Оптические свойства фотонно-кристаллических слоёв в окрестности резонансов

Илья Фрадкин

Наталия Салахова

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МФ'24
УлГУ-РНФ

Школа молодых ученых по микроволновой фотонике
Москва, Сколково, 6-7 ноября 2024 г.

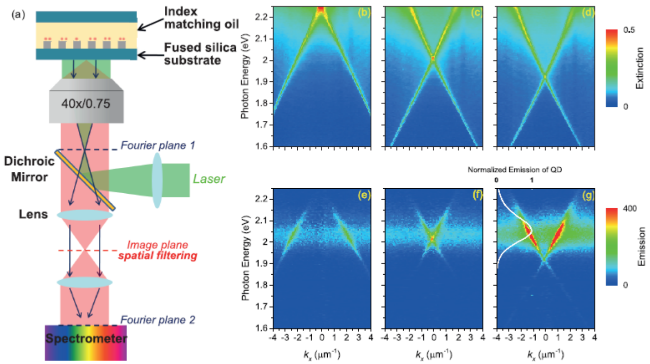
Plan

1. Introduction.
2. Resonances in photonic crystal slabs
3. How can we calculate the S-marix in these systems?
   - regular approach
   - effective dipole approximation
4. How can we calculate resonances in photonic crystal slabs?

Applications

Controlling quantum dot emission by plasmonic nanoarrays

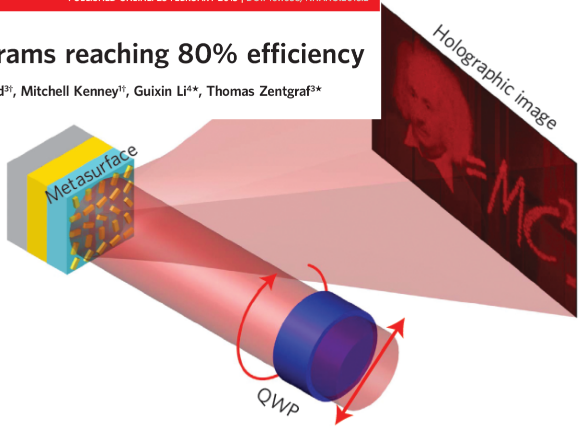
R. Guo,[1] S. Derom,[1] A. I. Väkeväinen,[1] R. J. A. van Dijk-Moes,[2] P. Liljeroth,[3] D. Vanmaekelbergh,[2] and P. Törmä[1,*]



nature nanotechnology
LETTERS
PUBLISHED ONLINE: 23 FEBRUARY 2015 | DOI: 10.1038/NNANO.2015.2

Metasurface holograms reaching 80% efficiency

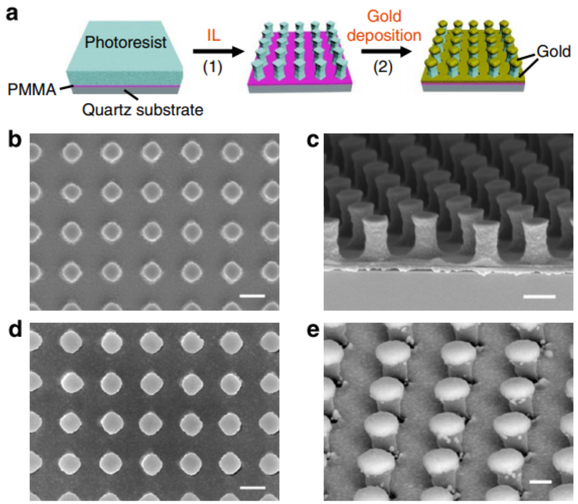
Guoxing Zheng[1,2†], Holger Mühlenbernd[3†], Mitchell Kenney[1†], Guixin Li[4*], Thomas Zentgraf[3*] and Shuang Zhang[1*]



ARTICLE
Received 4 Mar 2013 | Accepted 31 Jul 2013 | Published 27 Aug 2013
DOI: 10.1038/ncomms3381

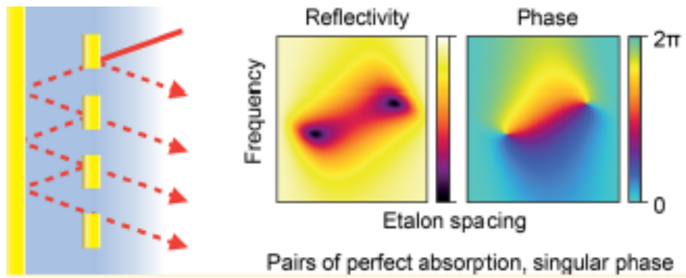
Plasmonic gold mushroom arrays with refractive index sensing figures of merit approaching the theoretical limit

Yang Shen[1,*], Jianhua Zhou[2,*], Tianran Liu[1], Yuting Tao[3], Ruibin Jiang[3], Mingxuan Liu[1], Guohui Xiao[1], Jinhao Zhu[1], Zhang-Kai Zhou[1], Xuehua Wang[1], Chongjun Jin[1] & Jianfang Wang[3]



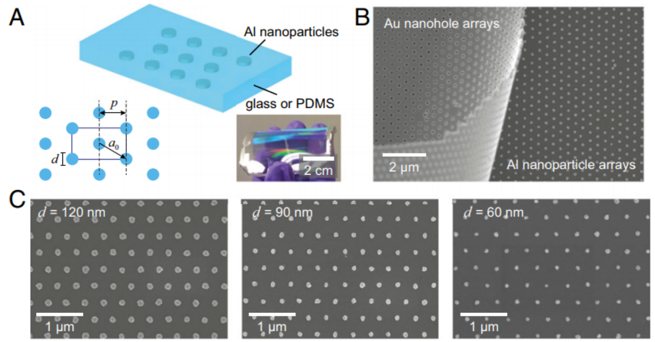
Perfect Absorption and Phase Singularities in Plasmon Antenna Array Etalons

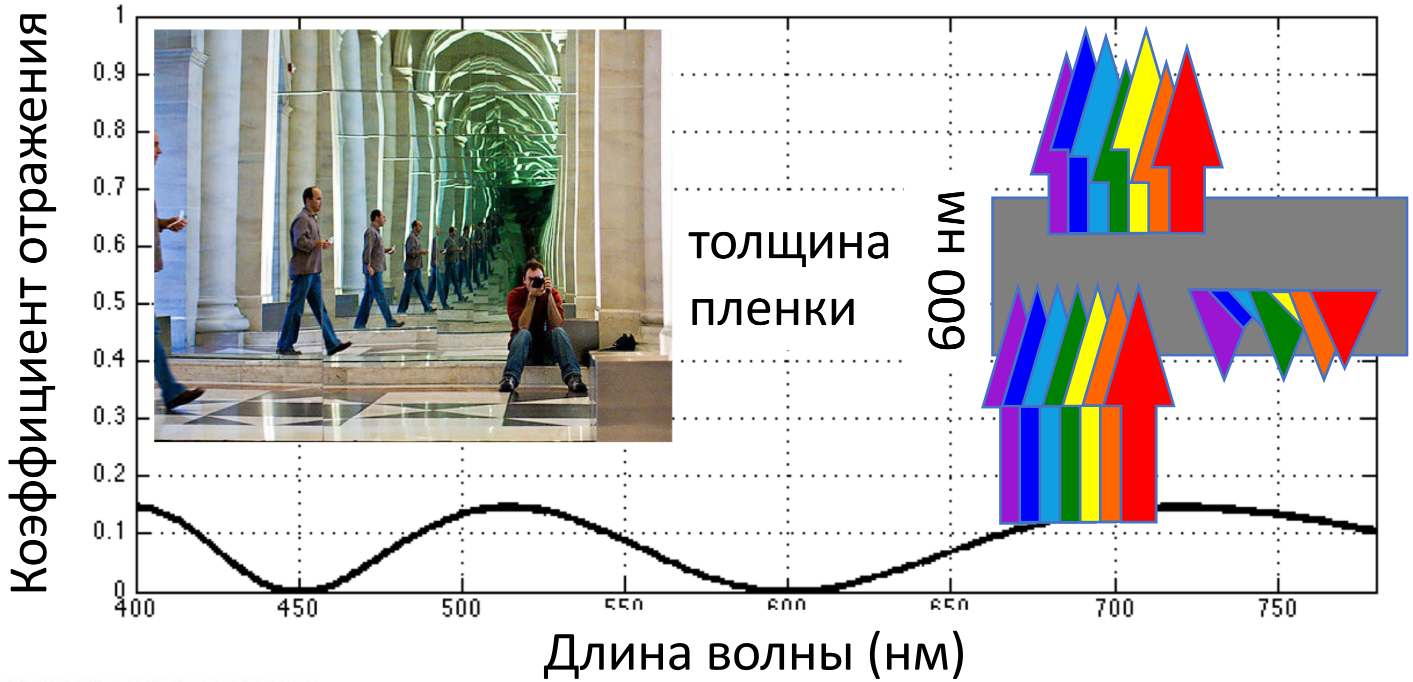
Annemarie Berkhout and A. Femius Koenderink*

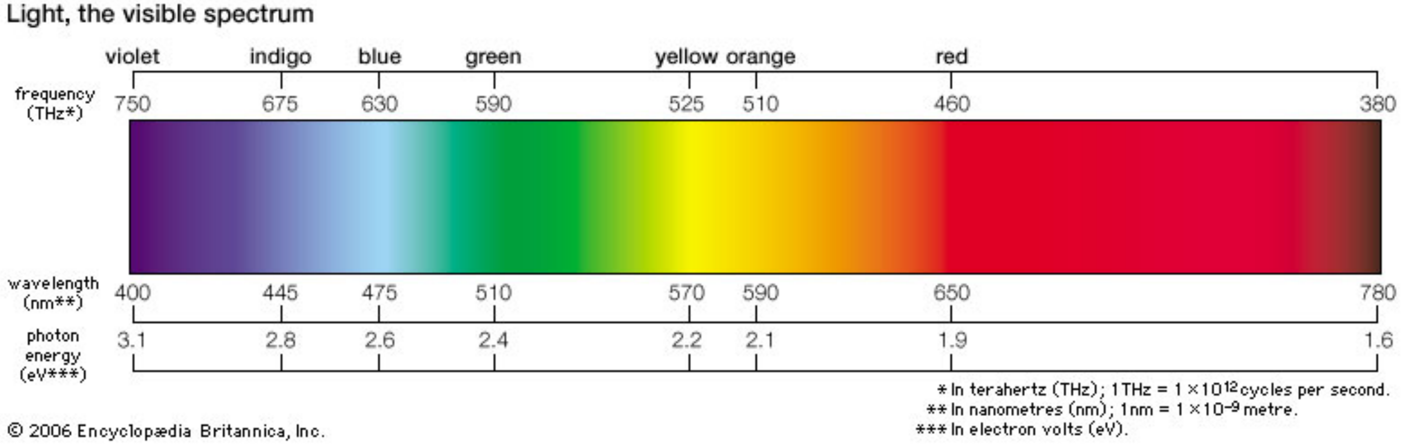


Programmable and reversible plasmon mode engineering

Ankun Yang[a], Alexander J. Hryn[a], Marc R. Bourgeois[b], Won-Kyu Lee[a], Jingtian Hu[a], George C. Schatz[b], and Teri W. Odom[a,b,1]




Коэффициент отражения
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
толщина
пленки
600 нм
400
450
500
700
750
Длина волны (нм)


Light, the visible spectrum
violet
indigo
blue
green
yellow orange
red
frequency (THz*)
750
675
630
590
525
510
460
380
wavelength (nm**)
400
445
475
510
570
590
650
780
photon energy (eV***)
3.1
2.8
2.6
2.4
2.2
2.1
1.9
1.6
* In terahertz (THz); 1 THz = 1 × 10¹² cycles per second.
** In nanometres (nm); 1 nm = 1 × 10⁻⁹ metre.
*** In electron volts (eV).
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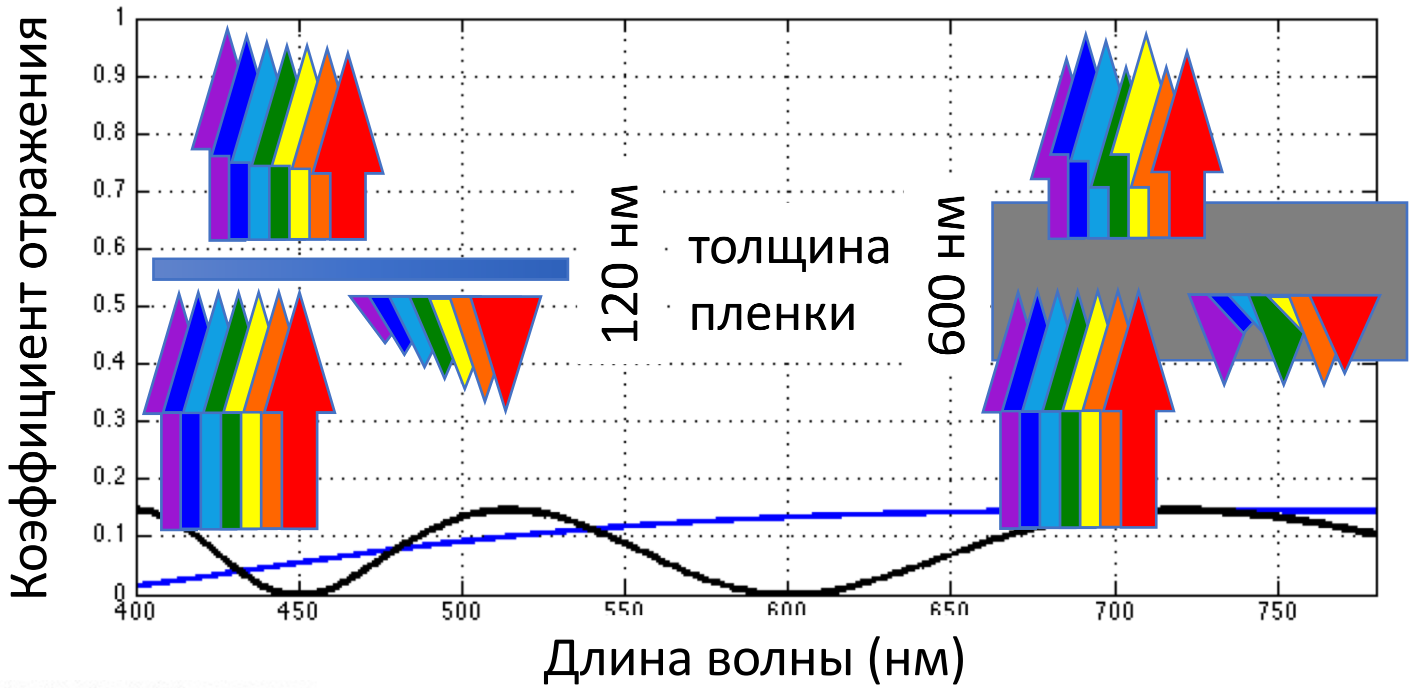
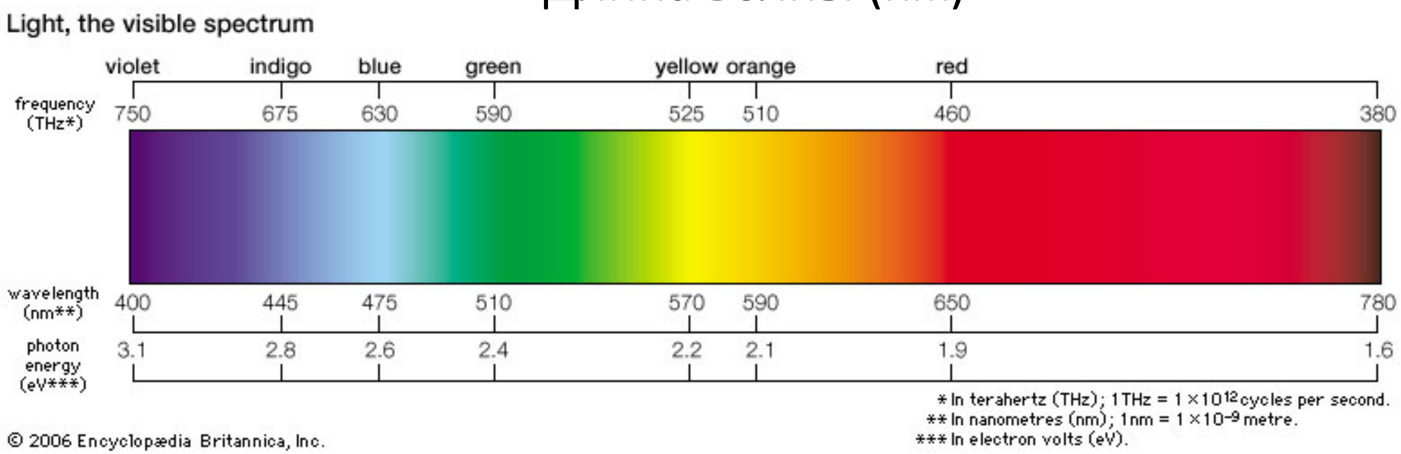

