)
- M. Csete et all: Journal of Nanophotonics (2012)



$p -> 3p$

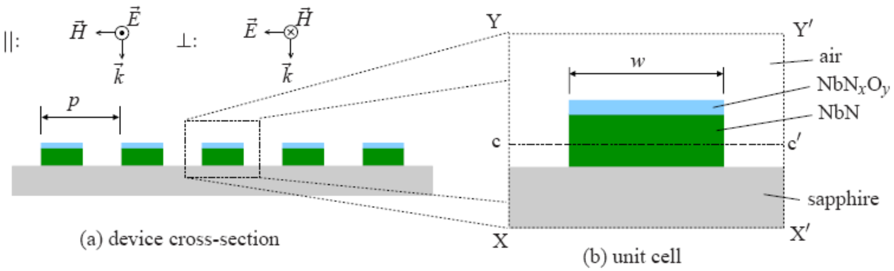
- Integrated metal **antenna-array**
  - Silver antenna: *DE*=96 %
    - $p_{NbN/Au}$=200 nm pitch
    - l_{HSQ} = 220 nm
    - No-gap between the antenna-NbN



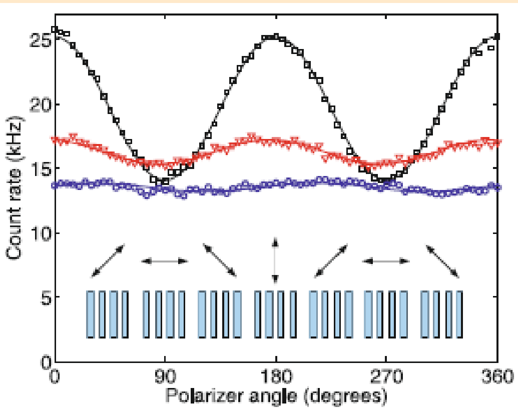
- X. Hu et all.: IEEE Transactions on Appl. Superc., VOL. **19/3**, 336-340 (2009)
- X. Hu et all.: Opt. Express, VOL. **19/1**,17-31 (2009)
- M. Csete et all: Opt. Express, VOL. **20/15**, 17065 (2012)

Second approach: illumination direction optimization

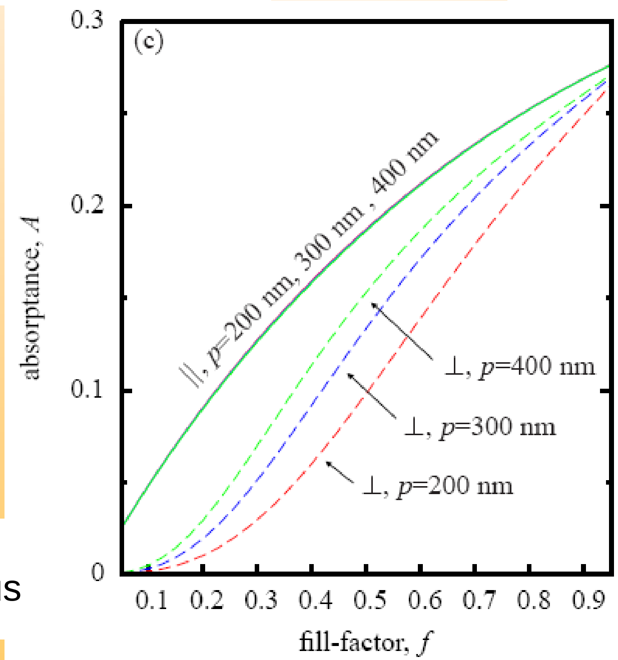
- Effect of **E**-field oscillation direction
  - Variation of the azimuthal angle



V. Anant et all.: Optics Express **16/14**, 2008



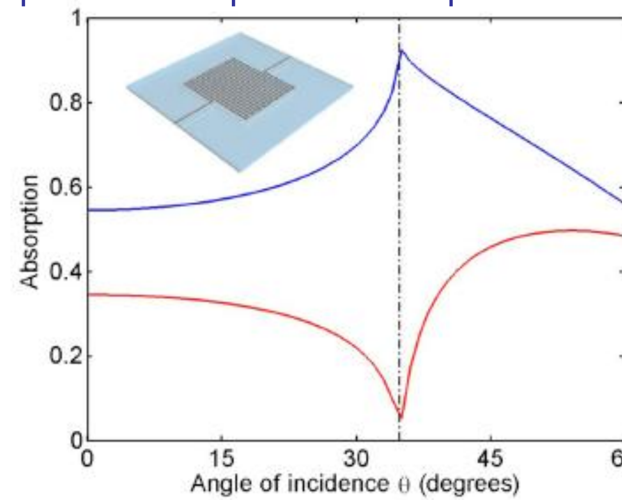
E-field oscillation parallel to the NbN wires is advantageous



E. F. C. Driessen et all.:
The European Journal of Applied Physics Vol. **47**, 1071/1-6 (2009)

- Effect of tilting
  - Variation of the polar angle
  - NbN pattern: lossy thin layer
  - absorption for *s*-polarized light: 100%

s-polarization: perfect absorptance at TIR



p-polarization: zero absorptance at TIR

E. F. C. Driessen and M. J. A. de Dood:
Applied Physics Letters Vol. **94**, 171109/1-3, 2009

M. Csete et all: Appl. Opt. **50(29)** 5949 (2011)

M. Csete et all: Journal of Nanophotonics (2012)

COMSOL 3.5, 4.2: RF module

Idea:
simulteneous optimization of device design + illumination directions

- **p-polarized light**, in P/S-orientation
- off-axes illumination: φ polar angle tuning
- conical mounting: γ azimuthal angle tuning
- Absorptance=Sum of the Resistive heating/Total power,
- Transmittance and Reflectance: Power out-flows at PMLs

Specification of **H** field

$$H_{x\_TM} \cdot \exp(-j(k_x \cdot x + k_y \cdot y + k_z \cdot z))$$

$$H_{y\_TM} \cdot \exp(-j(k_x \cdot x + k_y \cdot y + k_z \cdot z))$$

$$H_{z\_TM} \cdot \exp(-j(k_x \cdot x + k_y \cdot y + k_z \cdot z))$$

Components of **H** vector

$$H_{x\_TM} = H_0 \cdot \cos\gamma$$

$$H_{y\_TM} = -H_0 \cdot \sin\gamma$$

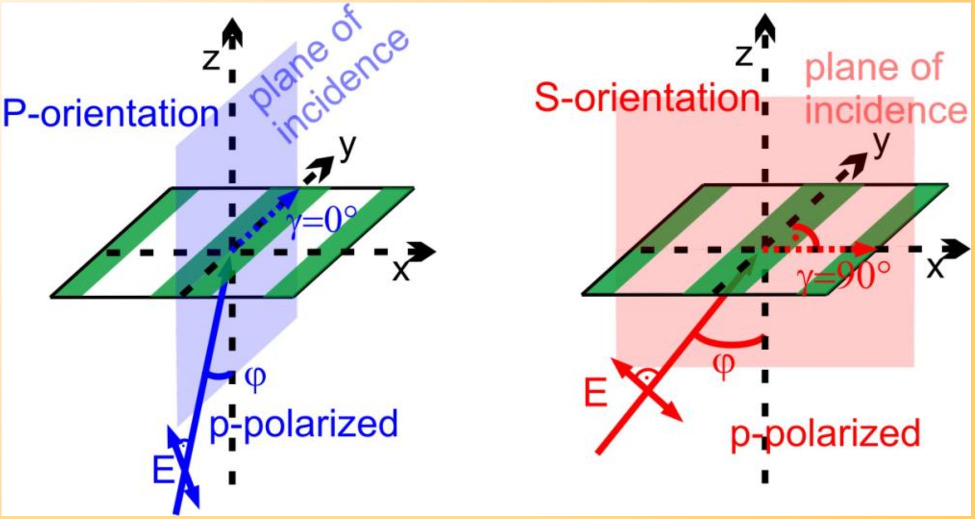
$$H_{z\_TM} = 0$$

Components of **k** vector of oblique incident beam

$$k_x = k_0 \cdot \sin\varphi \cdot \sin\gamma$$

$$k_y = k_0 \cdot \sin\varphi \cdot \cos\gamma$$

$$k_z = k_0 \cdot \cos\varphi$$

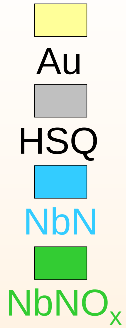


P/S-orientation:
- Intensity modulation along/perpendicular to NbN wires

Media
- Cauchy formulas
  - Sapphire, $NbNO_x$
- Tabulated datasets
  - Gold, NbN
    - M. A. Ordal, et all: *Appl. Opt.*, **22/7,** 1099-1119 (1983).

