Modeling plasmonic structure integrated single-photon detectors to maximize polarization contrast

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COMSOL CONFERENCE
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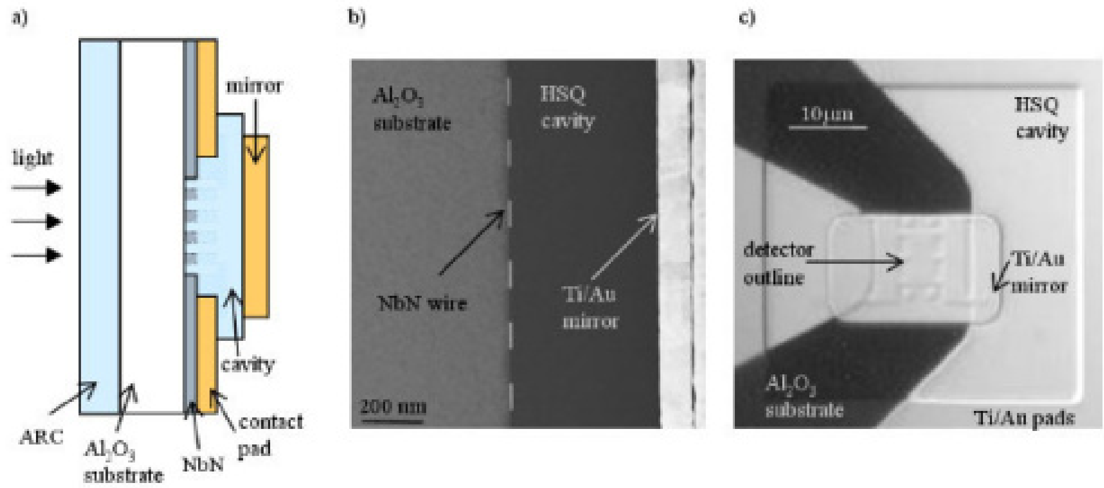
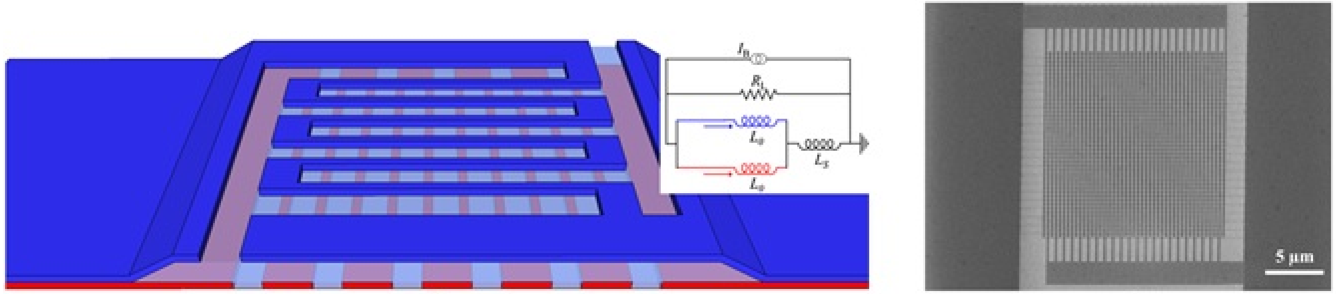
Dr. Mária Csete
COMSOL Conference, Boston, 2015

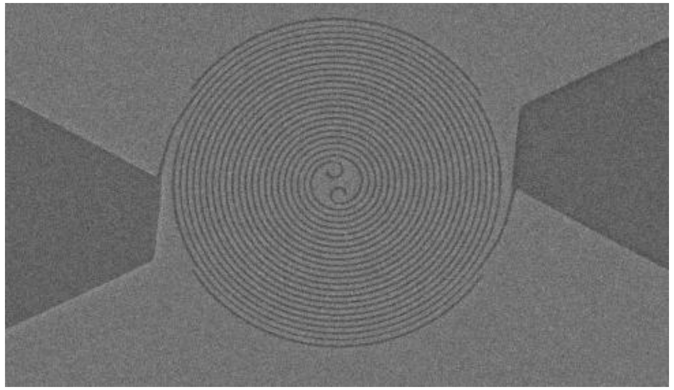


- SNSPDs are capable to detect a single-photon
  - Recovery time: <100 ns
  - Dark coundts: <100 1/s
  - Timing jitter: <100ps
- Application in Photonics, Quantum informatics and Astrology



(a) (b)

- Consist of
  - Meandered superconducting NbN wire
  - Different integrated nanostructures
    - Optical cavity array
    - Antenna array
    - Deflector array



- Two electrically connected crossed NbN patterns for polarization insensitive detection
- Spiral NbN pattern for polarization insensitive detection

Karl K. Breggen et al. „Nanowire Single-photon detector with an integrated optical cavity and anti-reflection coating” *Optics Express* **14,** 527, (2006)
Eric A. Dauler et al. „Review of superconducting nanowire single-photon detector system design options and demonstrated performance” *Optical Engineering* **53,** 081907, (2014)
D. Henrich et al. „Detection Efficiency of a Spiral Nanowire Superconducting Single-Photon Detector” *Applied Superconductivity* **23,** 2200405, (2013)