Коэффициент отражения
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
450
500
550
600
650
700
750
120 нм
толщина
пленки
600 нм
Длина волны (нм)


Light, the visible spectrum
violet
indigo
blue
green
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red
frequency (THz*)
750
675
630
590
525
510
460
380
wavelength (nm**)
400
445
475
510
570
590
650
780
photon energy (eV***)
3.1
2.8
2.6
2.4
2.2
2.1
1.9
1.6
* In terahertz (THz); 1 THz = 1 × 10^12 cycles per second.
** In nanometres (nm); 1 nm = 1 × 10^-9 metre.
*** In electron volts (eV).
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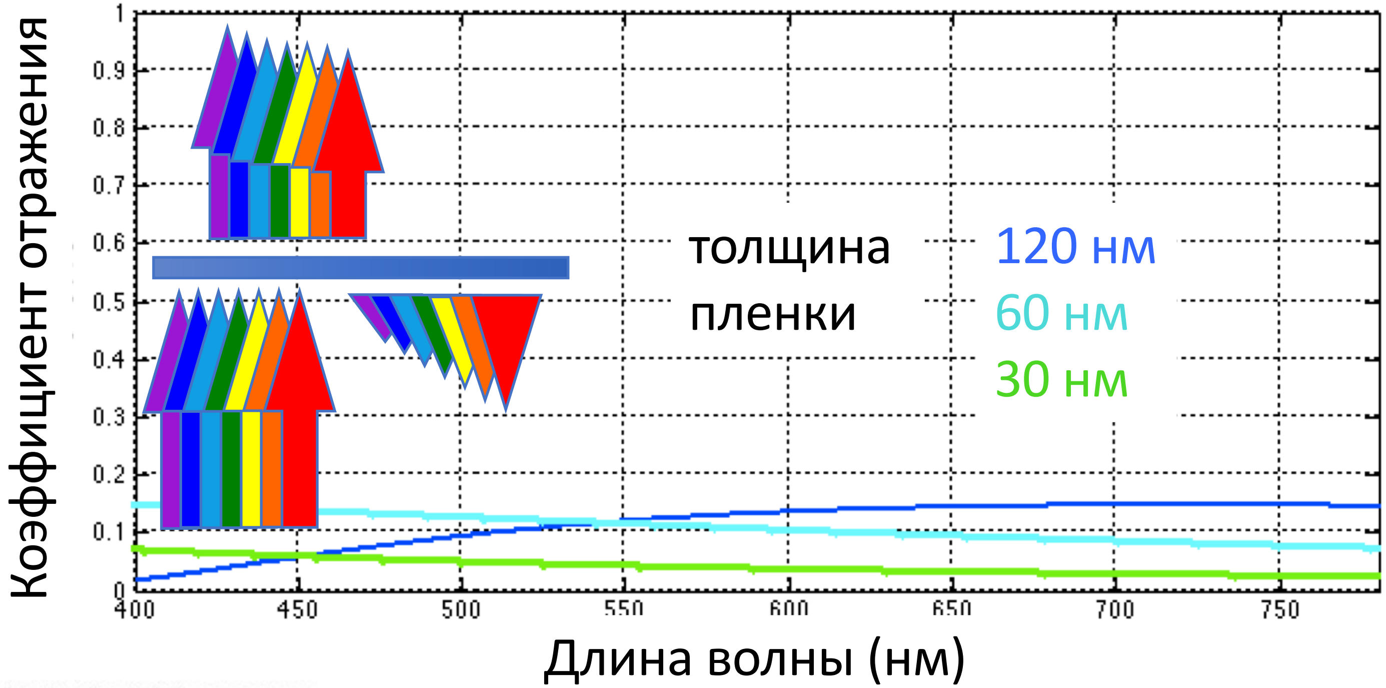
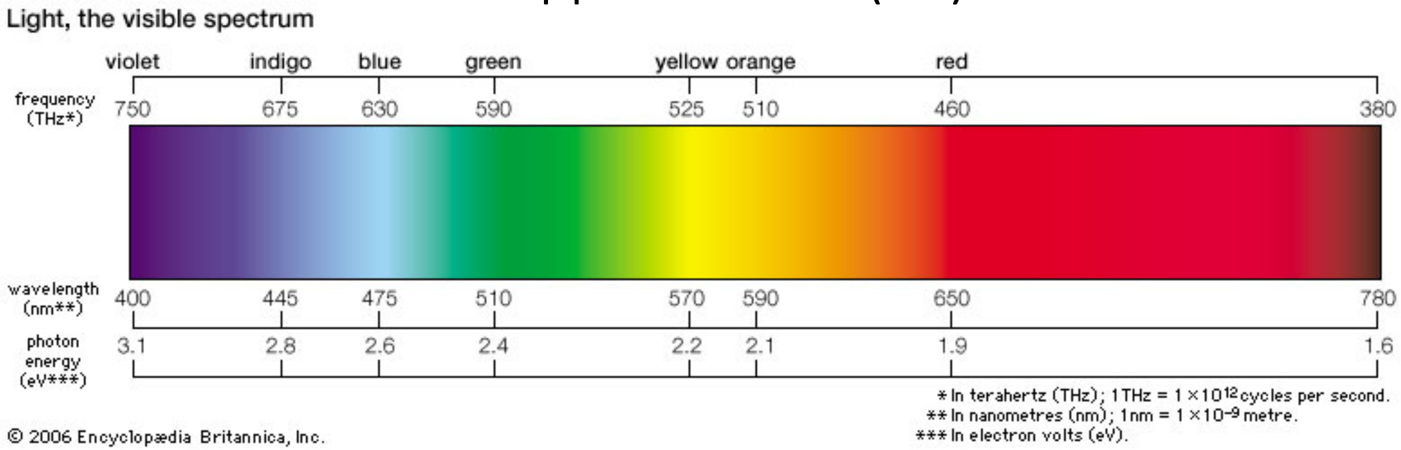

Коэффициент отражения
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
400
450
500
550
600
650
700
750
Длина волны (нм)
толщина
пленки
120 нм
60 нм
30 нм


Light, the visible spectrum
violet
indigo
blue
green
yellow orange
red
frequency (THz*)
750
675
630
590
525
510
460
380
wavelength (nm**)
400
445
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570
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650
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photon energy (eV***)
3.1
2.8
2.6
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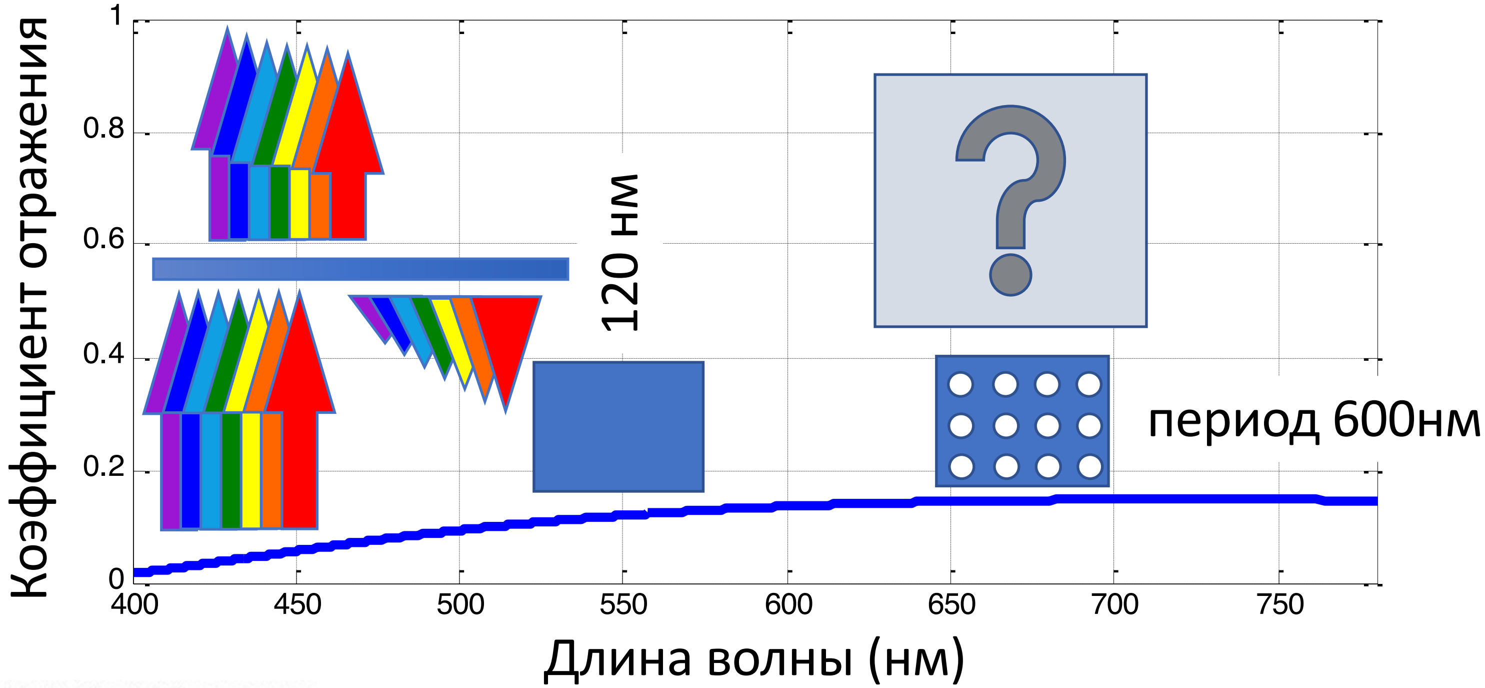
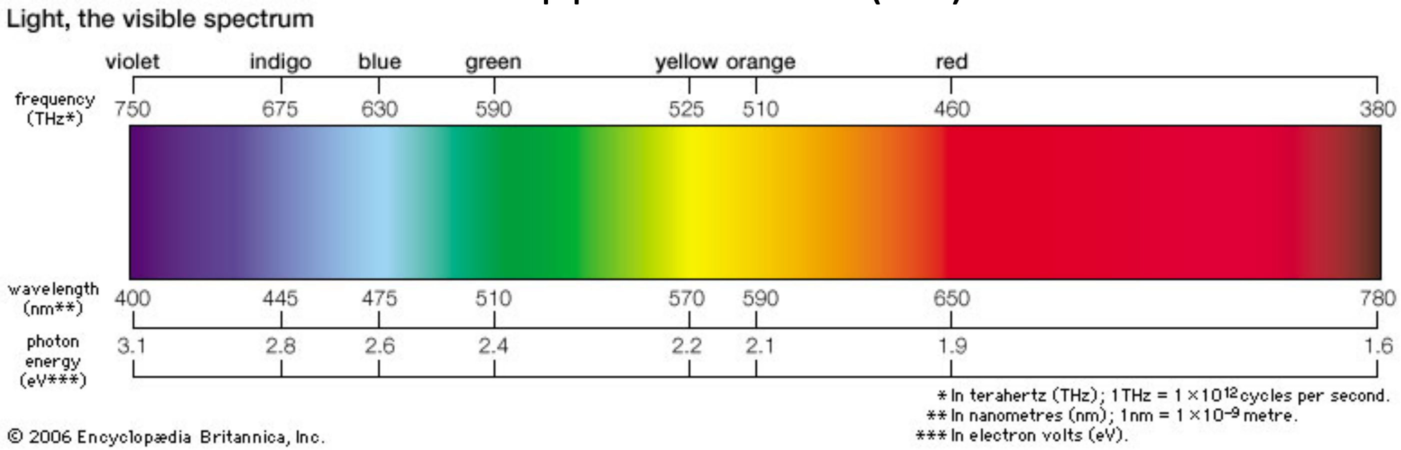

Коэффициент отражения
1
0.8
0.6
0.4
0.2
0
400
450
500
550
600
650
700
750
120 нм
период 600нм
Длина волны (нм)


Light, the visible spectrum
violet
indigo
blue
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frequency (THz*)
750
675
630
590
525
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460
380
wavelength (nm**)
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570
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650
780
photon energy (eV***)
3.1
2.8
2.6
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2.2
2.1
1.9
1.6
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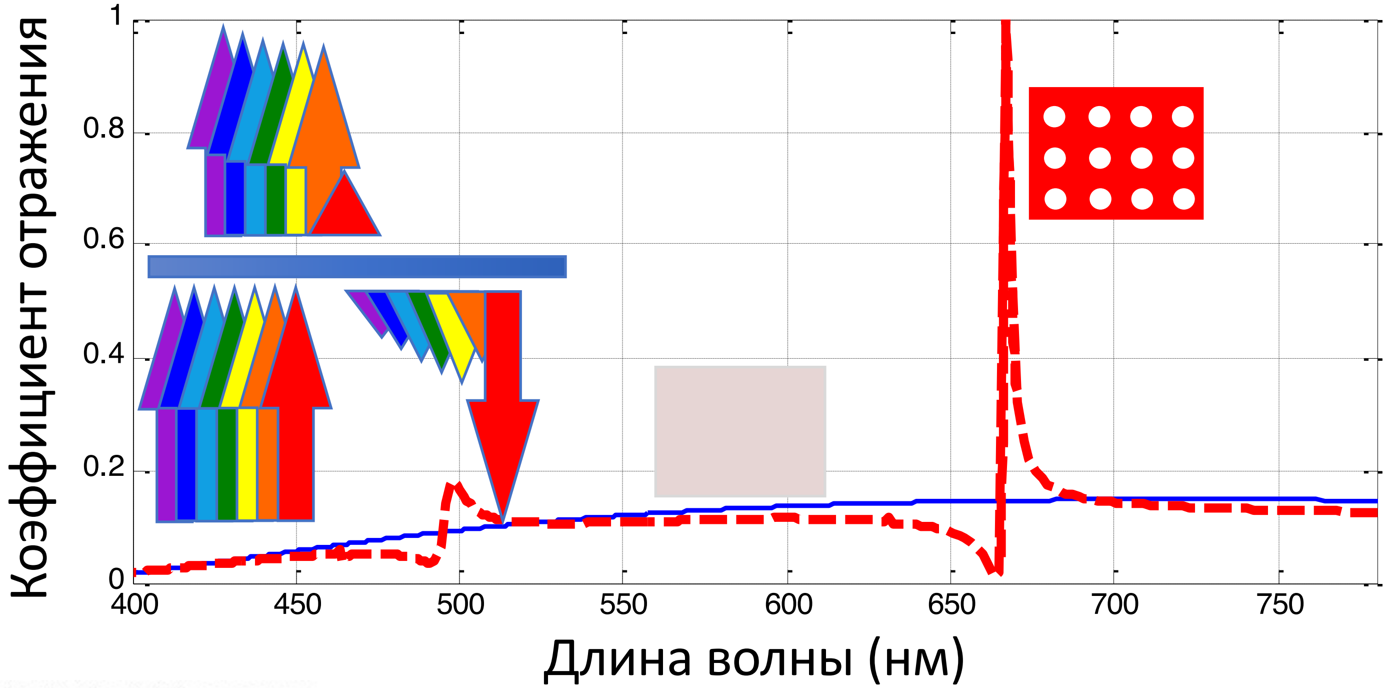
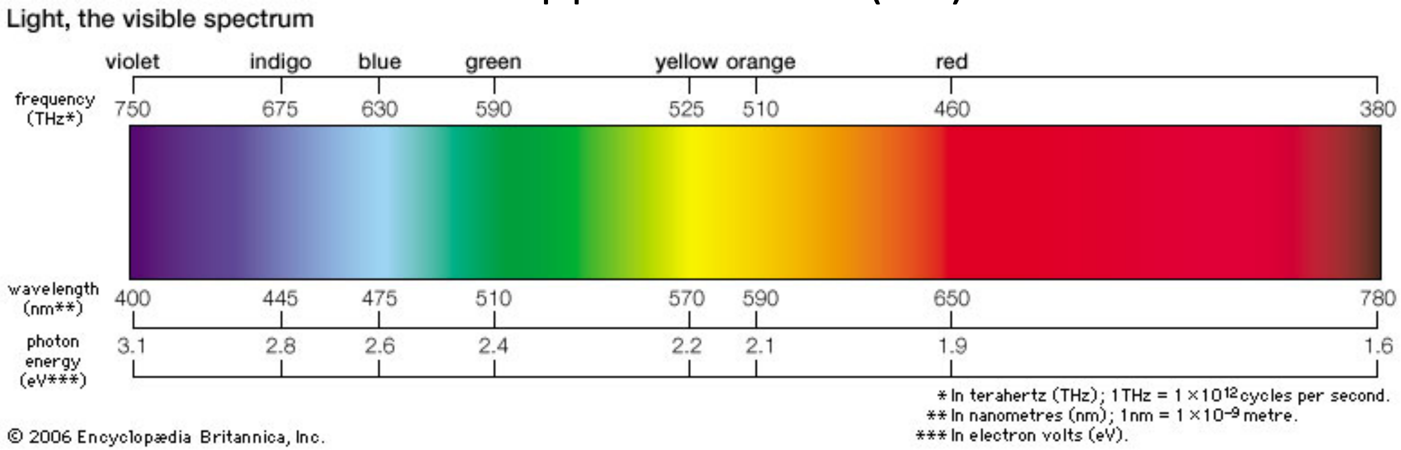

