Methods to optimize plasmonic structure integrated single-photon detector designs

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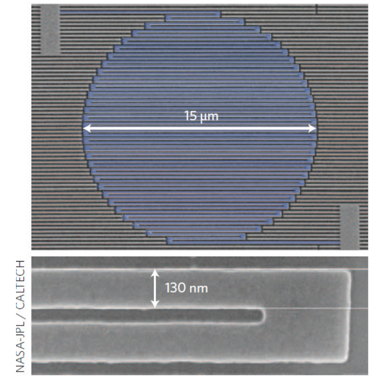
COMSOL CONFERENCE
2014 BOSTON

Design of Superconducting Nanowire Single Photon Detectors (SNSPD)

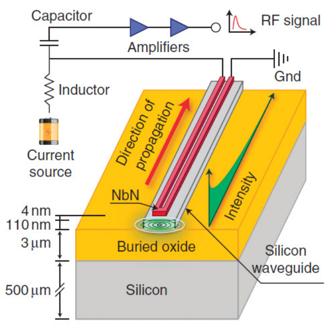
SNSPD

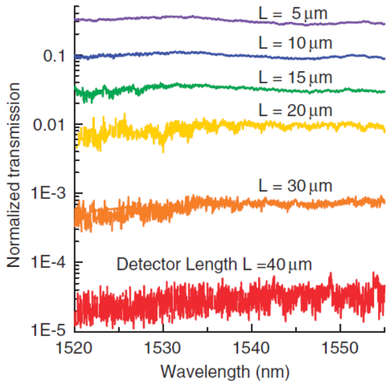
- IR photon counting, quantum cryptography, ultra-long range communication at 1550 nm
  - G. N. Gol'tsman et all: Appl. Phys. Lett. **79/6** 705-708 (2001).
  - E. Driessen: Nature Photonics **7** (2013) 168-169

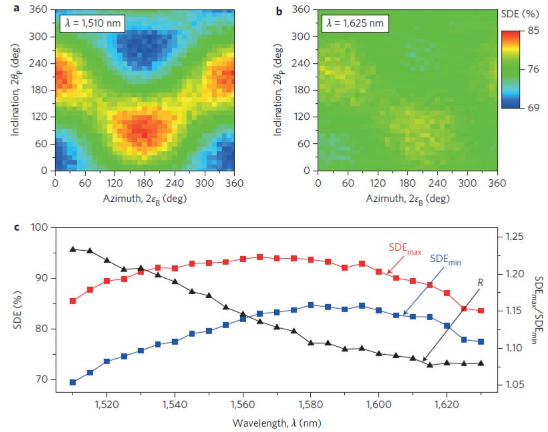


Device design development

- **Novel materials**: WSi wires on silicon based optical stack (93%)
  - F. Marsilli et al: Nature Photonics, DOI:10.1038/NPHOTO-2013-13
- integrated **optical cavity** (57%)
  - K. M. Rosfjord et al: Opt. Express **14/2**, 527-534 (2006)
- **waveguide** coupling (91%)
  - W. H. P. Penrice et al: Nature Communications, DOI:10.1038/ncomms2307





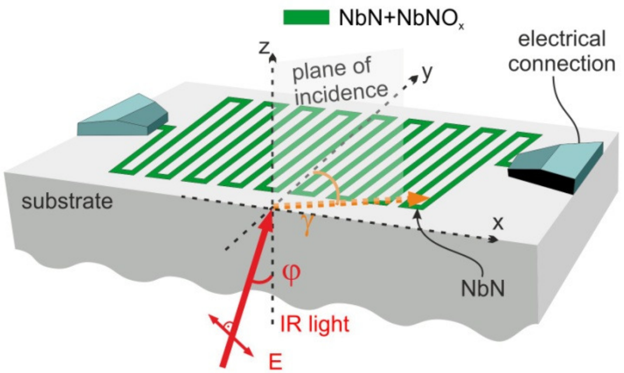


- integrated **plasmonic structure** (97%)
  - X. Hu et al: IEEE Transactions on Appl. Superc., **19/3**, 336-340 (2009)
  - X. Hu et al: Opt. Express, **19/1**,17-31 (2009)
  - R. W. Heeres et al: Nano Letters **10**, 661-664 (2010)
  - M. Csete et al: Journal of Nanophotonics **6/1**, 063523 (2012)
  - M. Csete et al: Opt. Express **20/15**, 17065 (2012)
  - M. Csete et al.: Scientific Reports **3** 2406 (2013)

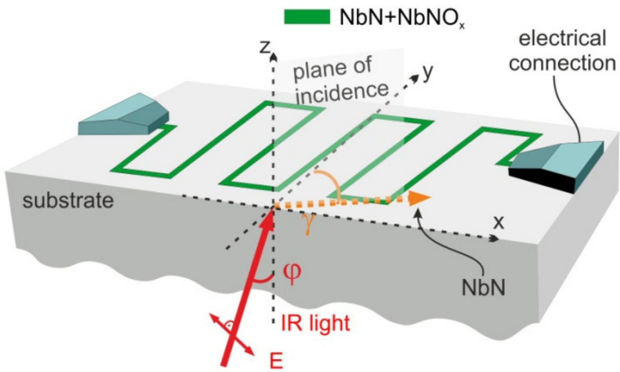
Optimization of plasmonic structure integrated SNSPD configuration

- **Challenges**
  - Optical optimization
    maximal effective absorption cross-section
  - Electrical optimization
    low dark count rate, low timing jitter, short reset time
  - Specific requirements of QIP: **high polarization contrast**

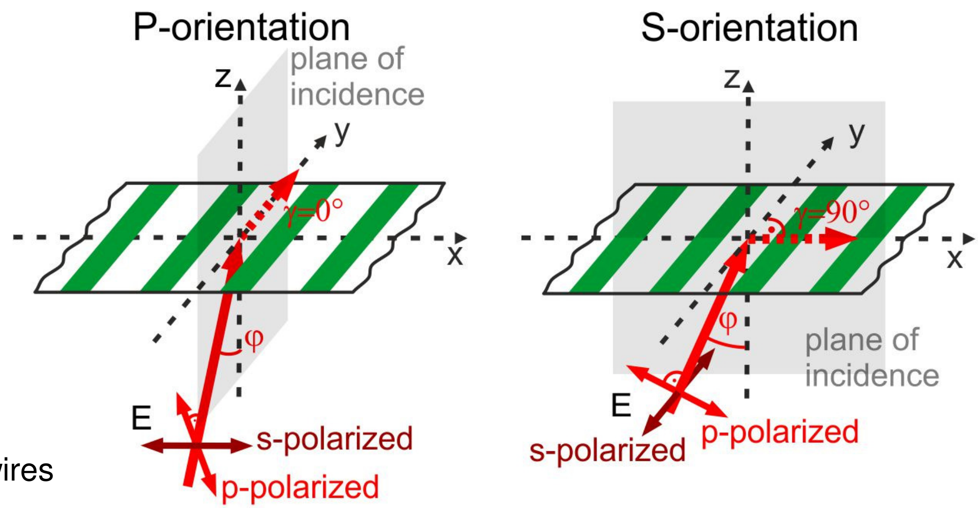
Absorptance maximization



Electrical optimization



- **Idea:**
  simultaneous optimization of device design + illumination directions
  configuration optimization

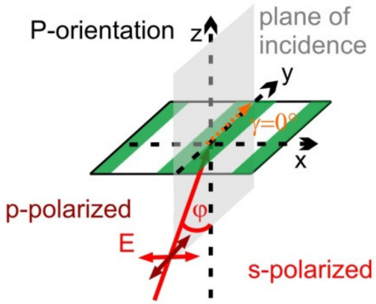


- **p/s-polarized light**, in P/S-orientation
- off-axes illumination: φ polar angle tuning
- conical mounting: γ azimuthal angle tuning

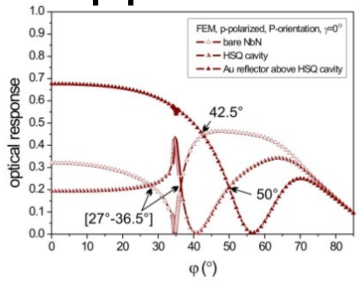
- P/S-orientation:
  - Intensity modulation along/perpendicularly to NbN wires

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

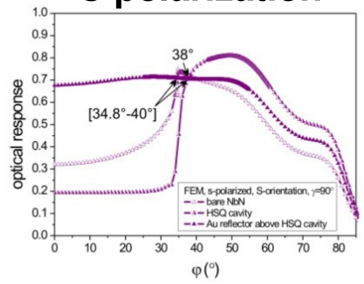
Basic SNSPD systems on sapphire substrate

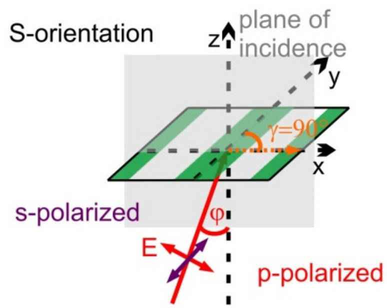


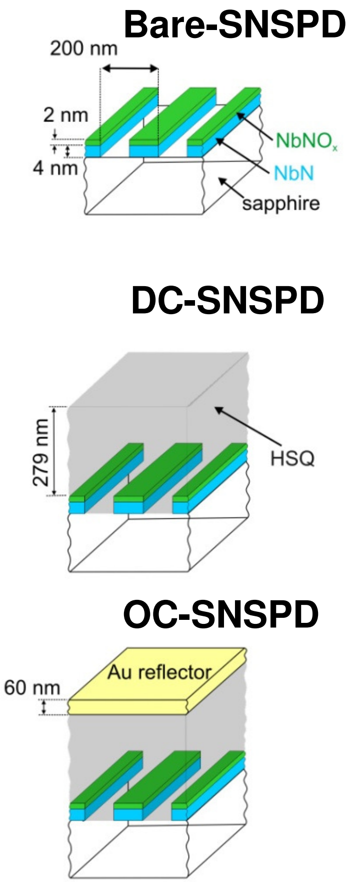
p-polarization

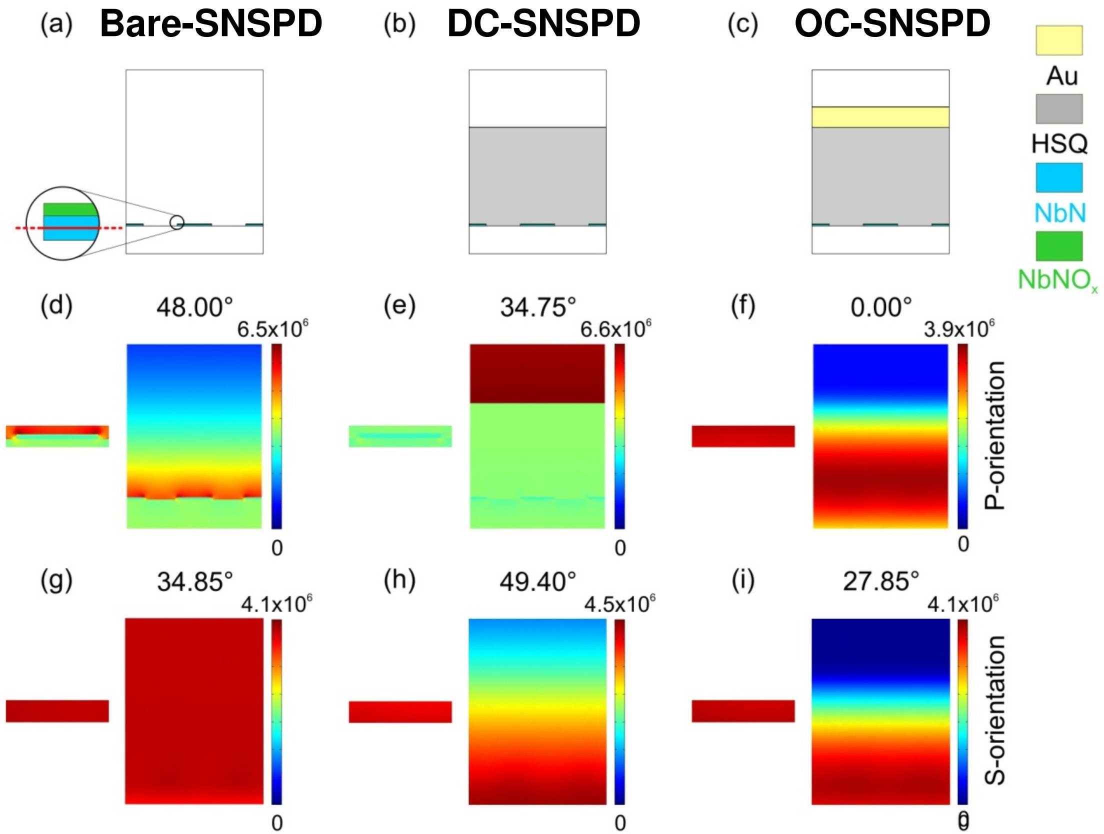


s-polarization





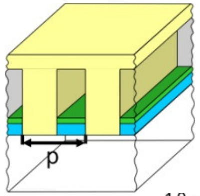


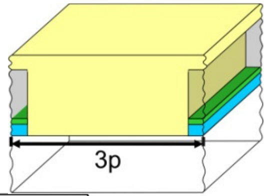


M. Csete et al: Appl. Opt. **50**/**29** 5949 (2011)

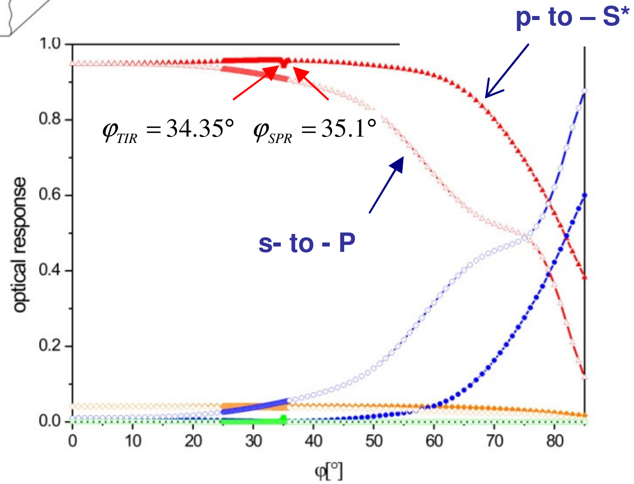
M. Csete et al: Journal of Nanophotonics **6**/**1** 063523 (2012)