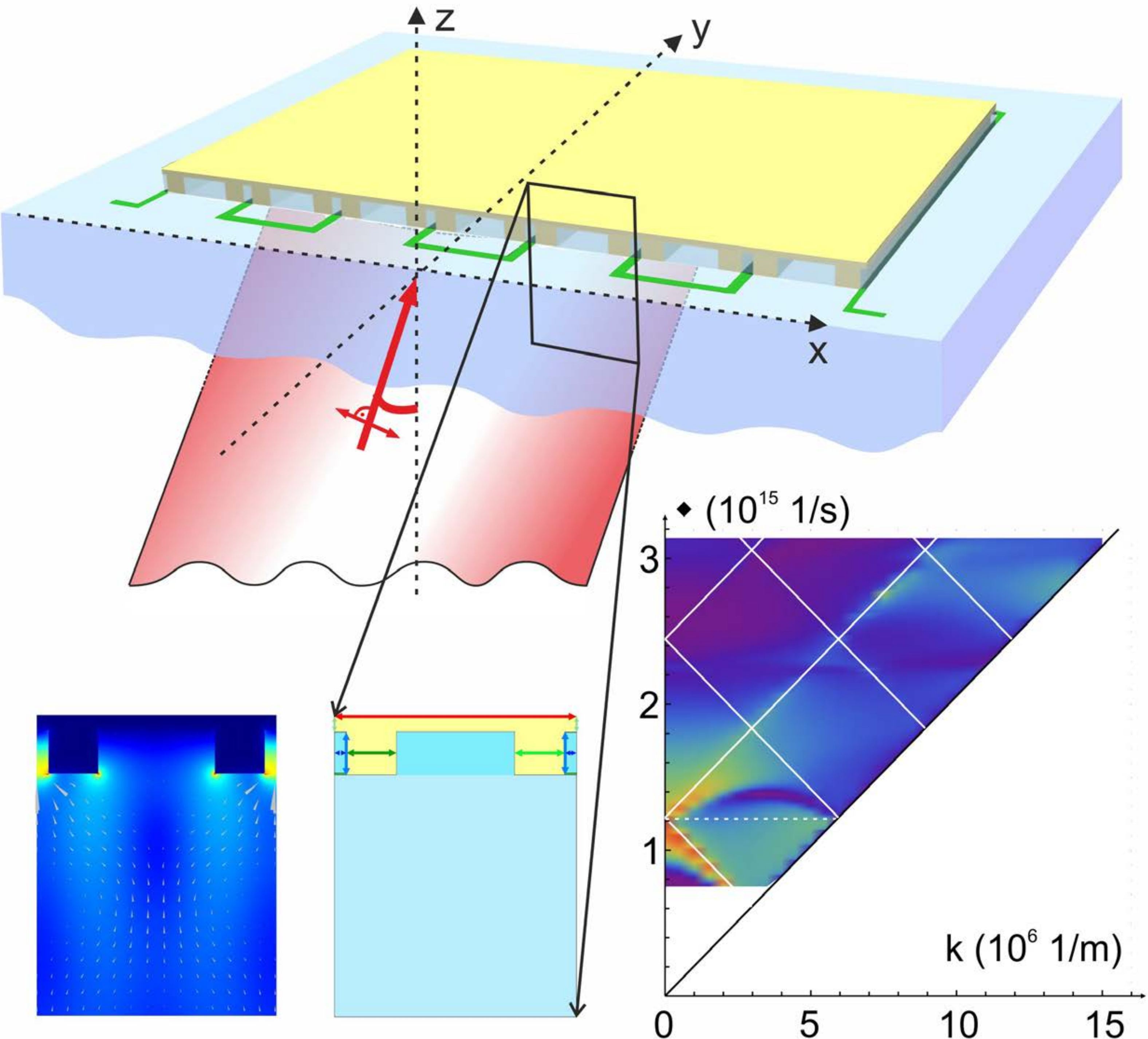
Outlook

oSNSPD

oAbsoption maximization: SNSPD-A

oPolarization contrast maximization
- Absolute: SNSPD-P
- Conditional: SNSPD-C

oMethodology
- Integrated plasmonic structure geometry
  - NCAI
  - NCDAI
  - NCDDAI
  - NCTAI
- Illuminaton direction
  - Azimuthal orientation
  - Polar angle



The GLOBAL Optimization Algorithm

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

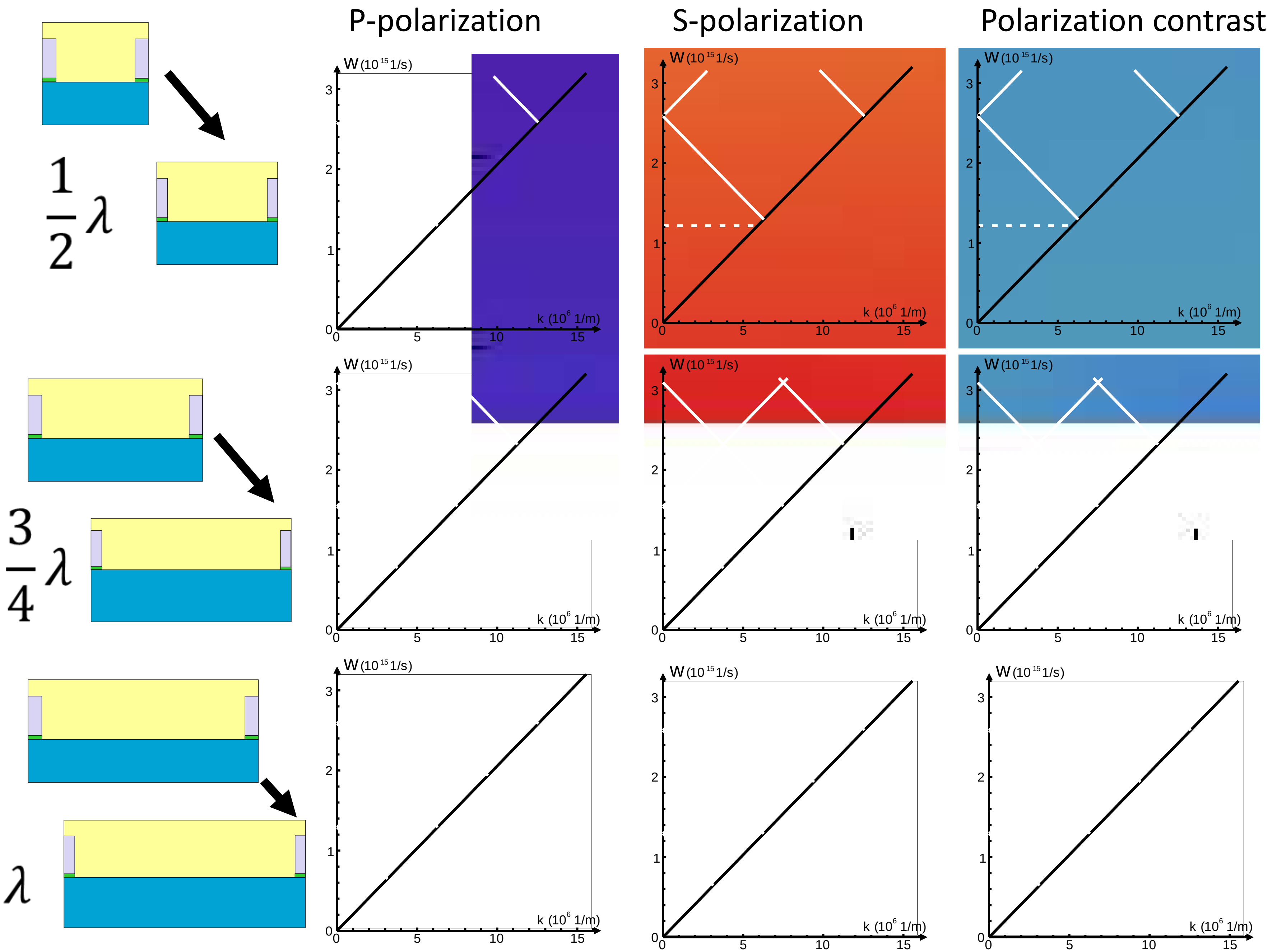
min f(x)
$x \in X$, $X = \{a_i \leq x_i \leq b_i, i = 1, 2, \ldots, n\}$,
where $f : R^n \rightarrow R$ is an arbitrary real nonlinear function, X is the set of feasibility,
an n-dimensional interval with vectors of lower and upper bounds of a and b, respectively. We applied the MATLAB version of the GLOBAL algorithm, a clustering stochastic global optimization technique. This method is capable to find the global optimizer points of moderate dimensional global optimization problems, when the relative size of the region of attraction of the global minimizer points are not very small.