Коэффициент отражения
1
0.8
0.6
0.4
0.2
0
400
450
500
550
600
650
700
750
Длина волны (нм)


Light, the visible spectrum
violet
indigo
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red
frequency (THz*)
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wavelength (nm**)
400
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780
photon energy (eV***)
3.1
2.8
2.6
2.4
2.2
2.1
1.9
1.6
* In terahertz (THz); 1 THz = 1 × 10^12 cycles per second.
** In nanometres (nm); 1 nm = 1 × 10^-9 metre.
*** In electron volts (eV).
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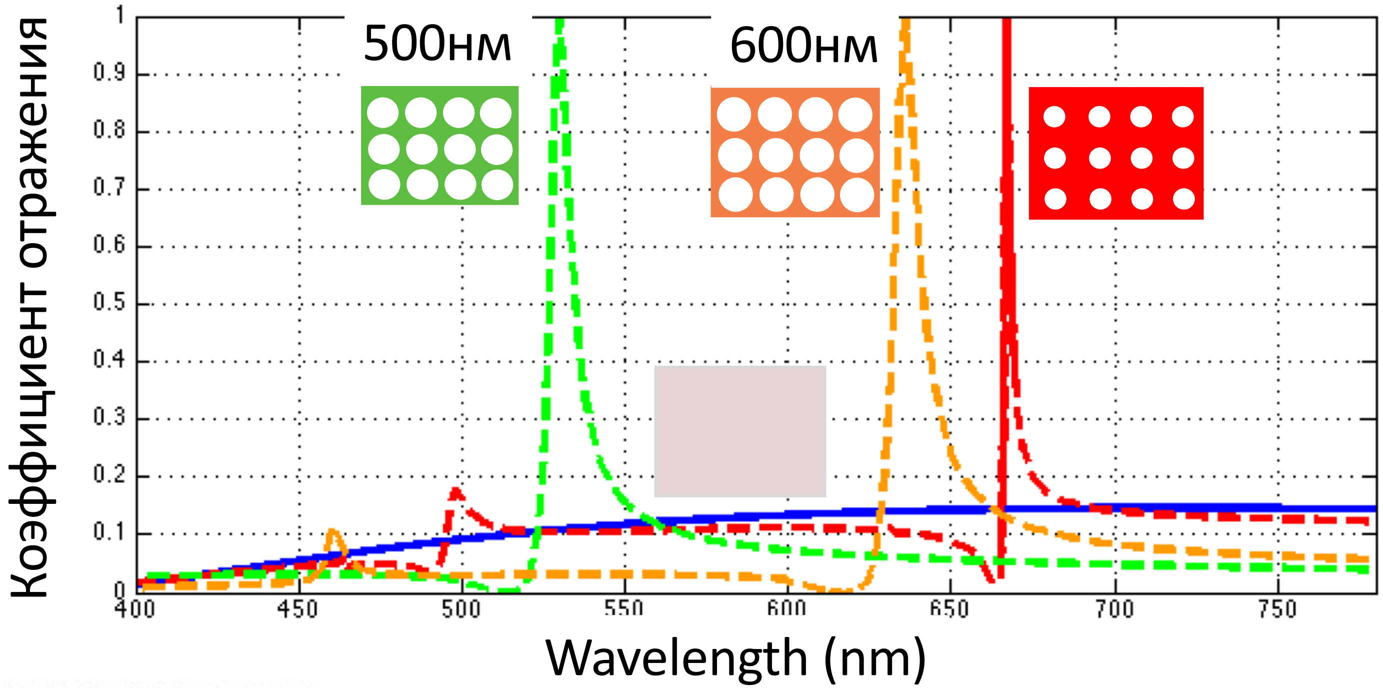
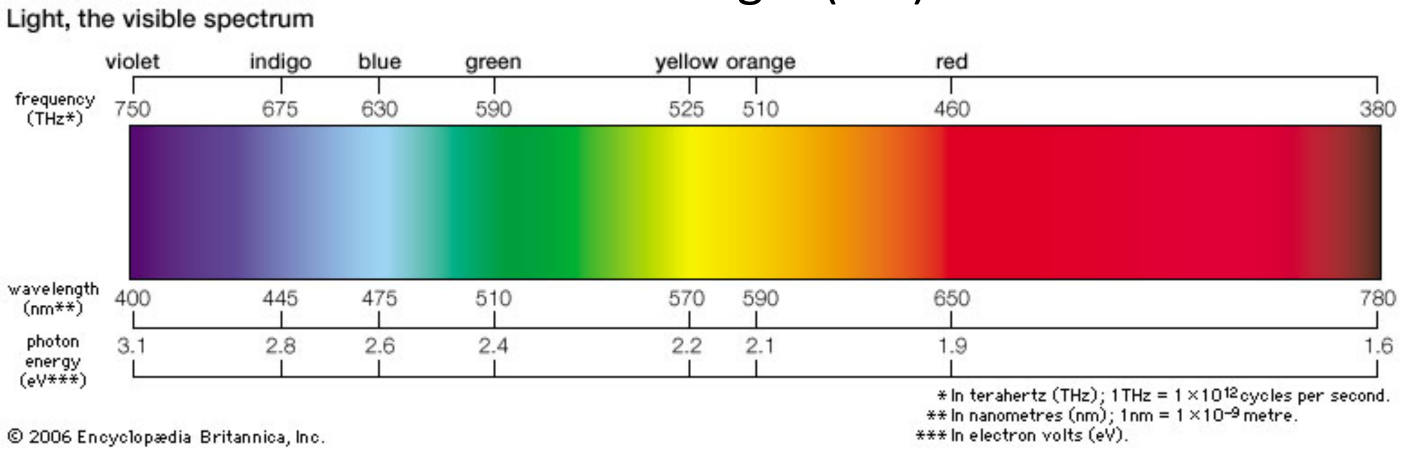


500нм
600нм
Коэффициент отражения
Wavelength (nm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
450
500
550
600
650
700
750



Light, the visible spectrum
violet
indigo
blue
green
yellow orange
red
frequency (THz*)
750
675
630
590
525
510
460
380
wavelength (nm**)
400
445
475
510
570
590
650
780
photon energy (eV***)
3.1
2.8
2.6
2.4
2.2
2.1
1.9
1.6
* In terahertz (THz); 1 THz = 1 × 10[12] cycles per second.
** In nanometres (nm); 1 nm = 1 × 10[-9] metre.
*** In electron volts (eV).
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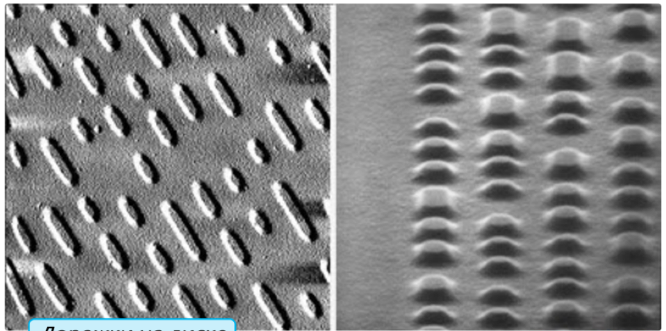
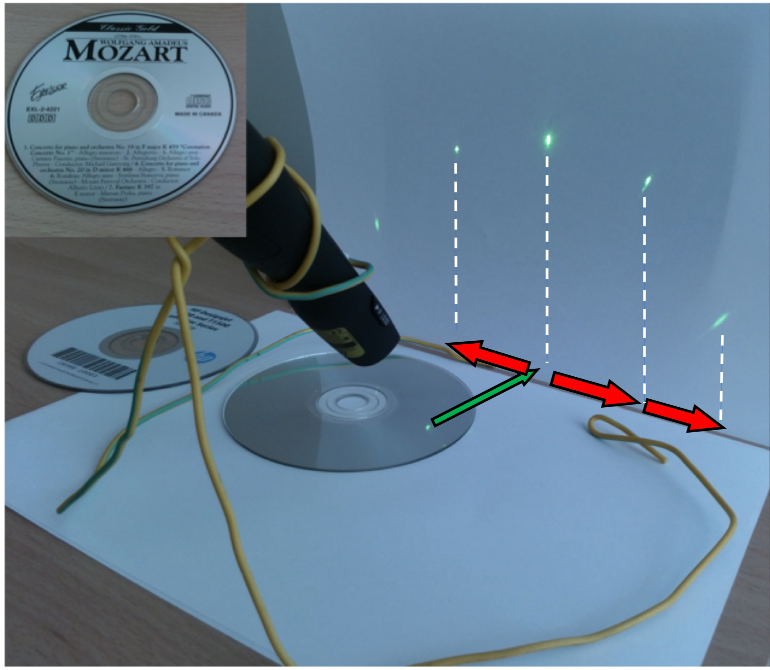
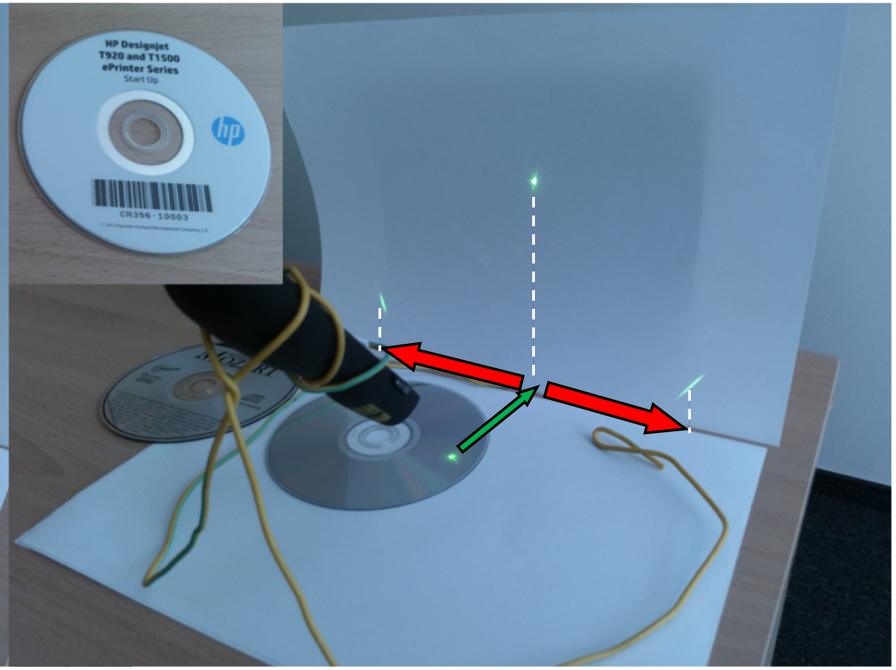
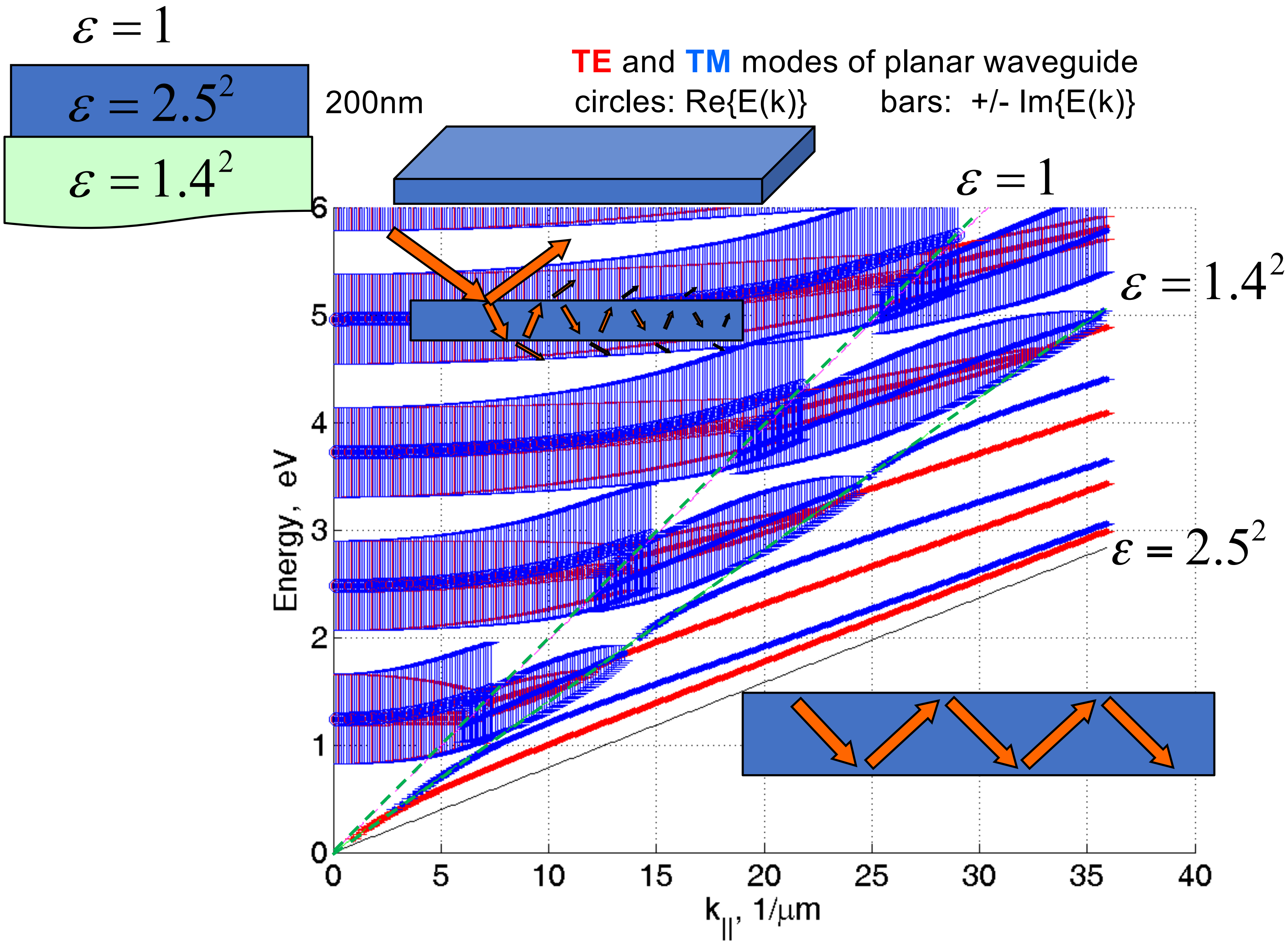


Дорожки на диске

	DVD	CD
размер штрихов (микрон)	0.4	0.83
ширина дорожки	0.74	1.6





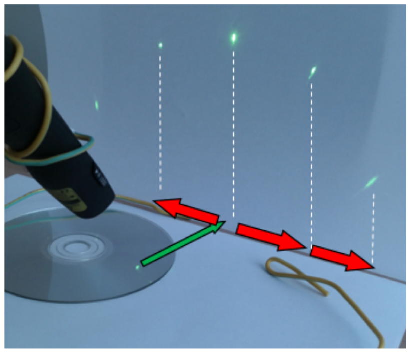


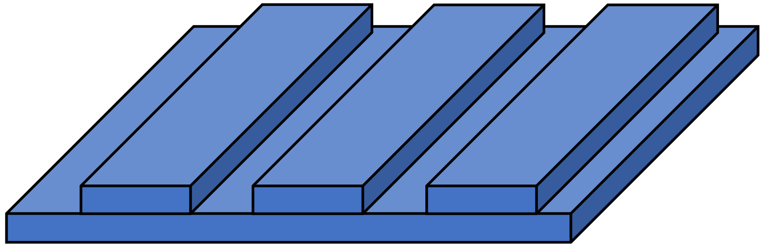
TE and TM modes of planar waveguide
circles: Re{E(k)}
bars: +/- Im{E(k)}
$\varepsilon = 1$
$\varepsilon = 2.5^2$
$\varepsilon = 1.4^2$
200nm
$\varepsilon = 1$
$\varepsilon = 1.4^2$
$\varepsilon = 2.5^2$
Energy, eV
$k_{||}$, 1/μm
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40

