Theoretical Investigation of the Optical Properties of Coupled Nano-Waveguides

Johannes Wilde

24.03.2017

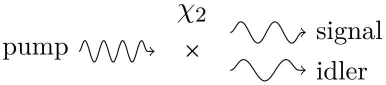
Introduction

Spontaneous parametric down-conversion

- control over spontaneous parametric down-conversion

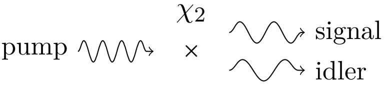
Spontaneous parametric down-conversion

- control over spontaneous parametric down-conversion



Spontaneous parametric down-conversion

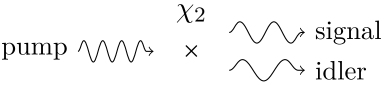
- control over spontaneous parametric down-conversion



- energy-conservation: $\omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}}$
- phase-matching: $k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}}$

Spontaneous parametric down-conversion

- control over spontaneous parametric down-conversion



- energy-conservation: $\omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}}$
- phase-matching: $k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}}$
- dispersion engineering for $\omega(k)$

Chosen Structure

- periodic structures great for dispersion engineering

Chosen Structure

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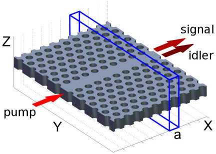
- approaches exist:
  - 2D photonic crystal [PC]

    nice optic properties

    hard to fabricate



[Saravi et al., Phys. Rev. A 92(6):063821, 2015]

Chosen Structure

- periodic structures great for dispersion engineering
- approaches exist:
  - 2D photonic crystal [PC]
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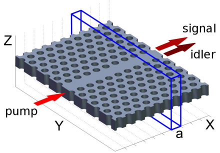
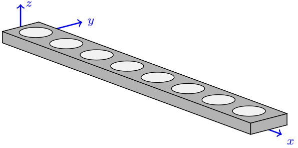


[Saravi et al., Phys. Rev. A 92(6):063821, 2015]

  - 1D periodic waveguide
    few parameters for
    dispersion engineering

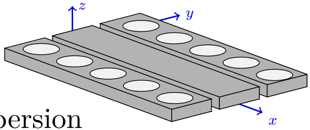


[Quintero-Bermudez et al., in *The Eur. Conf. on Lasers and Electro-Optics*, 2015]

- chosen:

  easier to fabricate than 2D PC

  coupling offers great control over dispersion



[Gutman et al., Opt. Express, 2012]

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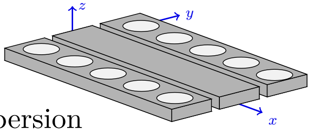


[Gutman et al., Opt. Express, 2012]

- aim:
  - design complicated dispersion
  - investigate effects on SPDC

Overview

Introduction

Linear Optic Design

Analytic Description of SPDC

Non-Linear Optical Properties

Conclusion

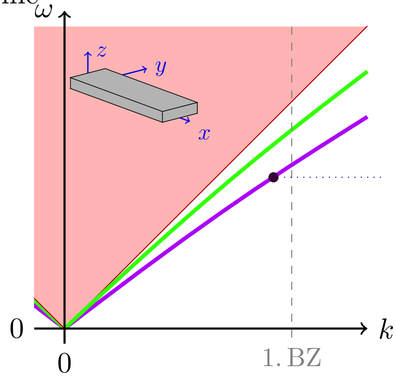
Linear Optic Design

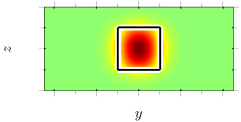
Simple Waveguide

- lithium niobate

Simple Waveguide

- lithium niobate
- schematic band diagram for a waveguide and one transversal mode profile

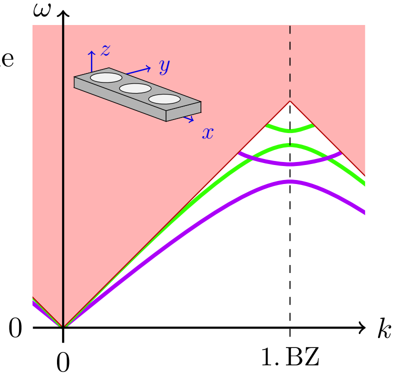




- guided WG modes and continuum of free-space modes

Structured Waveguide

- schematic band diagram for a structured waveguide



Structured Waveguide

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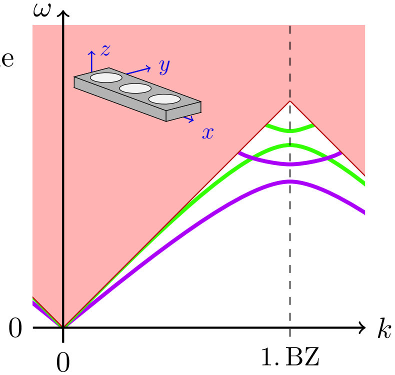

- band gaps at edge of 1. BZ

Structured Waveguide

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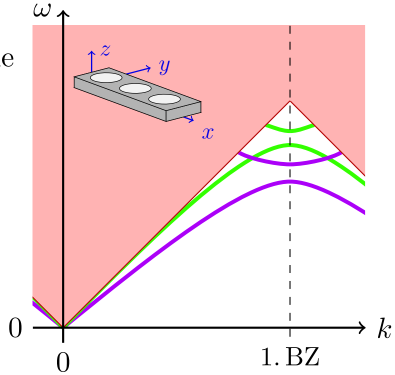
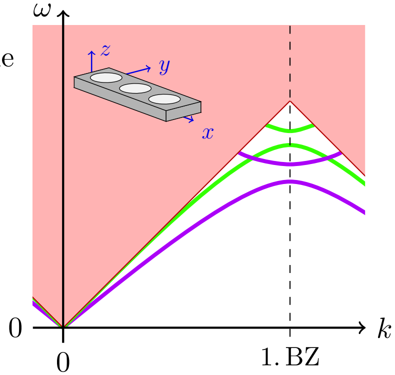


- band gaps at edge of 1. BZ
- forward $[v_{\mathrm{gr}} = \frac{\mathrm{d}\omega}{\mathrm{d}k} > 0]$ and backward $[v_{\mathrm{gr}} < 0]$ prop. modes

Structured Waveguide

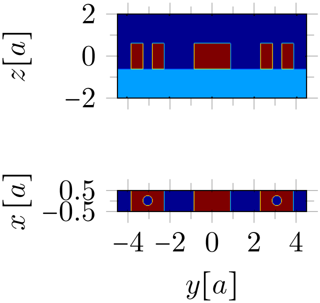
- schematic band diagram for a structured waveguide

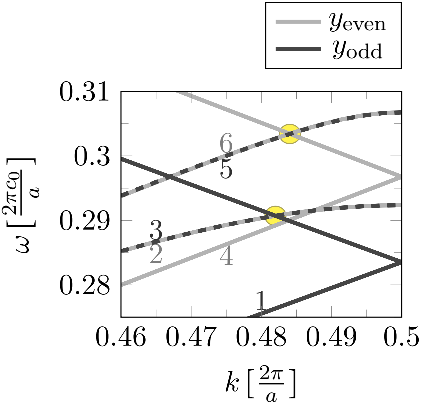


- band gaps at edge of 1. BZ
- forward $[v_{\mathrm{gr}} = \frac{\mathrm{d}\omega}{\mathrm{d}k} > 0]$ and backward $[v_{\mathrm{gr}} < 0]$ prop. modes
- group index: $n_{\mathrm{gr}} = \frac{c_0}{v_{\mathrm{gr}}}$

Full Structure

- full structure — uncoupled





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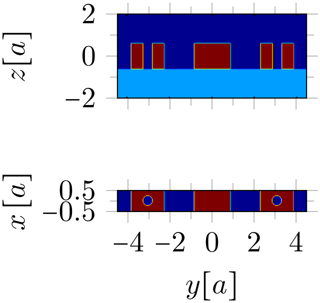

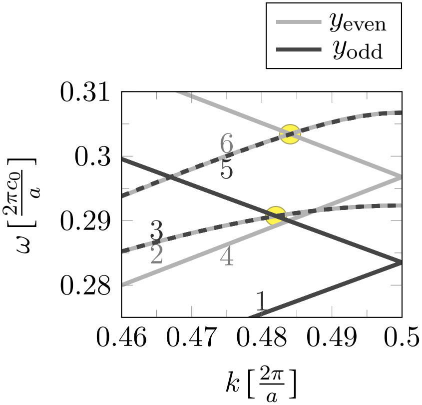

- bands 1,2 and 3 dominant E_y, bands 4,5 and 6 dominant E_z

Full Structure

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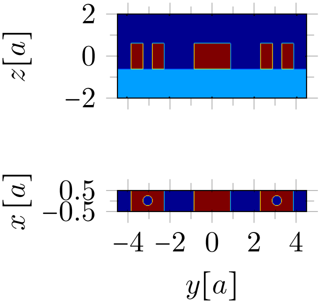
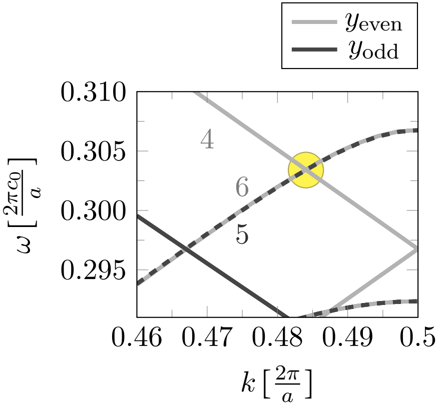
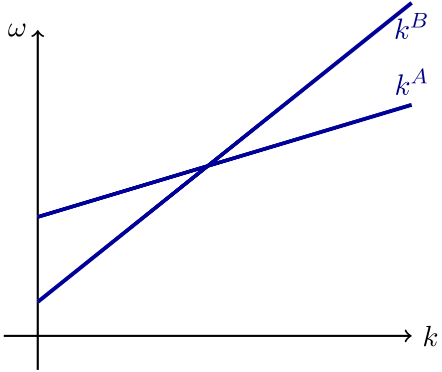




- bands 1,2 and 3 dominant E_y, bands 4,5 and 6 dominant E_z
- focus on upper crossing [pump]

Anti-Crossings

- effect of coupling



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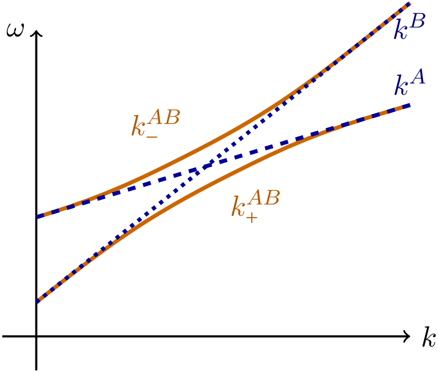

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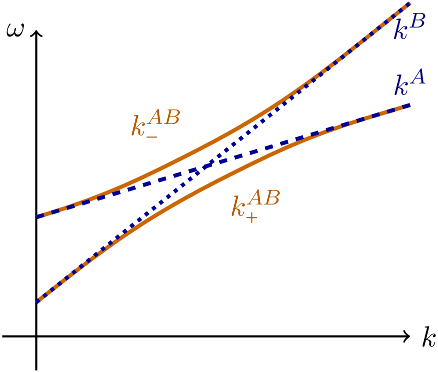