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. We add a nonnegative value proportional to how much the given condition was hurt, plus a fixed penalty term in case at least one of the properties was not satisfied.

Csendes, T., B. M. Garay, B. Banhelyi, \A verified optimization technique to locate chaotic regions
of a Henon system," Journal of Global Optimization Vol. 35, 145, 2006.



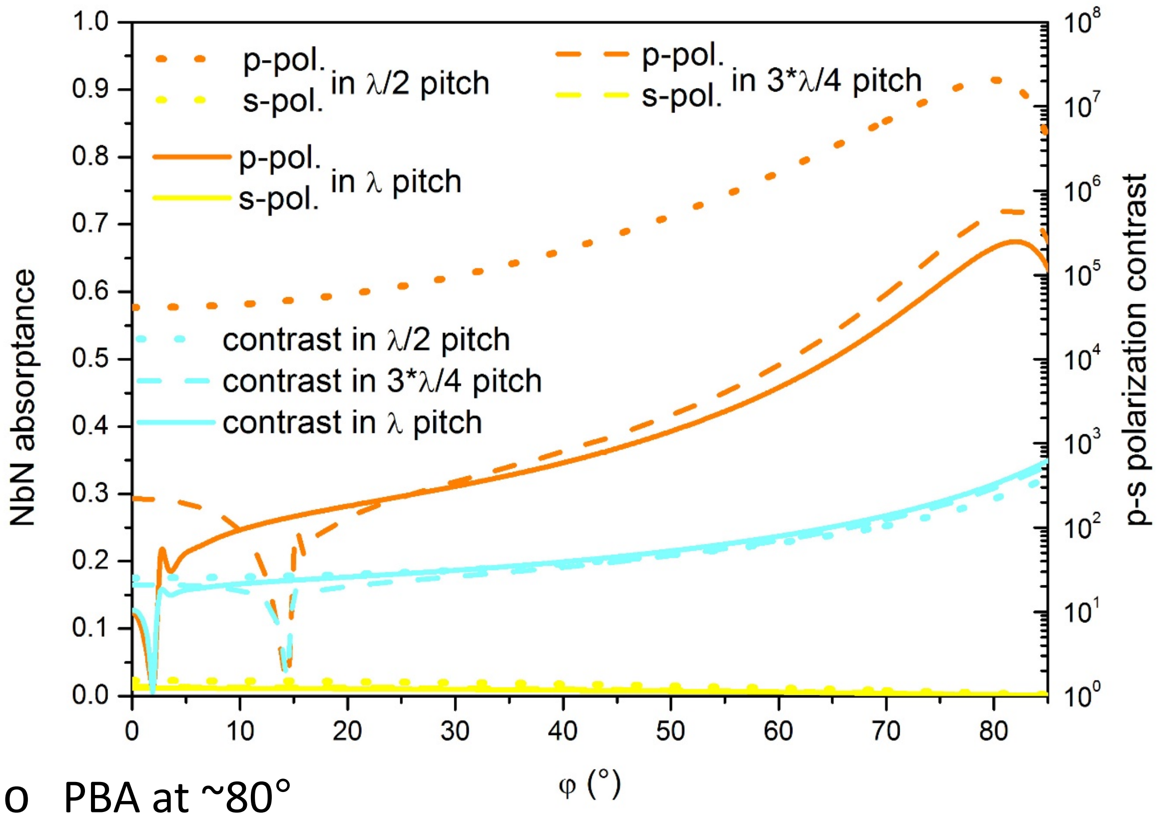
- *Geometry optimization to maximize contrast:*
  - **NbN periodicity increase**
  - **Cavity length decrease exception ¾ λ**
  - **Cavity width decrease**

- All cavities are shorter than $\lambda/4$

- Matching the maximum of Plasmonic Brewster angle phenomena corresponding to 1550 nm

- Highest contrast reached in BZ dependent on the periodicity

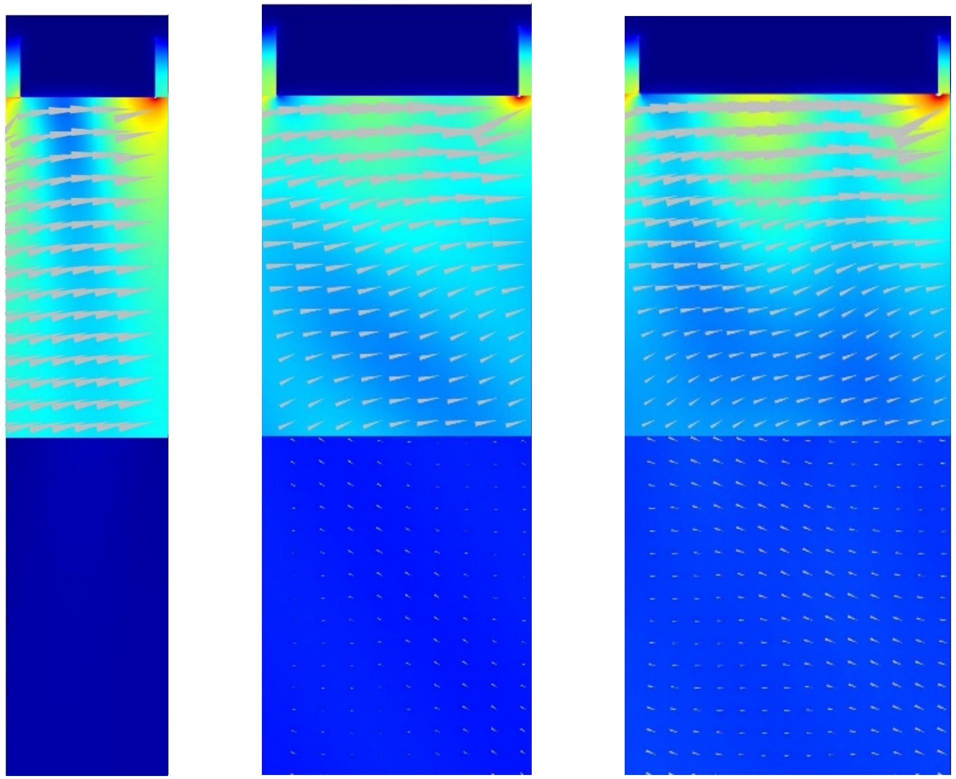
Polar angle dependent absorptance and contrast