Quasi-guided modes in *modulated* waveguide

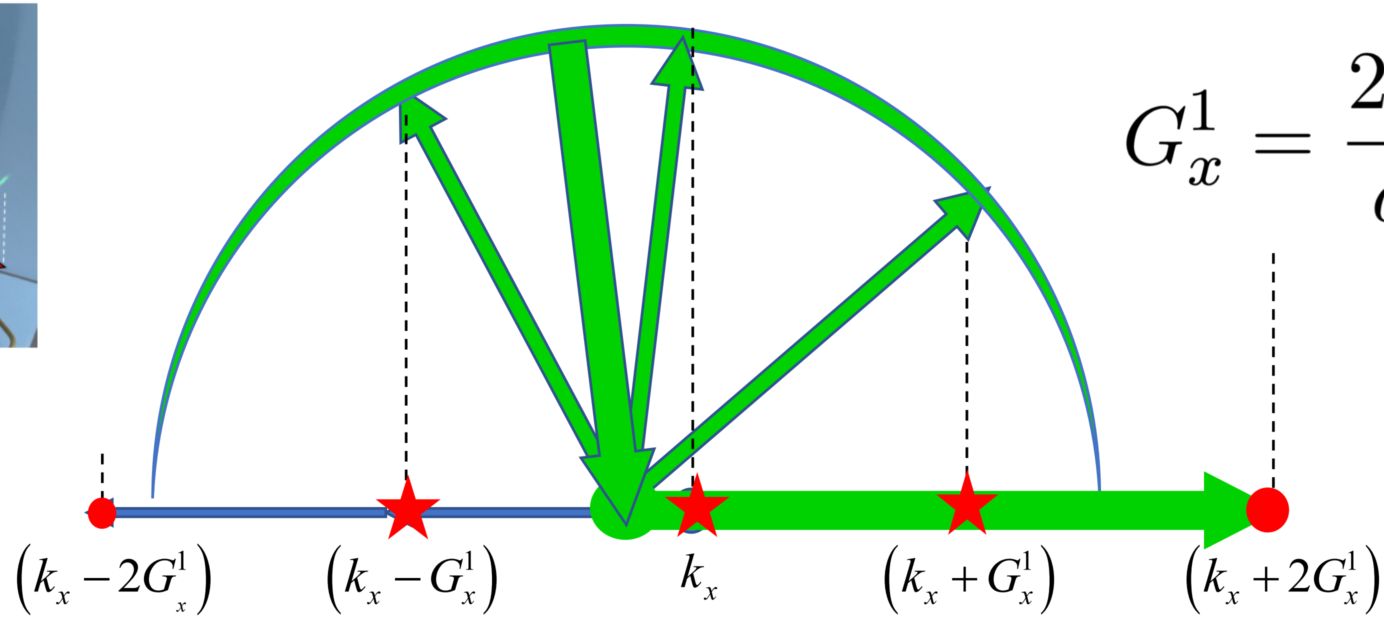
$$k_z\left(G_x^n\right) = \sqrt{\frac{\varepsilon_i}{c^2}\omega^2 - \left(k_x + G_x^n\right)^2}$$

$$E = \hbar\omega$$

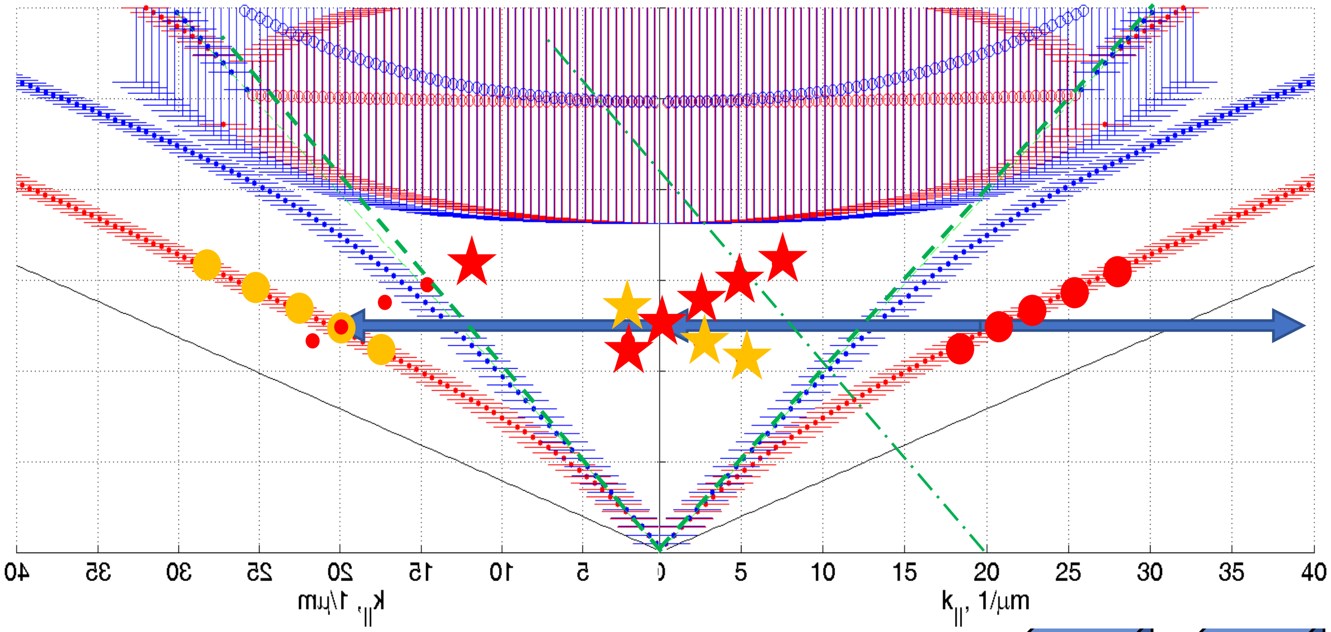




$$G_x^1 = \frac{2\pi}{d}$$

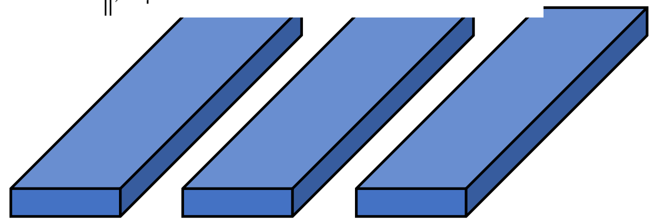


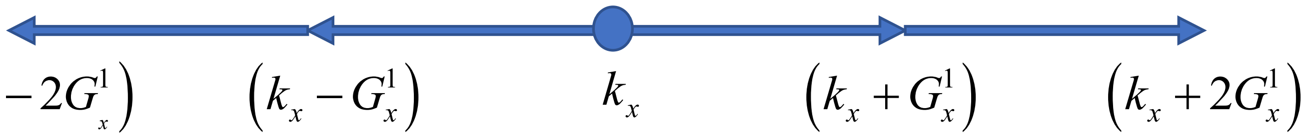
Quasi-guided modes in *modulated* waveguide



$$G_x^1 = \frac{2\pi}{d}$$

$$k_z\left(G_x^n\right) = \sqrt{\frac{\varepsilon_i}{c^2}\omega^2 - \left(k_x + G_x^n\right)^2}$$

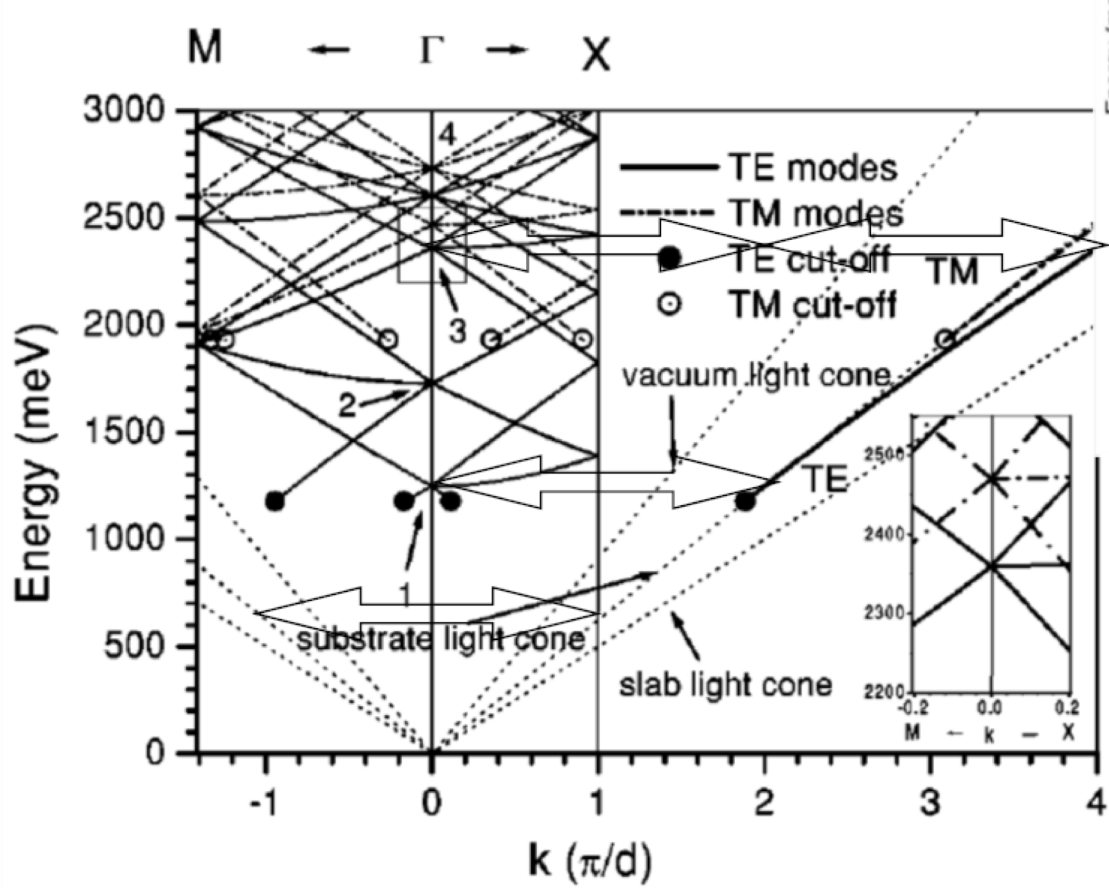


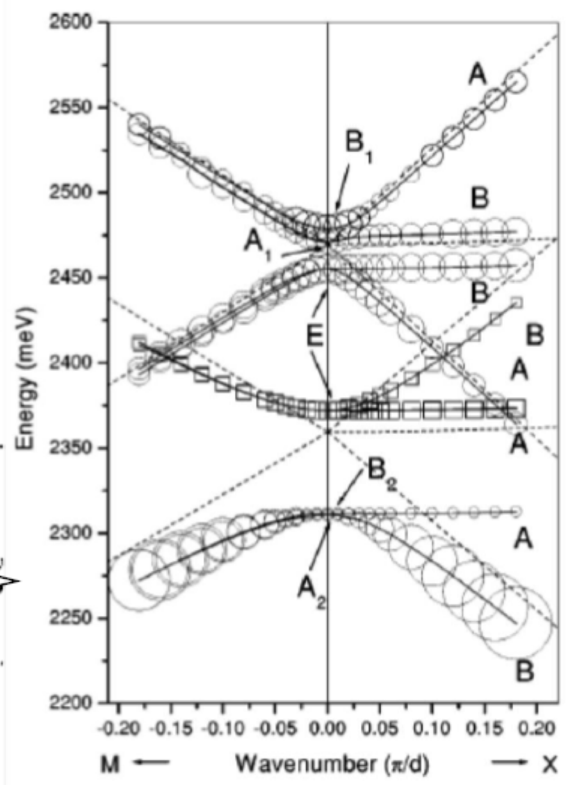


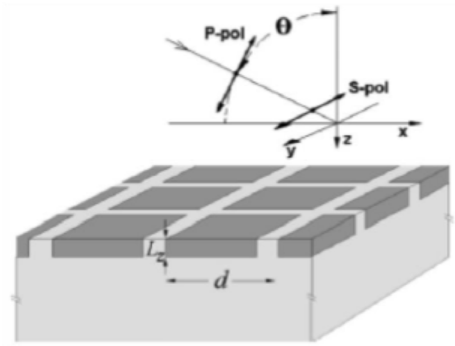
PHYSICAL REVIEW B **66**, 045102 (2002)

Quasiguided modes and optical properties of photonic crystal slabs

S. G. Tikhodeev,[1] A. L. Yablonskii,[1] E. A. Muljarov,[1,2] N. A. Gippius,[1,2] and Teruya Ishihara[2]
[1]*General Physics Institute RAS, Vavilova 38, Moscow 119991, Russia*
[2]*Institute of Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
(Received 12 February 2002; published 8 July 2002)







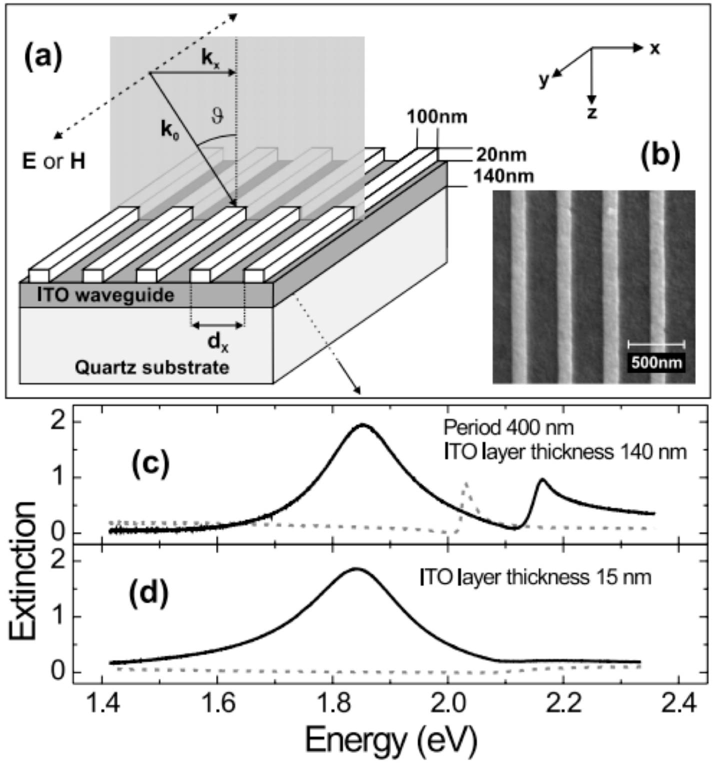
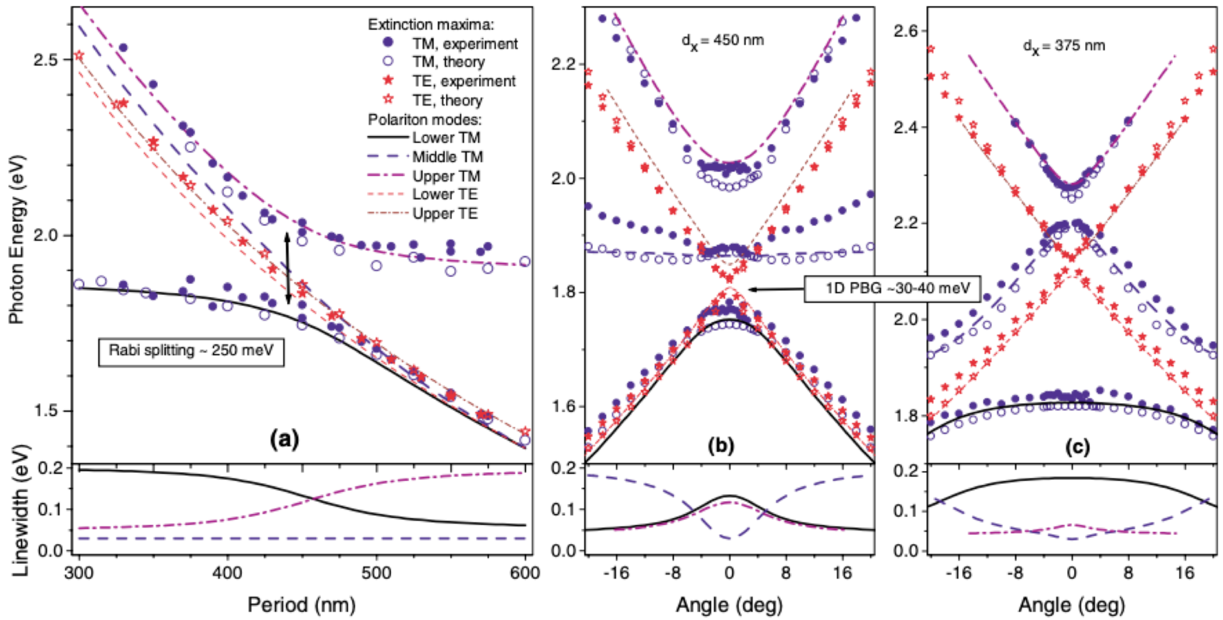


FIG. 1. Schematic view (a), electron micrograph (b), and measured extinction [$-\ln(T)$, T: transmission] spectra (c) of the gold wire array on top of a 140-nm-thick ITO waveguide; (d) same as (c) with a 15-nm-thick ITO layer. The dashed arrows in (a) show the electric (magnetic) field direction for TE (TM) polarization. $\mathbf{k}_0$ is the incident light wave vector. The extinction spectra are represented by solid lines and dashed lines for TM and TE polarization, respectively.