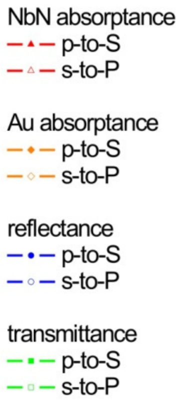
NCAI-SNSPDs on sapphire substrate



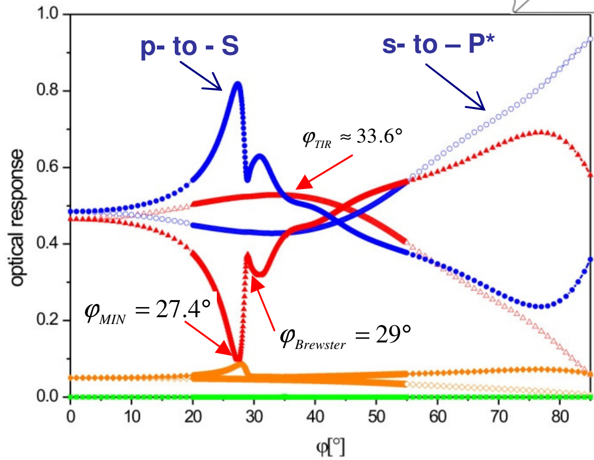


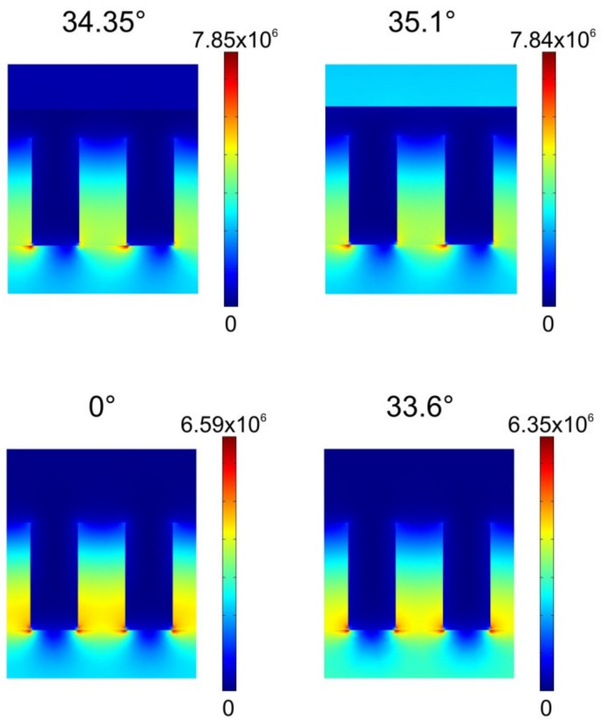
◈200-nm-pitch design

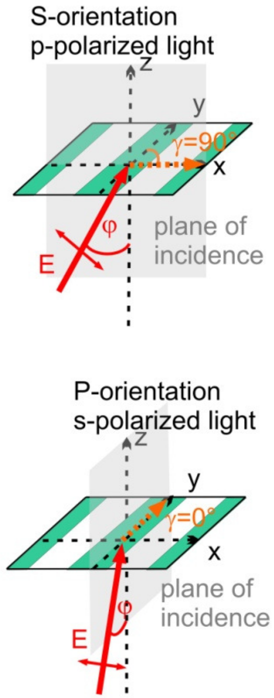


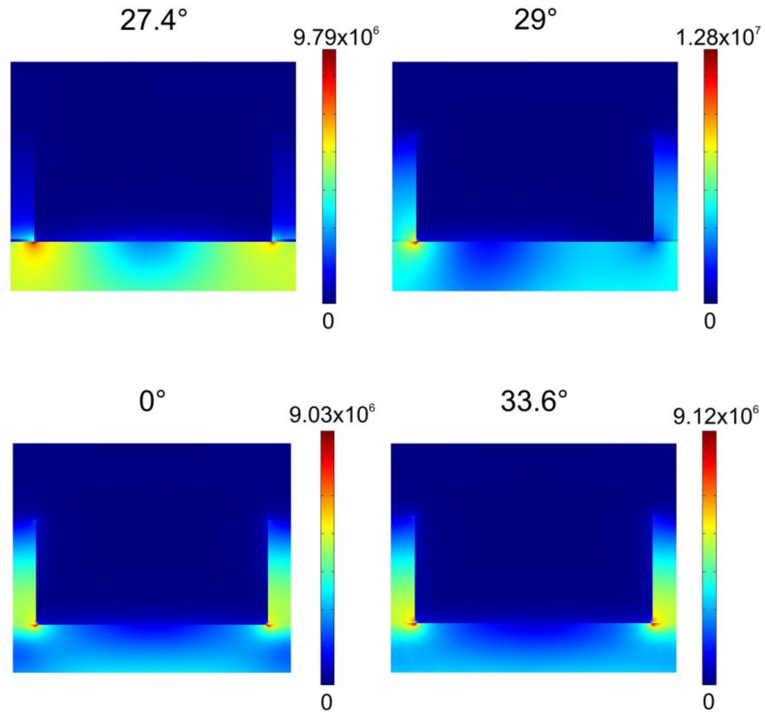


◈600-nm-pitch design







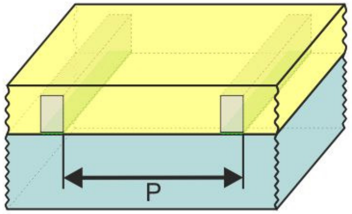


◈ M. Csete et all: Opt. Express, **20**/**15**, 17065 (2012)

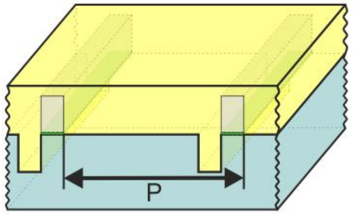
◈ M. Csete et all: Scientific Reports, **3**, 2406 (2013)

Plasmonic structure integrated SNSPD devices on silica substrate illuminated by 1550 nm p-polarized light

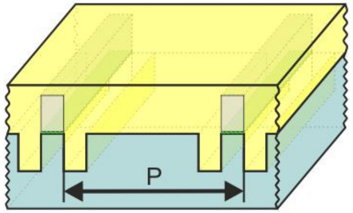
P = 792 nm (¾ * $\lambda_{plasmon}$), original designs



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



- **NCDAI-SNSPD**
  - 220 nm long vertical Au segments: deflectors at the anterior side of the nano-cavities



- **NCDDAI-SNSPD**
  - 220 nm long vertical Au segments at both sides of the cavities

Deflector design: A. Sánchez-Gil & A. A. Maradudin *Phys. Rev. B*, **60** (1999) 8359.

The GLOBAL Optimization Algorithm

The bound constrained global optimization problem
for which our stochastic algorithm was designed is

min $f(x)$
$x \in X$, $X = \{a_i \leq x_i \leq b_i, i = 1, 2, \ldots, n\}$,
where $f : R^n \rightarrow R$ is an arbitrary real nonlinear function, X is the set of feasibility,
in n-dimensional interval with vectors of lower and upper bounds of a and b, respectively.

The nonlinear constrained global optimization is

min $f(x)$
$g(x) <= 0$
$x \in X$, $X = \{a_i \leq x_i \leq b_i, i = 1, 2, \ldots, n\}$,
where $g : R^n \rightarrow R$ is again an arbitrary real nonlinear function.

In the latter case we used to apply the penalty approach
for transformation to the above problem class.

The GLOBAL Optimization Algorithm

Step 1: Draw N points with uniform distribution in the search space,
and add them to the current cumulative sample C.
Construct the transformed sample T
by taking the Y percent of the points in C with the lowest function value.
Step 2: Apply the clustering procedure to T one by one. If all points of T can be assigned to an existing cluster, go to Step 4
Step 3: Apply the local search procedure to the points in T not yet clustered.
Repeat Step 3 until every point has been assigned to a cluster.
Step 4: If a new local minimizer has been found, go to Step 1.
Step 5: Determine the smallest local minimum value found, and stop.

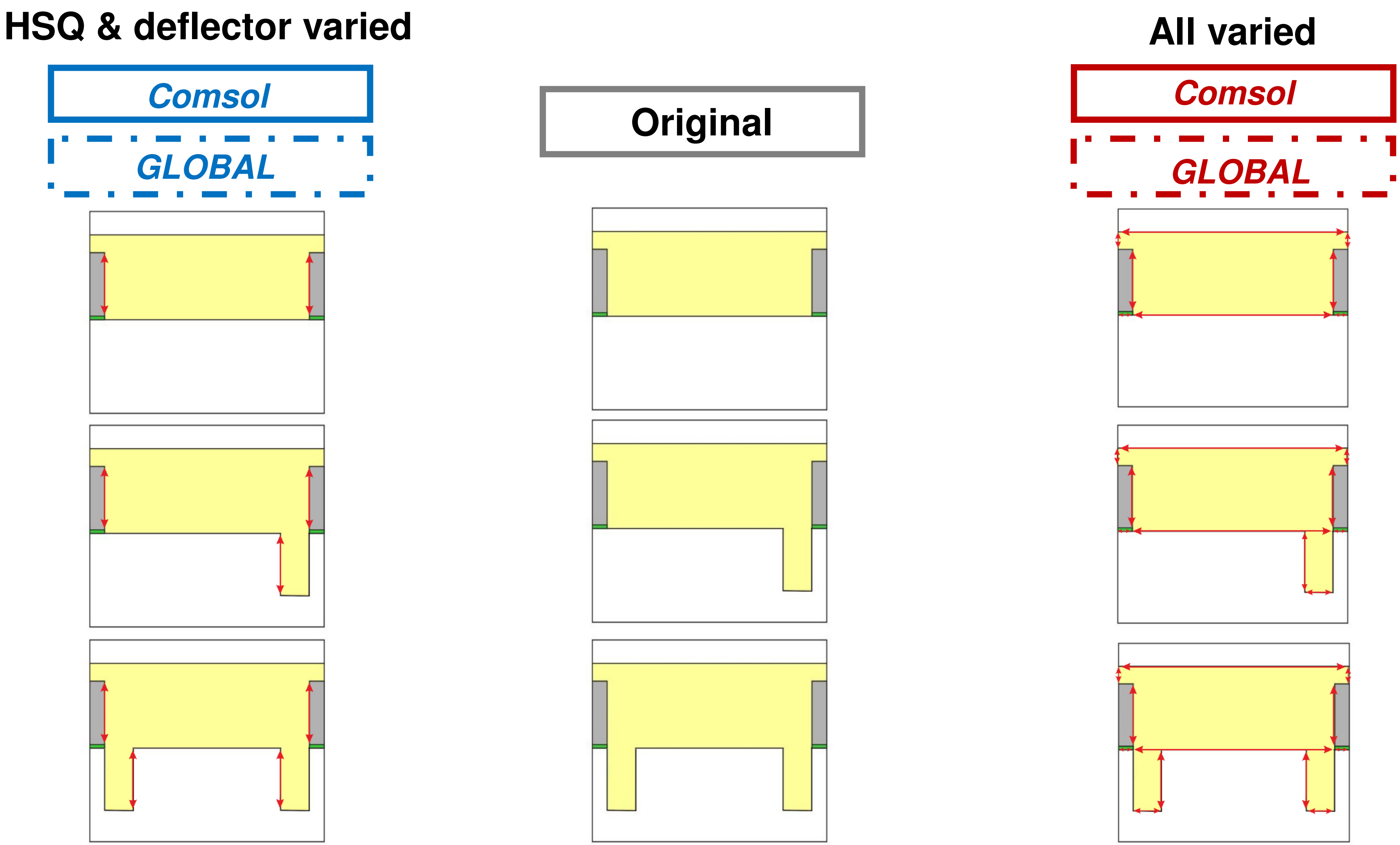
GLOBAL methodology include:
Sampling (Monte Carlo)
Clustering (Single-link)
Local searching (UNIRANDI, Random walk, BFGS)

COMSOL methodology include:
Sampling (Monte Carlo)
Local searching (Nelder-Mead)

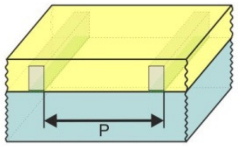
Tibor Csendes, László Pál, J. Oscar H. Sendín, Julio R. Banga: The GLOBAL Optimization Method Revisited, Optimization Letters 2(2008) 445-454.

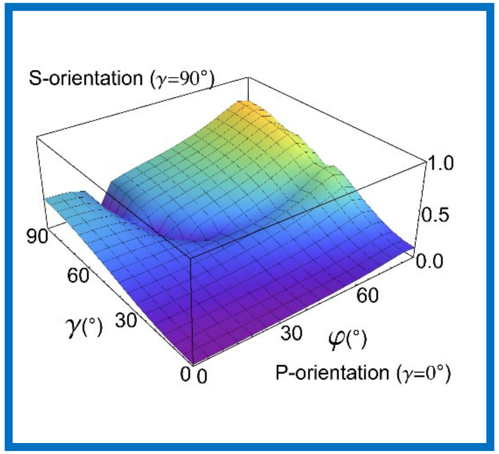
http://www.inf.u-szeged.hu/~csendes/Reg/regform.php

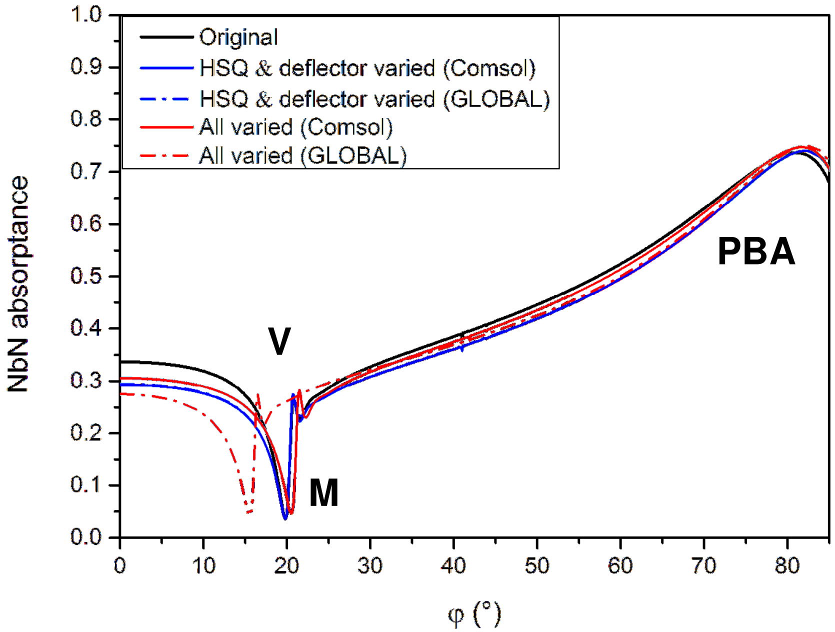
Optimization methods

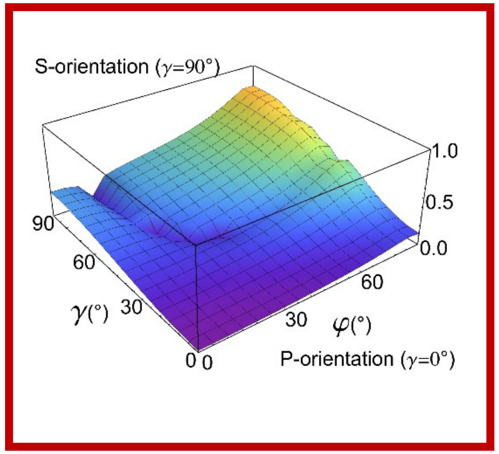


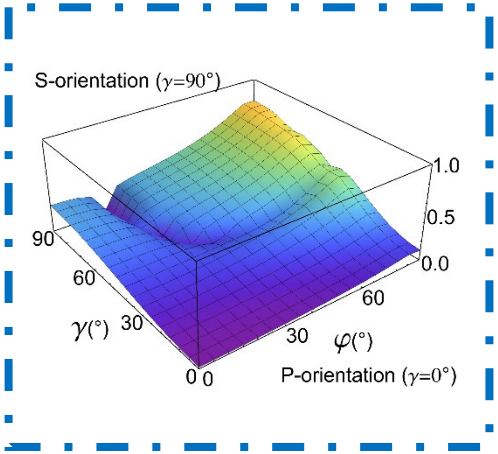
Orientation dependence of NbN absorptance in NCAI-SNSPD illuminated by p-polarized light