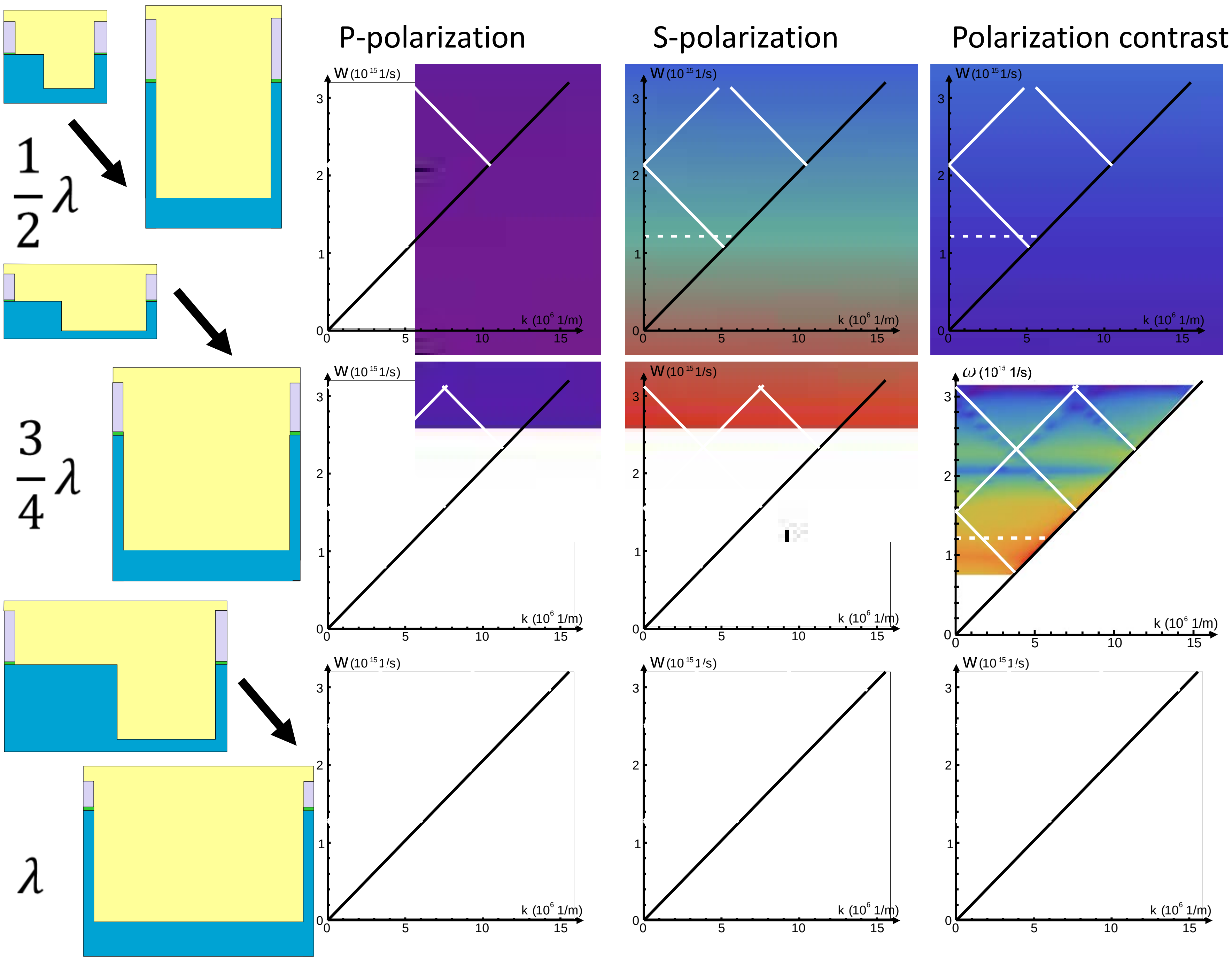
	SNSPD-A		SNSPD-P	
	Absorptance	Contrast	Absorptance	Contrast
λ/2	94.18%	1.47E+02	91.47%	2.20E+02
3λ/4	74.96%	2.02E+02	72.07%	2.93E+02
λ	72.82%	2.33E+02	67.44%	3.28E+02

- commensurate polarization contrast

- PBA at ~80°
- Polarization contrast determined by absorptance of p-polarized light
- Maximum of PBA phenomena suppressed by exponentially decaying s-polarized light



- Absorptance enhancement at the entrance of ~λ/4 cavities
- Power flow towards NbN segments



- *Geometry optimization to maximize contrast:*
  - **NbN periodicity increase**
  - **Cavity length increase**
  - **Cavity width decrease**
  - **Deflector length increase**
  - **Deflector width increase**

- Extended cavities are ~3λ/4

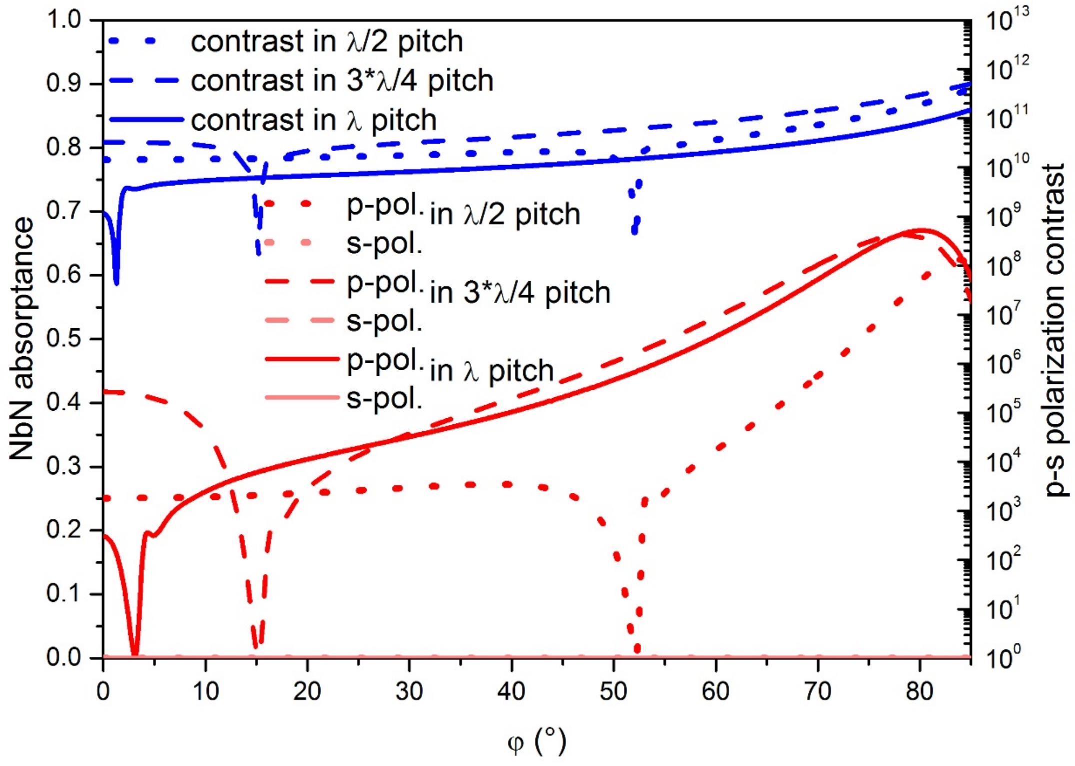
- Exception: wavelength-scaled NbN period & cavity length decrease Extended cavity ~λ/2!