VOLUME 91, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 2003

Waveguide-Plasmon Polaritons: Strong Coupling of Photonic and Electronic Resonances in a Metallic Photonic Crystal Slab

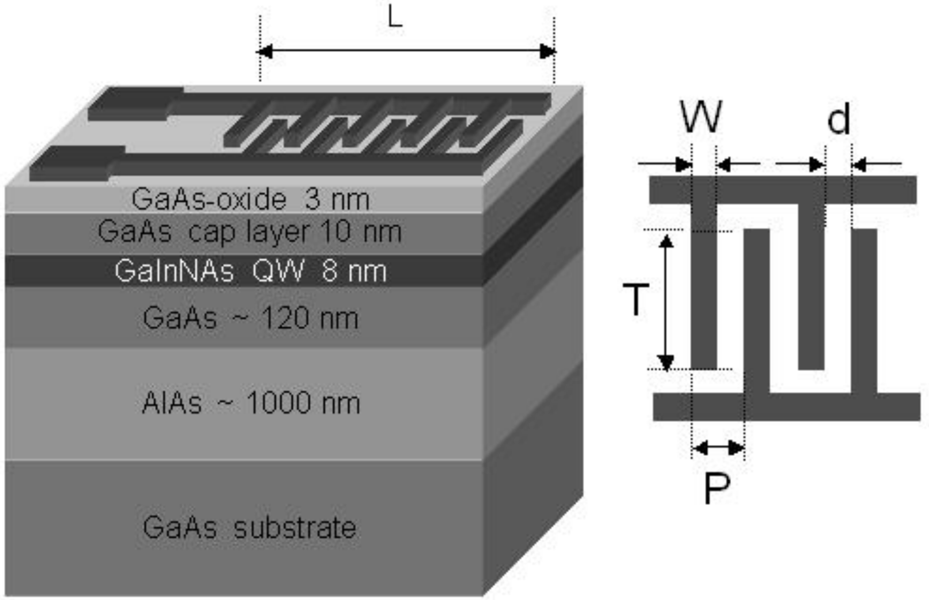
A. Christ,[1] S. G. Tikhodeev,[2,1] N. A. Gippius,[2,3] J. Kuhl,[1] and H. Giessen[4]
[1]*Max-Planck-Institut für Festkörperforschung, 70569 Stuttgart, Germany*
[2]*General Physics Institute RAS, Vavilova 38, Moscow 119991, Russia*
[3]*Institute of Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
[4]*Institute of Applied Physics, University of Bonn, 53115 Bonn, Germany*
(Received 20 December 2002; published 28 October 2003)

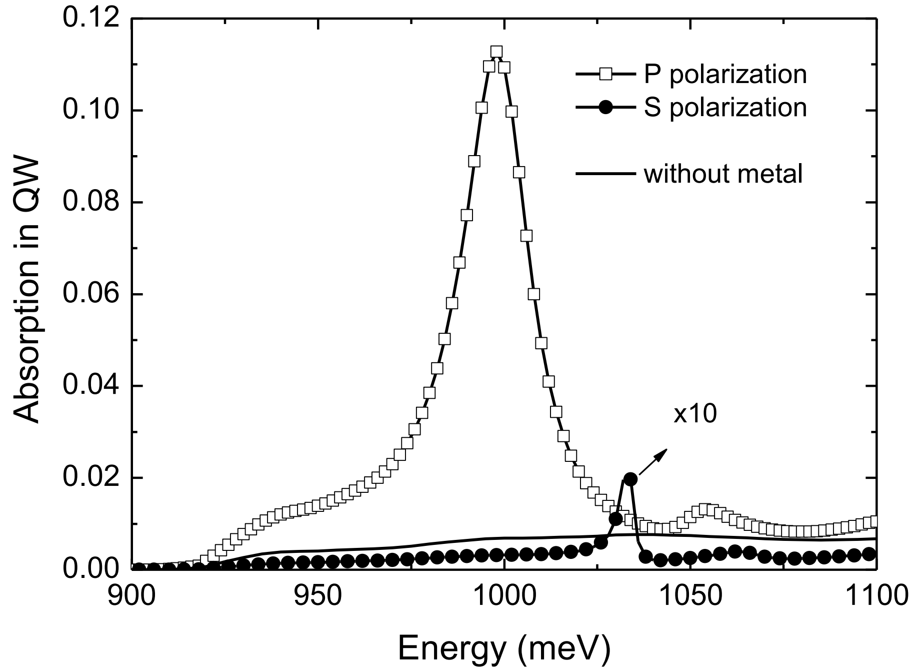


IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 43, NO. 10, OCTOBER 2007

Optimized Design of Plasmonic MSM Photodetector

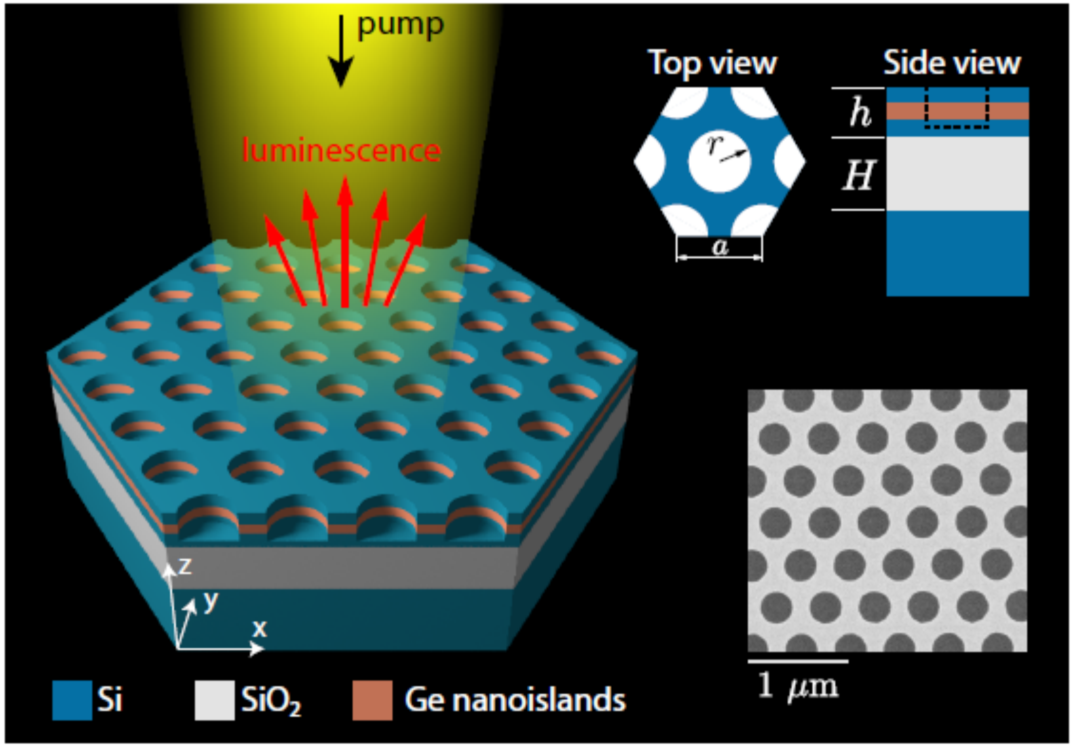
J. Hetterich, G. Bastian, N. A. Gippius, S. G. Tikhodeev,
G. von Plessen, U. Lemmer

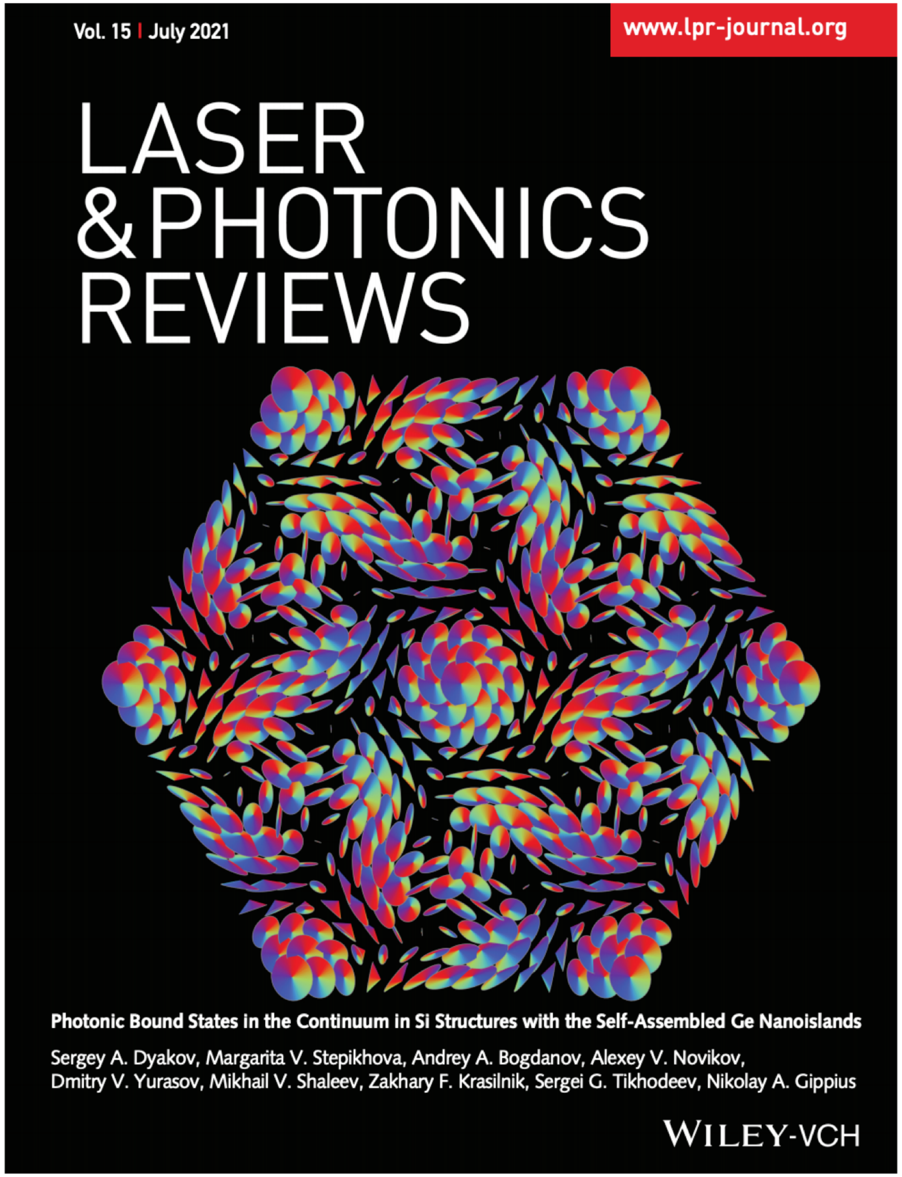




Optical resonances in photonic crystal slabs with hexagonal lattice of air holes

Photoluminescence enhancement of Ge nano-islands located in the photonic crystal slab



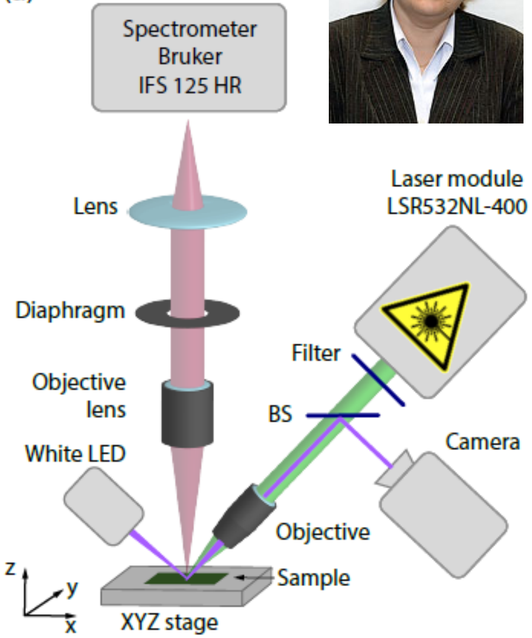


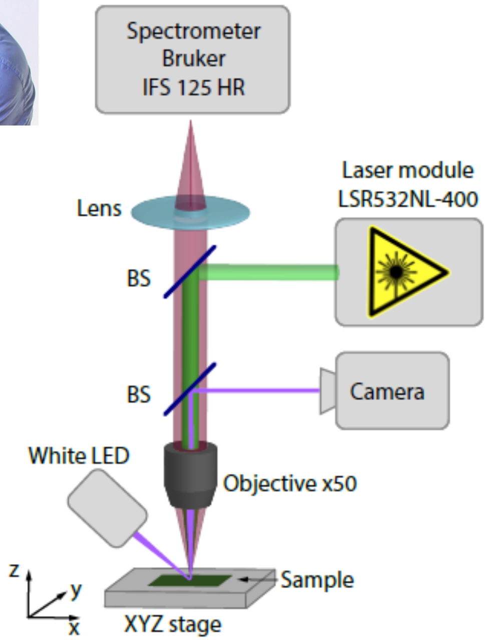
Photoluminescence setups

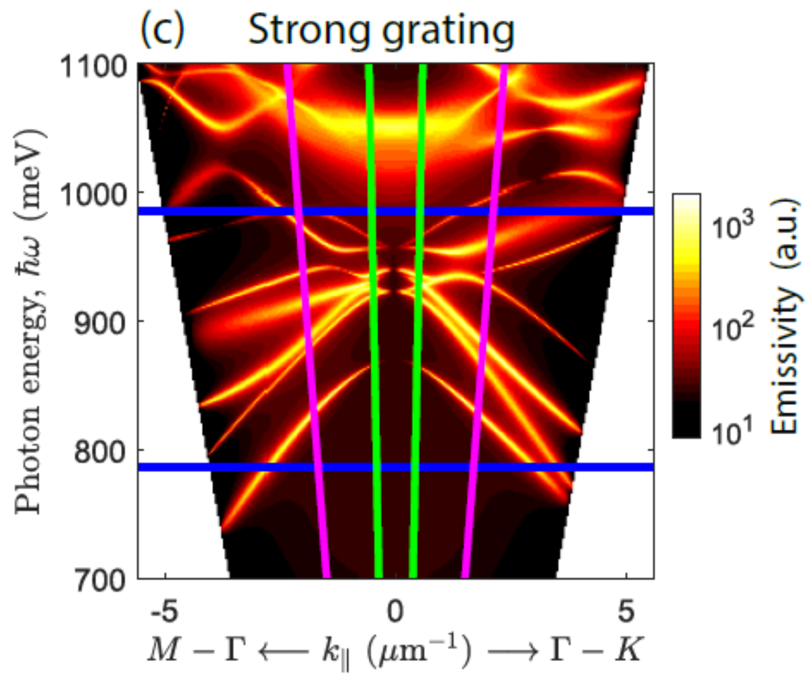
Institute for Physics of Microstructures RAS