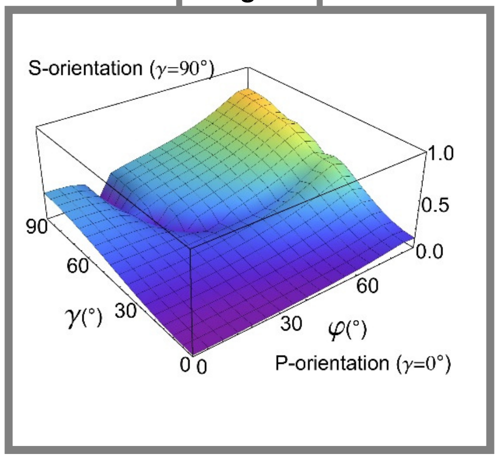




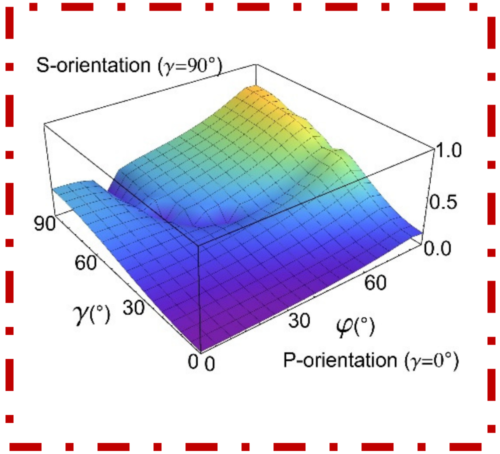
HSQ & deflector varied

Comsol *GLOBAL*

Original

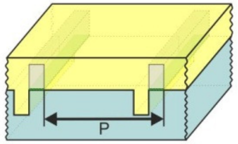


S-orientation is preferred,
E-field perpendicular to gold segments

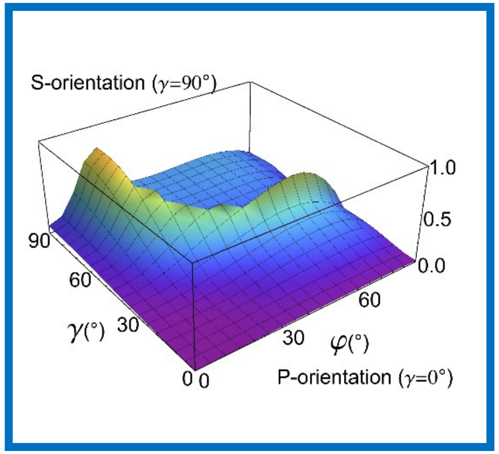


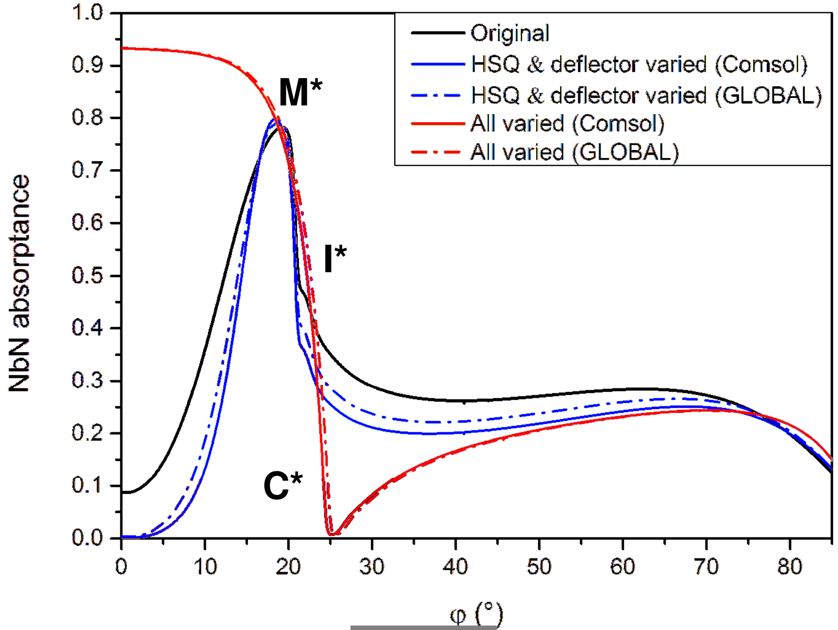
All varied

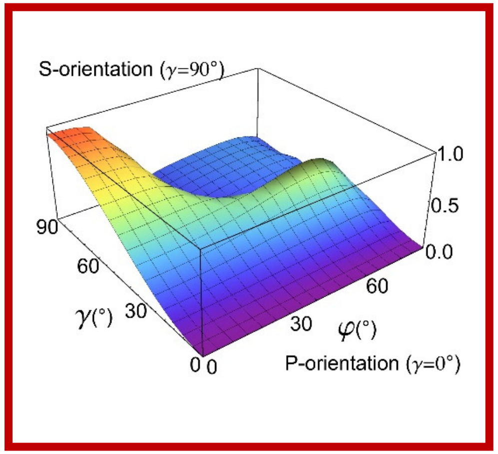
Comsol *GLOBAL*

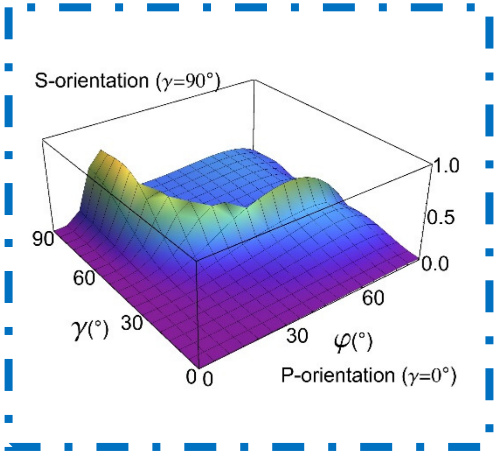


Orientation dependence of NbN absorptance in NCDAI-SNSPD illuminated by p-polarized light





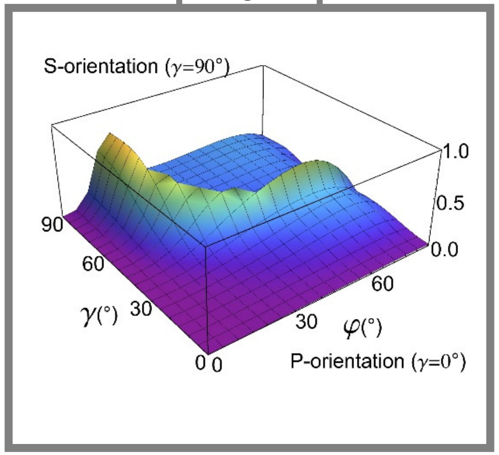




HSQ & deflector varied

Comsol *GLOBAL*

Original



S-orientation is preferred,
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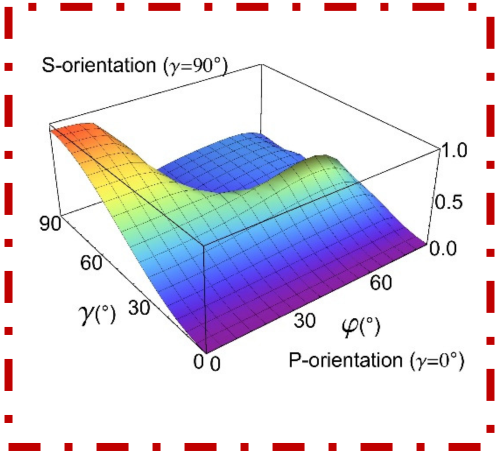
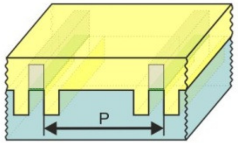
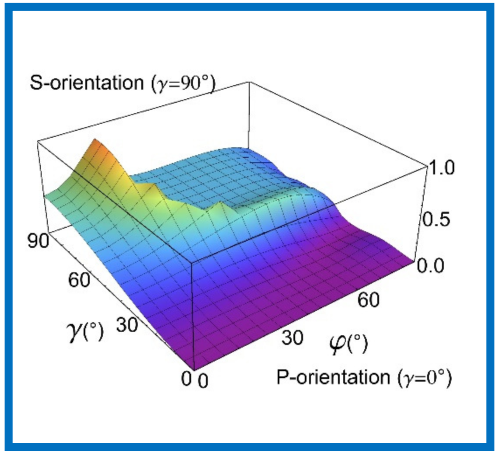


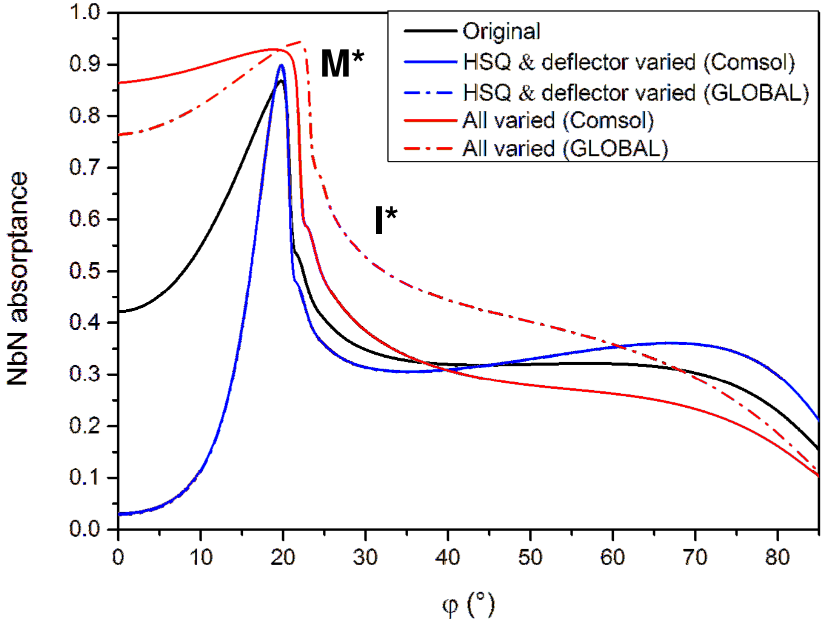
All varied

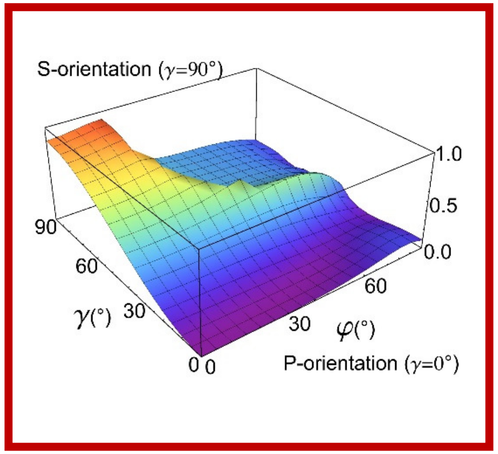
Comsol *GLOBAL*

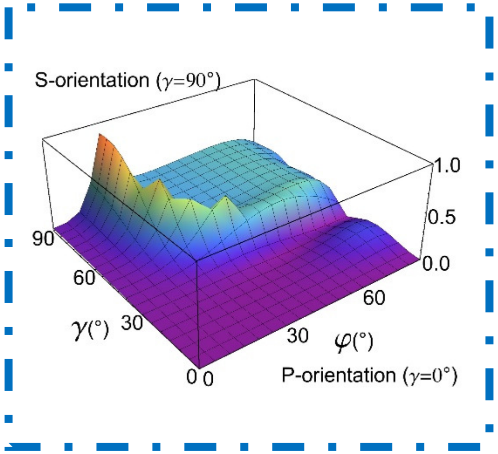


Orientation dependence of NbN absorptance in NCDDAI-SNSPD illuminated by p-polarized light





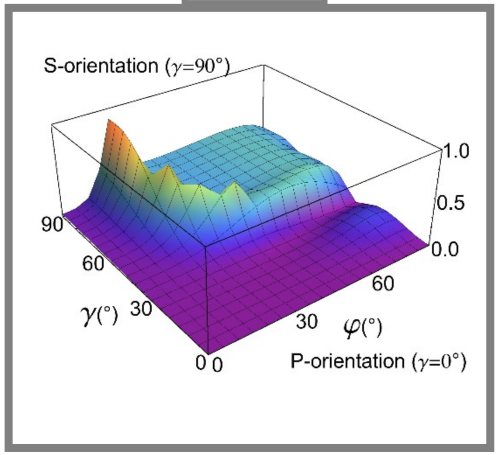




HSQ & deflector varied

Comsol GLOBAL

Original



S-orientation is preferred,
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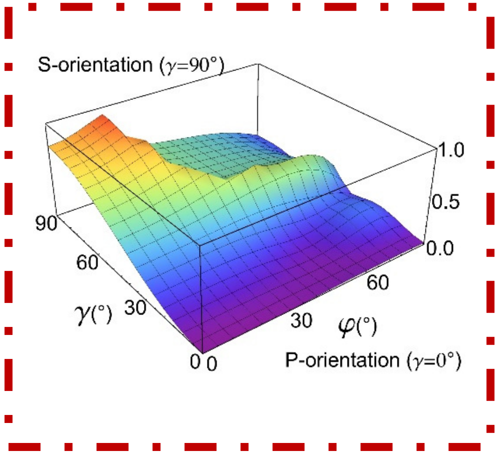
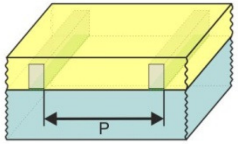