- Vertical gold segments compose an extended robust cavity grating

- Strongly depressed absorptance of s-polarized light over wide spectral interval

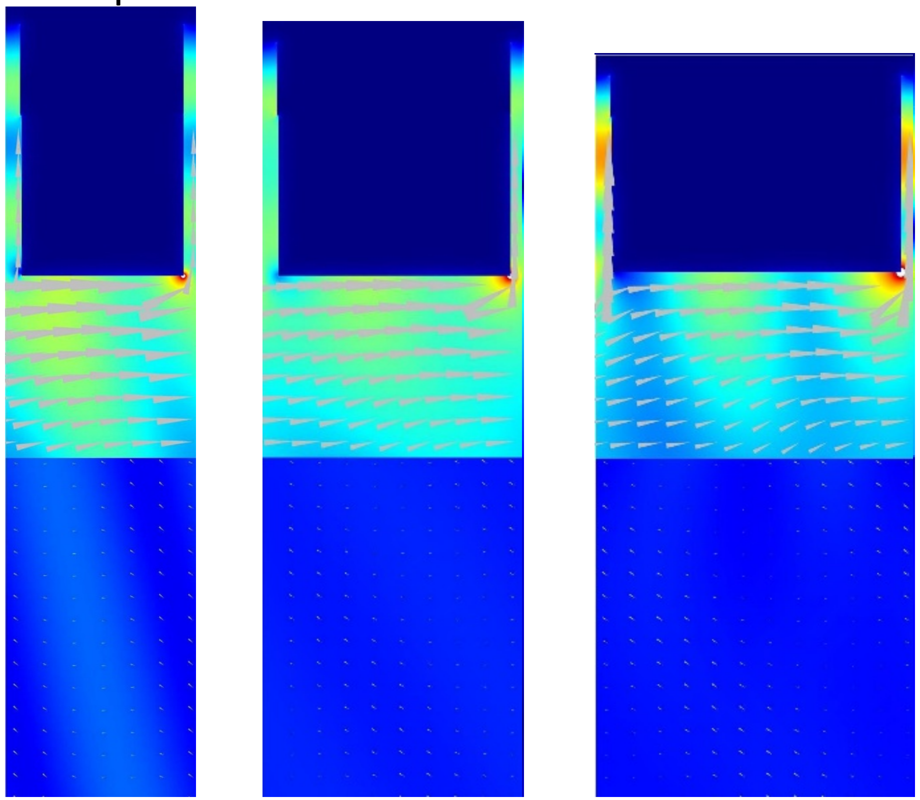
- Highest ontrast is reached in second BZ independent on the periodicity