- mode profiles strongly affected at interaction region

Anti-Crossings

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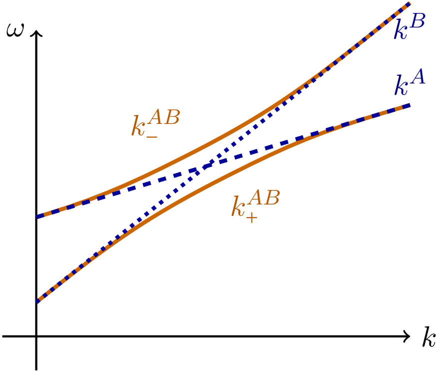
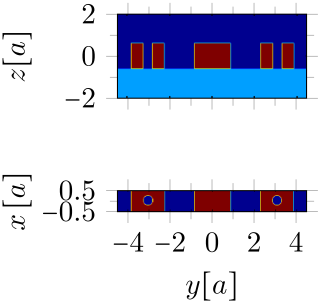
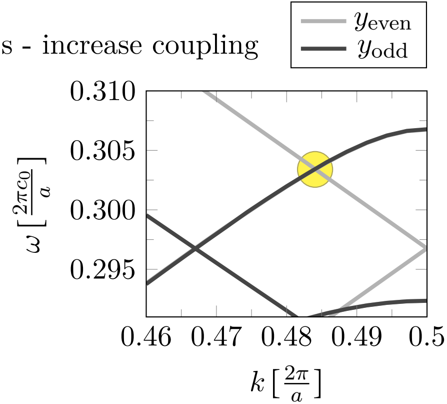


- mode profiles strongly affected at interaction region
- no coupling of modes of opposing symmetry

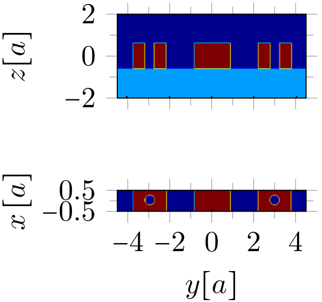
- decreasing distance of WGs - increase coupling

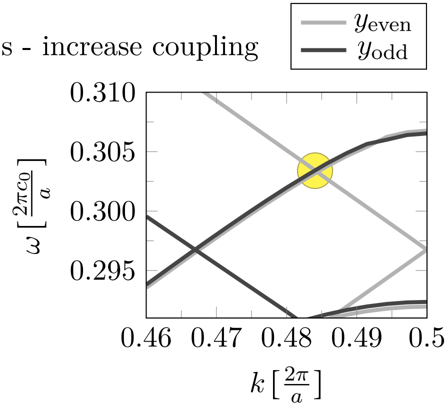




distance of neighboring WGs $1.4\,a$

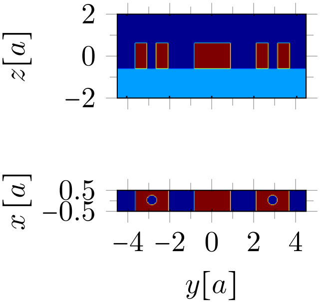
- decreasing distance of WGs - increase coupling

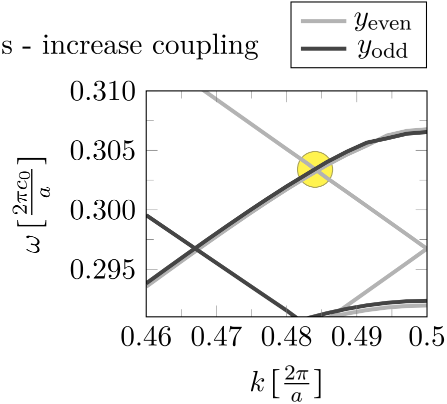




distance of neighboring WGs $1.3\,a$

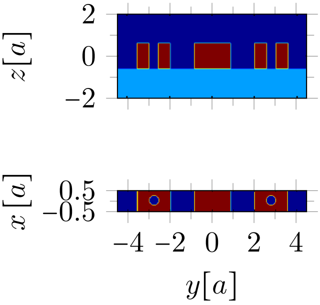
- decreasing distance of WGs - increase coupling

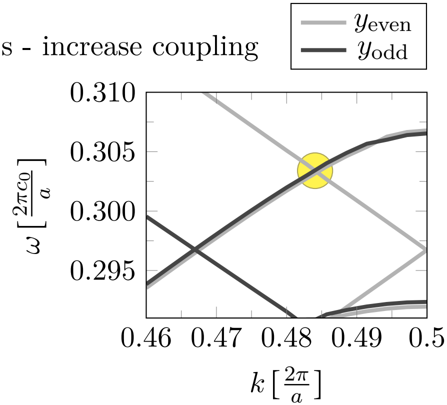




distance of neighboring WGs $1.2\,a$

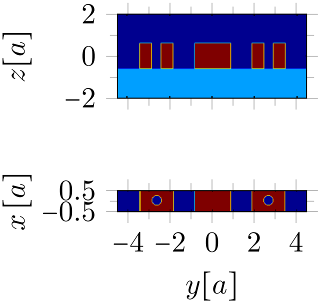
- decreasing distance of WGs - increase coupling

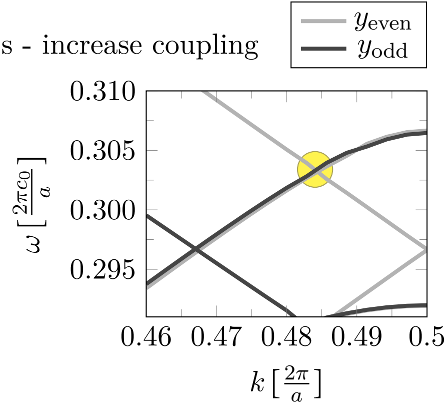




distance of neighboring WGs $1.1\,a$

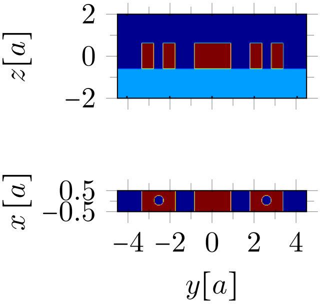
- decreasing distance of WGs - increase coupling

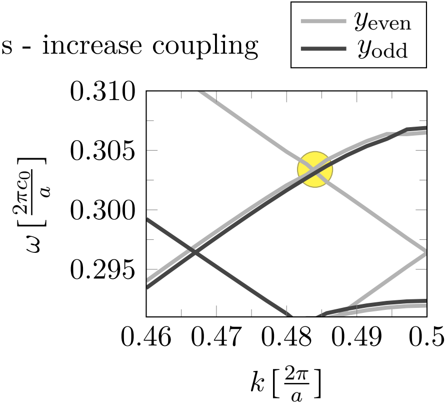




distance of neighboring WGs $1.0\,a$

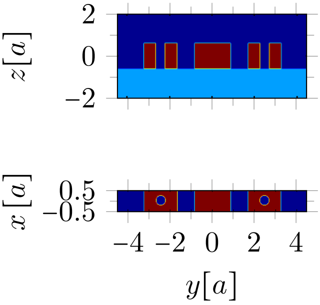
- decreasing distance of WGs - increase coupling

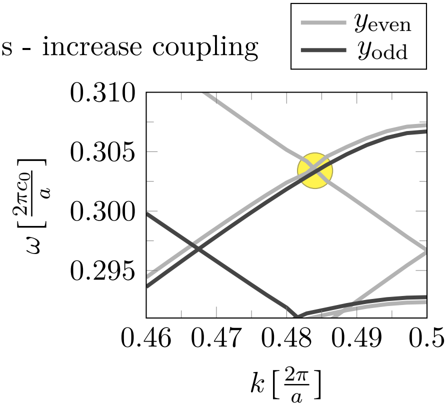




distance of neighboring WGs $0.9\,a$

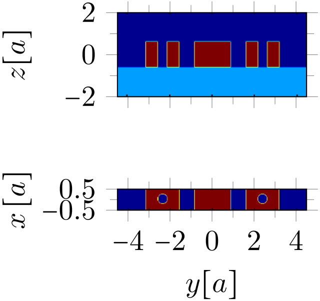
- decreasing distance of WGs - increase coupling

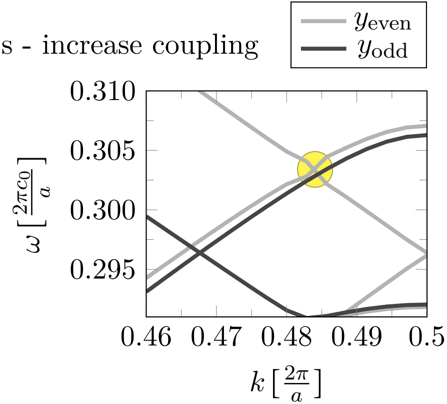




distance of neighboring WGs $0.8\,a$

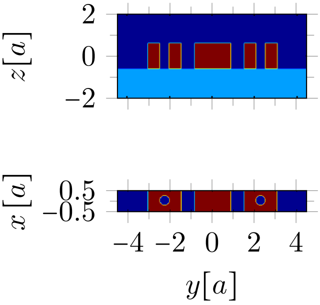
- decreasing distance of WGs - increase coupling

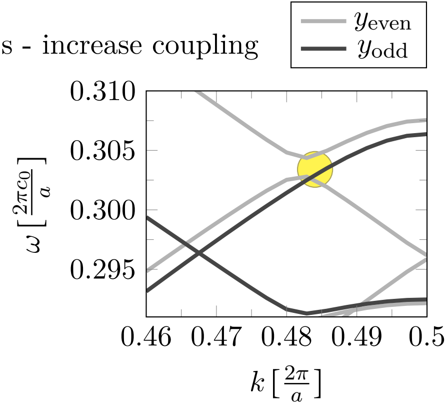




distance of neighboring WGs $0.7\,a$

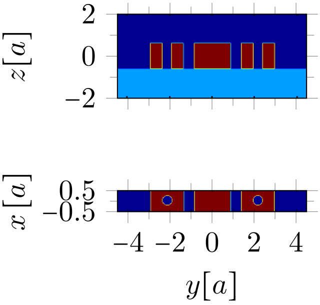
- decreasing distance of WGs - increase coupling

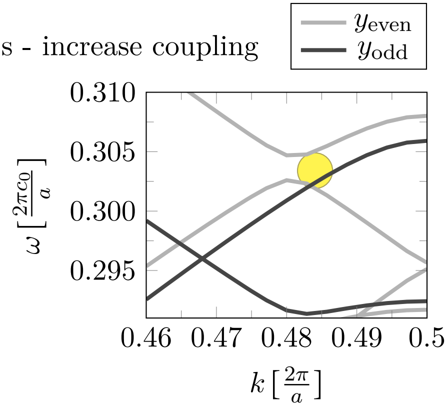




distance of neighboring WGs $0.6\,a$

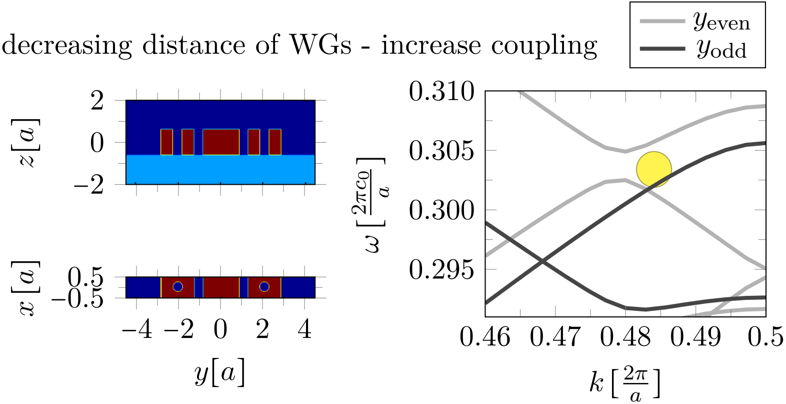
- decreasing distance of WGs - increase coupling