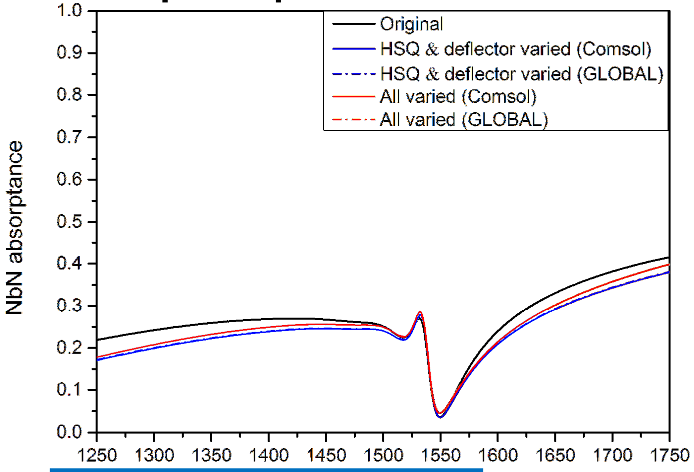
All varied

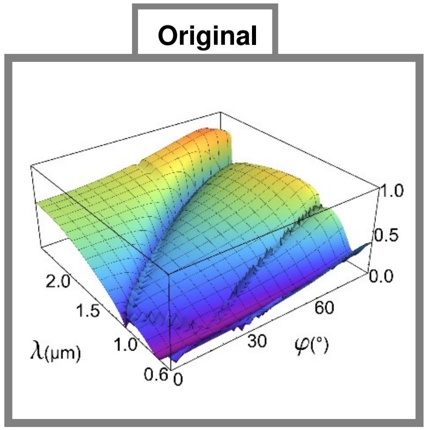
Comsol GLOBAL



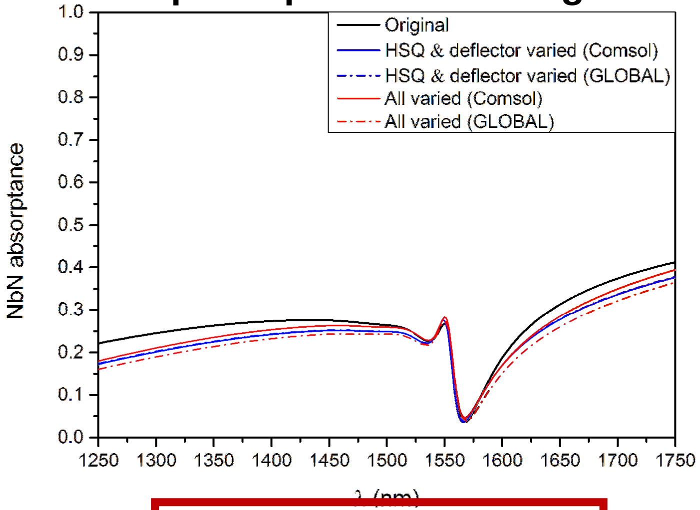
Wavelength dependence of NbN absorptance in NCAI-SNSPD illuminated by p-polarized light

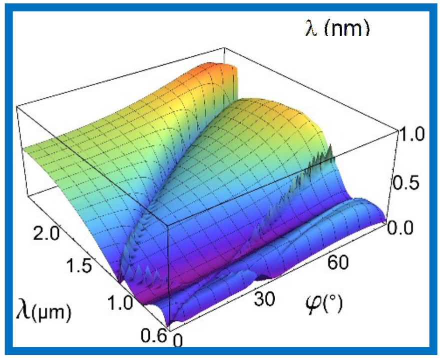
M point: pseudo PBG center

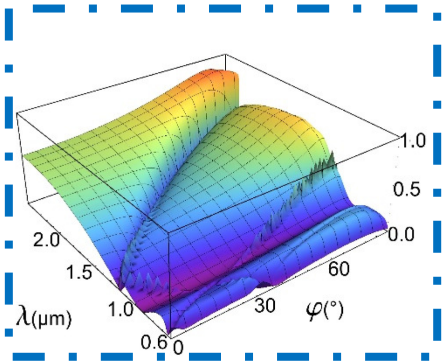




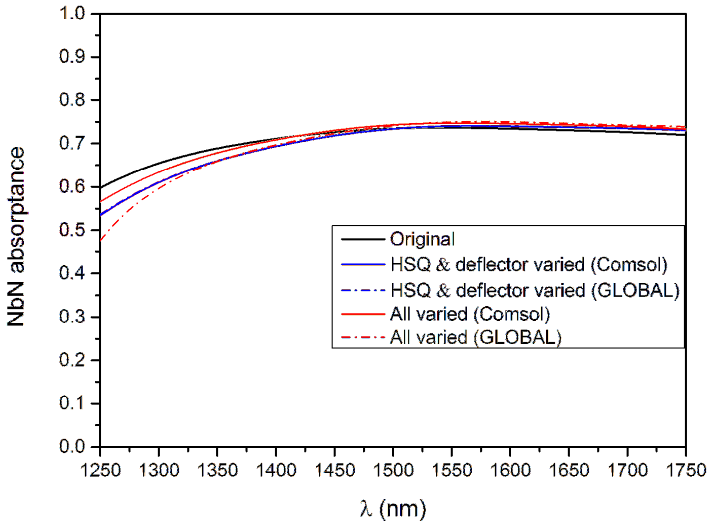
V point: pseudo PBG edge

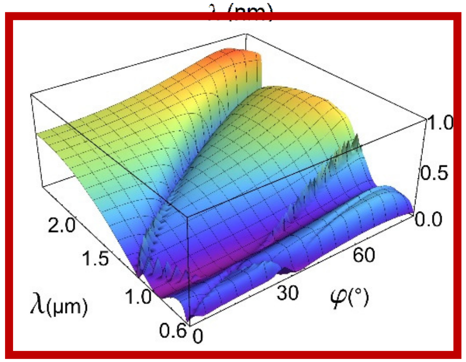


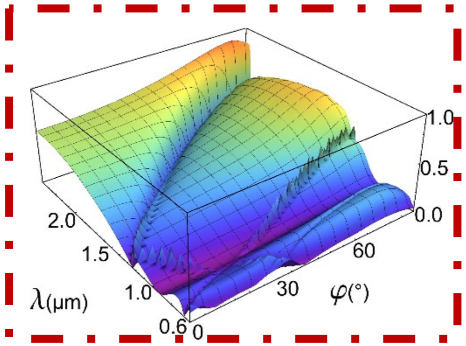




PBA point: wavelength independent

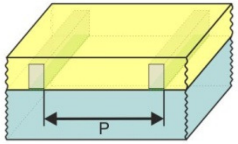




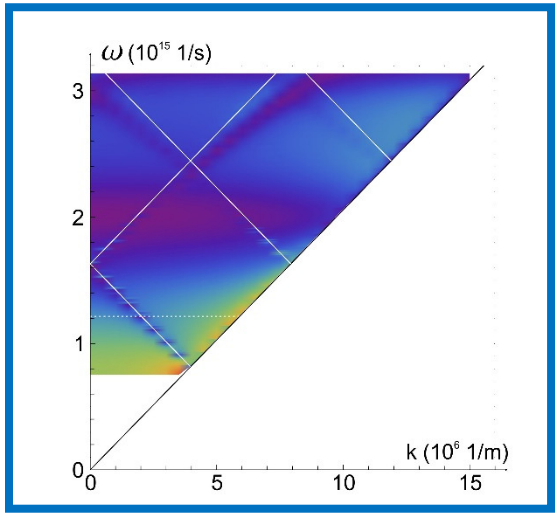


HSQ & deflector varied — *Comsol* | *GLOBAL*

All varied — *Comsol* | *GLOBAL*



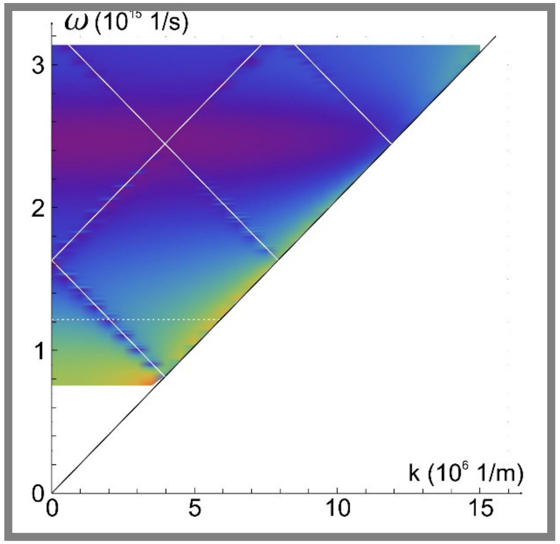
Dispersion relation of NbN absorptance in NCAI-SNSPD

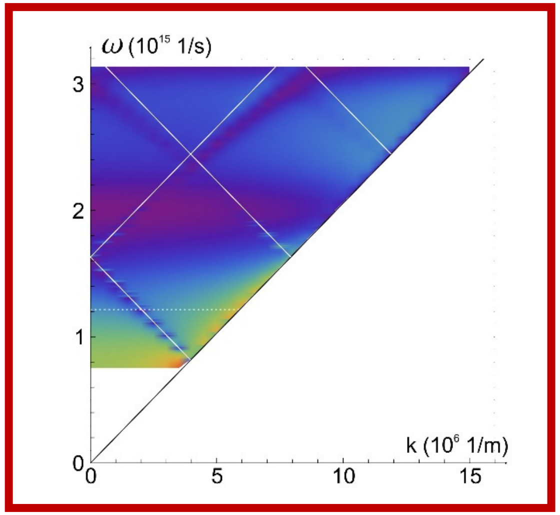


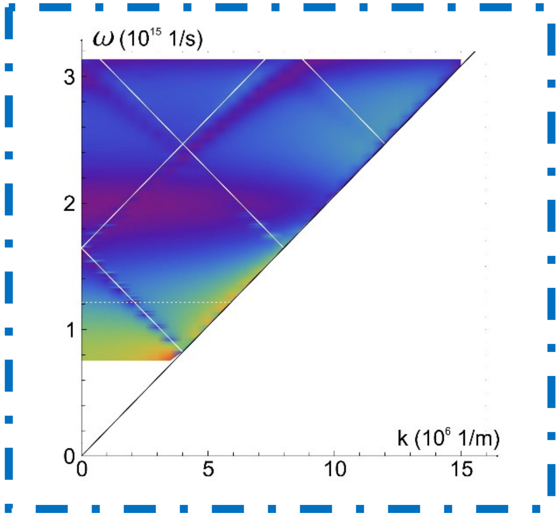
1550 nm: inside pseudo PBG

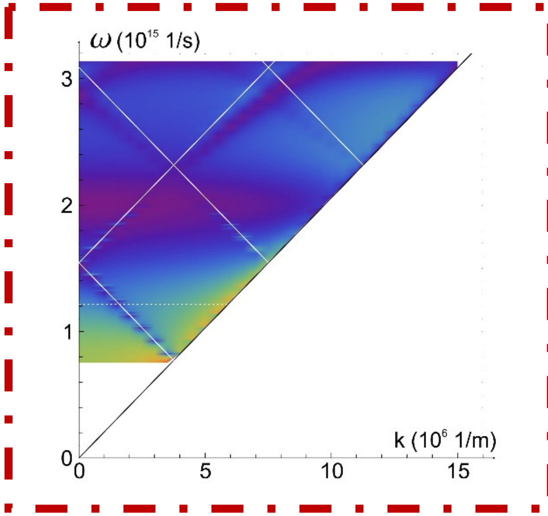
$$-k_{Surface\,Wave} = k_{photonic}\sin\varphi - k_{grating}$$

$$-k_{Surface\,Wave} + k_{grating} = k_{photonic}\sin\varphi$$





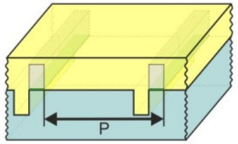




Original

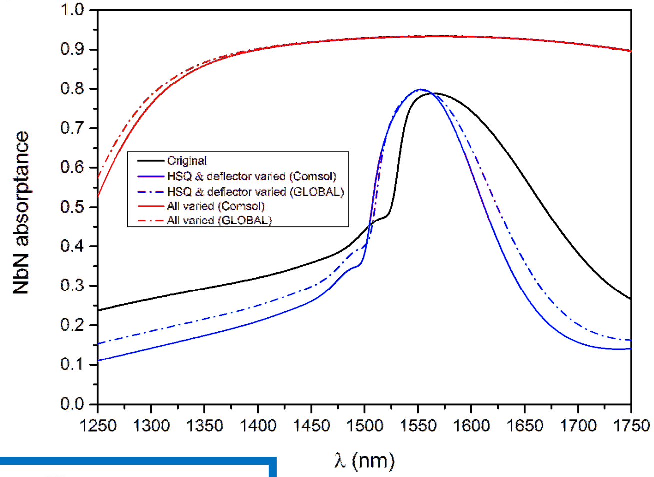
HSQ & deflector varied | **All varied**

Comsol *GLOBAL* *Comsol* *GLOBAL*

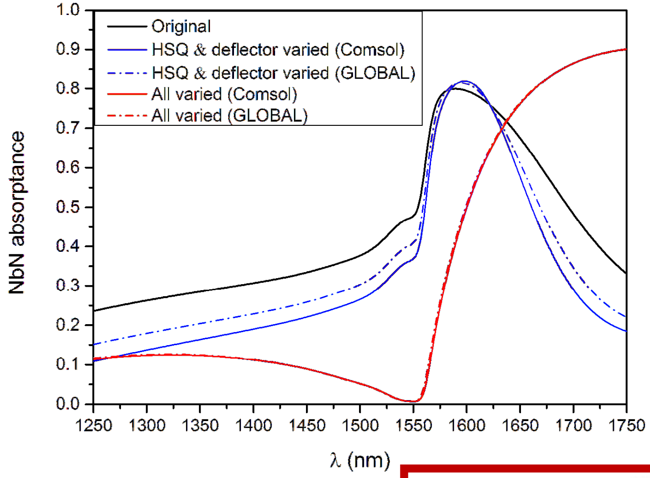


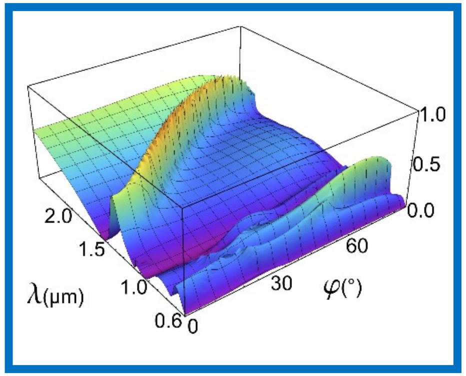
Wavelength dependence of NbN absorptance in NCDAI-SNSPD

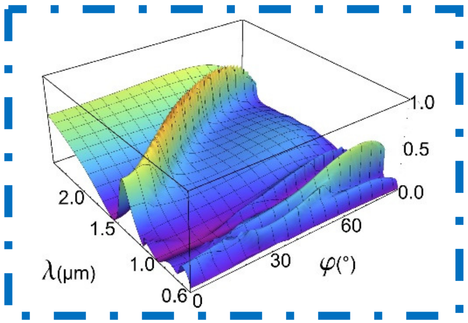
M*: inverted PBG center, broad pass band
perpendicular incidence: λ independent