Polar angle dependent absorptance and contrast

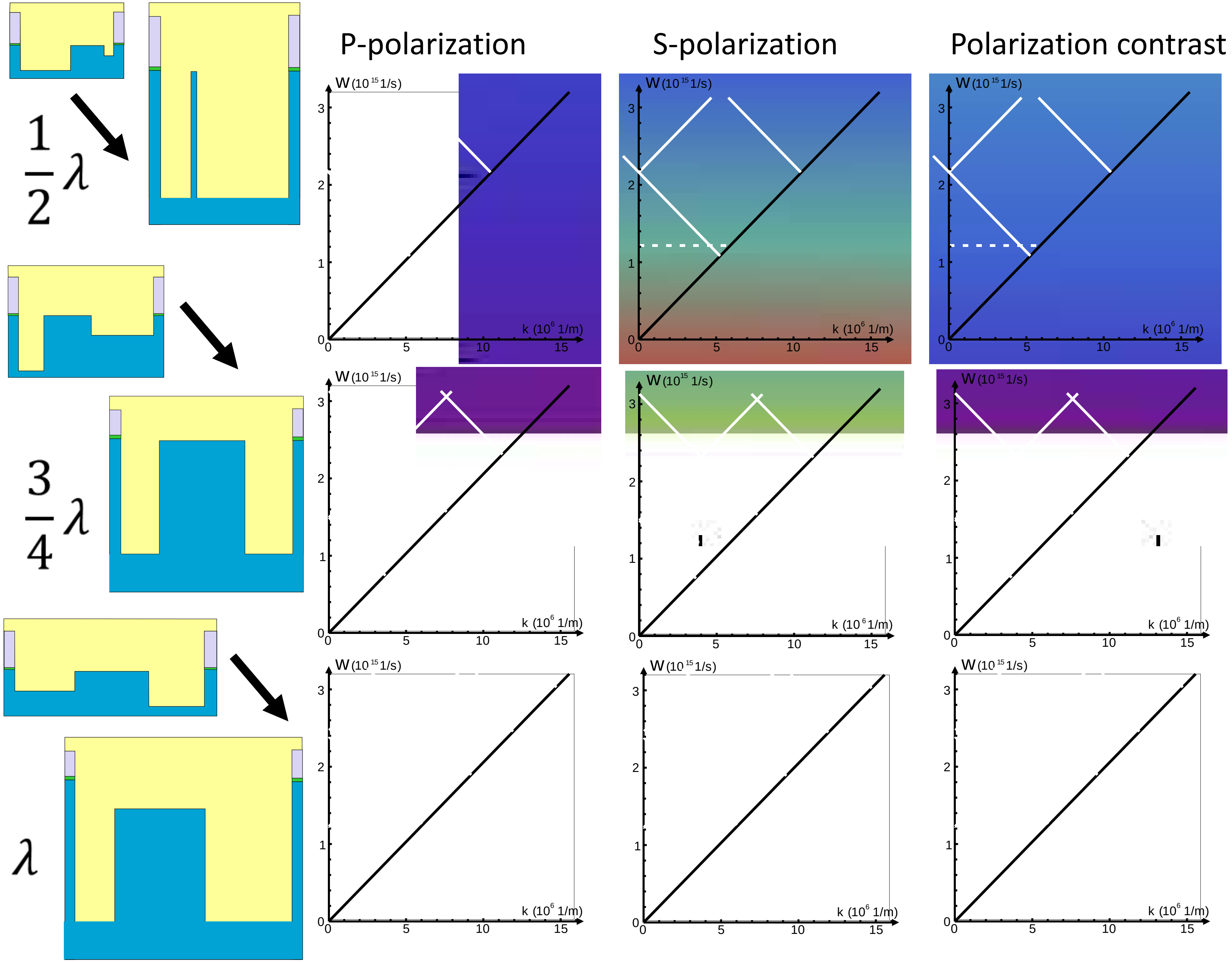


	SNSPD-A		SNSPD-P	
	Absorptance	Contrast	Absorptance	Contrast
λ/2	94.68%	1.34E+03	62.49%	1.93E+11
3λ/4	93.34%	4.65E+02	66.40%	3.06E+11
λ	85.77%	1.73E+03	67.04%	1.42E+11

- ~8 order of magnitude enhancement in polariztaion contrast

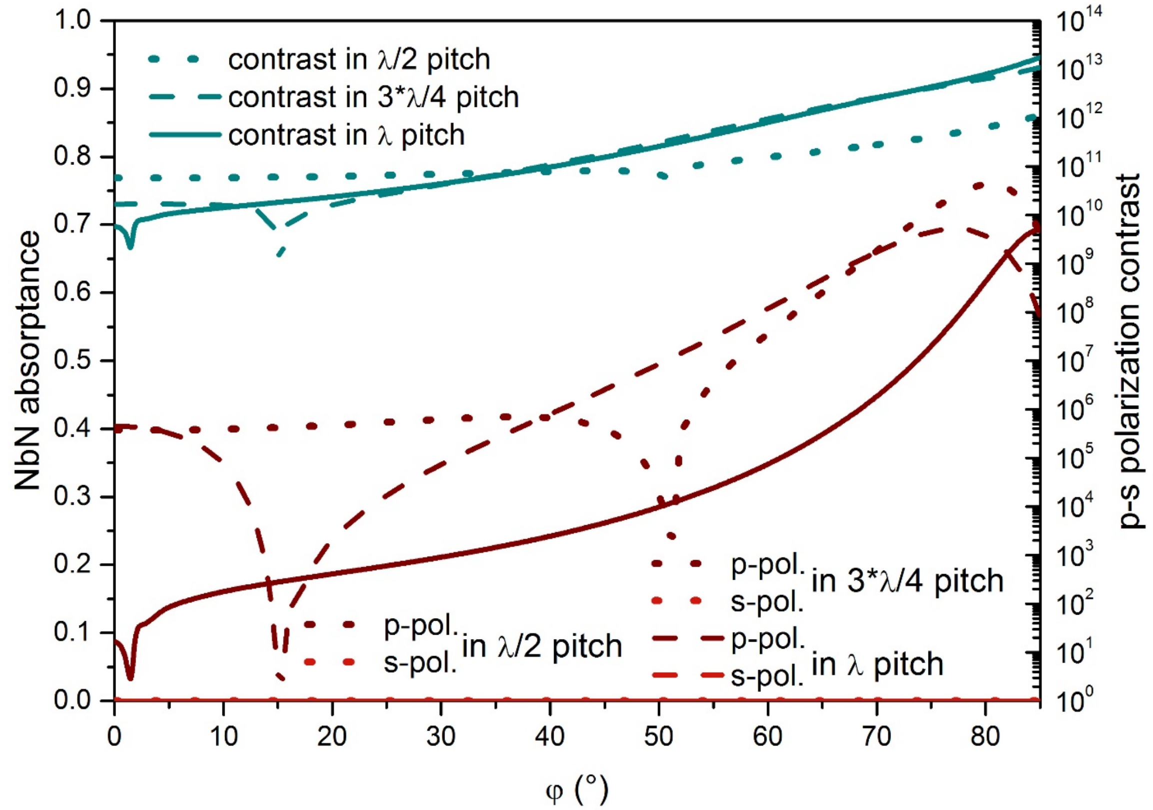


- Grating-coupling at 2°, 15° and 53°.
- Polarization contrast determined by absorptance of p-polarized light
- Maximum of PBA phenomena suppressed by exponentially decaying s-polarized light
- Squeezed modes in extended cavities, ~3λ/4, except in λ-scaled
- Power flow towards NbN segments



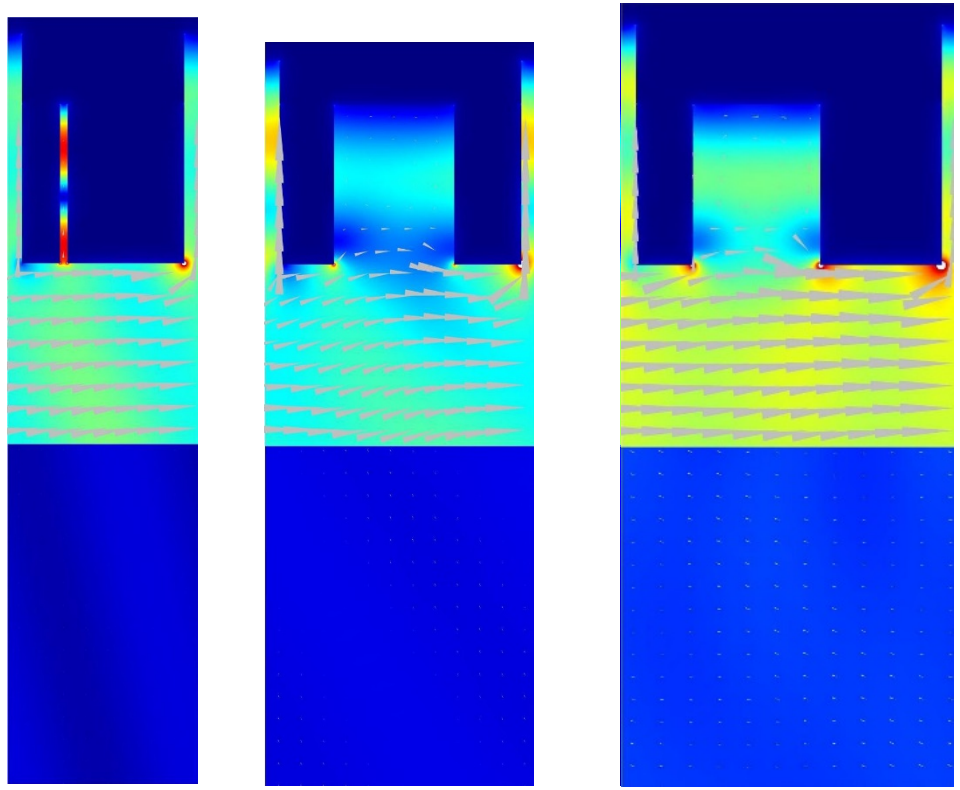
- *Geometry optimization to maximize contrast:*
  - **NbN periodicity increase**
  - **Cavity width decrease**
- Wide and long deflectors composing a narrow secondary cavity grating
- Extended cavities are ~3λ/4 except in 3λ/4-scaled
- More symmetric profile Narrower deflectors composing a secondary cavity grating
- Secondary cavity grating capable of increasing polarization contrast and absorptance
- Highest contrast achieved in second BZ independent on the periodicity