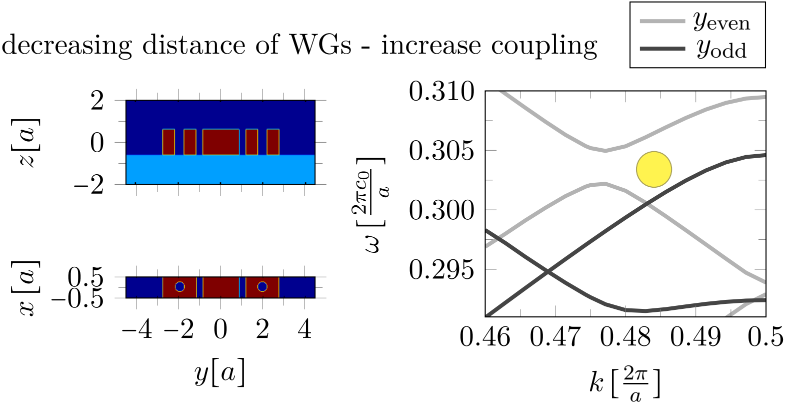
distance of neighboring WGs $0.5\,a$

- decreasing distance of WGs - increase coupling



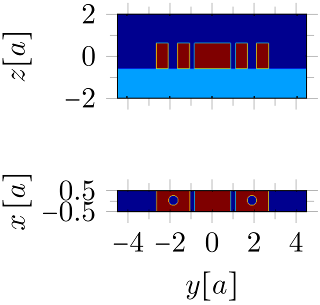
distance of neighboring WGs $\quad 0.4\,a$

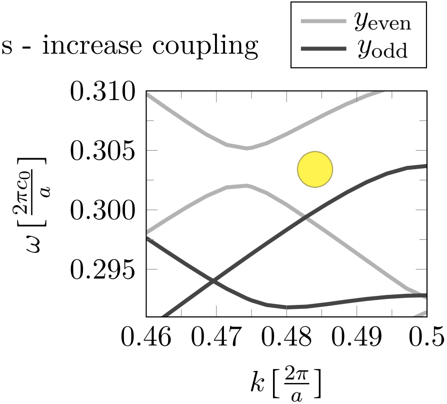
- decreasing distance of WGs - increase coupling



distance of neighboring WGs $0.3\,a$

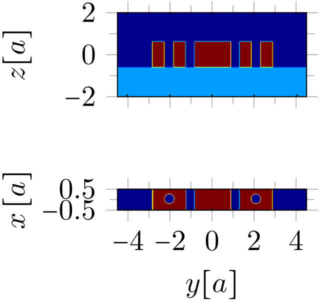
- decreasing distance of WGs - increase coupling

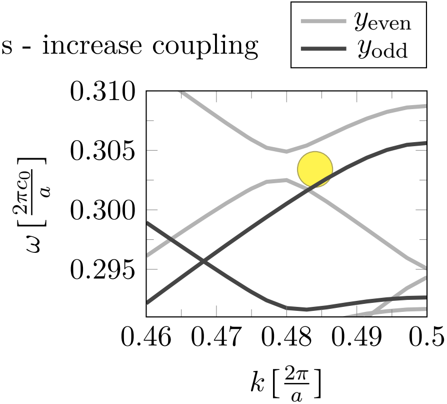




distance of neighboring WGs $0.2\,a$

- decreasing distance of WGs - increase coupling



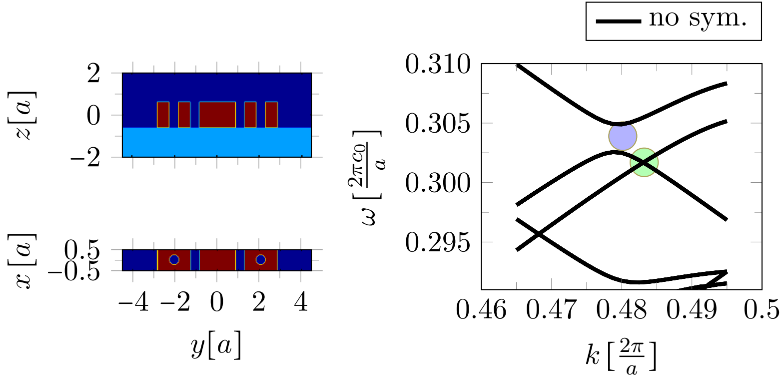


distance of neighboring WGs $0.4\,a$

- bands shifted → anti-crossing shifted

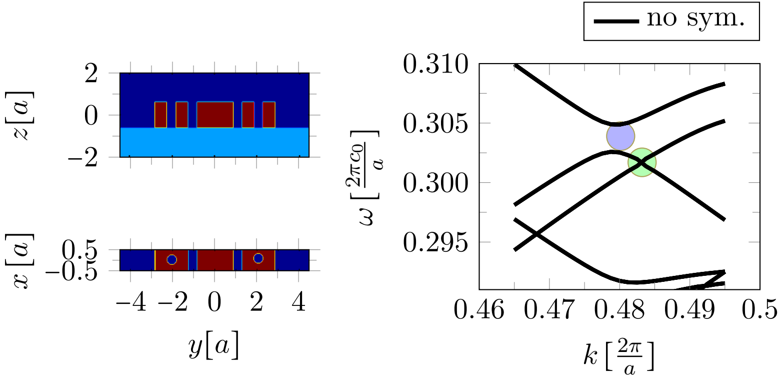
- stronger coupling → bigger frequency gap between bands

- breaking the y-symmetry - shifting the holes of one outer WG



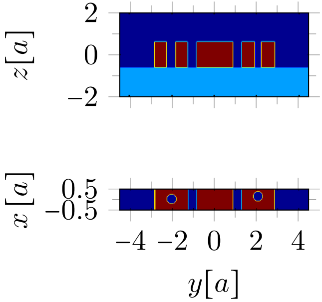
shifted of one row of holes in $\vec{e}_x$ by $0.00\,a$

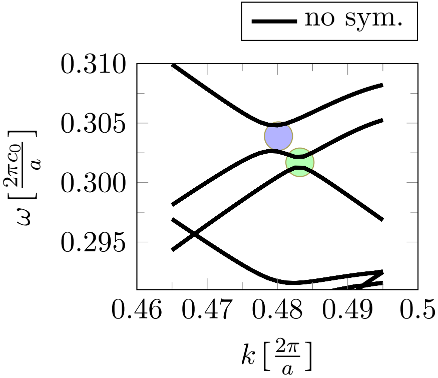
- breaking the y-symmetry - shifting the holes of one outer WG



shifted of one row of holes in $\vec{e}_x$ by $0.05\,a$

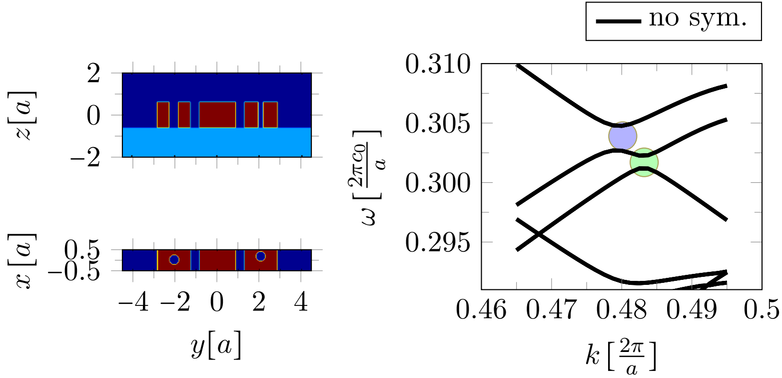
- breaking the y-symmetry - shifting the holes of one outer WG





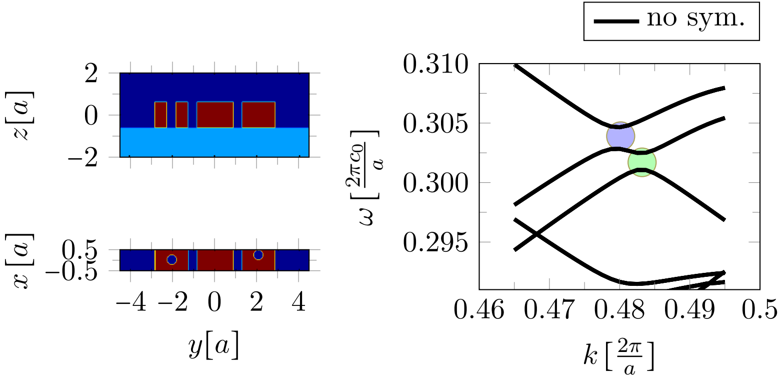
shifted of one row of holes in $\vec{e}_x$ by $0.10\,a$

- breaking the y-symmetry - shifting the holes of one outer WG



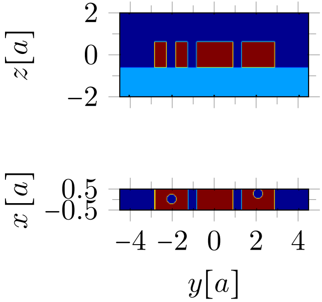
shifted of one row of holes in $\vec{e}_x$ by $0.15\,a$

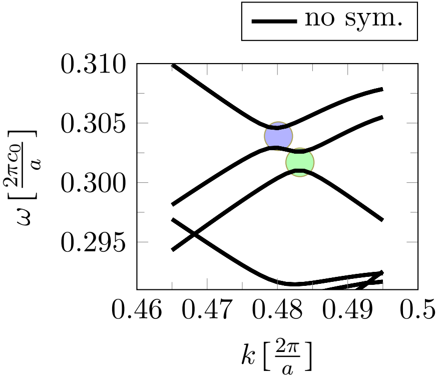
- breaking the y-symmetry - shifting the holes of one outer WG



shifted of one row of holes in $\vec{e}_x$ by $0.20\,a$

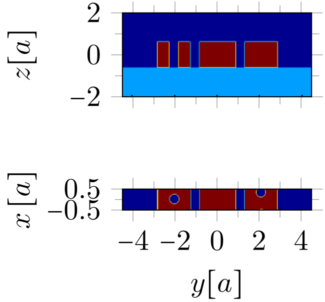
- breaking the y-symmetry - shifting the holes of one outer WG

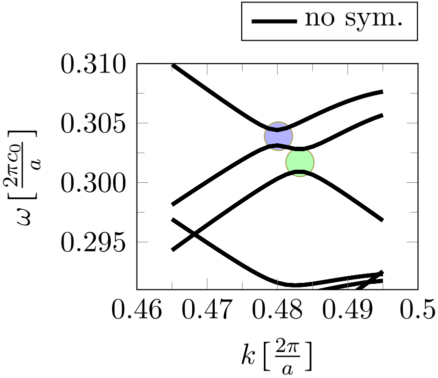




shifted of one row of holes in $\vec{e}_x$ by $0.25\,a$

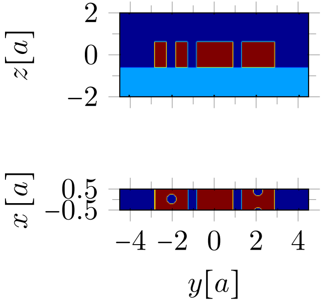
- breaking the y-symmetry - shifting the holes of one outer WG