Index of refraction	n1	n2
Sapphire	1.75	
NbNOx	2.28	
HSQ	1.39	
Gold	0.559	9.81
NbN	5.23	5.82

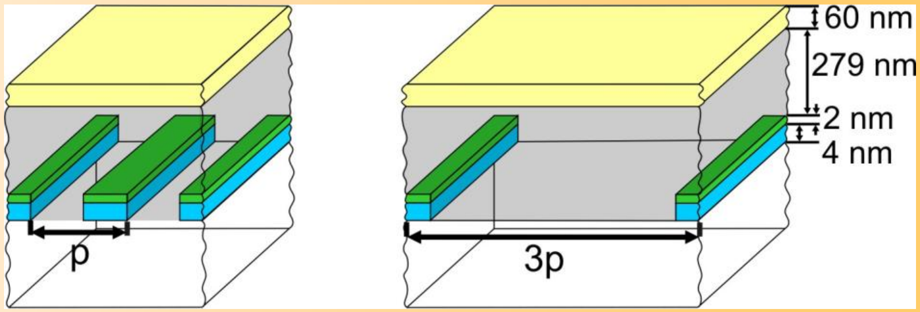
Optical systems illuminated by p-polarized light

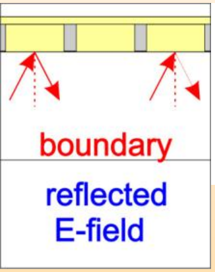


p=200/**220**/237 nm

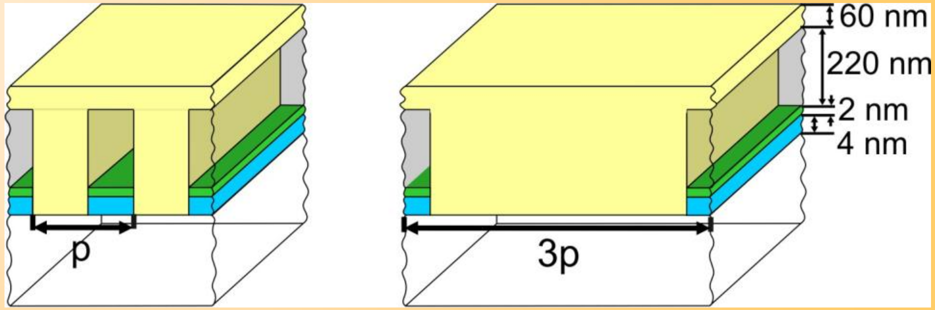
3p=600/**660**/710 nm

- OC-SNSPD
  - 60 nm Au reflector on 279 nm HSQ

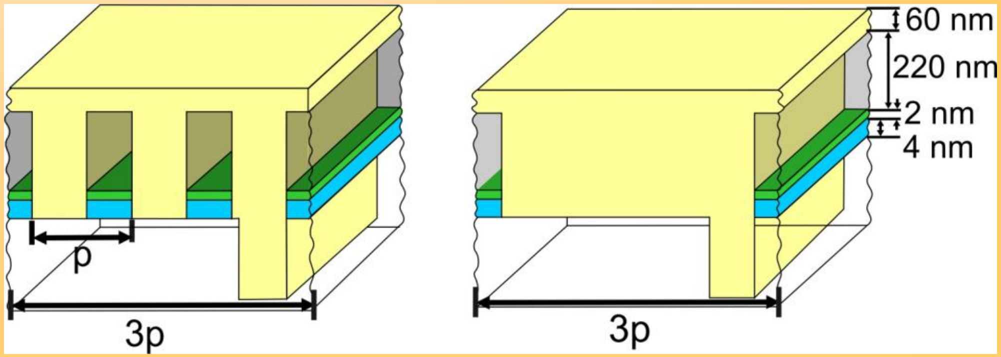




- NCAI-SNSPD
  - 220 nm long nano-cavities closed by vertical, horizontal Au segments



- NCDAI-SNSPD
  - longer vertical Au segments



- Parametric sweep

$$\varphi_{sweep}^{entire} = [0°, 85°]$$

$$\gamma_{sweep}^{entire} = [0°, 90°]$$

$$\Delta\varphi = \Delta\gamma = 5°$$

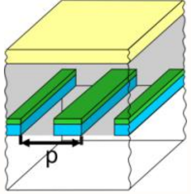
$$\varphi_{\text{sweep}}^{\text{1D, low}} = [0°,\ 90°]$$