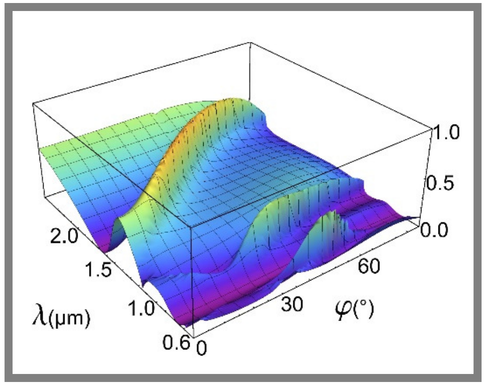


I*: inverted PBG edge, narrower pass-band
C*: cut-off







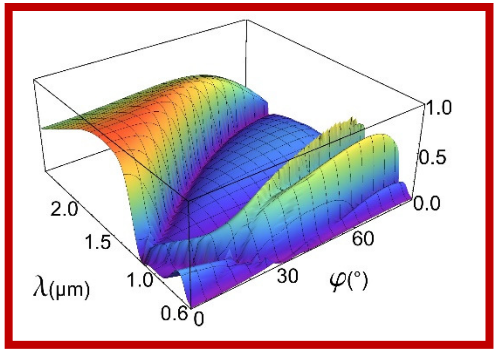


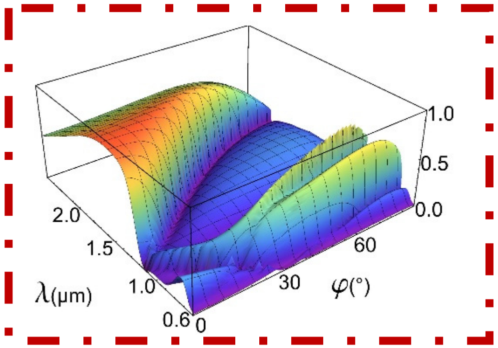
Original

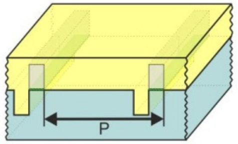
HSQ & deflector varied

All varied

Comsol ***GLOBAL*** ***Comsol*** ***GLOBAL***





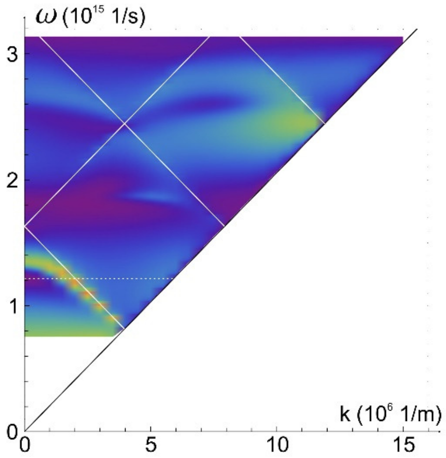


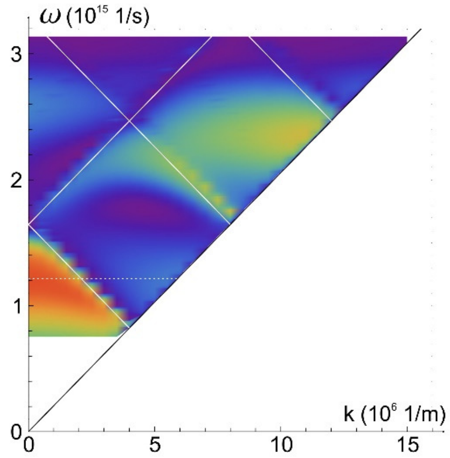
Dispersion relation of NbN absorptance in NCDAI-SNSPD

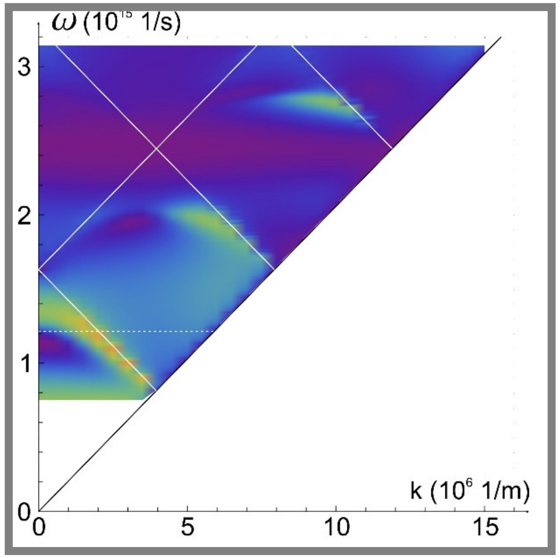
1550 nm:
inside inverted PBG, pass-band

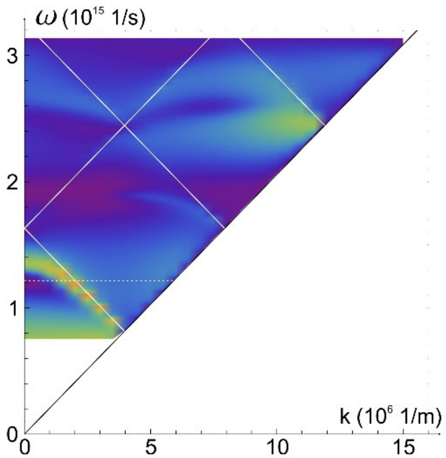
$$-k_{Surface\,Wave} = k_{photonic}\sin\varphi - k_{grating}$$

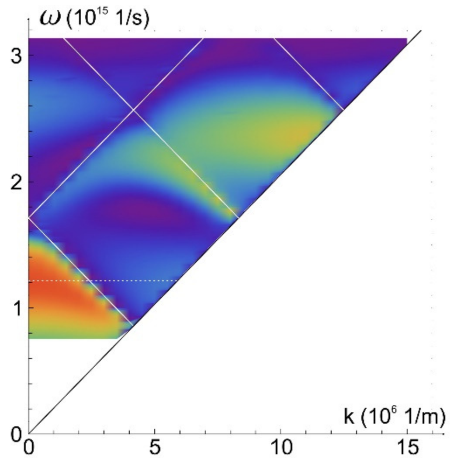
$$-k_{Surface\,Wave} + k_{grating} = k_{photonic}\sin\varphi$$







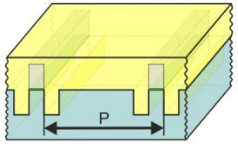




Original

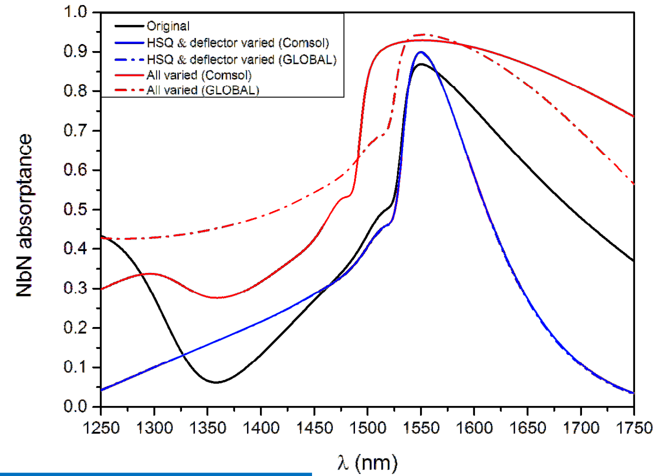
HSQ & deflector varied — *Comsol* *GLOBAL*

All varied — *Comsol* *GLOBAL*

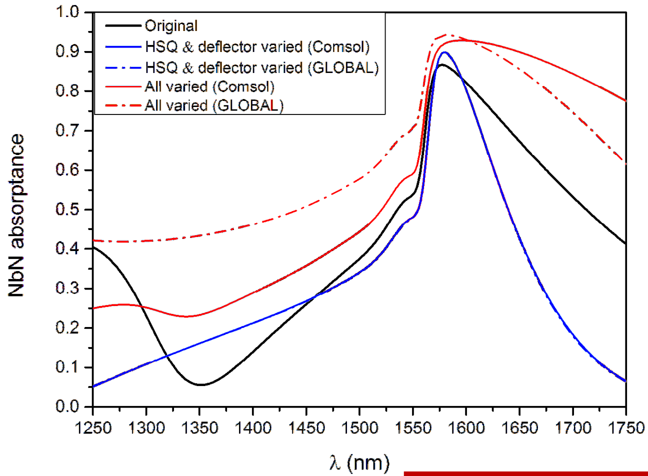


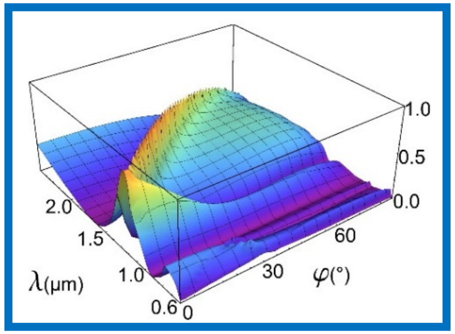
Wavelength dependence of NbN absorptance in NCDDAI-SNSPD

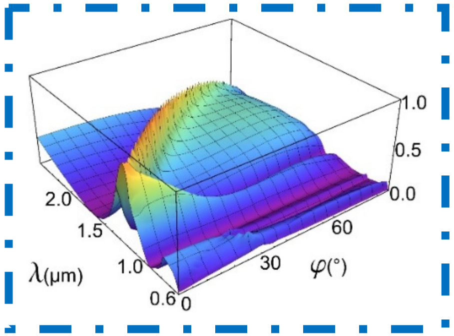
M* point: inverted PBG center, broad pass band

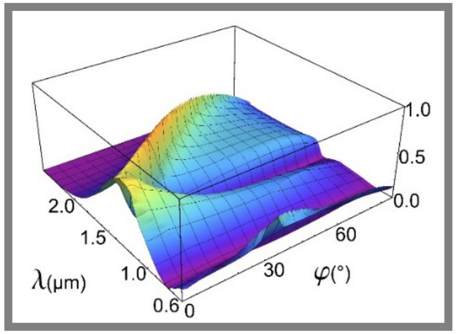


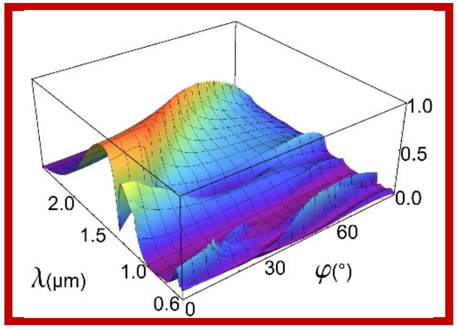
I*: inverted PBG edge narrower pass band

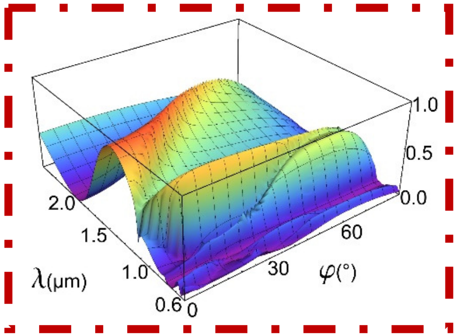








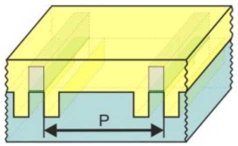




Original

HSQ & deflector varied *Comsol* *GLOBAL*

All varied *Comsol* *GLOBAL*

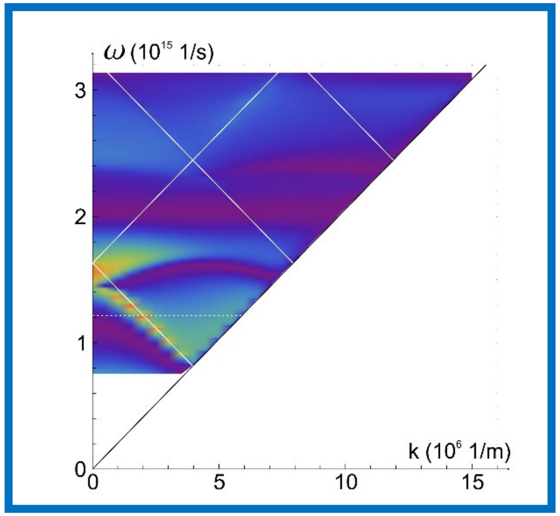


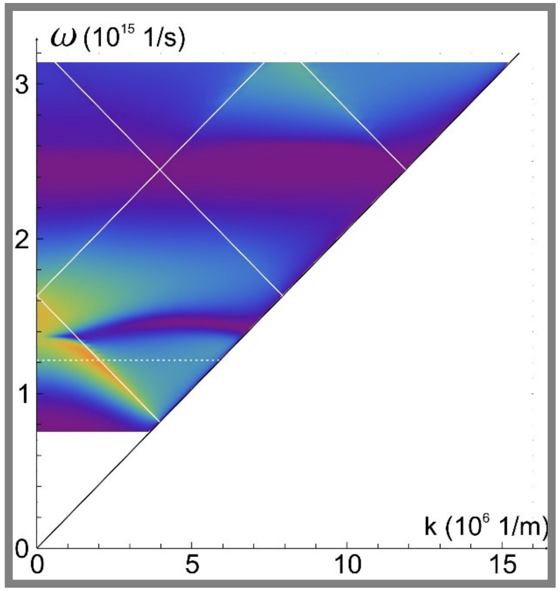
Dispersion relation of NbN absorptance in NCDDAI-SNSPD

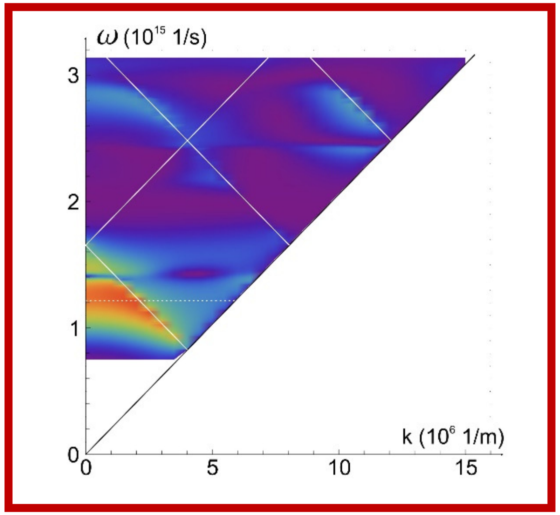
1550 nm:
inside inverted PBG, pass-band

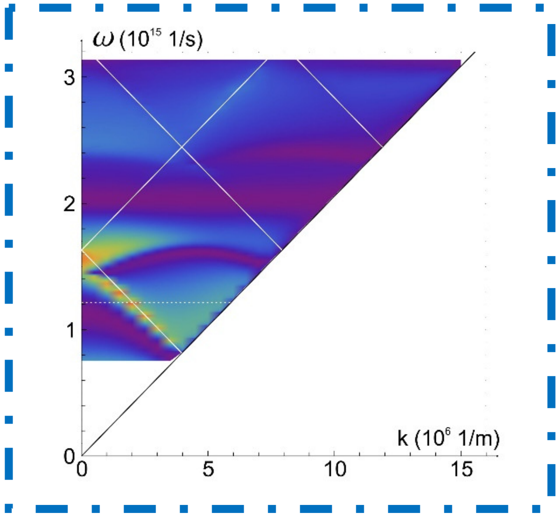
$$-k_{Surface\,Wave} = k_{photonic}\sin\varphi - k_{grating}$$

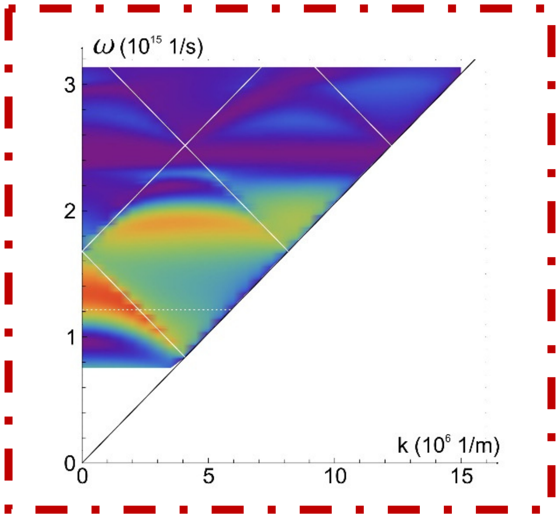
$$-k_{Surface\,Wave} + k_{grating} = k_{photonic}\sin\varphi$$