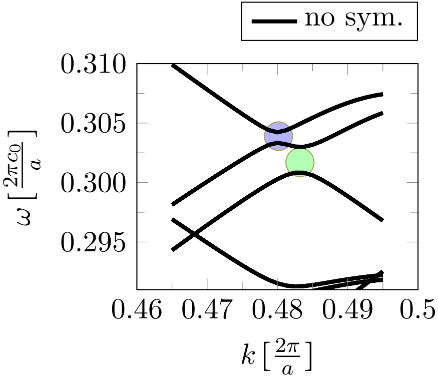




shifted of one row of holes in $\vec{e}_x$ by $0.30\,a$

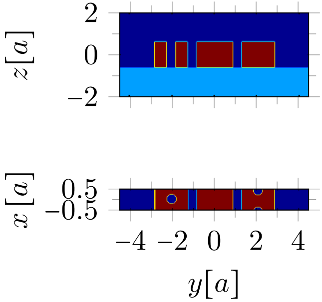
- breaking the y-symmetry - shifting the holes of one outer WG

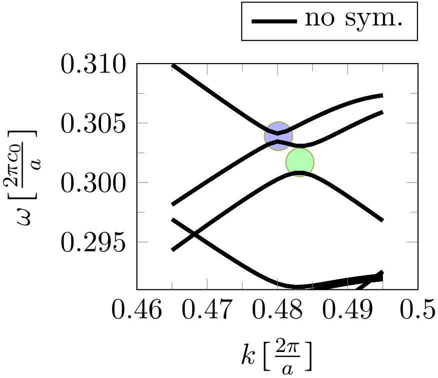




shifted of one row of holes in $\vec{e}_x$ by $0.35\,a$

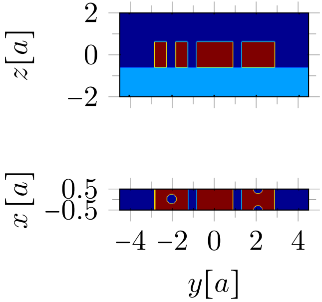
- breaking the y-symmetry - shifting the holes of one outer WG

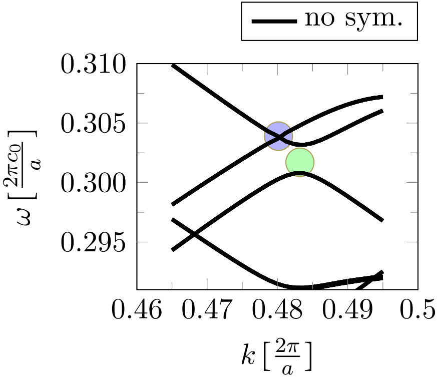




shifted of one row of holes in $\vec{e}_x$ by $0.40\,a$

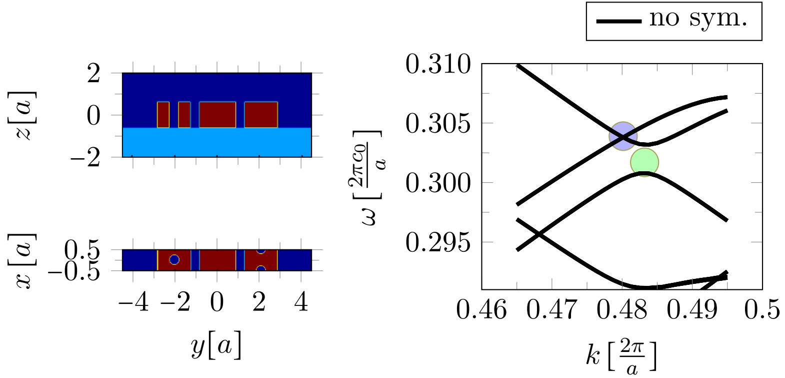
- breaking the y-symmetry - shifting the holes of one outer WG





shifted of one row of holes in $\vec{e}_x$ by $0.45\,a$

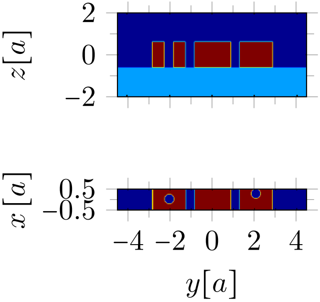
- breaking the y-symmetry - shifting the holes of one outer WG

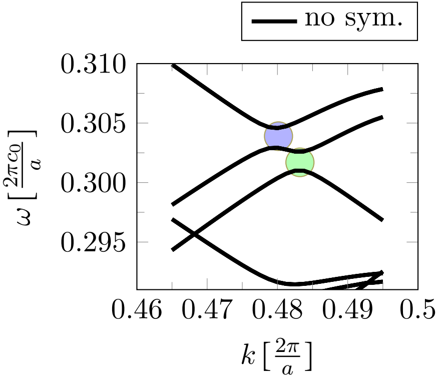


shifted of one row of holes in $\vec{e}_x$ by $0.50\,a$

- previously crossing bands with the same dominant field component couple

- breaking the y-symmetry - shifting the holes of one outer WG



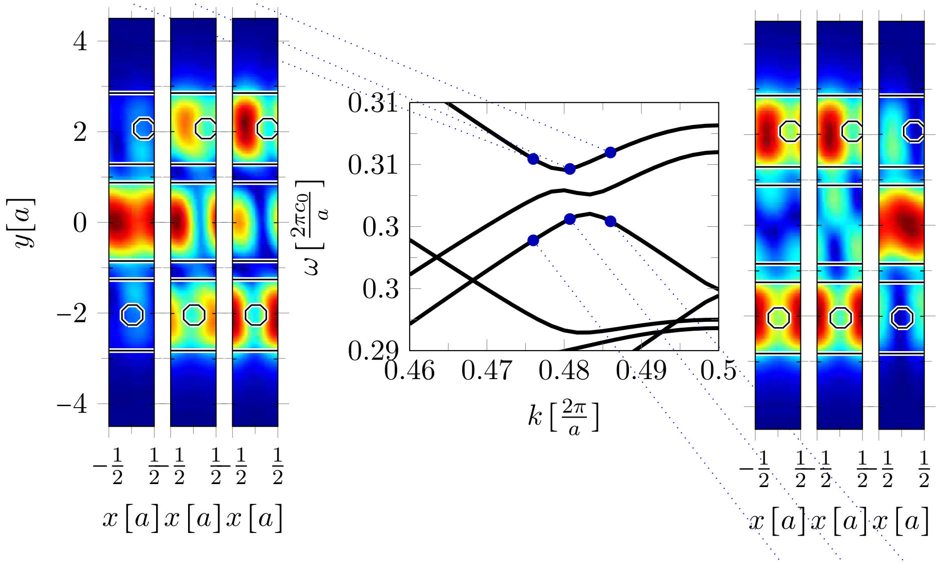


shifted of one row of holes in $\vec{e}_x$ by $0.25\,a$

- previously crossing bands with the same dominant field component couple

- selected shift of $0.25\,a$

- mode profiles vary strongly over one band at anti-crossings



Pump Modes

- pump for SPDC $\left[\,\omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}} \quad , \quad k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}}\right]$

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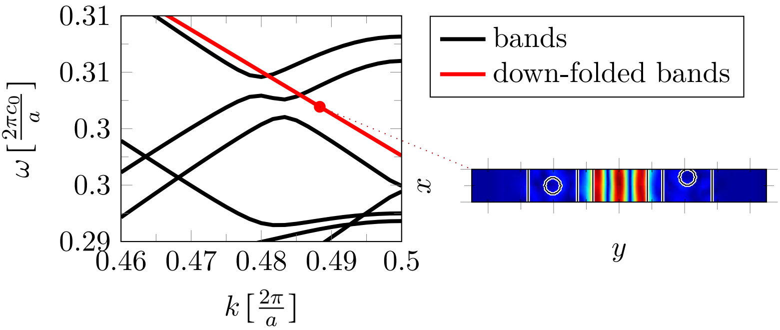

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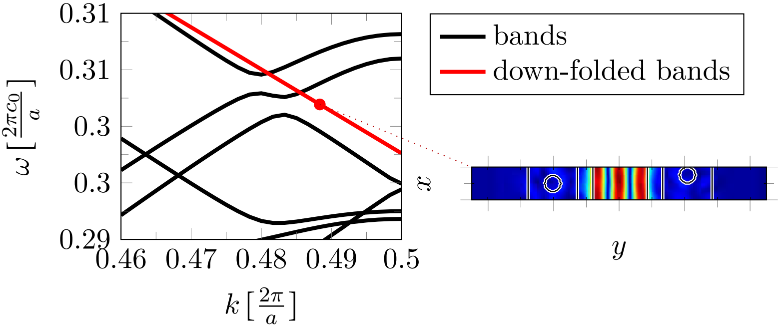

- pump mode does not see periodicity

Analytic Description of SPDC

Bloch Modes

- 1D periodic structure with period a along $\vec{e}_x$

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- Fourier components of the electric field can be written as:

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- Bloch mode profile $\vec{e}$, periodic: $\vec{e}(\vec{r}) = \vec{e}(\vec{r} + a\,\vec{e}_x)$

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  - Bloch mode profile $\vec{e}$, periodic: $\vec{e}(\vec{r}) = \vec{e}(\vec{r} + a\,\vec{e}_x)$
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- generalized phase-matching condition

$$\Delta k := k^{(p)} - k^{(s)} - k^{(i)} + \overbrace{\left[\mathfrak{n}^{(p)} - \mathfrak{n}^{(s)} - \mathfrak{n}^{(i)}\right]}^{=:\Delta\mathfrak{n}}\ \frac{2\pi}{a}$$

Spontaneous Parametric Down-Conversion

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- result:

$$|\Psi_{\text{end}}\rangle = |\Psi_0\rangle + \int \mathrm{d}\omega_s \, \mathrm{d}\omega_i \;\; \text{JSA}(\omega_p, \omega_s, \omega_i) \;\; |1^{(s)}, 1^{(i)}\rangle$$

p - pump, s - signal, i - idler and $\omega_p = \omega_s + \omega_i$

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- joint spectral amplitude [JSA]
- physical meaning: $|\mathrm{JSA}|^2$ is creation probability density

- JSA at the end of the structure $[x = L]$ is:

$$\mathrm{JSA} = \mathrm{i}\, A^{(p)}(\omega_s + \omega_i)\, \frac{1}{c_0} \sqrt{\omega_s \omega_i} \sqrt{\left|{n_{\mathrm{gr}}}^{(s)}\right| \left|{n_{\mathrm{gr}}}^{(i)}\right|}$$

$$\iiint_{\mathrm{UC}} \mathrm{d}^3 r\, \varepsilon_0\, \chi_2^{\alpha\beta\gamma}\, e_\alpha^{(p)}\, e_\beta^{(s)\,*}\, e_\gamma^{(i)\,*}\, \mathrm{e}^{-\,\mathrm{i}\,\Delta\mathfrak{n}\,\frac{2\pi}{a}\,x}$$

$$\cdot\, \mathrm{e}^{\mathrm{i}\,\Delta k\,\frac{L}{2}}\; N\; \mathrm{sinc}\left(\Delta k\,\frac{L}{2}\right)$$

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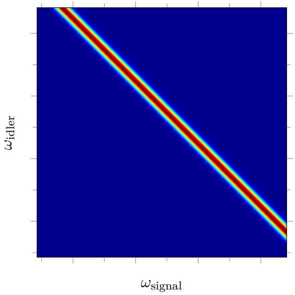
$$\cdot \mathrm{e}^{\mathrm{i}\, \Delta k \frac{L}{2}}\, N\, \mathrm{sinc}\left(\Delta k \frac{L}{2}\right)$$