$$\Delta\varphi = 1°$$

$$\varphi_{\text{sweep}}^{\text{1D,high}} : \text{around maxima}$$

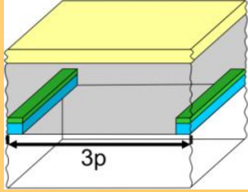
$$\Delta\varphi = 0.05°$$

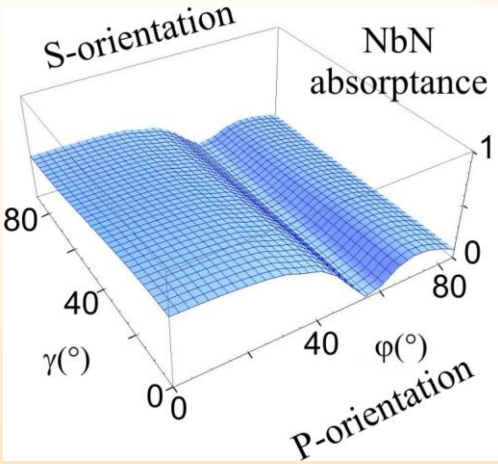
Optical response in OC-SNSPDs

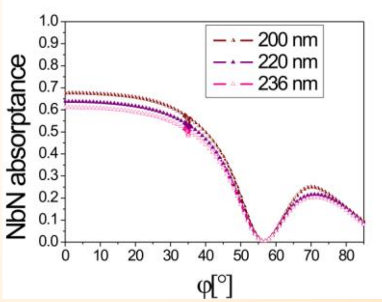


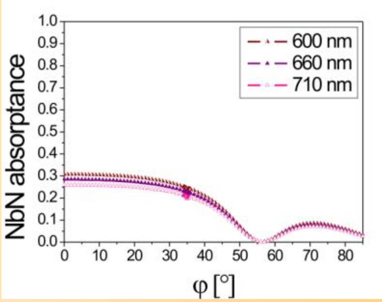
p=200/**220**/237 nm

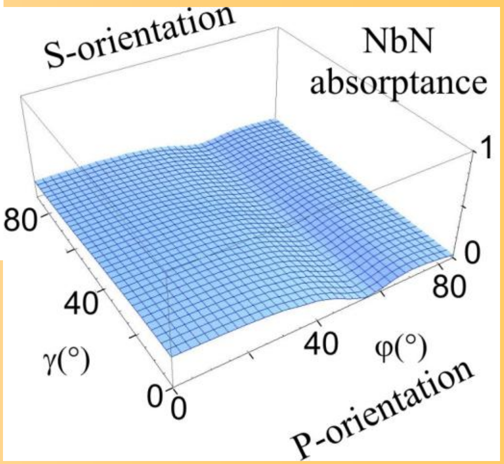
3p=600/**660**/710 nm



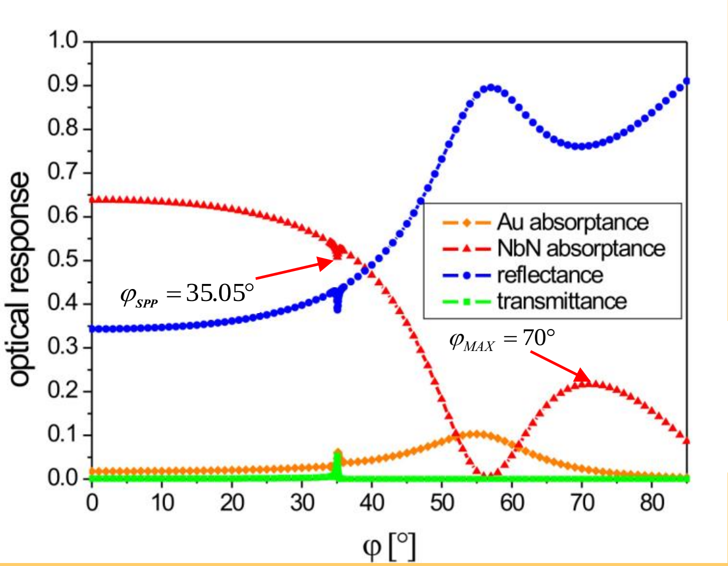








- Larger absorptance in P-orientation
- **E**-field oscillation parallel to NbN wires
- perpendicular incidence in P-orientation

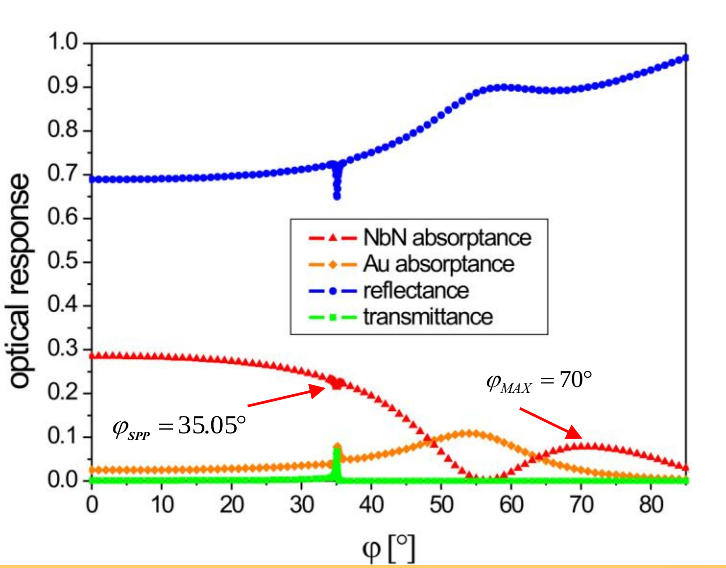


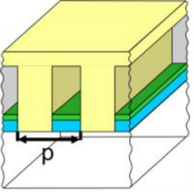
ATIR characteristics

NbN absorptance
<-63.8 %, 28.5 %->
global maximum at 0°
local maximum at ATIR

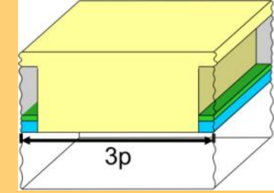
Au absorptance
local maximum at 35.15°
global maximum at 55°

little near-field at TIR



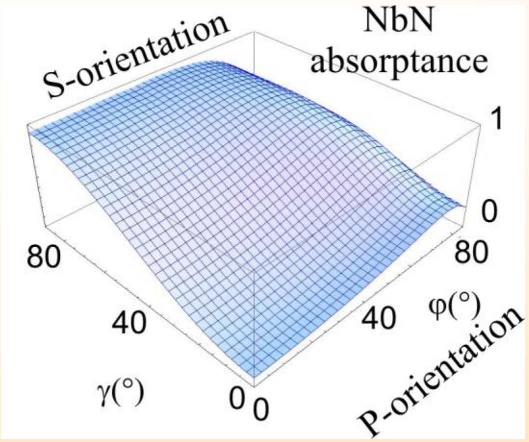


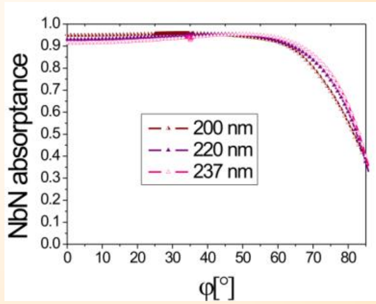
Optical response in NCAI-SNSPDs

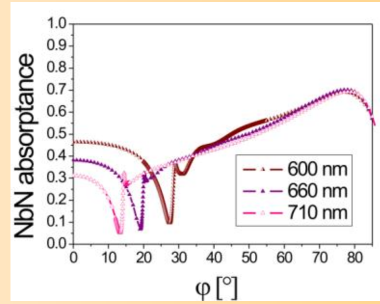


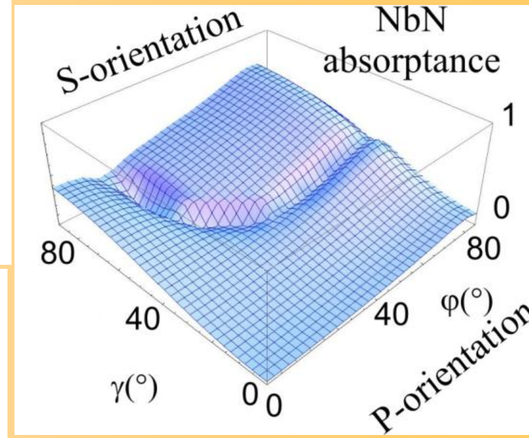
p=200/**220**/237 nm

3p=600/**660**/710 nm



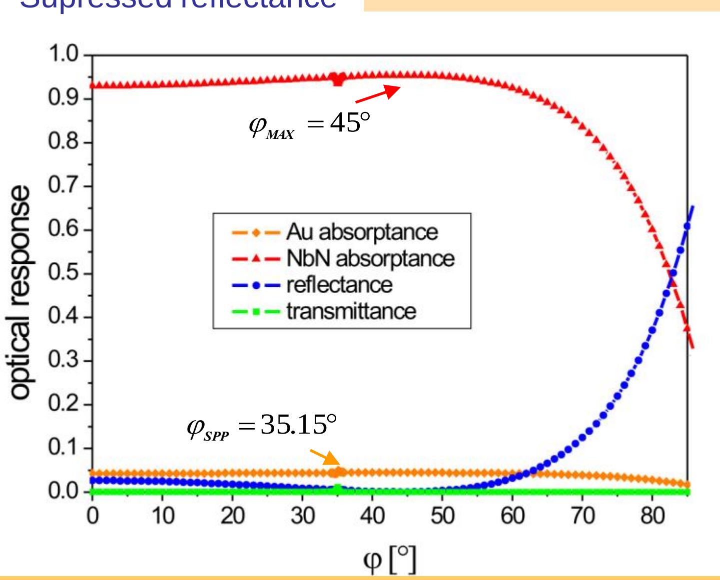






- Larger absorptance in S-orientation
- **E**-field oscillation perpendicular to NbN wires
- perpendicular incidence in S-orientation