M. Stepikhova
IPM RAS

A. Novikov
IPM RAS







Microphotoliminescence setup (μPL)

Directional photoluminescence setup (DPL)

Ge nanoislands emission line

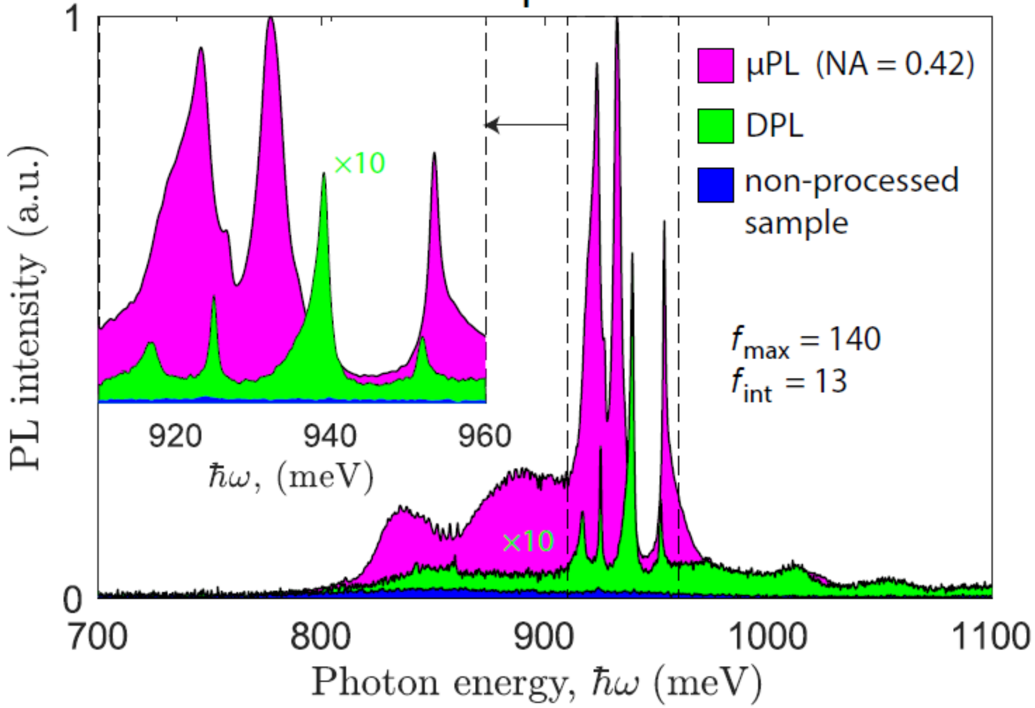
Photoluminescence setups

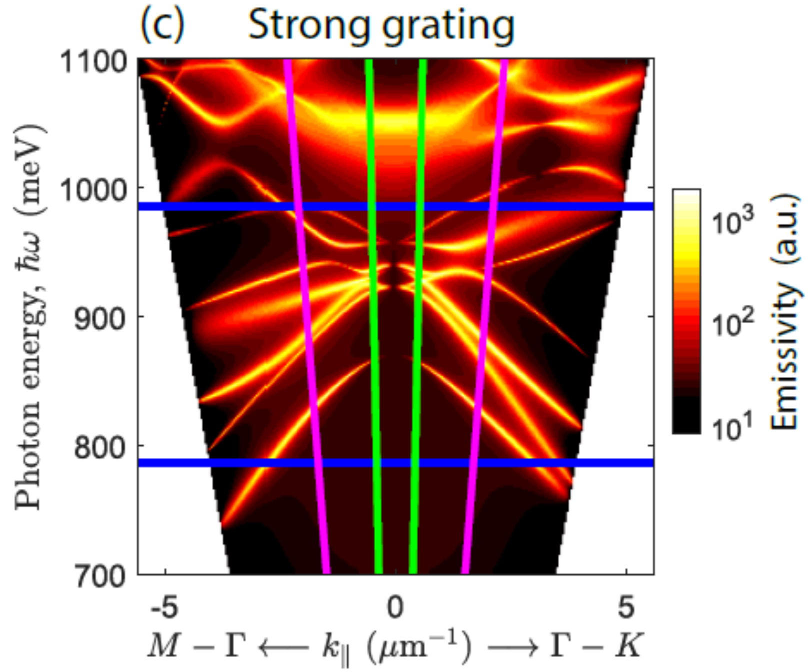
Institute for Physics of Microstructures RAS

M. Stepikhova
IPM RAS

A. Novikov
IPM RAS

PL spectra





Ge nanoislands emission line

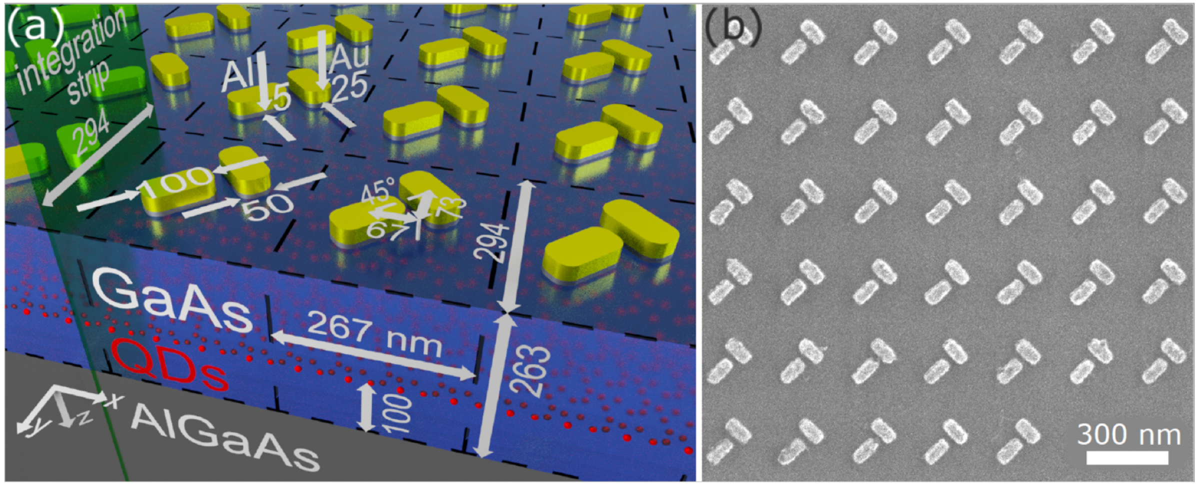
Вывод циркулярно-поляризованного света из волновода с использованием плазмонной решетки

Skoltech
Skolkovo Institute of Science and Technology
Center for Engineering Physics

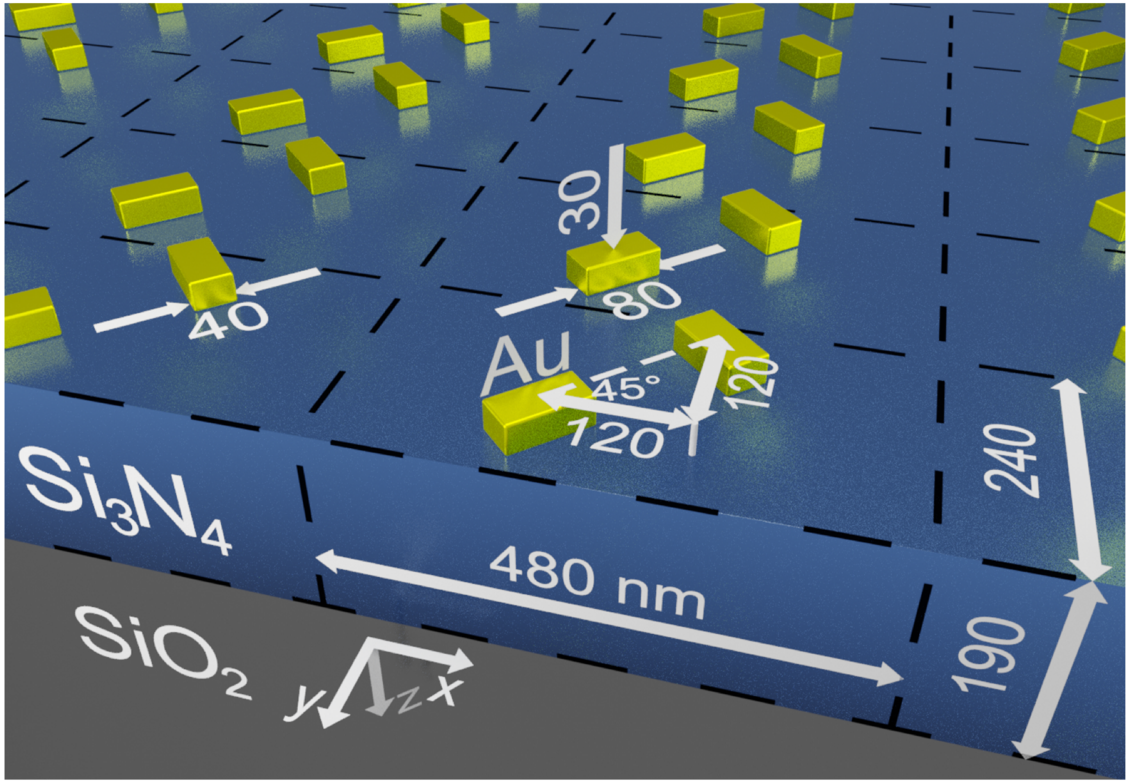
ИФТТ РАН
ISSP RAS

Ilia Fradkin | Vladimir Kulakovskiy | Andrey Demenev | Vladimir Antonov | Nikolay Gippius

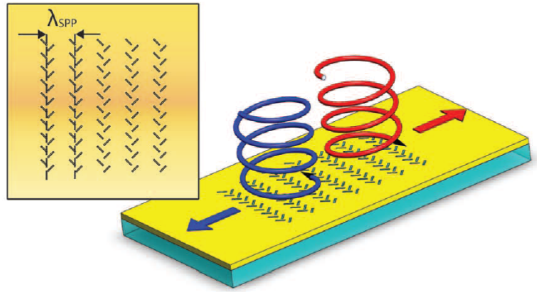
Fradkin, I. M., Demenev, A. A., Kulakovskii, V. D., Antonov, V. N., & Gippius, N. A. *Appl. Phys. Lett.*, 2022, *120*, 17, 171702.

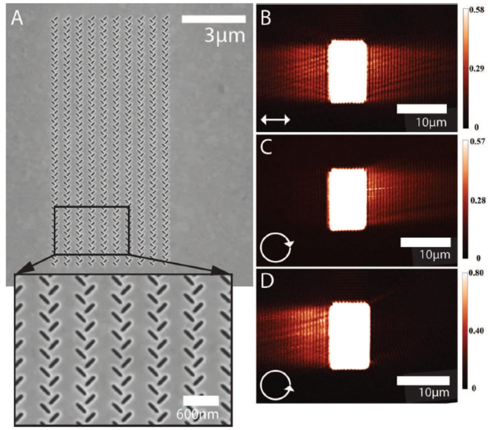


Lattice with basis



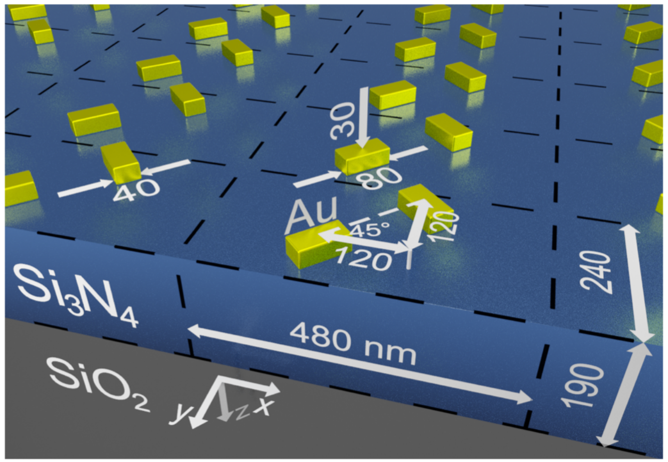
[I.M. Fradkin, S.A. Dyakov, and N.A. Gippius, Phys. Rev. B 102, 045432]

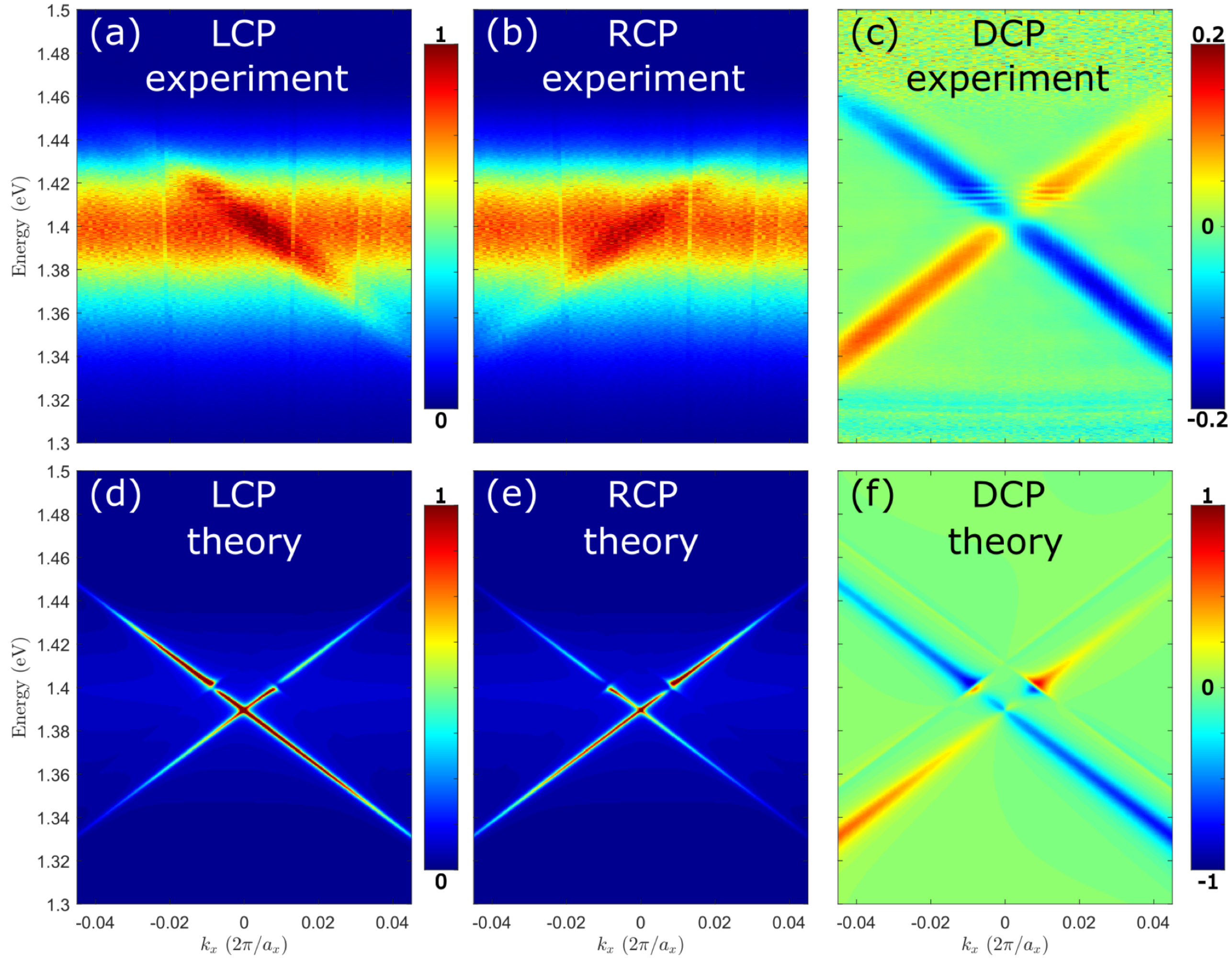




Lin, J., Mueller, J. B., Wang, Q., Yuan, G., Antoniou, N., Yuan, X. C., & Capasso, F. (2013). Polarization-controlled tunable directional coupling of surface plasmon polaritons. *Science*, *340*(6130), 331-334.

Spectra of lattice with basis





Plan

1. Introduction.
2. Resonances in photonic crystal slabs
3. How can we calculate the S-marix in these systems?
   - regular approach
   - effective dipole approximation
4. How can we calculate resonances in photonic crystal slabs?