Polar angle dependent absorptance and contrast



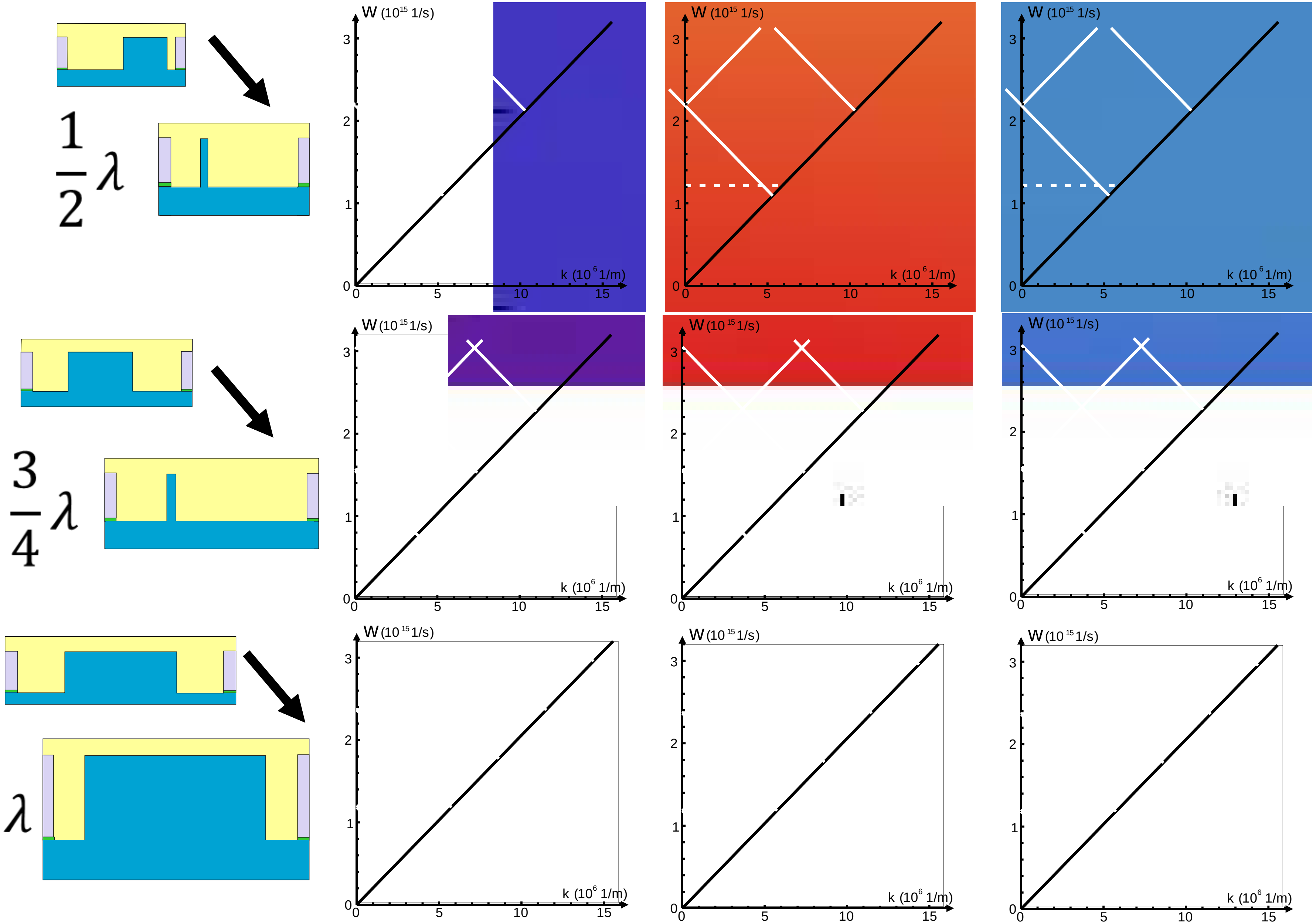
	SNSPD-A		SNSPD-P	
	Absorptance	Contrast	Absorptance	Contrast
λ/2	94.60%	1.95E+03	75.98%	6.34E+11
3λ/4	94.34%	1.45E+04	69.42%	6.38E+12
λ	93.00%	2.07E+04	68.59%	7.87E+12