Supressed reflectance



NbN absorptance

<-95.4%, 38.2% ->

<-global maximum at ATIR

local maximum (32.3%)

at PBG-edge->

Au absorptance

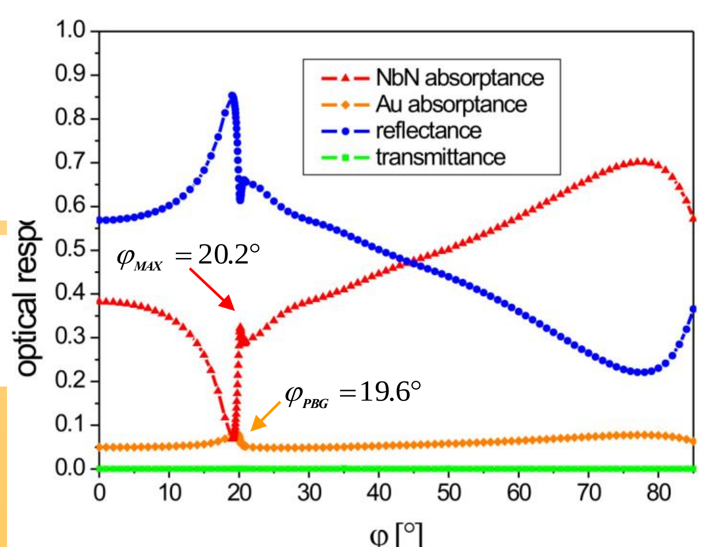
<-global maximum at SPP

global maximum at PBG->

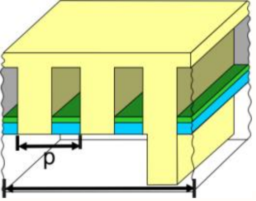
<-little near-field at TIR

supressed transmittance->

ATIR characteristics

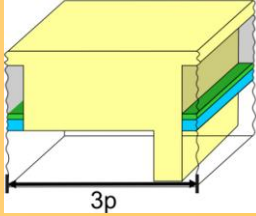


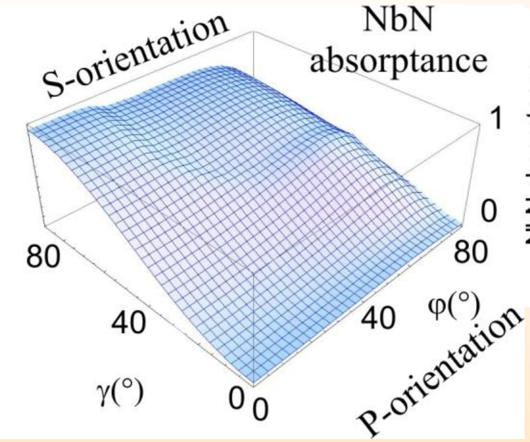
Optical response in NCDAI-SNSPDs

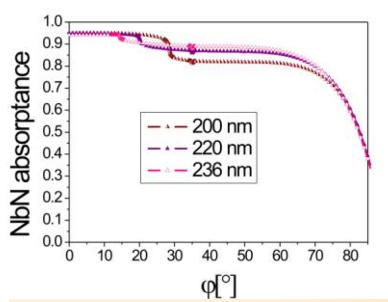


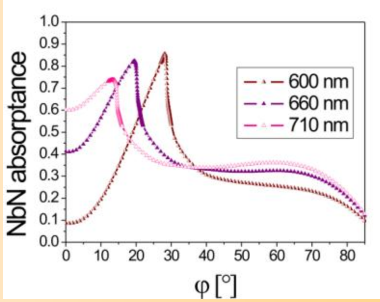
p=200/**220**/237 nm

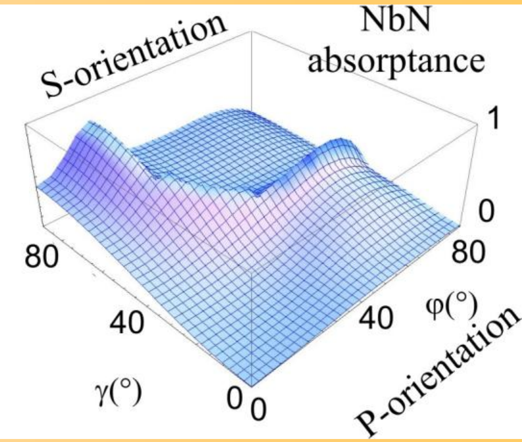
3p=600/**660**/710 nm



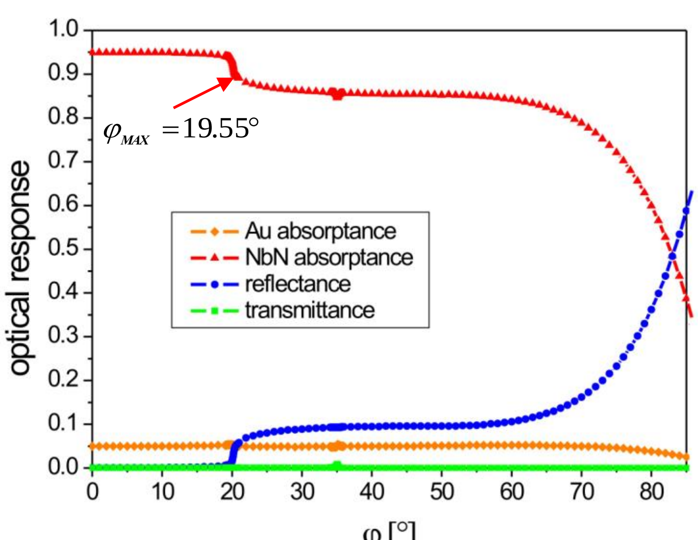








- Larger absorptance in S-orientation
- **E**-field oscillation perpendicular to NbN wires
- p: perpendicular incidence in S-orientation
- 3p: tilting to Plasmonic-Band-Gap