Theoretical consideration

Universal methods

FDTD

exact solution

too computationally expensive

FEM

Fourier modal method
(Rigorous coupled-wave analysis)

specialized for periodic structures

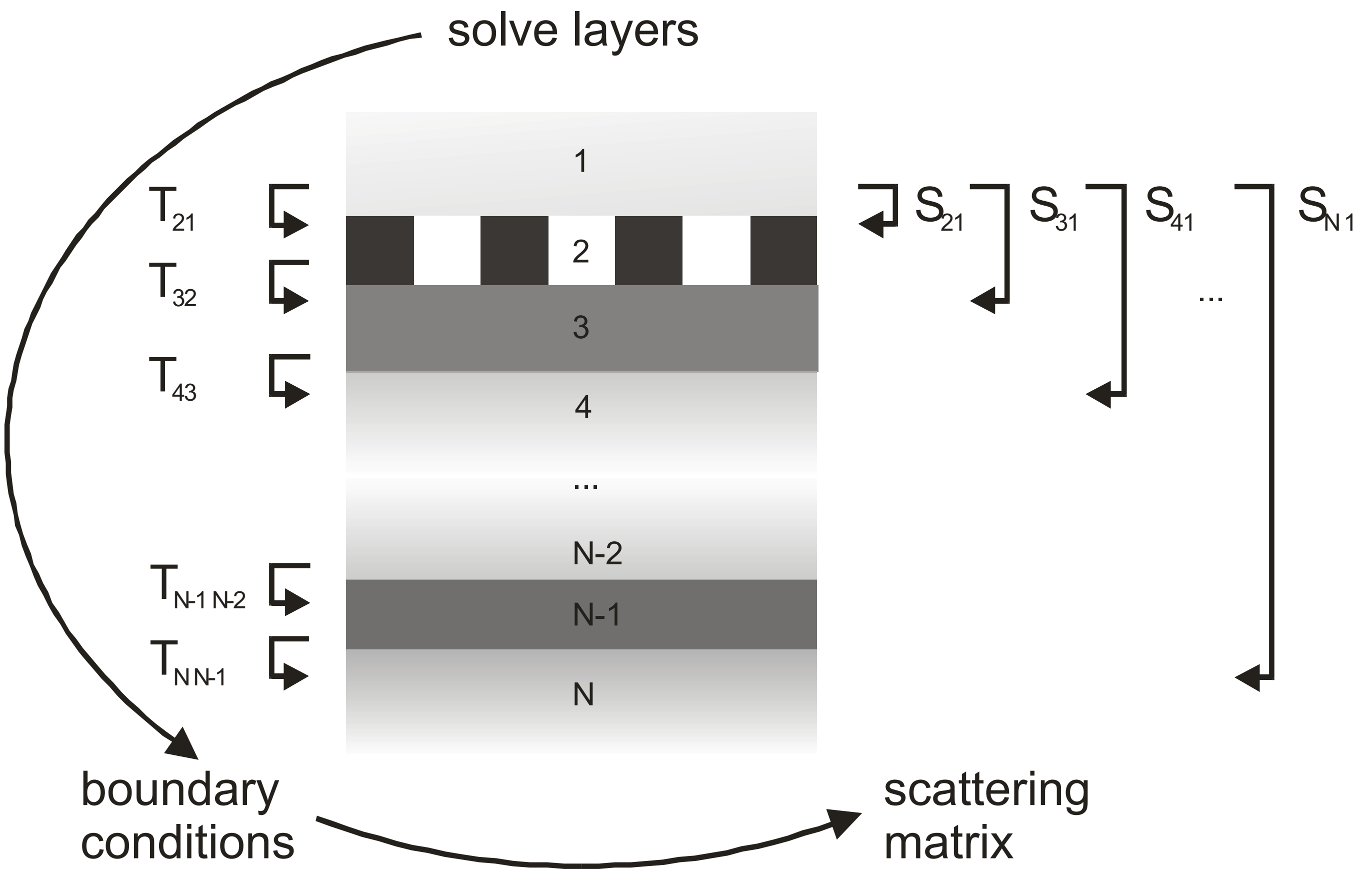
too many diffraction orders should be taken into account

Discrete dipole approximation

fast and efficient

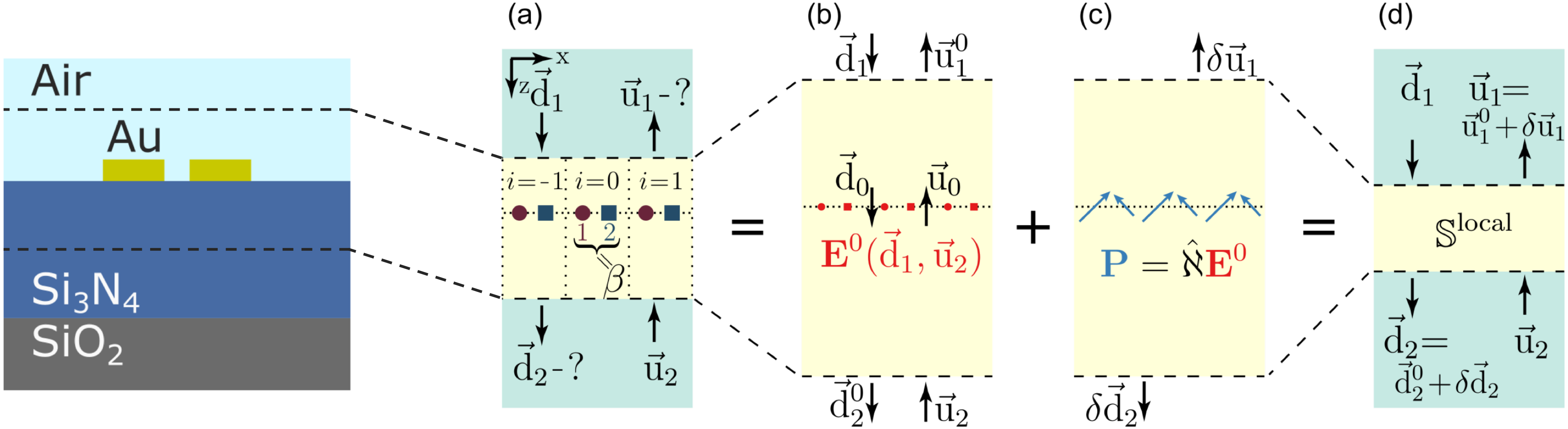
Our aim is to **combine** two methods for a consideration of **layered structures** with inclusions of **plasmonic lattices**

Метод матрицы рассеяния



D. M. Whittaker, I. S. Culshaw, Phys. Rev. B **60**, 2610 (1999)   S. G. Tikhodeev et al. , Phys. Rev. B **66**, 45102 (2002)

Scattering matrix calculation



$$\begin{pmatrix} \mathbf{E}^{\text{bg}}_{\beta=1} \\ \mathbf{E}^{\text{bg}}_{\beta=2} \\ \vdots \end{pmatrix} = \begin{pmatrix} \mathbf{E}^{0}_{\beta=1} \\ \mathbf{E}^{0}_{\beta=2} \\ \vdots \end{pmatrix} + \begin{pmatrix} \hat{C}_{11} & \hat{C}_{12} & \vdots \\ \hat{C}_{21} & \hat{C}_{22} & \vdots \\ \dots & \dots & \ddots \end{pmatrix} \begin{pmatrix} \hat{\alpha}_1 & 0 & 0 \\ 0 & \hat{\alpha}_2 & 0 \\ 0 & 0 & \ddots \end{pmatrix} \begin{pmatrix} \mathbf{E}^{\text{bg}}_{\beta=1} \\ \mathbf{E}^{\text{bg}}_{\beta=2} \\ \vdots \end{pmatrix}$$

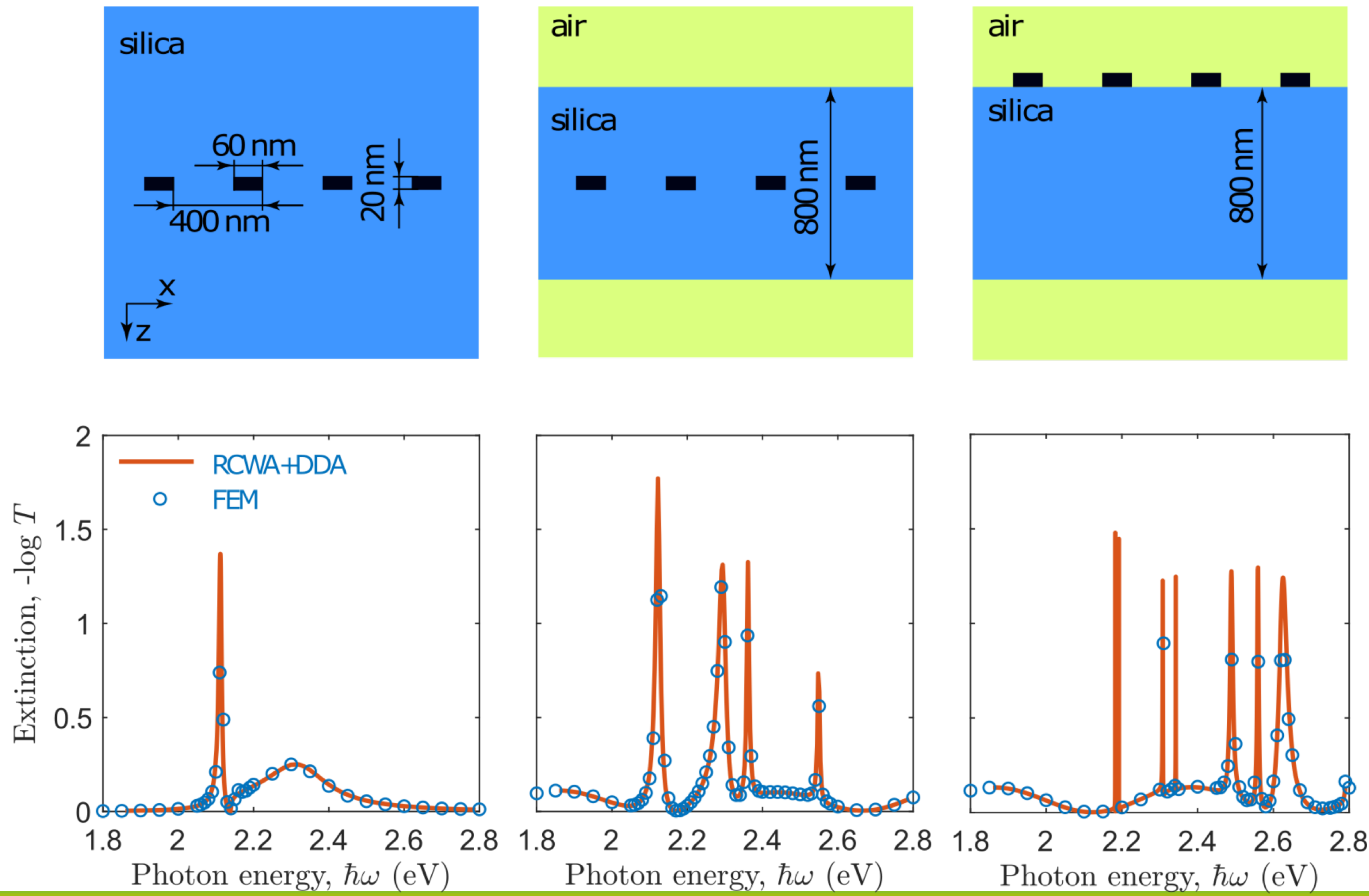
$$\hat{C}_{\beta\gamma}(\mathbf{k}_\parallel) = \begin{cases} \sum_{j\neq i} \hat{G}(\mathbf{r}_{\beta,i}, \mathbf{r}_{\beta,j}) e^{i\mathbf{k}_\parallel (\mathbf{r}_{\beta,j} - \mathbf{r}_{\beta,i})} & \text{for } \beta = \gamma \\ \sum_{j} \hat{G}(\mathbf{r}_{\beta,i}, \mathbf{r}_{\gamma,j}) e^{i\mathbf{k}_\parallel (\mathbf{r}_{\gamma,j} - \mathbf{r}_{\gamma,i})} & \text{for } \beta \neq \gamma \end{cases}$$

We solve the equations for several particles in unit cell.

$$\hat{\aleph} = \begin{pmatrix} \hat{\alpha}_1 & 0 & 0 \\ 0 & \hat{\alpha}_2 & 0 \\ 0 & 0 & \ddots \end{pmatrix} \times \left[\hat{I} - \begin{pmatrix} \hat{C}_{11} & \hat{C}_{12} & \vdots \\ \hat{C}_{21} & \hat{C}_{22} & \vdots \\ \dots & \dots & \ddots \end{pmatrix} \begin{pmatrix} \hat{\alpha}_1 & 0 & 0 \\ 0 & \hat{\alpha}_2 & 0 \\ 0 & 0 & \ddots \end{pmatrix} \right]^{-1}$$

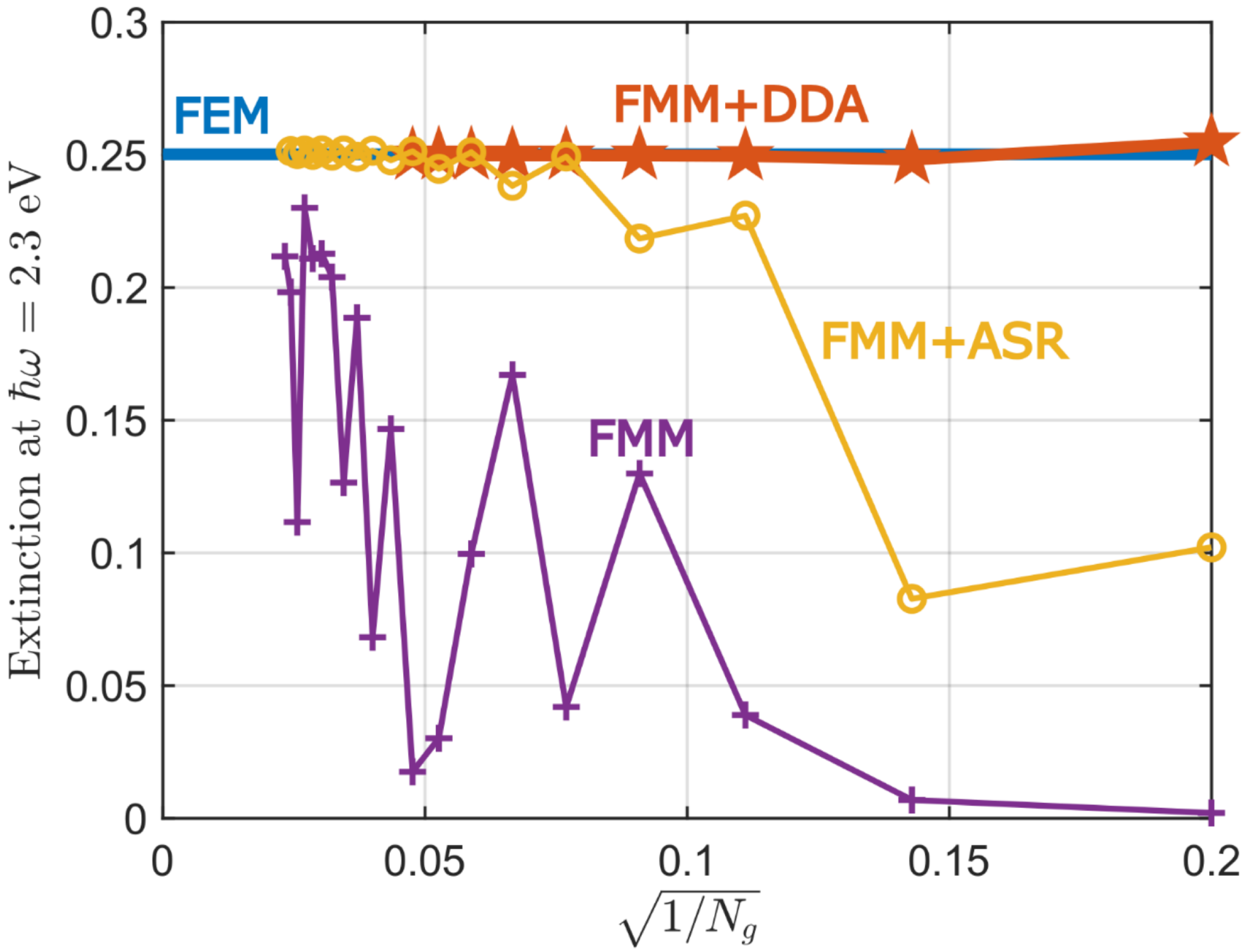
And obtain generalized effective polarizability tensor