- pump amplitude:



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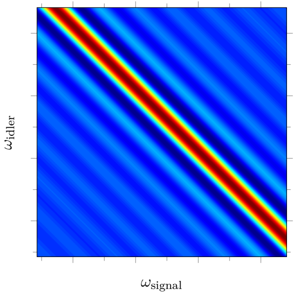
- $\boxed{\text{PM}}$:



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- $\boxed{n_{\mathrm{gr}}}$: strongly mode- and frequency-dependent

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- $\boxed{\mathrm{MO}}$: strongly mode- and frequency-dependent

- JSA at the end of the structure $[x = L]$ is:

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$$\cdot\, \mathrm{e}^{\mathrm{i}\,\Delta k\,\frac{L}{2}}\, N\, \mathrm{sinc}\left(\Delta k\, \frac{L}{2}\right)$$

- allows to calculate JSA from linear optical modes

Non-Linear Optical Properties

- experimental observable: propagation direction
- distinguish $\rightarrow\rightarrow$, $\rightarrow\leftarrow$ and $\leftarrow\leftarrow$ photon-pairs

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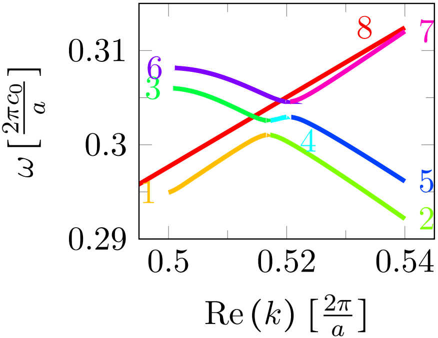
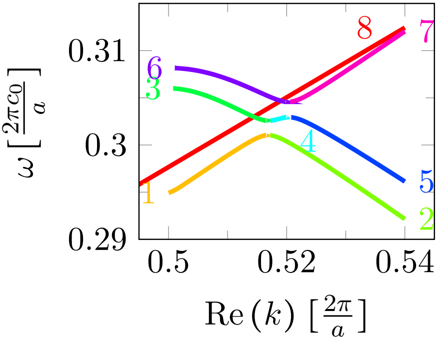


- down-folded pump [band 8]

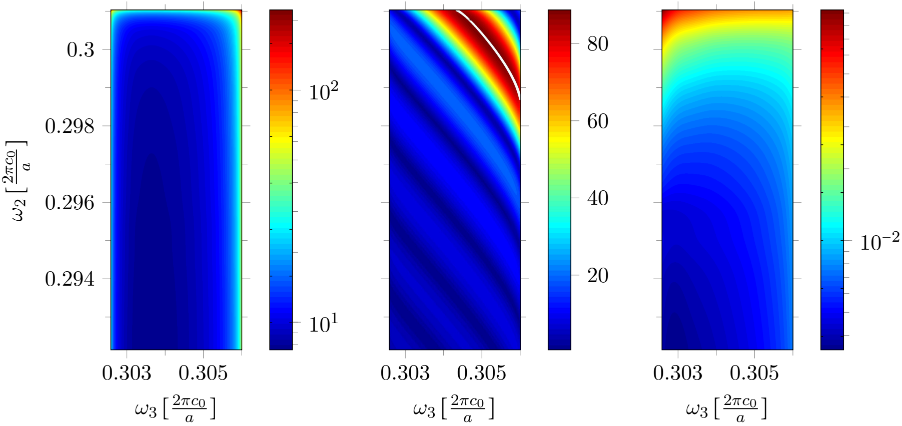
- experimental observable: propagation direction
- distinguish $\rightarrow\rightarrow$, $\rightarrow\leftarrow$ and $\leftarrow\leftarrow$ photon-pairs



- down-folded pump [band 8]
- for full JSA all possible combinations

Single Photon-Pair JSA Parts

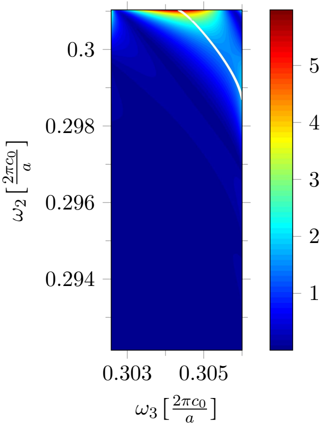
- Exemplary depiction of parts of the JSA for bandlets 2 and 3



$\left|\boxed{n_{\mathrm{gr}}}_{3\,2}\right|$ $\left|\boxed{\mathrm{PM}}_{8\,3\,2}\right|$ $\left|\boxed{\mathrm{MO}}_{8\,3\,2}\right|$

Single Photon-Pair JSA

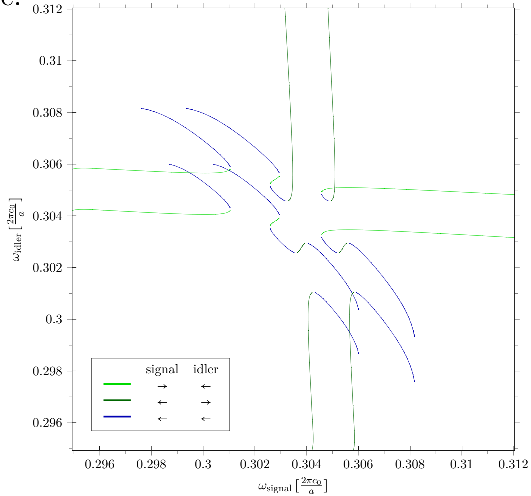
- Full JSA for bandlets 2 and 3 $[A^{(p)} \equiv 1]$



$|\mathrm{JSA}_{8\,3\,2}|$

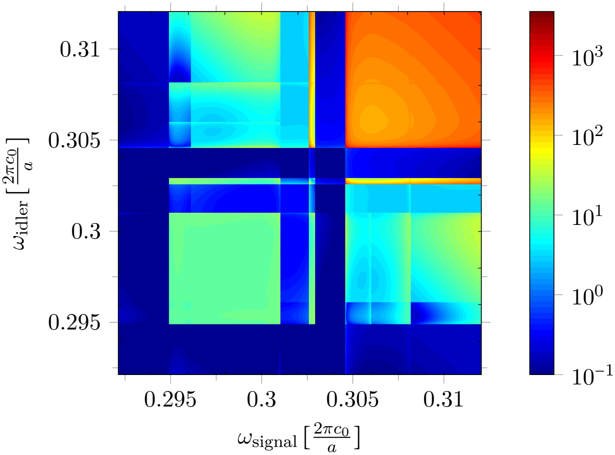
Phase Matching Positions

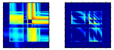
- Positions of optimal phase-matching for the designed structure:



Complete Calculated JSA

- propagation-direction and frequency resolved results: →→





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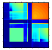

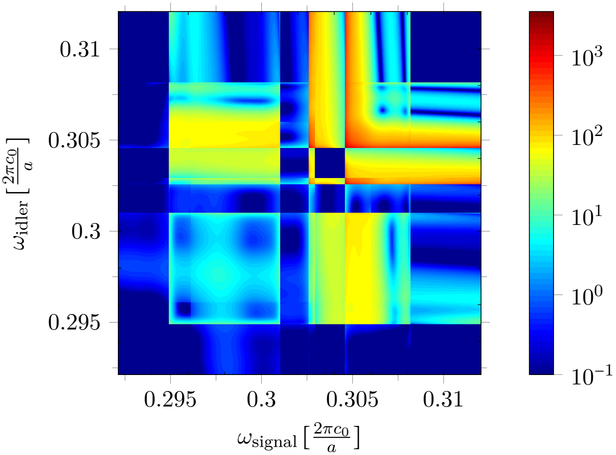

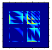

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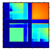
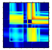
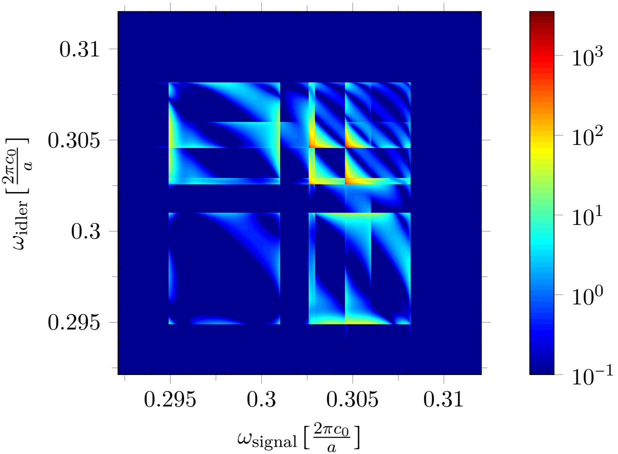
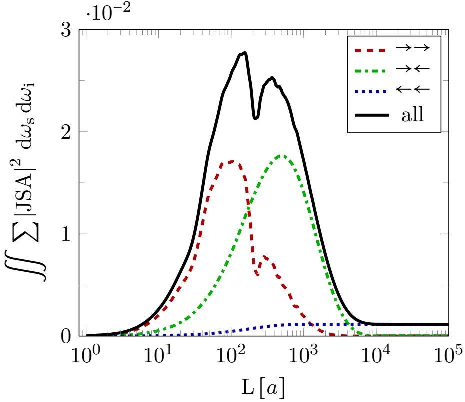




Length Dependence

- integrated probabilities for photon-pairs resolved by propagation-direction:

$A^{(p)} \equiv 1$



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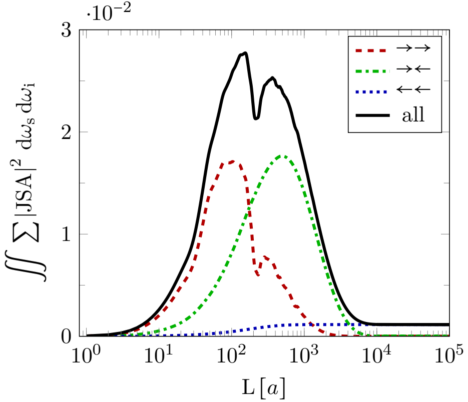
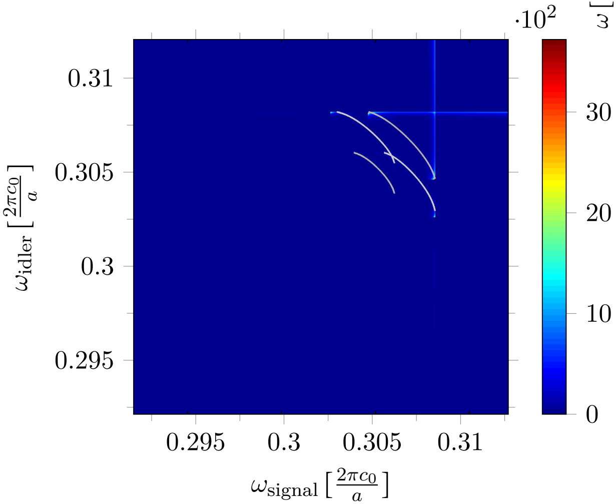
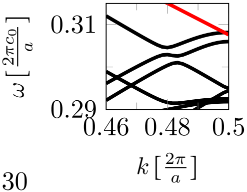