NbN absorptance

<-94.9%

global maximum at φ=0°

82.3%->

global maximum at PBG

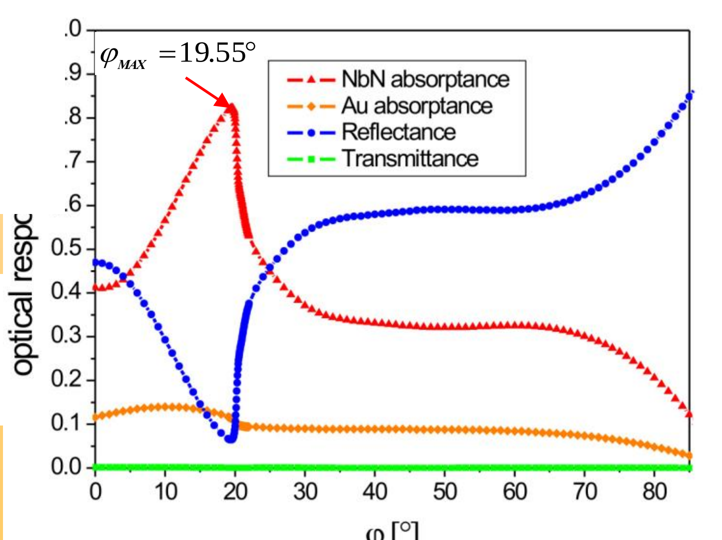
Au absorptance

<-global maximum at SPP

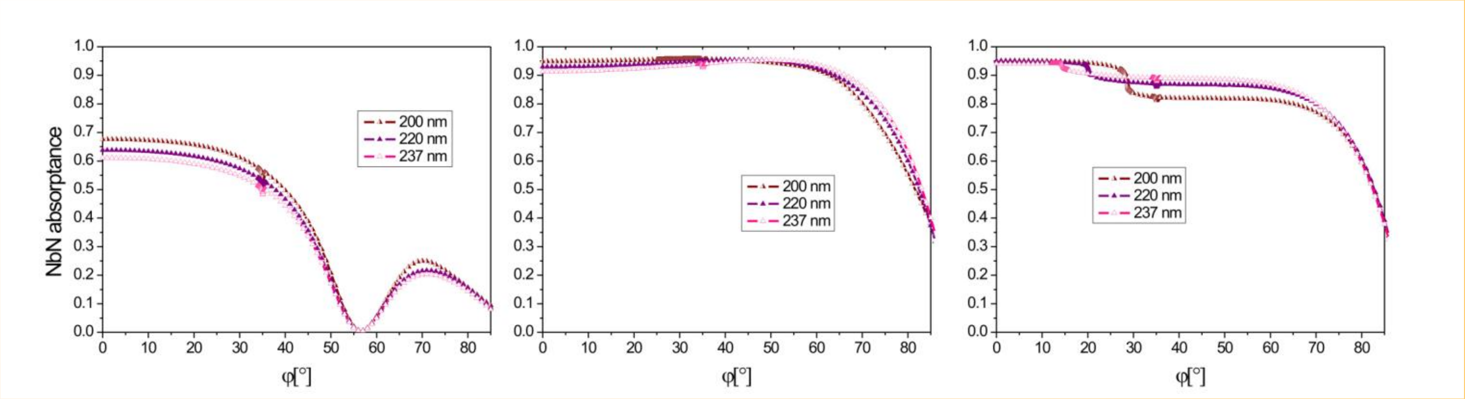
inflection at PBG->

<-little near-field at TIR

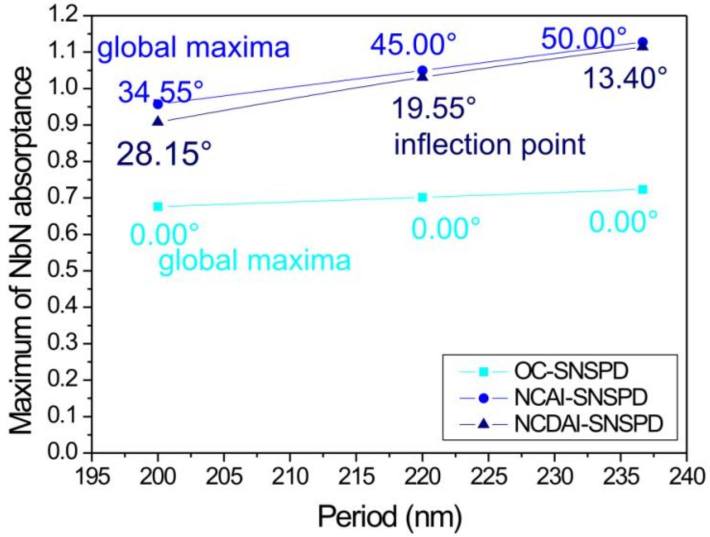
supressed transmittance->



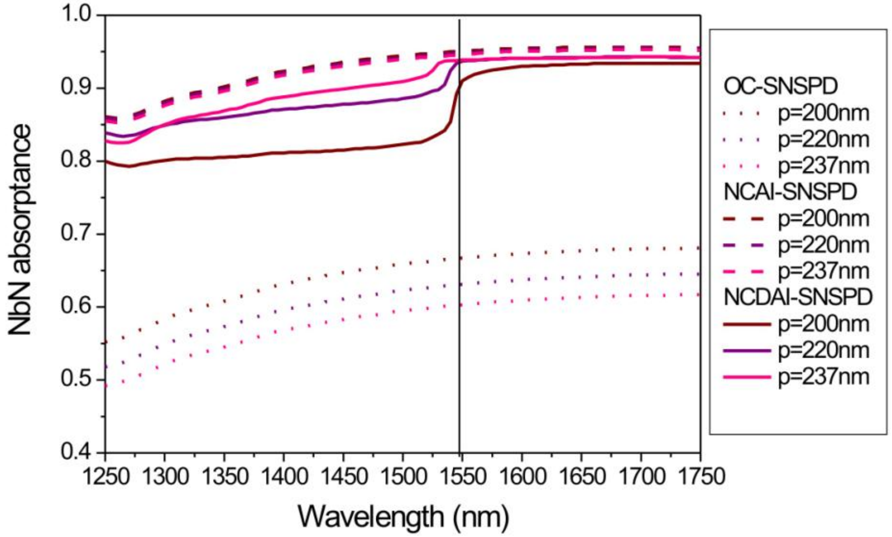
Comparison of NbN absorptances in p-periodic designs



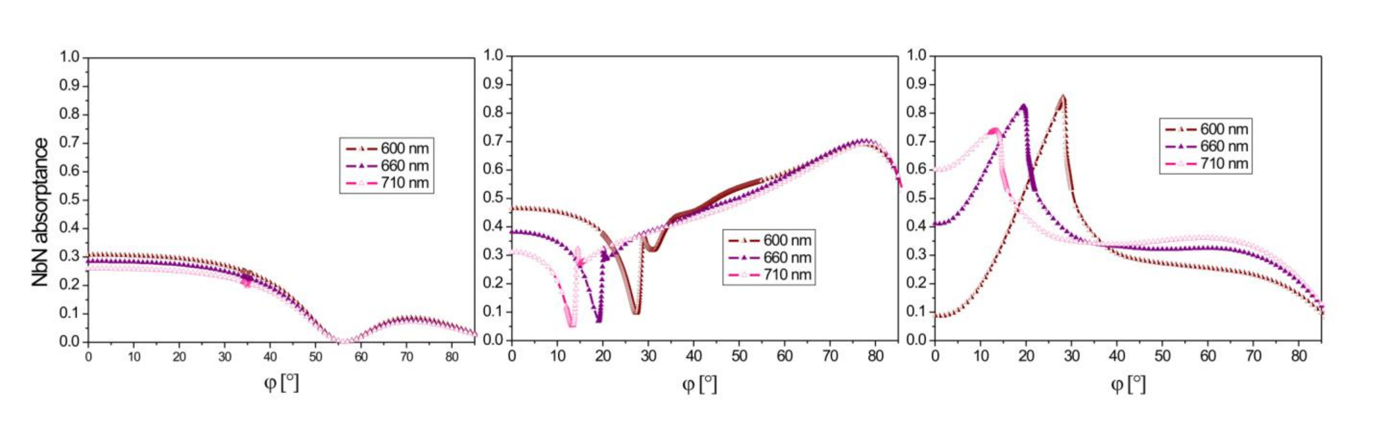
Largest slope of normalized NbN absorptance
in NCDAI-SNSPDs



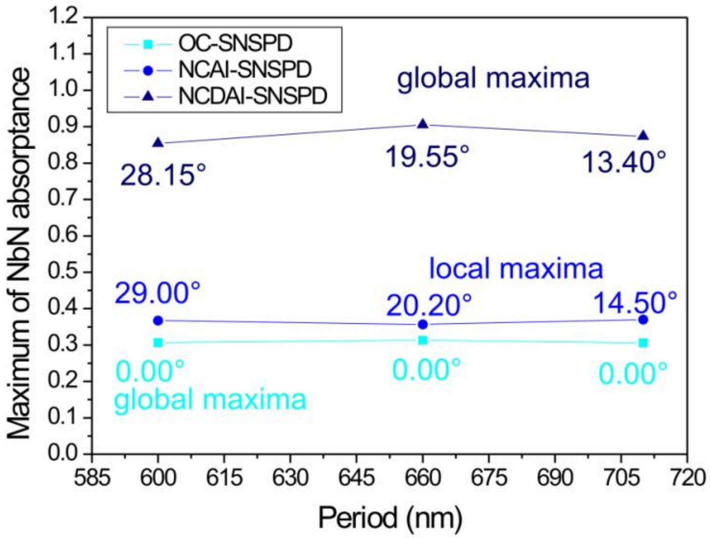
steep slope on NbN absorptance
at 1550 nm in 220 nm design