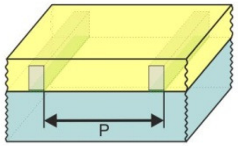


Original

HSQ & deflector varied

All varied

Comsol *GLOBAL* *Comsol* *GLOBAL*



Near-field of NCAI-SNSPD
M: global minimum / pseudo PBG center

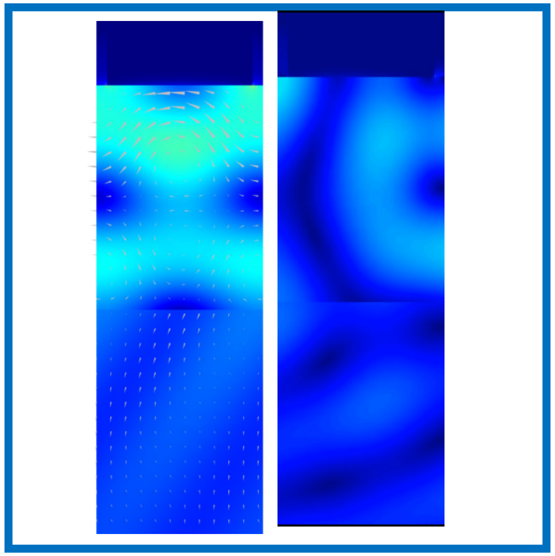
Original

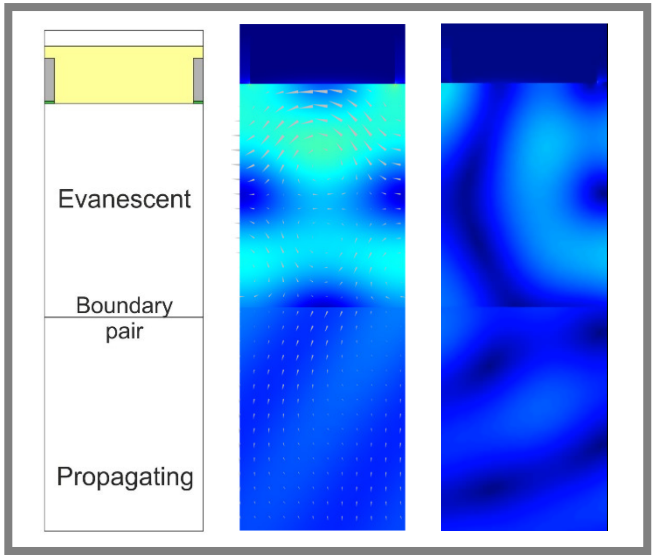
HSQ & deflector varied

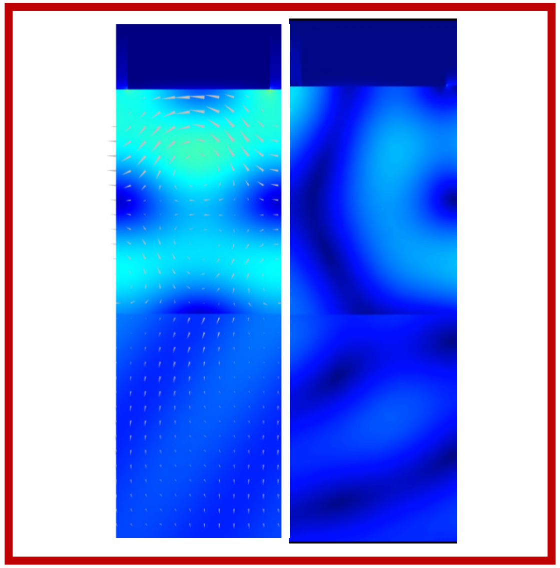
Comsol | GLOBAL

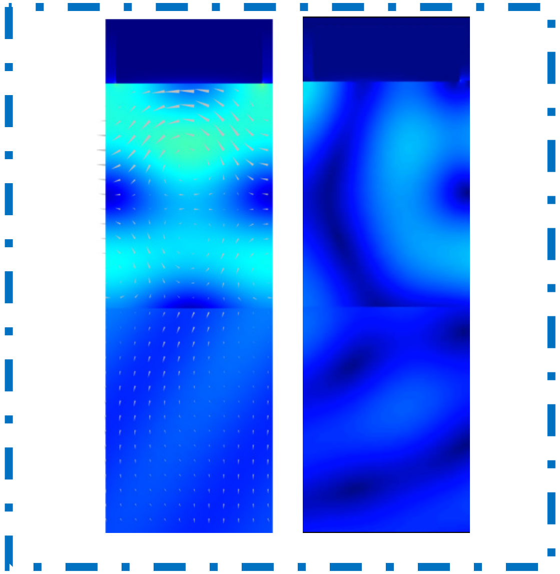
All varied

Comsol | GLOBAL









de-synchronized
Brewster-Zenneck waves

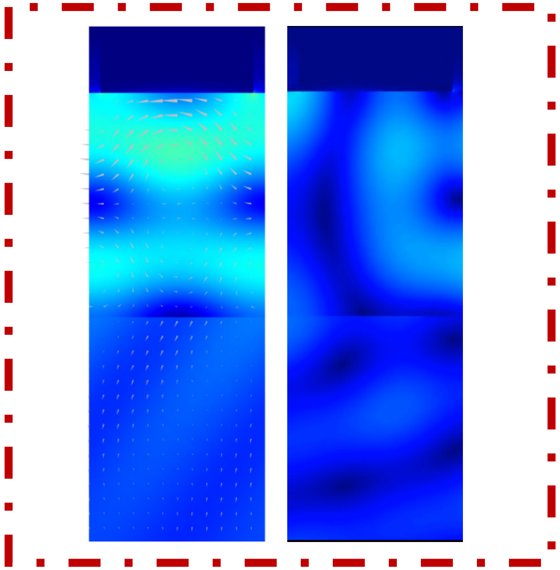
$\lambda \sim \lambda_{SPP}$

at the pseudo PBG center

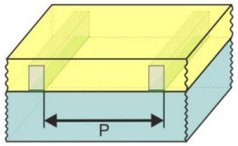
$$\sin\varphi^{m,k} = \frac{m\lambda / n_{sapphire}}{kp}$$

Wood
m = 1, k = 4

$$-\frac{2\pi}{\lambda_{Brewster-Zenneck\ wave}} = \frac{2\pi}{\lambda}\sin\varphi - \frac{2\pi}{P}$$

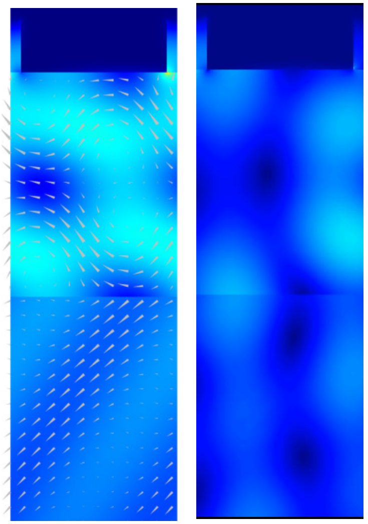


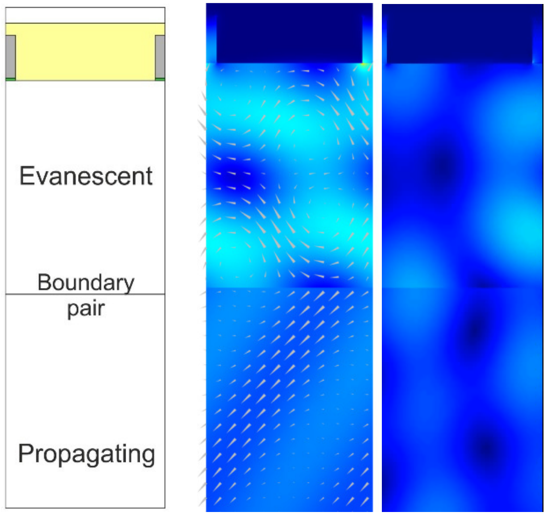
R. W. Wood: Phys. Rev. 15, 928–937 (1935).

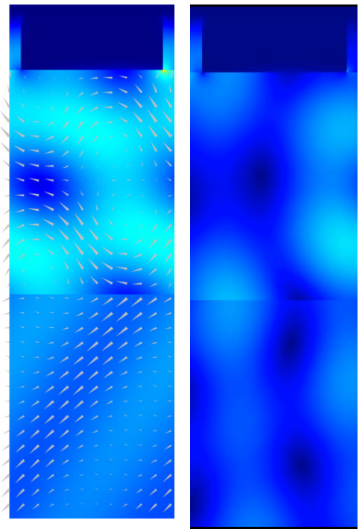


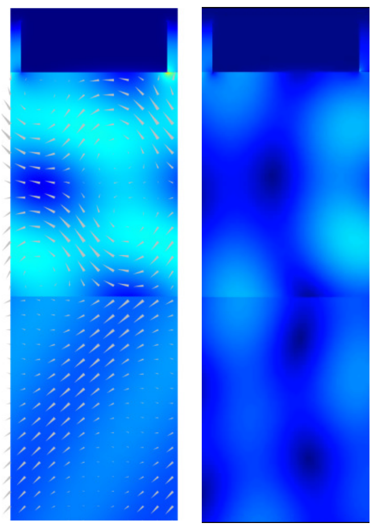
Near-field of NCAI-SNSPD
V: local maximum / pseudo PBG edge

Original







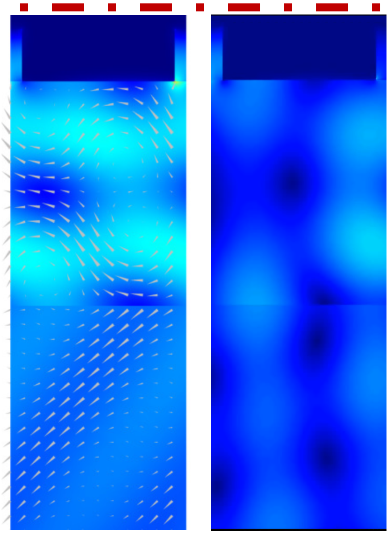


better synchronized
Brewster-Zenneck waves
at the pseudo PBG-edge

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

Wood
m = 1, k = 4

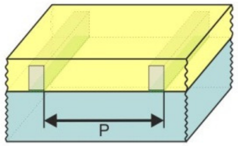
$$-\frac{2\pi}{\lambda_{Brewster-Zenneck\ wave}} = \frac{2\pi}{\lambda}\sin\varphi - \frac{2\pi}{P}$$



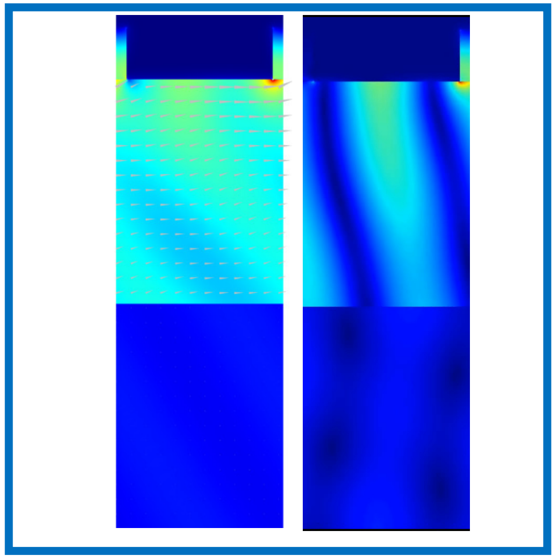
HSQ & deflector varied — *Comsol* / *GLOBAL*

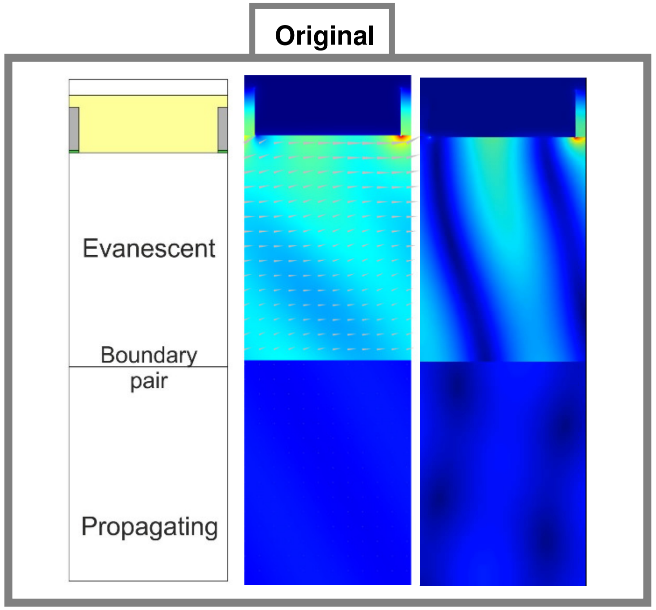
All varied — *Comsol* / *GLOBAL*

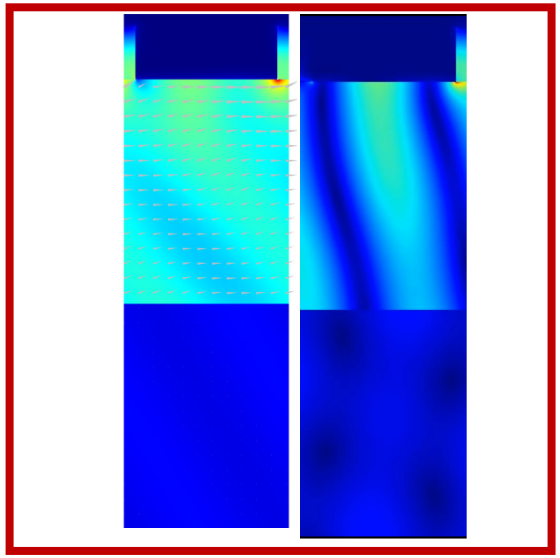
R. W. Wood: Phys. Rev. 15, 928–937 (1935).