- 8 order of magnitude enhancement in polariztaion contrast



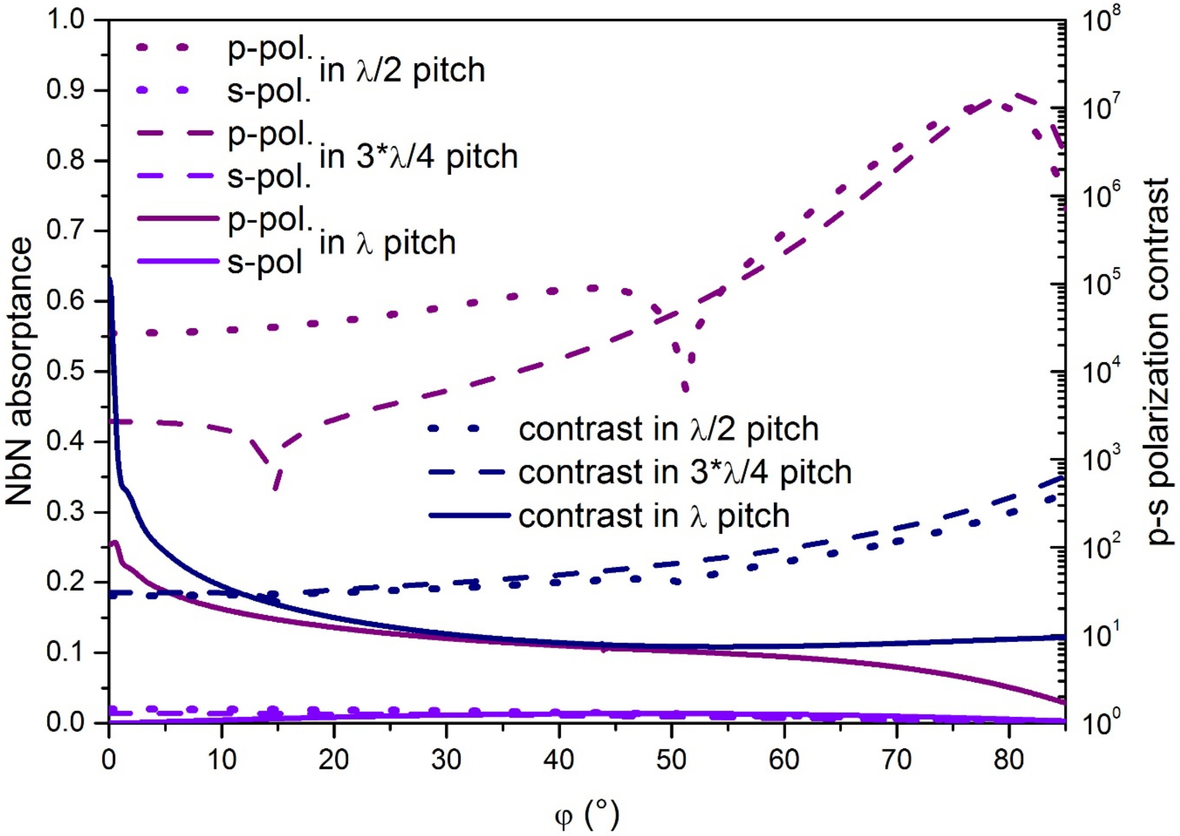
- Polarization contrast determined by absorptance of p-polarized light
- Maximum of PBA phenomena suppressed by exponentially decaying s-polarized light
- Squeezed modes in extended- and secondary cavities ~3λ/4, except in 3λ/4-scaled
- Power flow towards NbN segments

P-polarization | S-polarization | Polarization contrast



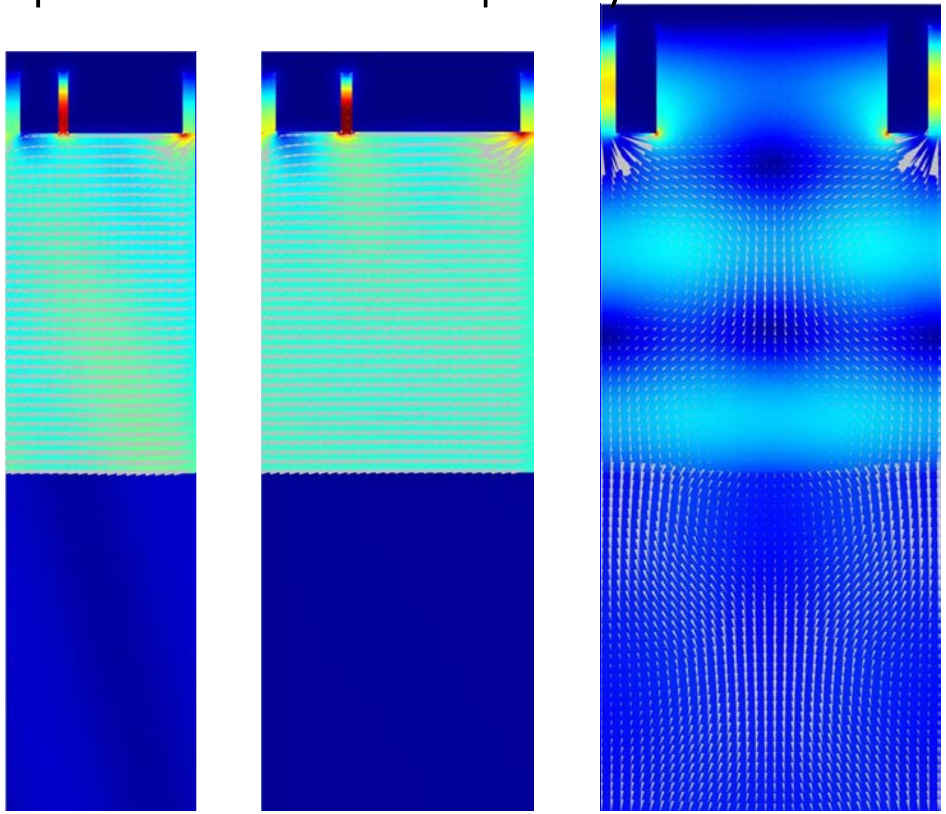
- *Geometry optimization to maximize contrast:*
  - **NbN periodicity increase**
  - **Cavity length increase**
  - **Cavity width decrease**
- Extended cavities are $(<,<,>)\ \lambda/4$
- Wider cavity walls composing a narrow secondary cavity grating
- Absence of deflectors results in higher absorptance of p-polarized light and relatively high absorptance of s-polarized light as well
- Symmetric profile and strongly depressed absorptance of p-polarized light
- Effect appears in second BZ independent on the periodicity

Polar angle dependent absroptance and contrast



	SNSPD-A		SNSPD-P	
	Absorptance	Contrast	Absorptance	Contrast
λ/2	94.49%	5.53E+01	87.93%	2.46E+02
3λ/4	94.95%	5.00E+01	89.29%	3.66E+02
λ	95.05%	1.24E+02	25.69%	1.15E+05

- 1 order of magnitude enhancement, except in λ-scaled: 70% absorptance decrease is the penalty of contrast increase



- Polarization contrast determined by absorptance of p-polarized light
- Maximum of PBA phenomena suppressed by exponentially decaying s-polarized light
- Large **E**-field enhancement in narrow secondary cavities ~λ/4
- Power flow towards NbN segments

Conclusion

- SNSPD-A: high absorptance – low polarization contrast
- SNSPD-P: high polarization contrast – low absorptance
- SNSPD-C: high polarization contrast & conditional absorptance is met

- Right set of objective function and constraints

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