Comparison of NbN absorptances in 3p-periodic designs



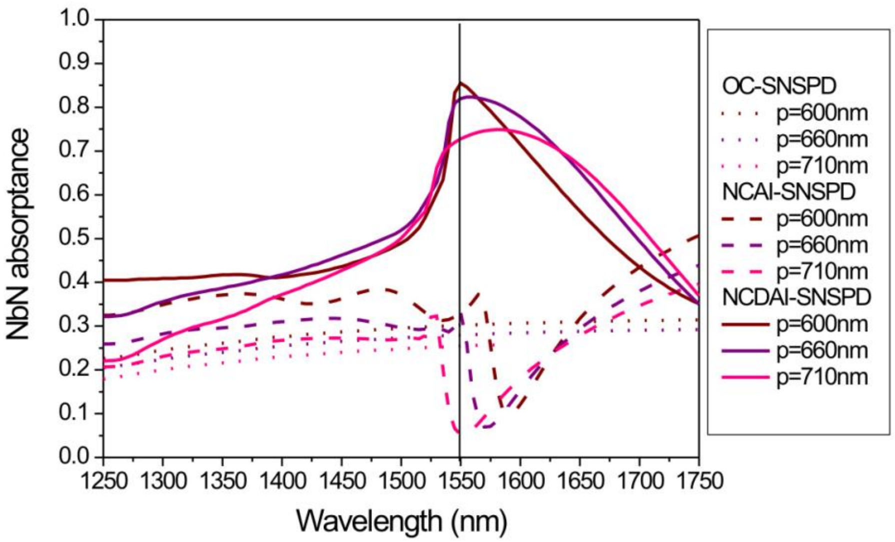
local maxima on normalized NbN absorptance at 660 nm in OC-SNSPD and NCDAI-SNSPDs



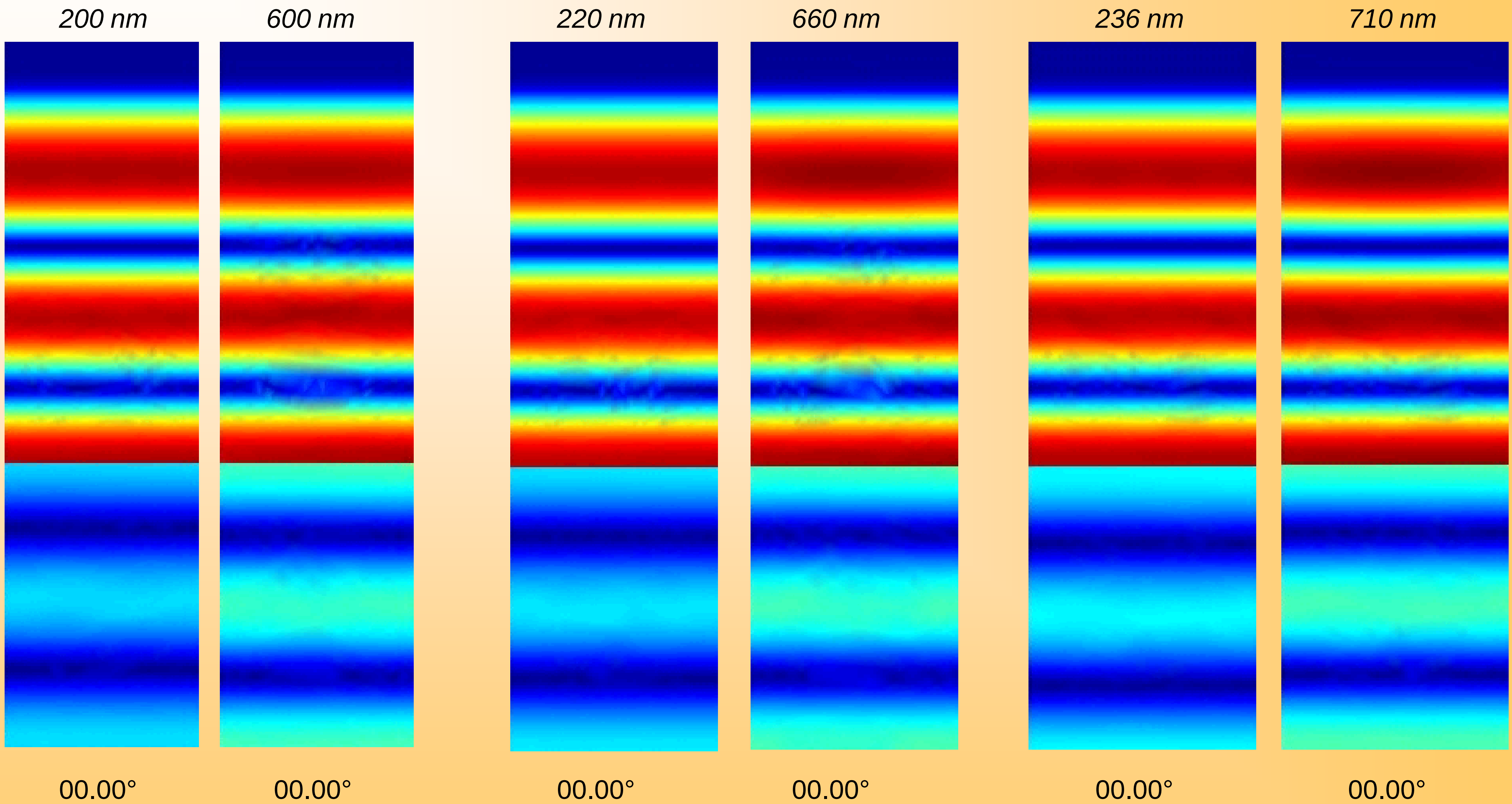
monotonous increase in OC-SNSPD

local maxima at 1550 nm in 660 nm design in NCAI-SNSPD

huge global maxima at 1550/**1561**/1585 nm in NCDAI-SNSPDs

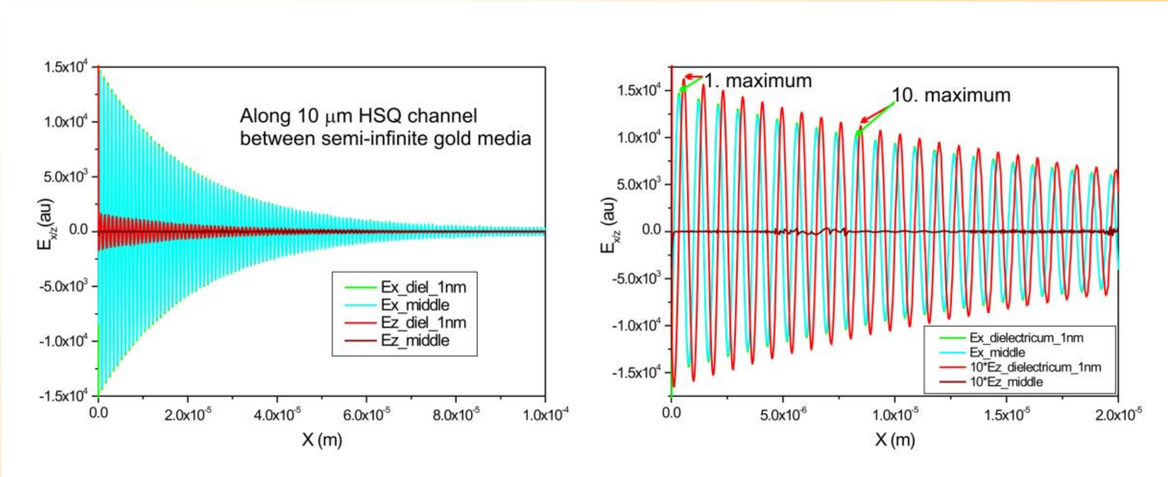


Time evolution of the E-field in OC-SNSPDs



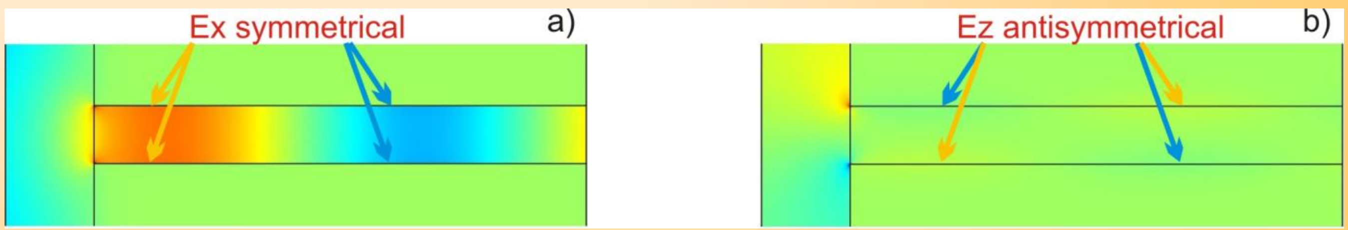
E-field antinode at sapphire-NbN interface