- phase-matching becomes more important for longer structures

Tuning the Pump

- pump shifted in frequency by +0.010 $\frac{2\pi c_0}{a}$



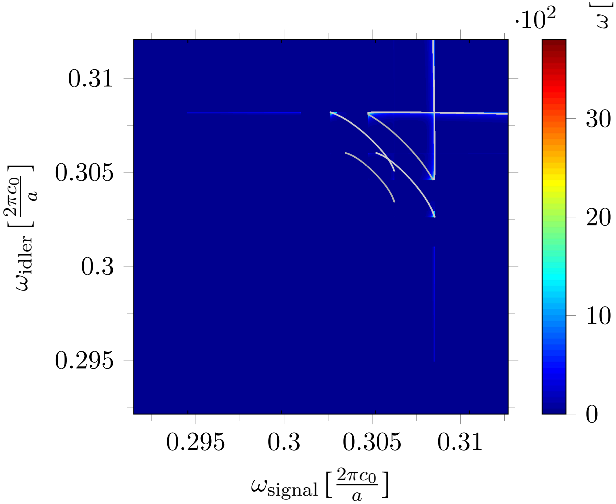


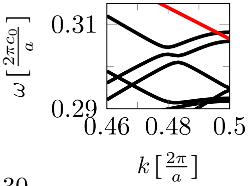
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $+0.009\ \frac{2\pi c_0}{a}$



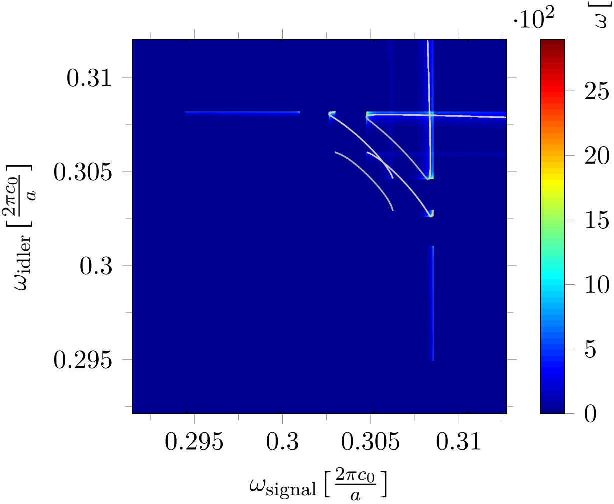


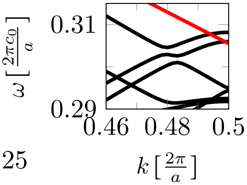
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $+0.008\ \frac{2\pi c_0}{a}$



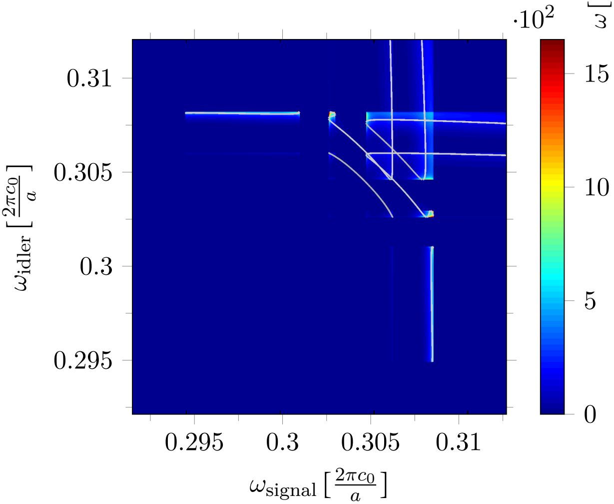


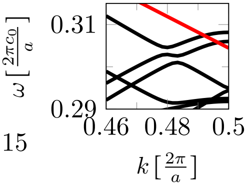
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $+0.007\ \frac{2\pi c_0}{a}$



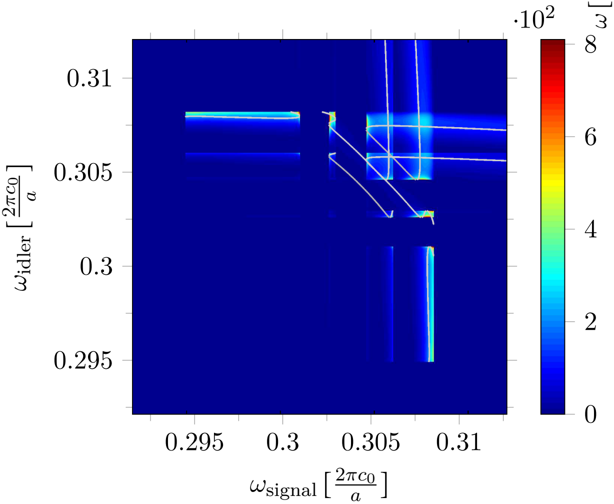


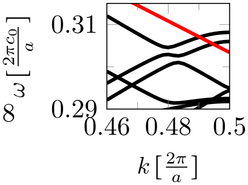
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by +0.006 $\frac{2\pi c_0}{a}$



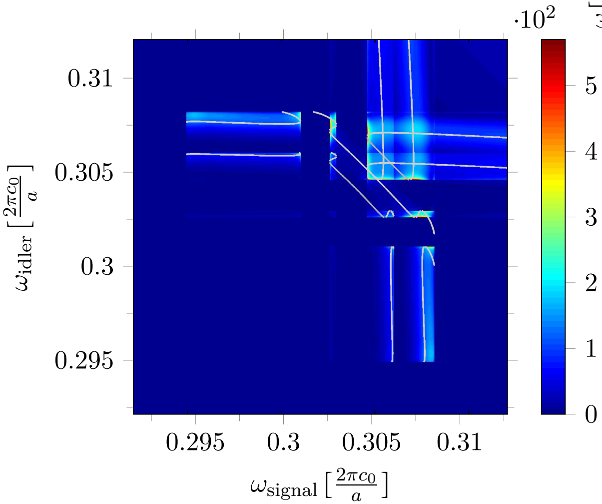


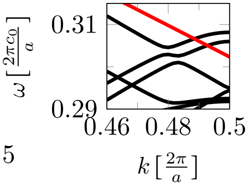
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by +0.005 $\frac{2\pi c_0}{a}$



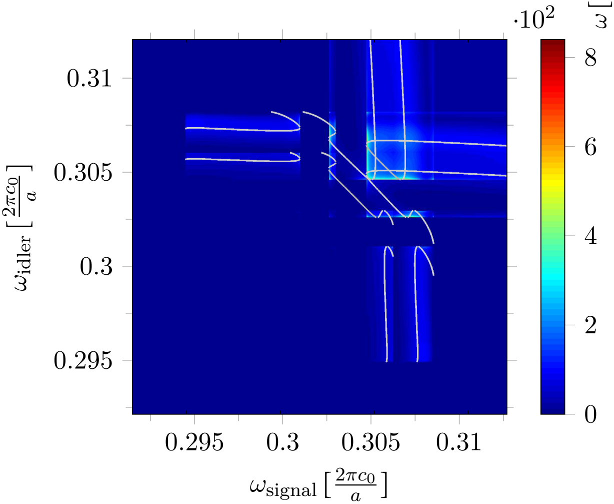


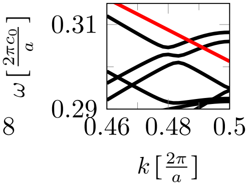
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $+0.004\ \frac{2\pi c_0}{a}$





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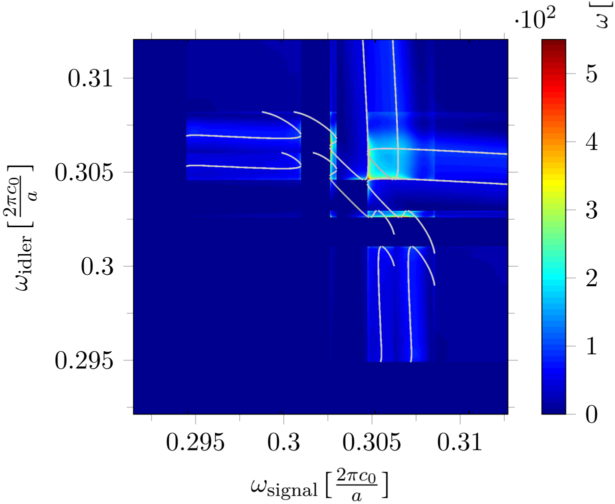
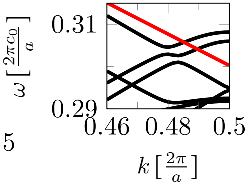
$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by +0.003 $\frac{2\pi c_0}{a}$



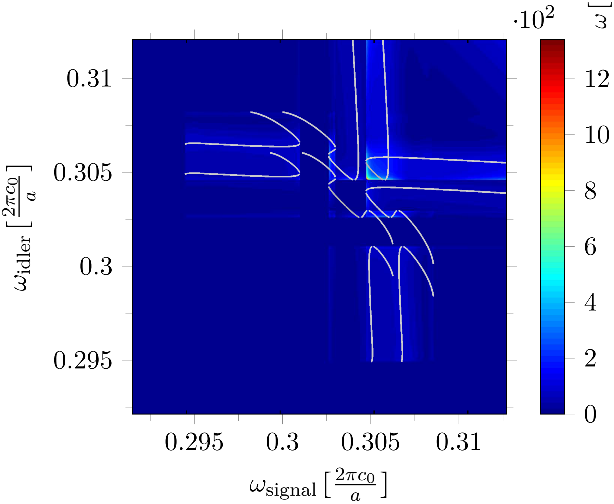


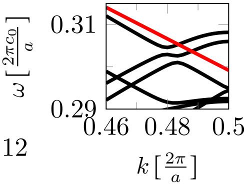
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by +0.002 $\frac{2\pi c_0}{a}$

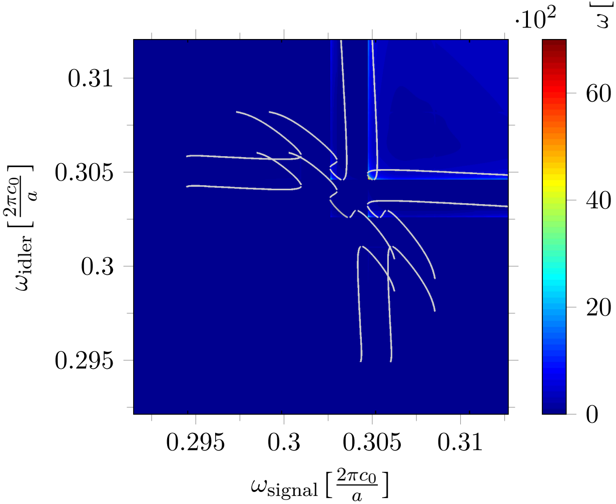


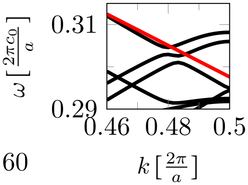


$A^{(p)} \equiv 1$
$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $0.000 \ \frac{2\pi c_0}{a}$



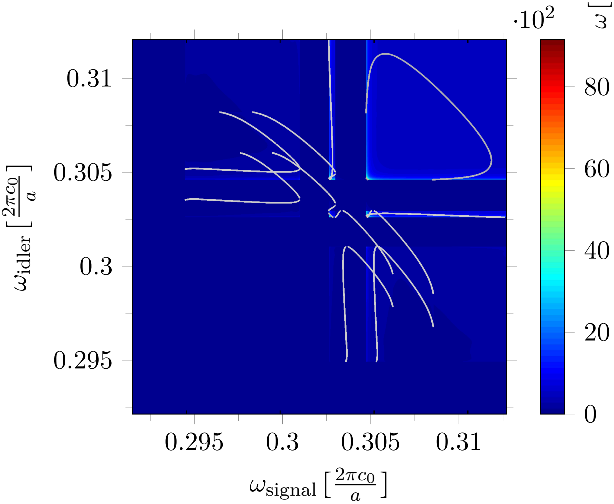


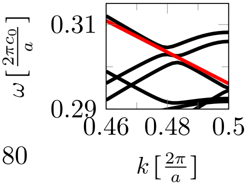
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.002\ \frac{2\pi c_0}{a}$