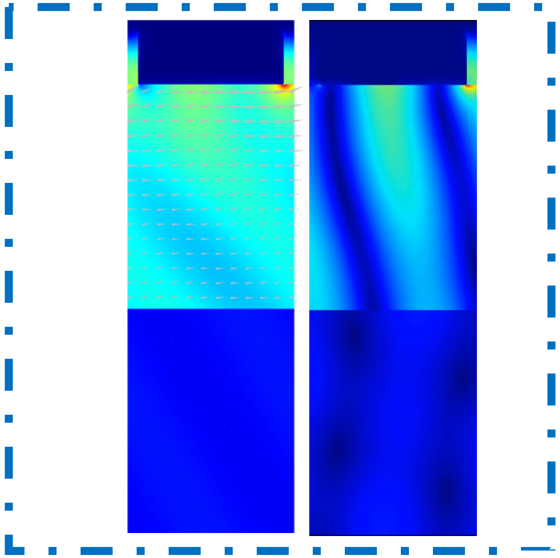


Near-field of NCAI-SNSPD
PBA: global maximum / wavelength independent



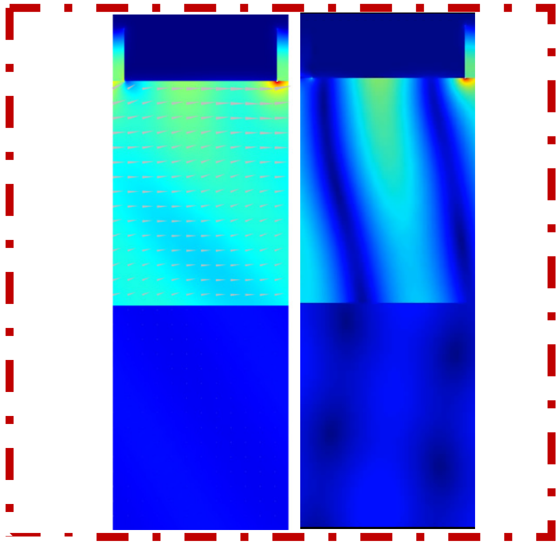






PBA:
transversal wave number
⇔
Brewster-Zenneck waves

$$\cos\varphi = \left(k_{surface\ wave} w\right) / \left(k_{photonic}\, p\right)$$



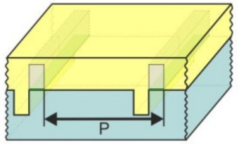
HSQ & deflector varied

Comsol *GLOBAL*

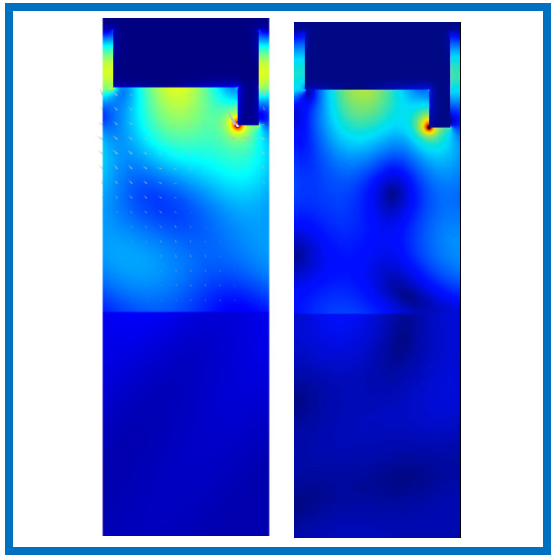
All varied

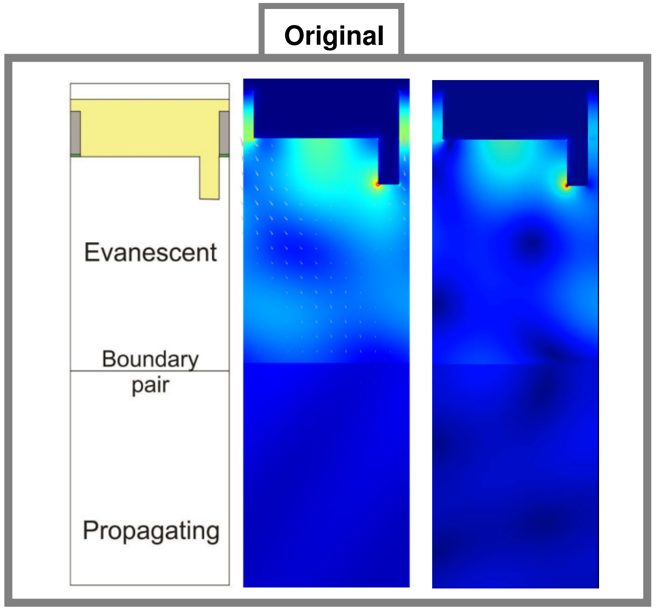
Comsol *GLOBAL*

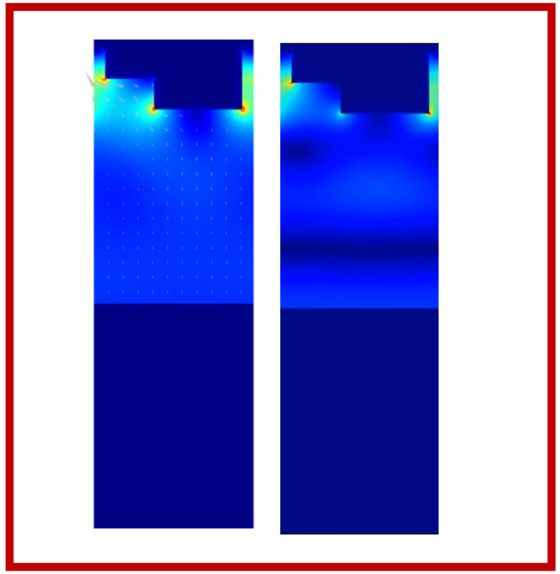
PBA: A. Alú: Phys. Rev. Lett. 106, 123902 (2011).

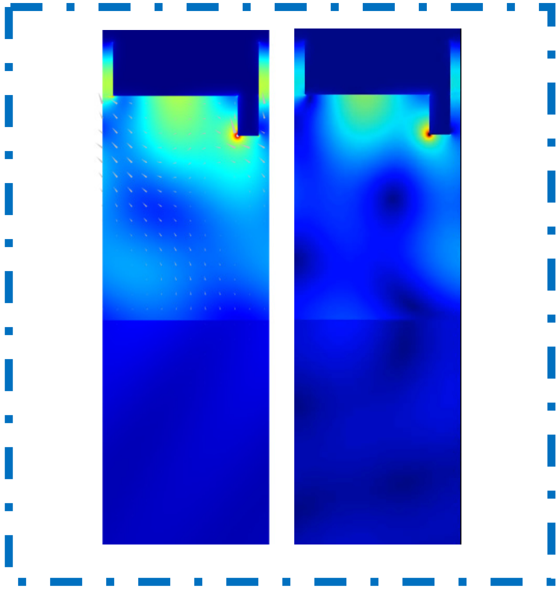


Near-field of NCDAI-SNSPD
M* & 0°: global maximum / pass-band-center



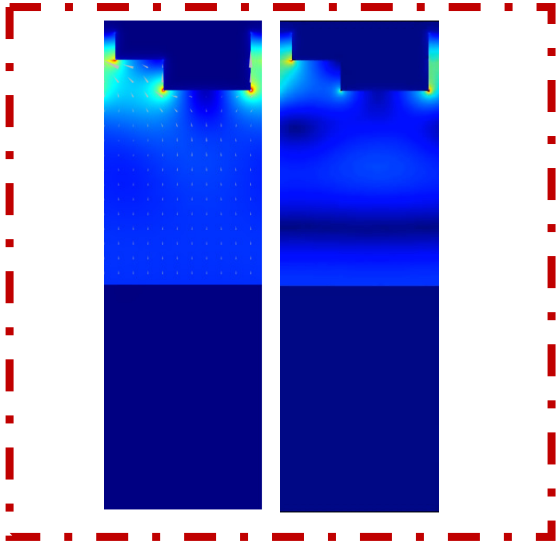






laterally synchronized
Brewster-Zenneck waves
with $\lambda \sim \lambda_{SPP}$ at the middle of
inverted pseudo PBG ⇔ pass-band

No reflected waves at the center
of pass-band region
at perpendicular incidence

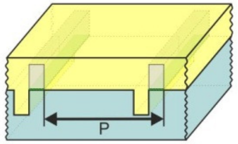


HSQ & deflector varied

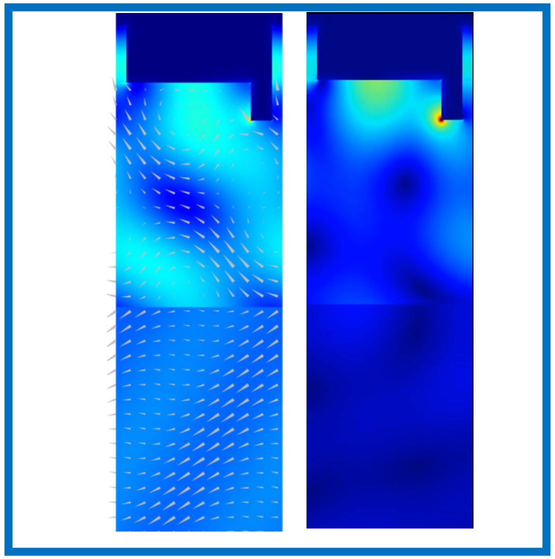
Comsol *GLOBAL*

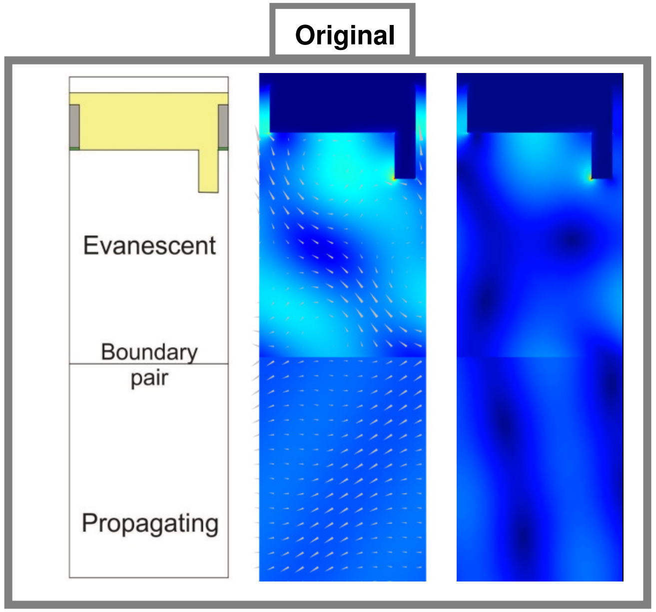
All varied

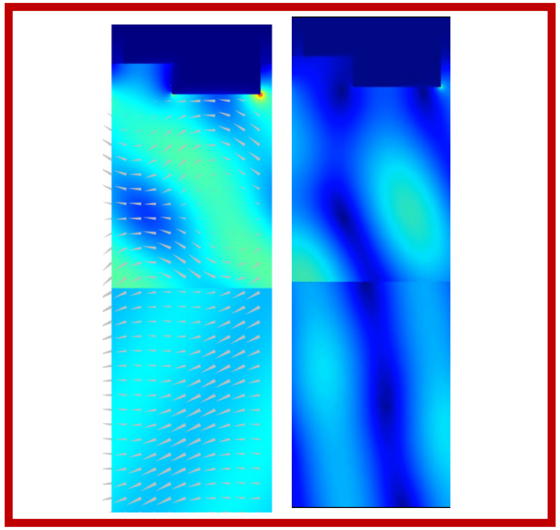
Comsol *GLOBAL*

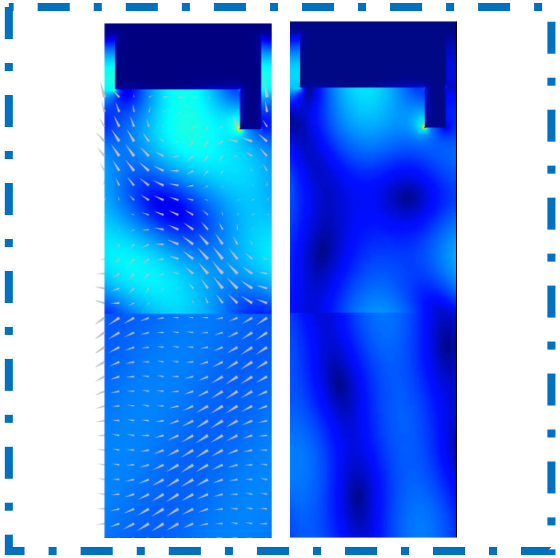


Near-field of NCDAI-SNSPD
I*: inflection point at pass-band edge / C*: cut-off point



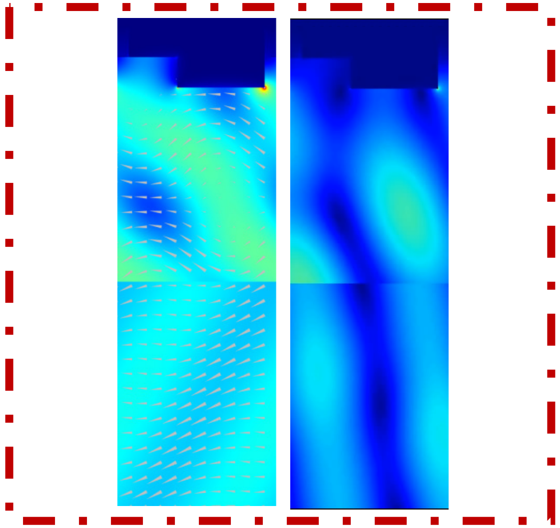






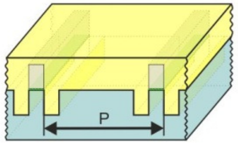
partially de-synchronized
Brewster-Zenneck waves
with $\lambda \sim\lambda_{SPP}$ at the I* edge of
inverted pseudo PBG ⇔ pass-band

In contempt of backward
propagating coupled waves
cut-off at C* point

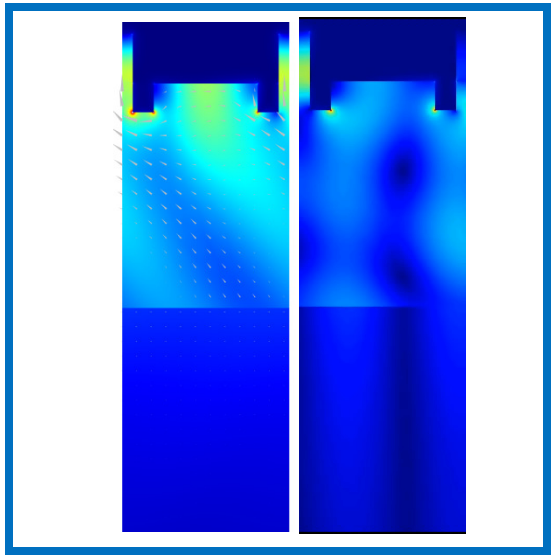


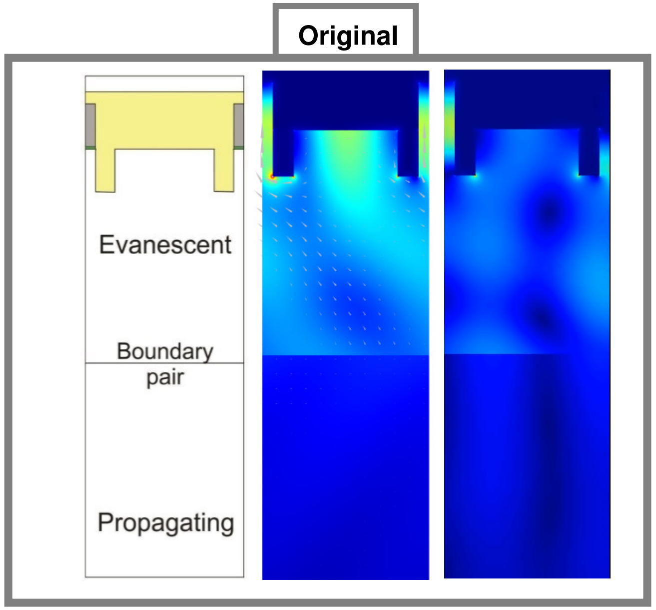
HSQ & deflector varied — *Comsol* | *GLOBAL*