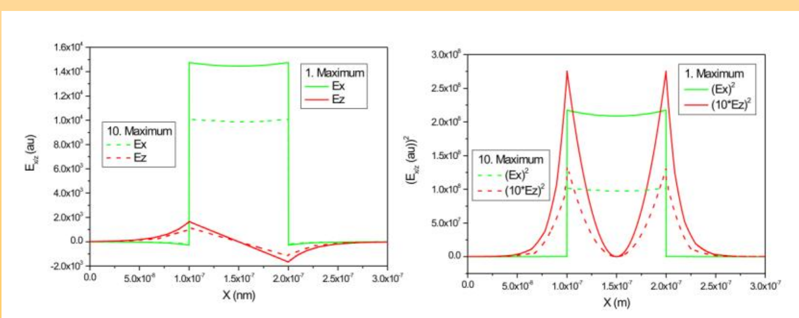
Near-field explanation: plamonic modes in MIM channels

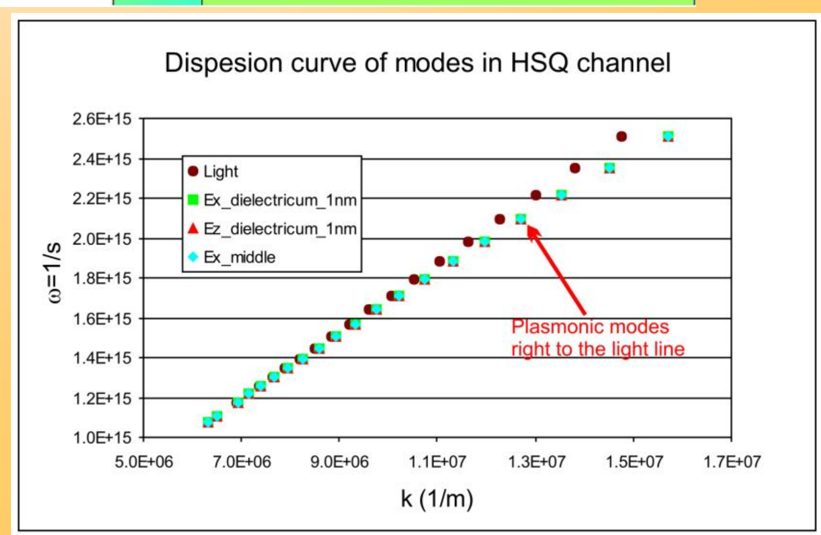


$$\omega_p^{Gold} = \sqrt{\frac{ne^2}{m\varepsilon}} = 1.21479 \cdot 10^{17}\ \frac{1}{s}$$

$$\frac{E_{transversal}}{E_{longitudinal}} = \frac{E_x}{E_z} = \sqrt{\frac{\omega_p^2 - \omega^2}{\varepsilon_1 \cdot \omega^2}} = 10.206$$







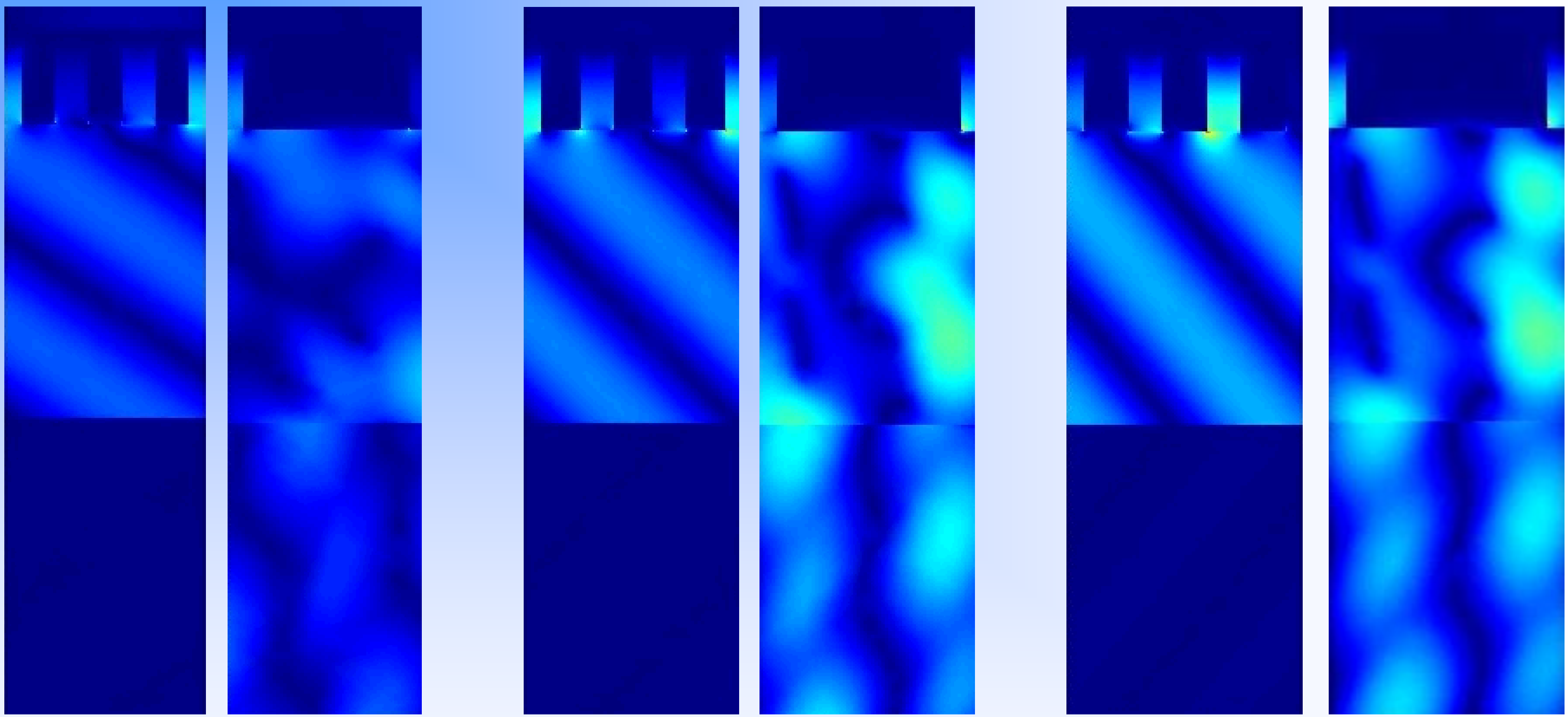
Time evolution of the E-field in NCAI-SNSPDs