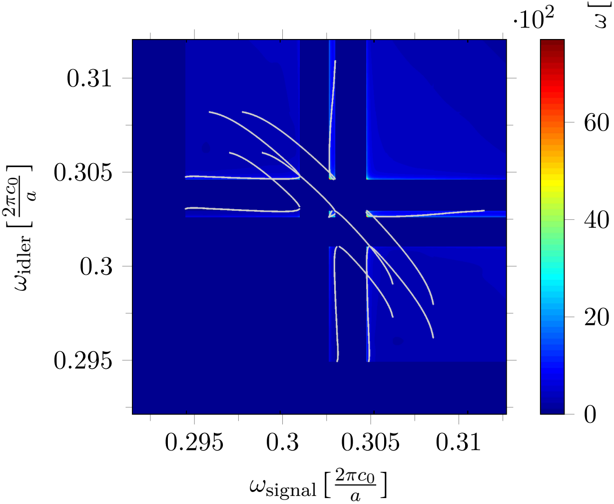


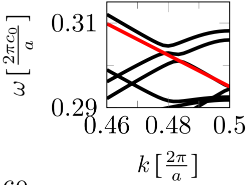
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.003\ \frac{2\pi c_0}{a}$



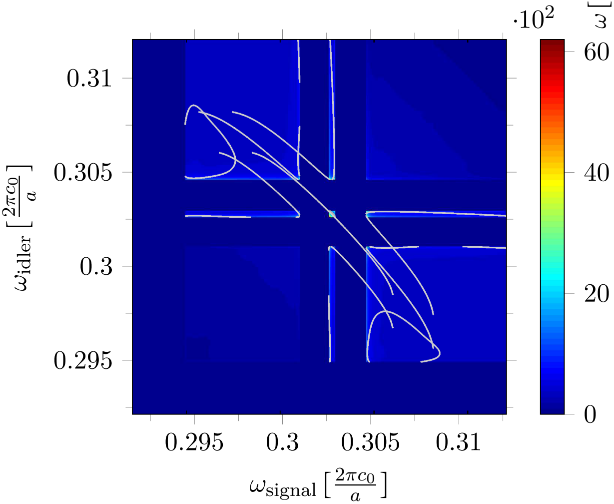


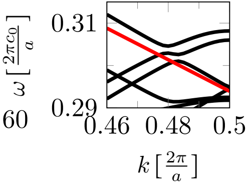
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.004 \ \frac{2\pi c_0}{a}$



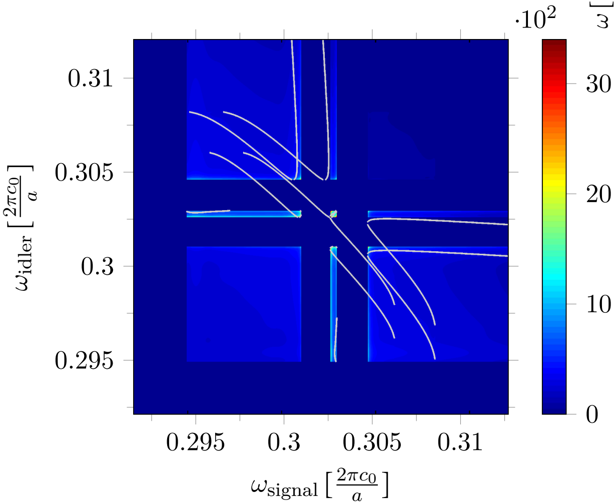


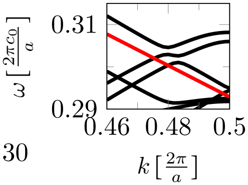
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.005\ \frac{2\pi c_0}{a}$

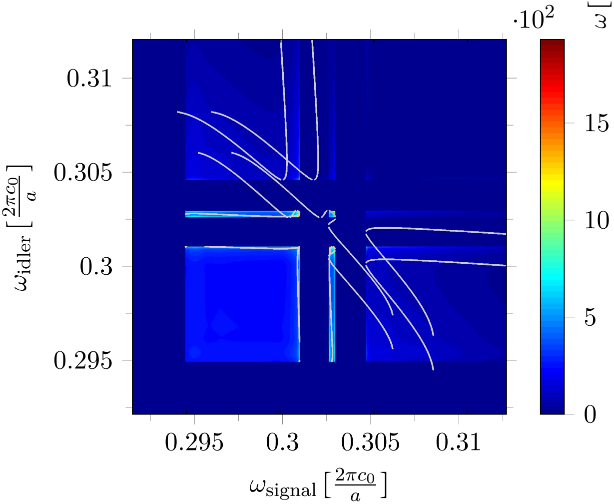


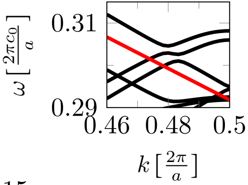


$A^{(p)} \equiv 1$
$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.006\ \frac{2\pi c_0}{a}$



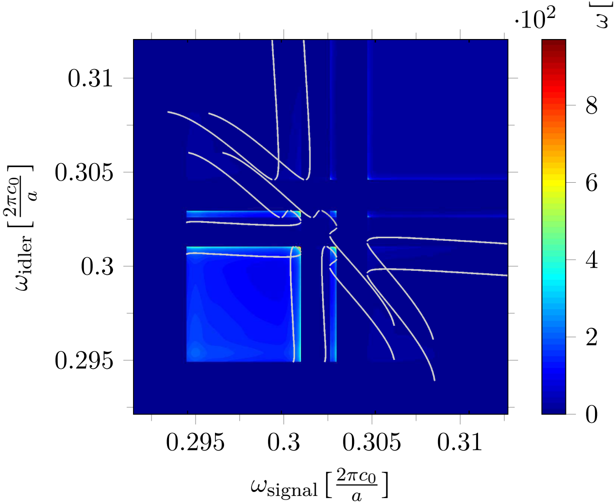


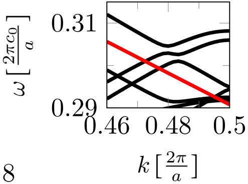
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.007\ \frac{2\pi c_0}{a}$

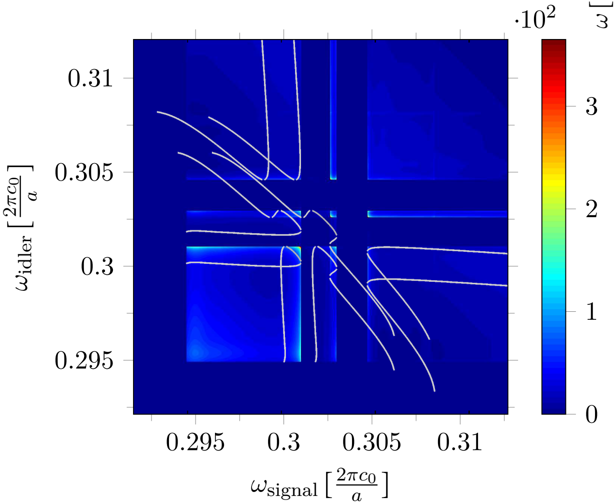


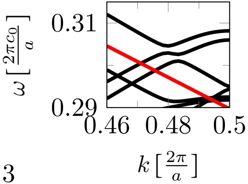


$A^{(p)} \equiv 1$
$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.008\ \frac{2\pi c_0}{a}$



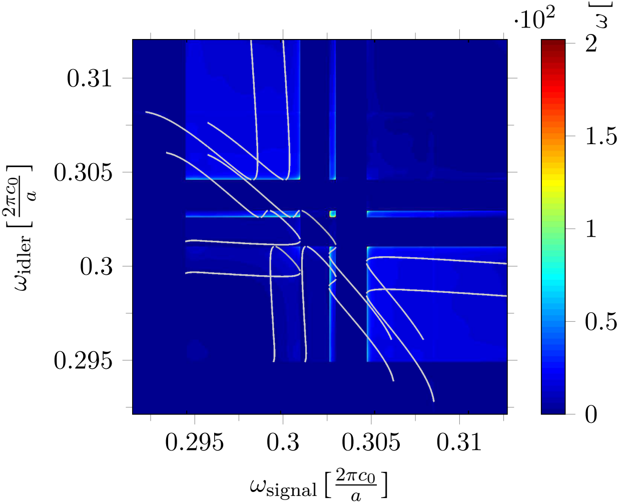


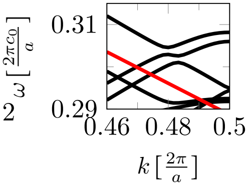
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.009\ \frac{2\pi c_0}{a}$



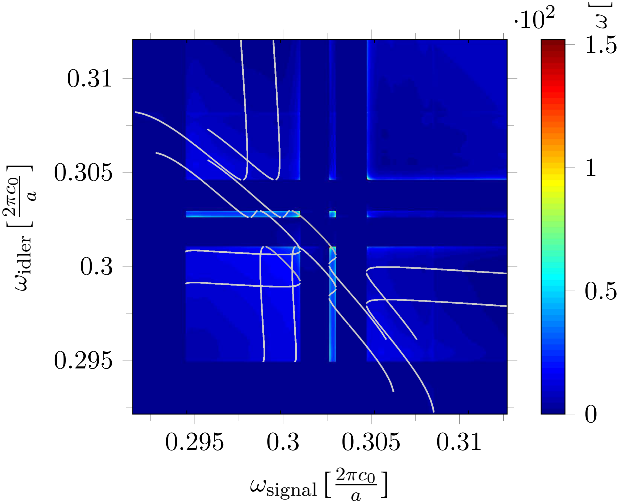


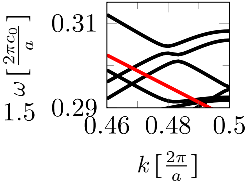
$A^{(p)} \equiv 1$

$L = 100\,a$

Tuning the Pump

- pump shifted in frequency by $-0.010\ \frac{2\pi c_0}{a}$





$A^{(p)} \equiv 1$

$L = 100\,a$

Conclusion

Conclusion

- designed structure with complicated dispersion [on substrate]
- implemented JSA numerically [with losses]
- a huge variety of effects shown

Thank you for your attention!

Mirror-Symmetry

Mirror Symmetries

For the modes of a structure to be able to be called even or odd in x^α, the structure has to have a mirror-symmetry in the same direction.

label of the mode	possible symmetries of the solutions					
	$E_x(\vec{r},\omega)$	$E_y(\vec{r},\omega)$	$E_z(\vec{r},\omega)$	$H_x(\vec{r},\omega)$	$H_y(\vec{r},\omega)$	$H_z(\vec{r},\omega)$
x_{even}	even(x)	odd(x)	odd(x)	odd(x)	even(x)	even(x)
x_{odd}	odd(x)	even(x)	even(x)	even(x)	odd(x)	odd(x)
y_{odd}	odd(y)	even(y)	odd(y)	even(y)	odd(y)	even(y)
y_{even}	even(y)	odd(y)	even(y)	odd(y)	even(y)	odd(y)
z_{even}	odd(z)	odd(z)	even(z)	even(z)	even(z)	odd(z)
z_{odd}	even(z)	even(z)	odd(z)	odd(z)	odd(z)	even(z)

Combinations of symmetries are possible.