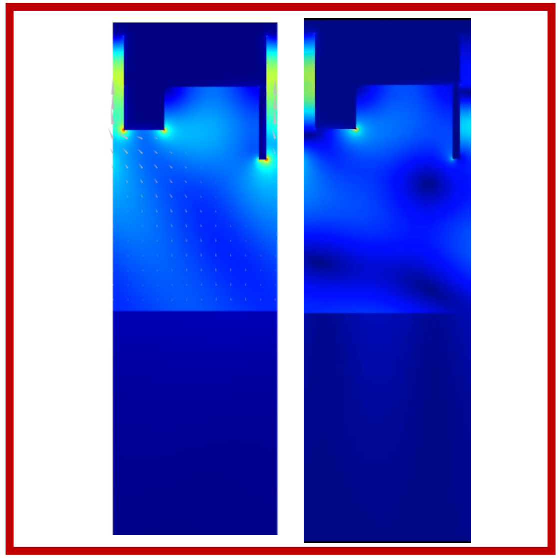
All varied — *Comsol* | *GLOBAL*

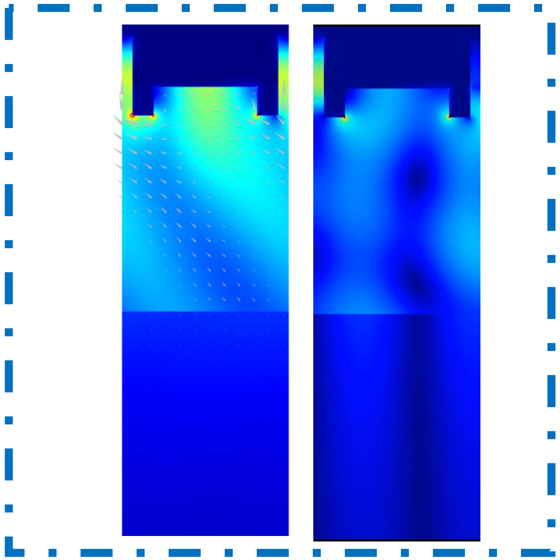


Near-field of NCDDAI-SNSPD
M*: global maximum at the pass-band-center

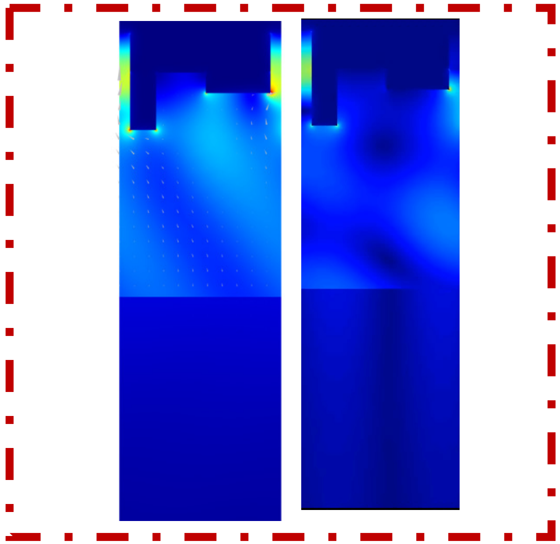






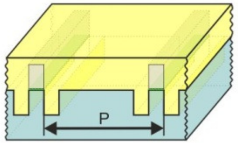


laterally synchronized
Brewster-Zenneck waves
with $\lambda \sim\lambda_{SPP}$ at the middle of
inverted pseudo PBG ⇔ pass-band

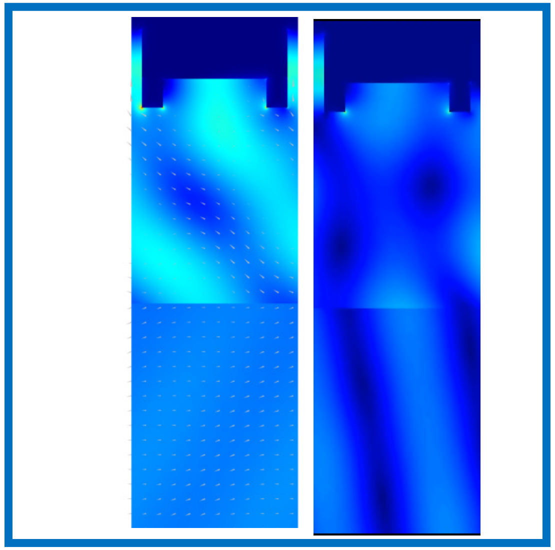


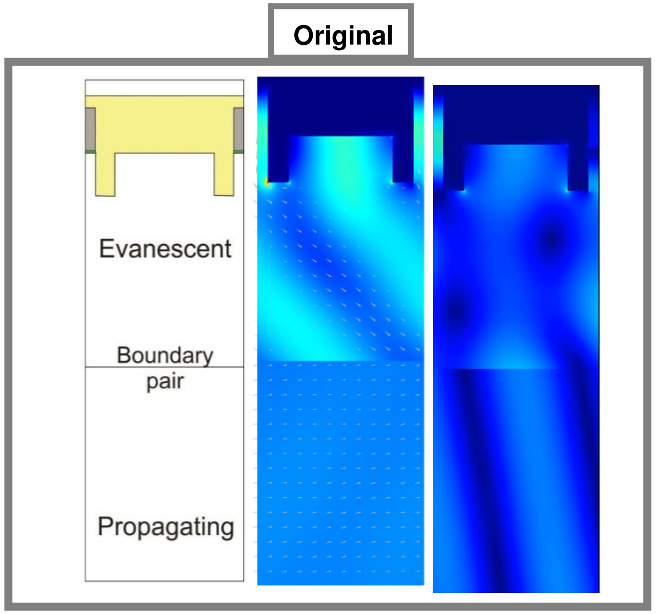
HSQ & deflector varied — *Comsol* | *GLOBAL*

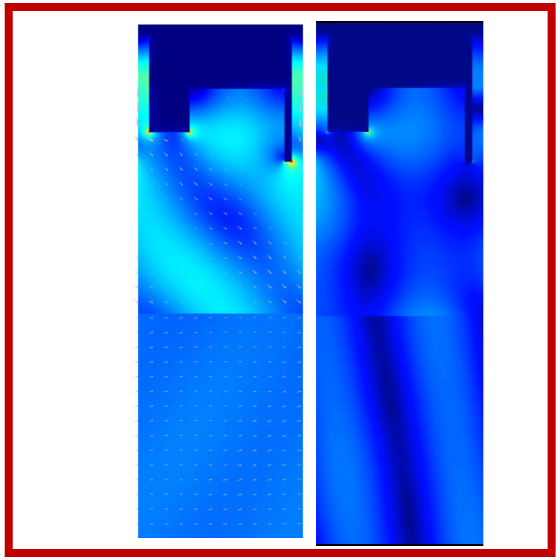
All varied — *Comsol* | *GLOBAL*

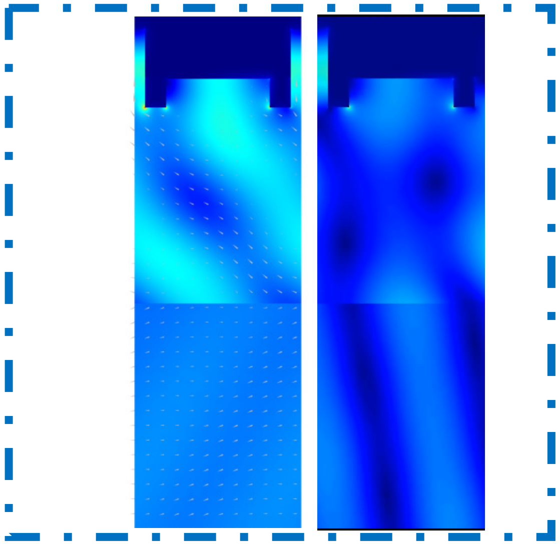


Near-field of NCDDAI-SNSPD
I*: inflection point at pass-band-edge

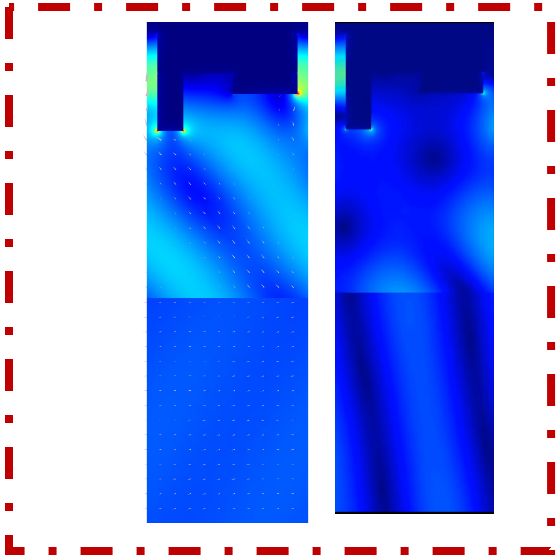








partially de-synchronized
Brewster-Zenneck waves
with λ ~λ_{SPP} at the I* edge of
inverted pseudo PBG ⇔ pass-band



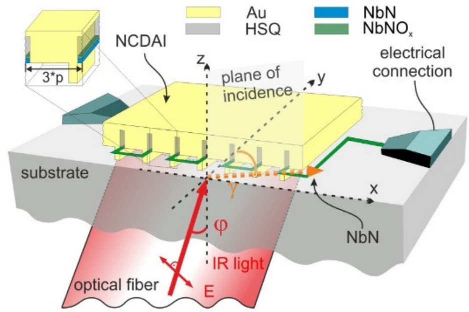
HSQ & deflector varied

Comsol *GLOBAL*

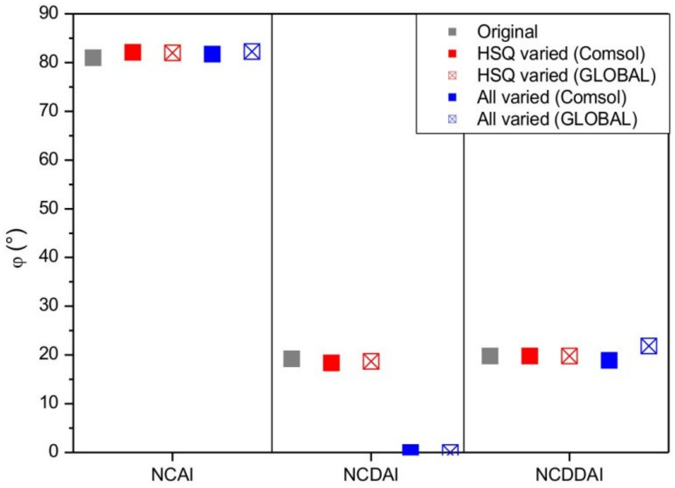
All varied

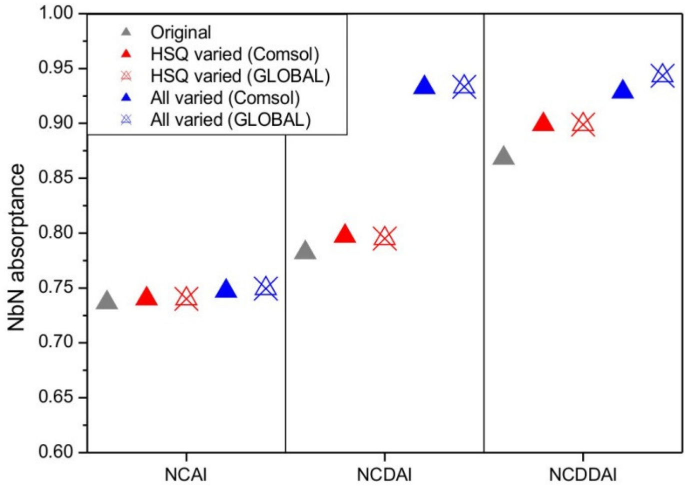
Comsol *GLOBAL*

Summary

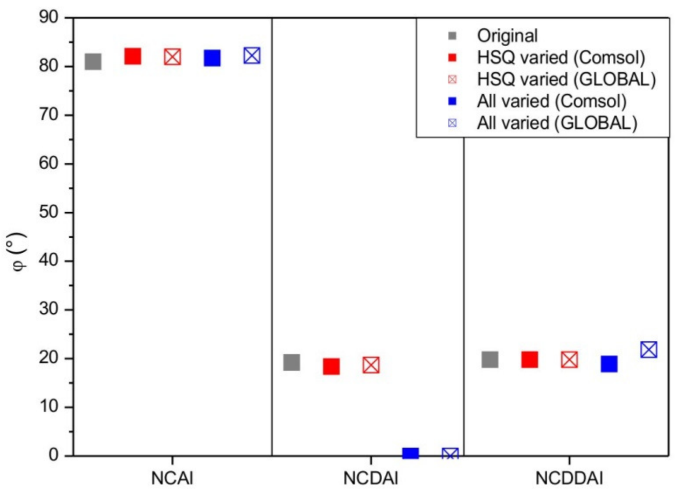


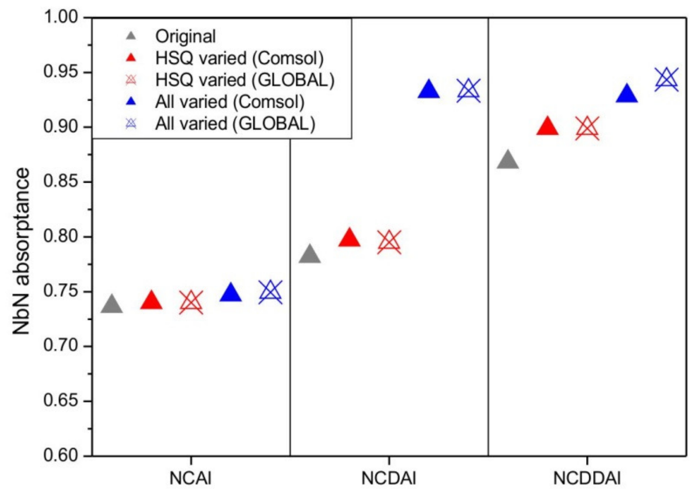
- Optimization results in higher absorptance, when
  - all parameters are varied
  - GLOBAL is used as a special algorithm sequence
- NCAI-SNSPD: COMSOL~GLOBAL
  - maximal absorptance at PBA, almost wavelength independent
  - PBG, Fano-lines, Brewster-Zenneck waves coupled at specific orientations
- NCDAI: COMSOL < GLOBAL, different!
  - inverted PBG <=> pass-band / maximal absorptance at perpendicular incidence, wide bandwidth / almost wavelength independent
  - synchronization of Brewster-Zenneck waves depends on grating profile / no reflection
- NCDDAI-SNSPD: COMSOL (cannot be fabricated) < GLOBAL
  - maximal absorptance at inverted PBG => pass-band, in wide spectral interval
  - cavity effect & lateral synchronization





	NCAI		NCDAI		NCDDAI	
	ϕ (°)	*NbN Abs*	*ϕ (°)*	*NbN Abs*	*ϕ (°)*	*NbN Abs*
Original	**81**	**73.66%**	**19.2**	**78.22%**	**19.8**	**86.84%**
HSQ varied (Comsol)	**82.08**	**74.00%**	**18.37**	**79.72%**	**19.8**	**89.90%**
HSQ varied (GLOBAL)	**82.01**	**74.00%**	**18.68**	**79.52%**	**19.79**	**89.90%**
All varied (Comsol)	**81.72**	**74.70%**	**0**	**93.26%**	**18.89**	**92.87%**
All varied (GLOBAL)	**82.24**	**74.96%**	**0**	**93.34%**	**21.85**	**94.34%**





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