Maximal cavity filling: m=1, k=3,4,5

$$\sin\varphi^{m,k} = \frac{m\dfrac{\lambda}{n_{sapphire}}}{kp}$$

Enhancement at Au-air

Supressed reflection in p-periodic designs

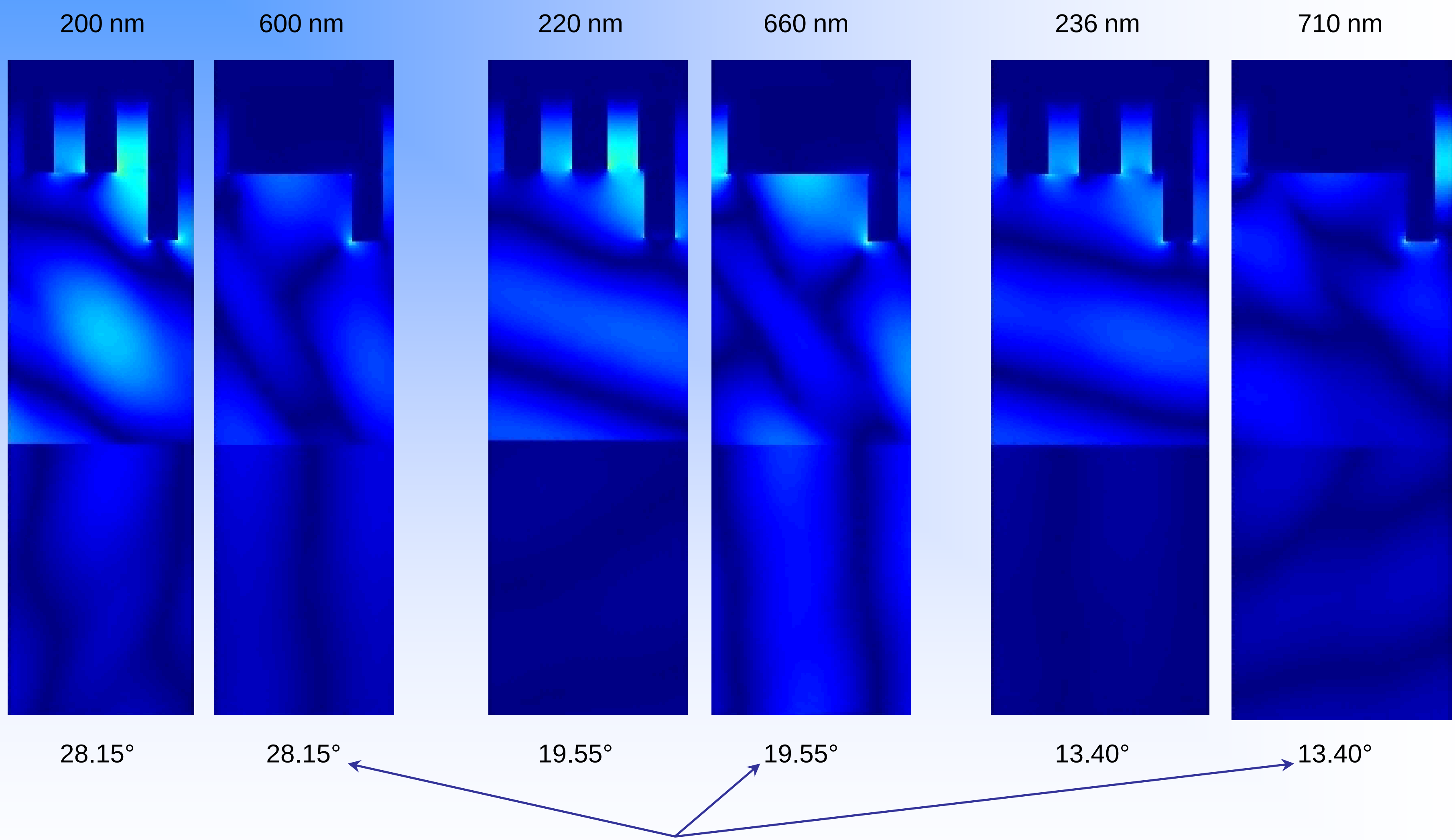


Backward propagating waves with wavelength (889nm) larger than λ/n:
Brewster waves at PBG-edge

$$-\frac{2\pi}{\lambda_{Brewster\ \ wave}} = \frac{2\pi}{\lambda}\sin\varphi - \frac{2\pi}{3\boldsymbol{p}}$$

Time evolution of the E-field in NCDAI-SNSPDs

$$-\frac{2\pi}{\lambda_{SPP}} = \frac{2\pi}{\lambda}\sin\varphi - \frac{2\pi}{3\boldsymbol{p}}$$

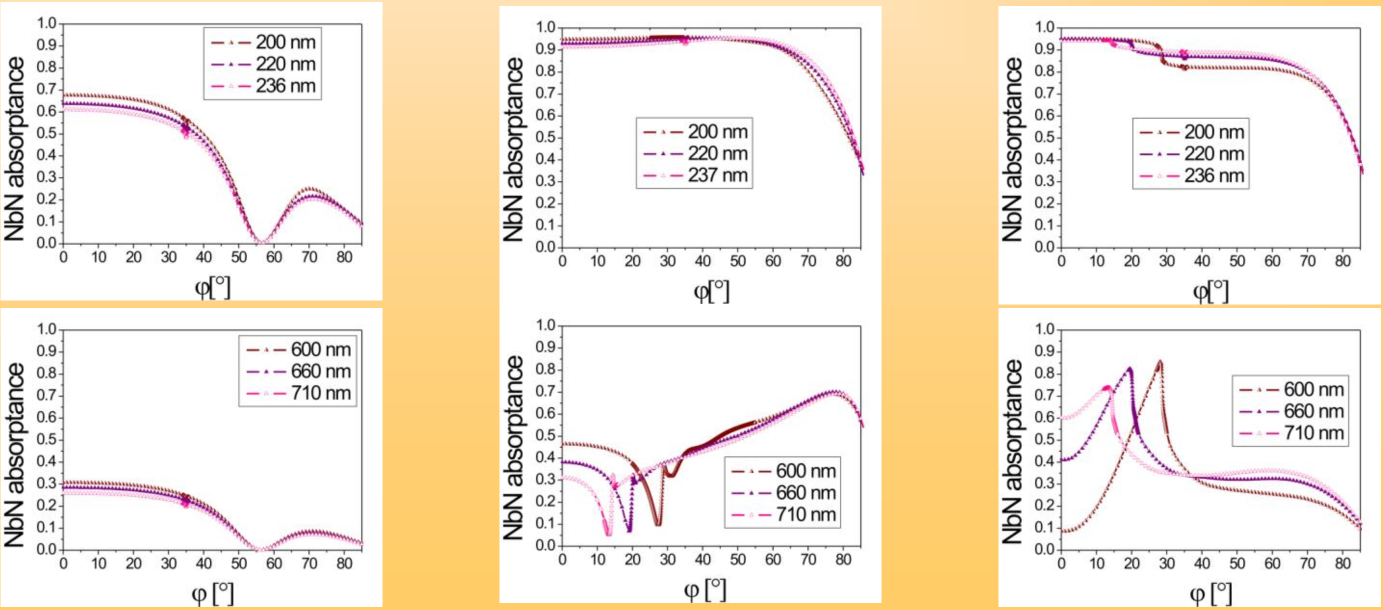


Backward propagating waves with wavelength (878 nm) corresponding to λ_{SPP}:
back-deflected plasmonic waves at the middle of the PBG opening in p and 3p periodic designs

Summary and outlook

- Photodetectors might be optimized via plasmonic structures
    - synchronous polar-azimuthal orientation to optimize the near-field distribution and to maximize the absorptance
    - Each device has optimal polar-azimuthal orientation

- SNSPD
    - OC: cavity-resonant mode
    - NCAI:
        - coupled resonances on p-periodic NCA,
        - coupling prohibited via propagating waves on 3p-periodic NCA,
    - NCDAI
        - Highest efficiency via coupled localized and propagating modes



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