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

Mária Csete, András Szenes, Gábor Szekeres, Balázs Bánhelyi, Tibor Csendes, Gábor Szabó

Department of Optics and Quantum Electronics
Department of Computational Optimization
University of Szeged, Hungary

mcsete@physx.u-szeged.hu

Dr. Mária Csete
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SNSPDs are capable to detect a single-photon
- Recovery time: <100 ns
- Dark counts: <100 1/s
- Timing jitter: <100ps

Application in Photonics, Quantum informatics and Astrology

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

Outlook

- SNSPD

- Absorption maximization: SNSPD-A

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

Methodology

- Integrated plasmonic structure geometry
  - NCAI
  - NCDAI
  - NCDDAI
  - NCTAI

- Illumination direction
  - Azimuthal orientation
  - Polar angle
The bound constrained global optimization problem for which our stochastic algorithm was designed is

\[
\min_{x} f(x) \\
x \in X, \quad X = \{a_i \leq x_i \leq b_i, \ i = 1, 2, \ldots, n\},
\]

where \( f : \mathbb{R}^n \rightarrow \mathbb{R} \) 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

\[
\min_{x} f(x) \\
g(x) \leq 0 \\
x \in X, \quad X = \{a_i \leq x_i \leq b_i, \ i = 1, 2, \ldots, n\},
\]

where \( g : \mathbb{R}^n \rightarrow \mathbb{R} \) 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.

Geometry optimization to maximize contrast:
- NbN periodicity increase
- Cavity length decrease exception $\frac{3}{4} \lambda$
- 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

- 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

<table>
<thead>
<tr>
<th></th>
<th>SNSPD-A</th>
<th>SNSPD-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorptance</td>
<td>Contr.</td>
<td>Absorptance</td>
</tr>
<tr>
<td>λ/2</td>
<td>94.18%</td>
<td>1.47E+02</td>
</tr>
<tr>
<td>3λ/4</td>
<td>74.96%</td>
<td>2.02E+02</td>
</tr>
<tr>
<td>λ</td>
<td>72.82%</td>
<td>2.33E+02</td>
</tr>
</tbody>
</table>

○ commensurate polarization contrast
Geometry optimization to maximize contrast:

- NbN periodicity increase
- Cavity length increase
- Cavity width decrease
- Deflector length increase
- Deflector width increase

Extended cavities are $\sim 3\lambda/4$

Exception: wavelength-scaled NbN period & cavity length decrease

Extended cavity $\sim \lambda/2$!

Vertical gold segments compose an extended robust cavity grating

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

Highest contrast is reached in second BZ independent on the periodicity
Polar angle dependent absorptance and 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, \( \lambda/2 \), except in \( \lambda \)-scaled
- Power flow towards NbN segments

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<tr>
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<th>SNSPD-P</th>
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<tbody>
<tr>
<td></td>
<td>Absorptance</td>
<td>Contrast</td>
<td>Absorptance</td>
</tr>
<tr>
<td>( \lambda/2 )</td>
<td>94.68%</td>
<td>1.34E+03</td>
<td>62.49%</td>
</tr>
<tr>
<td>( 3\lambda/4 )</td>
<td>93.34%</td>
<td>4.65E+02</td>
<td>66.40%</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>85.77%</td>
<td>1.73E+03</td>
<td>67.04%</td>
</tr>
</tbody>
</table>

- \( \approx 8 \) order of magnitude enhancement in polarization contrast
Geometry optimization to maximize contrast:
- NbN periodicity increase
- Cavity width decrease

- Wide and long deflectors composing a narrow secondary cavity grating

- Extended cavities are $\sim 3\lambda/4$ except in $3\lambda/4$-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

- 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 ~3\(\lambda/4\), except in 3\(\lambda/4\)-scaled
- Power flow towards NbN segments

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<tr>
<td></td>
<td>Absorptance</td>
<td>Contrast</td>
<td>Absorptance</td>
<td>Contrast</td>
</tr>
<tr>
<td>(\lambda/2)</td>
<td>94.60%</td>
<td>1.95E+03</td>
<td>75.98%</td>
<td>6.34E+11</td>
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<tr>
<td>(3\lambda/4)</td>
<td>94.34%</td>
<td>1.45E+04</td>
<td>69.42%</td>
<td>6.38E+12</td>
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<tr>
<td>(\lambda)</td>
<td>93.00%</td>
<td>2.07E+04</td>
<td>68.59%</td>
<td>7.87E+12</td>
</tr>
</tbody>
</table>

- 8 order of magnitude enhancement in polarization contrast
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

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 absorptance and contrast

- 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 $\sim \lambda/4$
- Power flow towards NbN segments

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<th>SNSPD-P</th>
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<tr>
<td>$\lambda/2$</td>
<td>94.49%</td>
<td>87.93%</td>
</tr>
<tr>
<td></td>
<td>5.53E+01</td>
<td>2.46E+02</td>
</tr>
<tr>
<td>$3\lambda/4$</td>
<td>94.95%</td>
<td>89.29%</td>
</tr>
<tr>
<td></td>
<td>5.00E+01</td>
<td>3.66E+02</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>95.05%</td>
<td>25.69%</td>
</tr>
<tr>
<td></td>
<td>1.24E+02</td>
<td>1.15E+05</td>
</tr>
</tbody>
</table>

○ 1 order of magnitude enhancement, except in $\lambda$-scaled: 70% absorptance decrease is the penalty of contrast increase.
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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