Material Properties

Material Properties

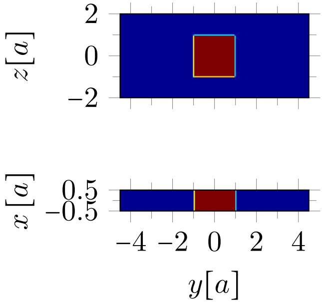
	signal/idler	pump
λ_0	$1500\,\mathrm{nm}$	$750\,\mathrm{nm}$
n_{air}	1	1
$n_{\mathrm{SiO_2}}$ [3]	1.445	1.454
$\hat{n}_{\mathrm{LiNbO_3}}$ [6]	$\begin{pmatrix} 2.213 & 0 & 0 \\ 0 & 2.213 & 0 \\ 0 & 0 & 2.139 \end{pmatrix}$	$\begin{pmatrix} 2.262 & 0 & 0 \\ 0 & 2.262 & 0 \\ 0 & 0 & 2.182 \end{pmatrix}$

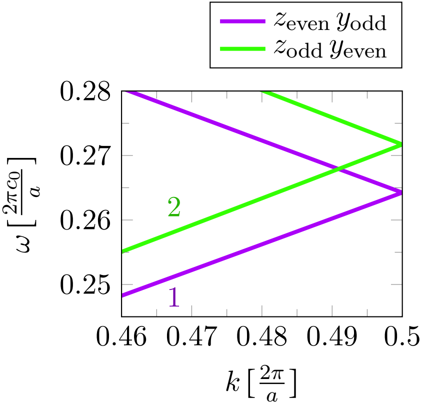
$\hat{d}_{\mathrm{LiNbO_3}}$ [1]

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 30 & -3 \\ -3 & 3 & 0 & 30 & 0 & 0 \\ -5 & -5 & 30 & 0 & 0 & 0 \end{pmatrix} \frac{\mathrm{pm}}{\mathrm{V}}$$

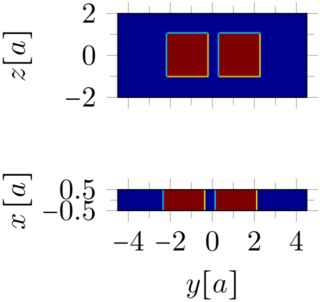
Waveguide Coupling

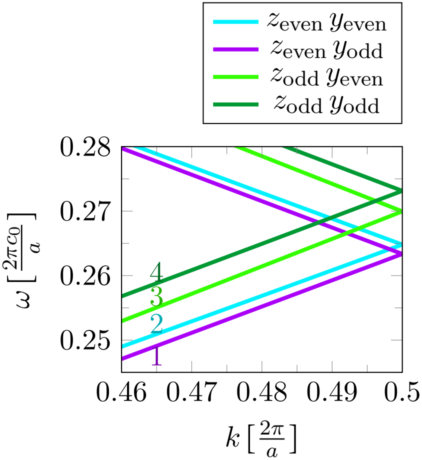
- single waveguide:



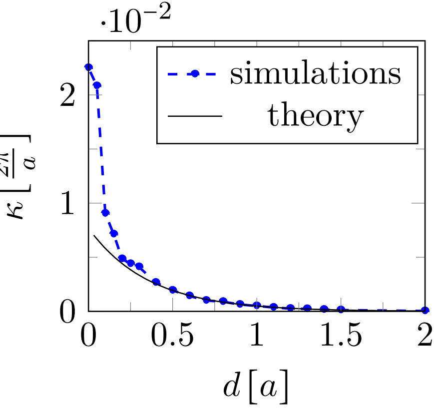


- two waveguides:

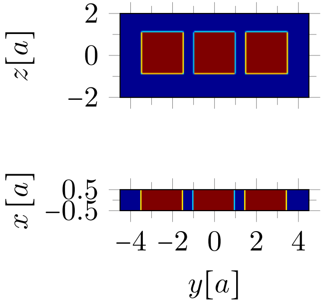


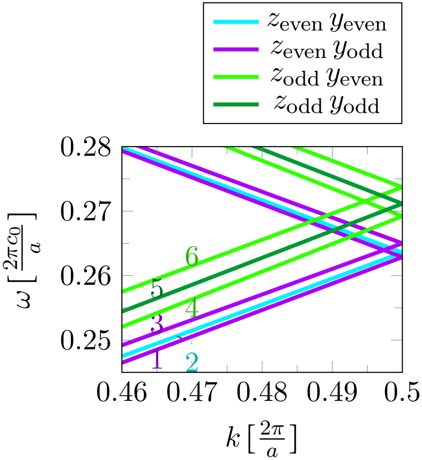


- shift of the lowest two bands for two coupled WGs over the distance between those two WGs:



- three waveguides:

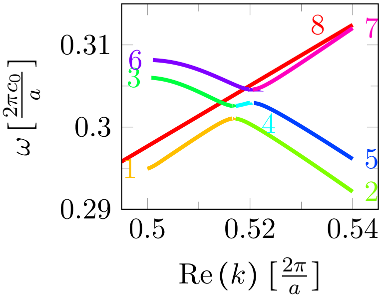


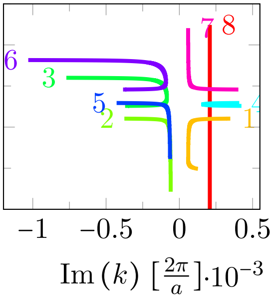


Additional JSA Info

Lossy Bandlets

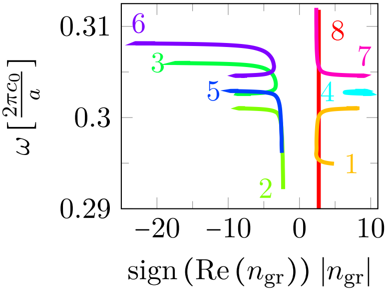
- Approximatively calculated lossy bandlets assuming $\mathrm{Im}\,(\varepsilon_r) = 0.001$:

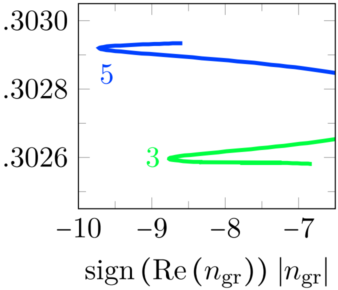




Lossy Group Indices

- From the lossy bandlets calculated group indices $n_{\text{gr}} = c_0 \frac{\mathrm{d}k}{\mathrm{d}\omega}$

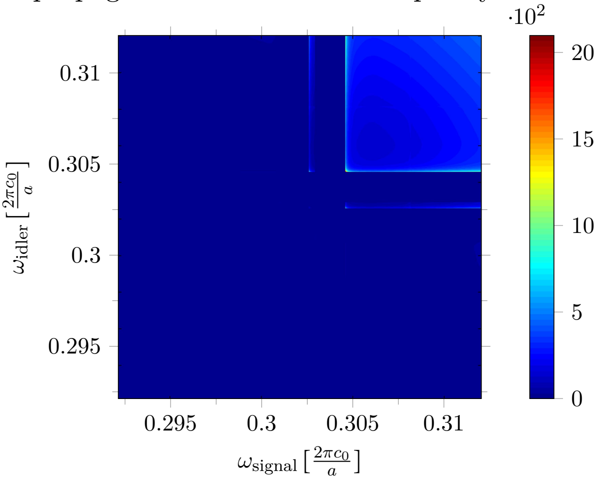


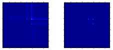


Zoomed in excerpt on the right, to show the extrema of the bandlets 3 and 5 at anti-crossings [all bandlets show this behavior].

Complete Calculated JSA - linear

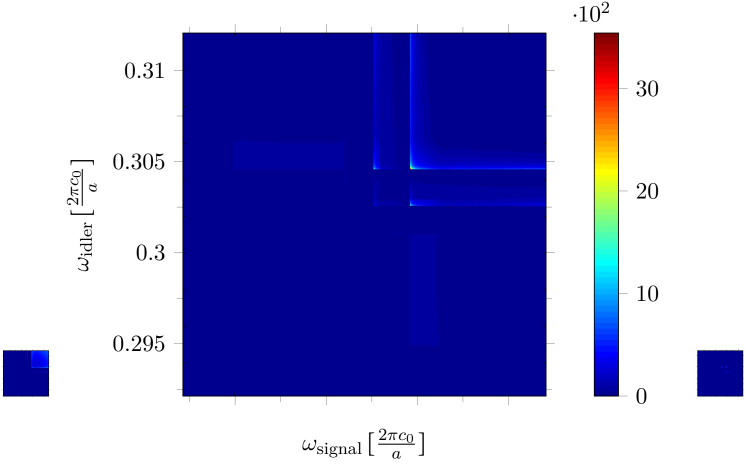
- propagation-direction and frequency resolved results: →→





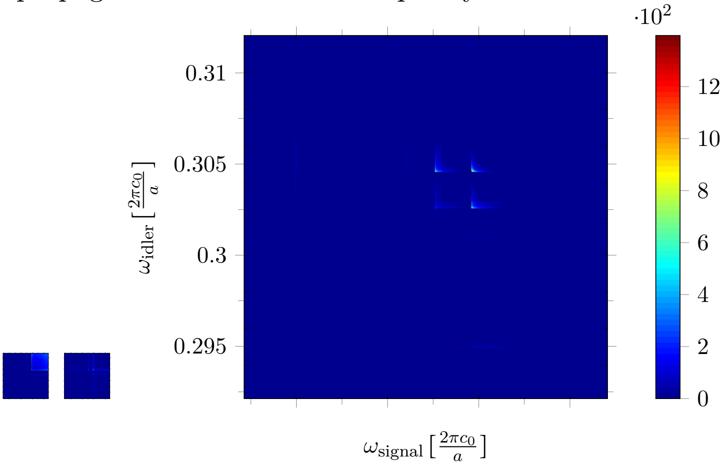
Complete Calculated JSA - linear

- propagation-direction and frequency resolved results: →←



Complete Calculated JSA - linear

- propagation-direction and frequency resolved results: ←←



Literature

Literature I

[1] *INRAD Lithium Niobate Datasheet.* http://www.lambdaphoto.co.uk/pdfs/Inrad_datasheet_LNB.pdf.

[2] GUTMAN, NADAV, W. HUGO DUPREE, YUE SUN, ANDREY A. SUKHORUKOV and C. MARTIJN DE STERKE: *Frozen and broadband slow light in coupled periodic nanowire waveguides.* Opt. Express, 20(4):3519–3528, feb 2012.

[3] MALITSON, I. H.: *Interspecimen Comparison of the Refractive Index of Fused Silica.* JOSA, 55(10):1205–1209, 1965.

[4] QUINTERO-BERMUDEZ, RAFAEL, SINA SARAVI, FRANK SETZPFANDT and THOMAS PERTSCH: *Slow-Light Enhanced Second-Harmonic Generation in Periodic Nanobeam Waveguides.* In *The European Conference on Lasers and Electro-Optics*, page CK_P_8. Optical Society of America, 2015.

[5] SARAVI, SINA, SÉVERINE DIZIAIN, MATTHIAS ZILK, FRANK SETZPFANDT and THOMAS PERTSCH: *Phase-matched second-harmonic generation in slow-light photonic crystal waveguides.* Physical Review A, 92(6):063821, 2015.

Literature II

[6] Zelmon, David E., David L. Small and Dieter Jundt: *Infrared corrected Sellmeier coefficients for congruently grown lithium niobate and 5 mol.% magnesium oxide–doped lithium niobate*. JOSA B, 14(12):3319–3322, 1997.