Spectra of plasmonic lattices



[I.M. Fradkin, S.A. Dyakov, and N.A. Gippius, Phys. Rev. B 99, 075310]

Convergence



DDA enhanced FMM converges much faster than FMM with adaptive spatial resolution* and conventional FMM and provides very precise results

*FMM+ASR calculations are provided by prof. Thomas Weiss

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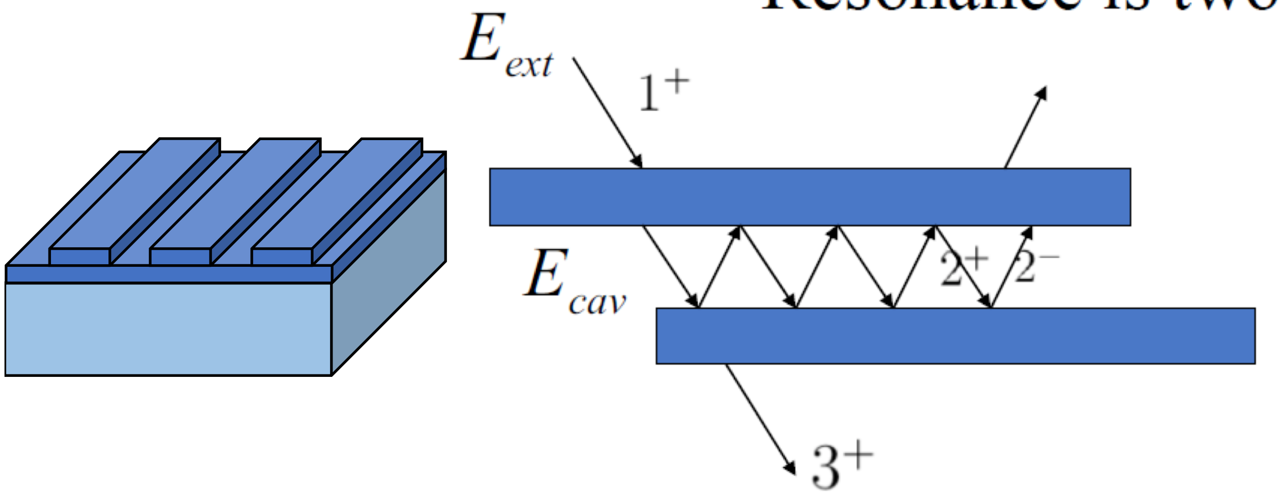
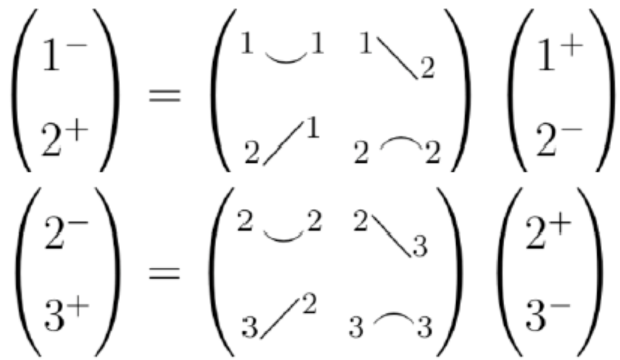
4. How can we calculate resonances in photonic crystal slabs?

Resonance is two S-matrix problem

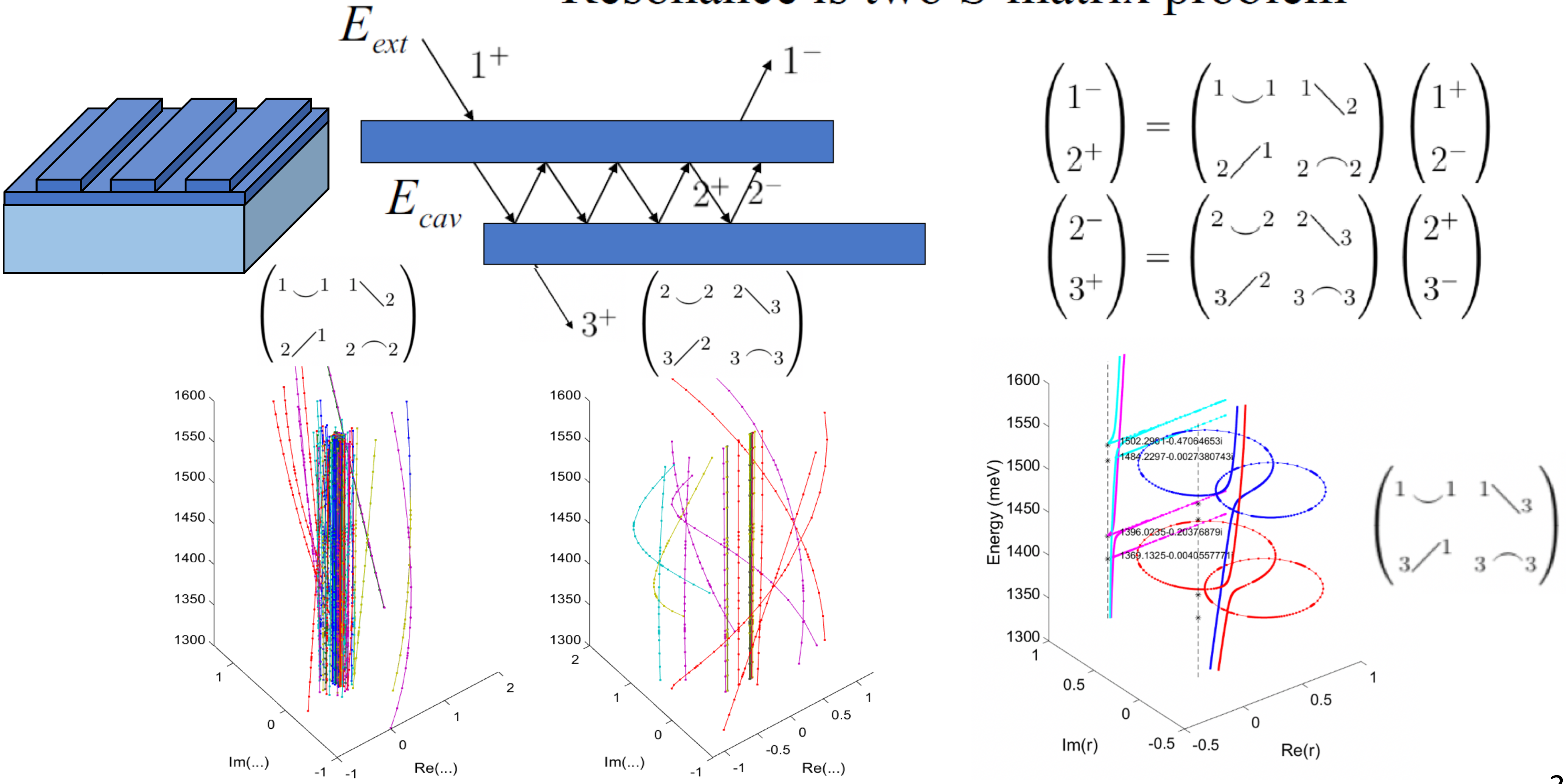




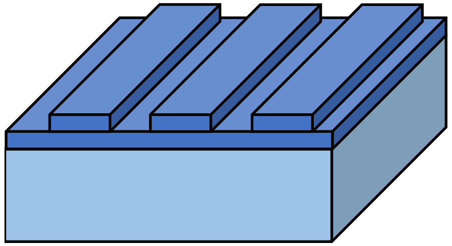
$$E_{cav} = \frac{1}{\omega - \omega_{cav}} \alpha E_{ext}$$

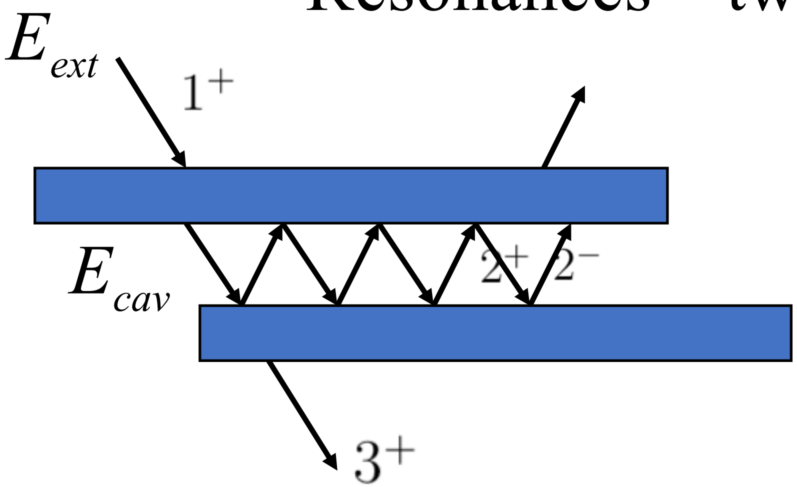
$$\omega_{cav} = \Omega_0 - i\gamma_0$$

Resonance is two S-matrix problem



Resonances – two S-marix problem





$$\begin{pmatrix} 1^- \\ 2^+ \end{pmatrix} = \begin{pmatrix} {}^1\smile^1 & {}^1\searrow_2 \\ {}_2\nearrow^1 & {}_2\frown_2 \end{pmatrix} \begin{pmatrix} 1^+ \\ 2^- \end{pmatrix}$$

$$\begin{pmatrix} 2^- \\ 3^+ \end{pmatrix} = \begin{pmatrix} {}^2\smile^2 & {}^2\searrow_3 \\ {}_3\nearrow^2 & {}_3\frown_3 \end{pmatrix} \begin{pmatrix} 2^+ \\ 3^- \end{pmatrix}$$

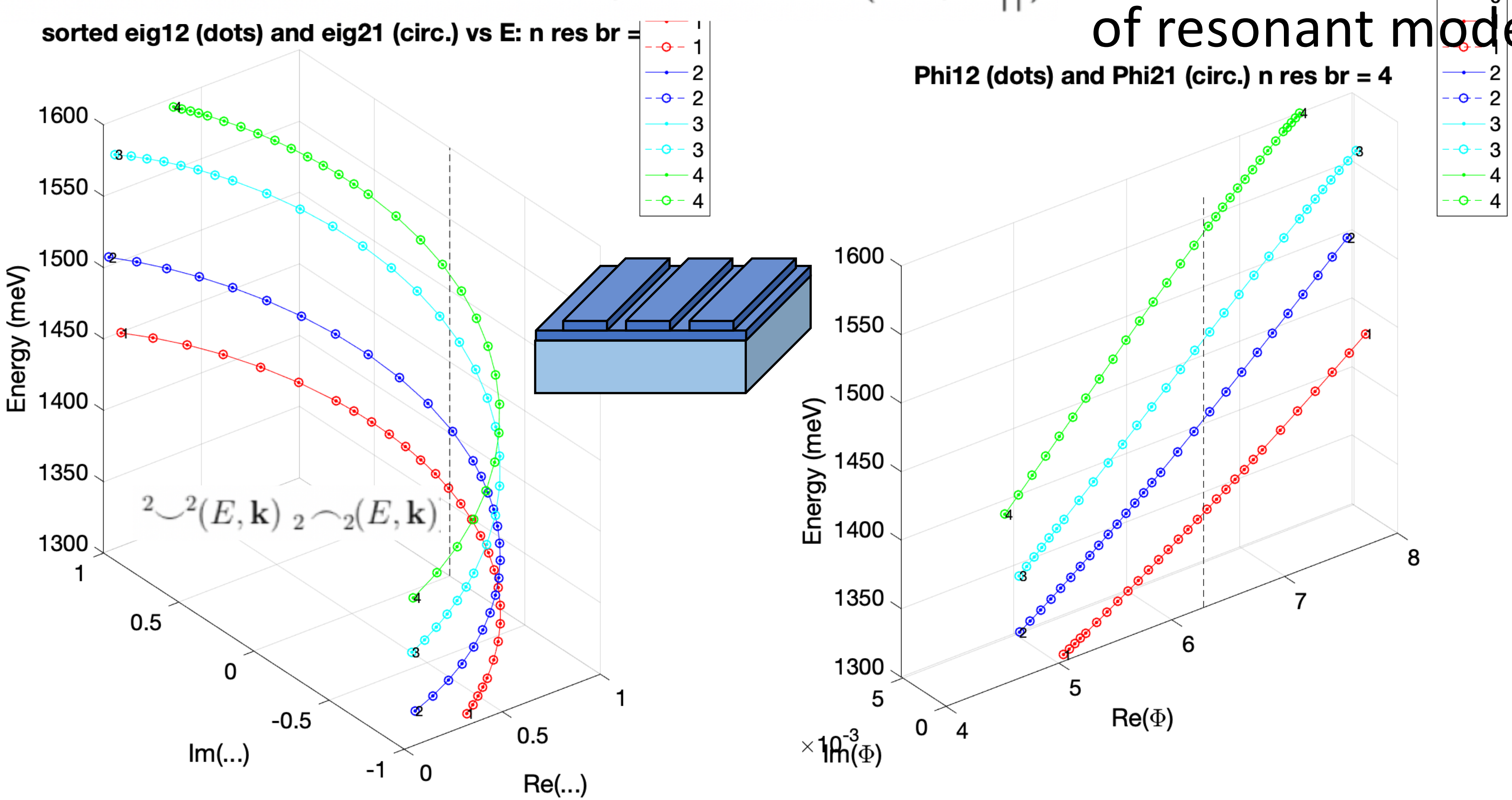
$$\begin{pmatrix} {}^1\smile^1 & {}^1\searrow_3 \\ {}_3\nearrow^1 & {}_3\frown_3 \end{pmatrix} = \begin{pmatrix} {}^1\smile^1 + {}^1\searrow^2_2\smile^2_2\nearrow^1 + \dots & {}^1\searrow^2_2\searrow_3 + {}^1\searrow^2_2\smile^2_2\frown^2_2\searrow_3 + \dots \\ {}_3\nearrow^2_2\nearrow^1 + {}_3\nearrow^2_2\frown^2_2\smile^2_2\nearrow^1 + \dots & {}_3\frown_3 + {}_3\nearrow^2_2\frown^2_2\searrow_3 + \dots \end{pmatrix}$$

$$[1 - {}^2\smile^2(E,\mathbf{k})\ {}_2\frown_2(E,\mathbf{k})]^{-1}$$

$$[1 - {}_2\frown_2(E,\mathbf{k})\,{}^2\smile^2(E,\mathbf{k})]^{-1}$$

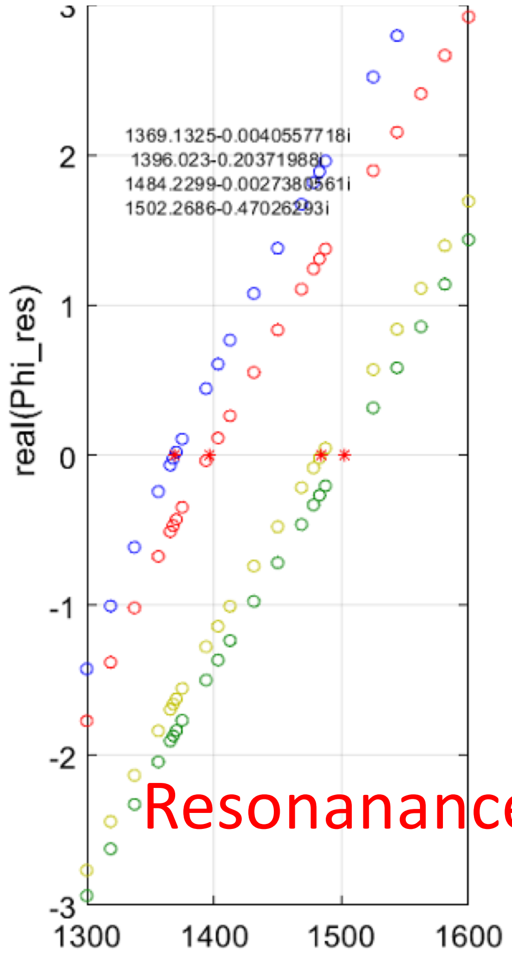
$$ {}^2\smile^2(E,\mathbf{k})\,{}_2\frown_2(E,\mathbf{k})X = Xe^{i\Phi}, \quad \Phi = \Phi(k_0, k_{||}) $$

Roundtrip phase of resonant mode

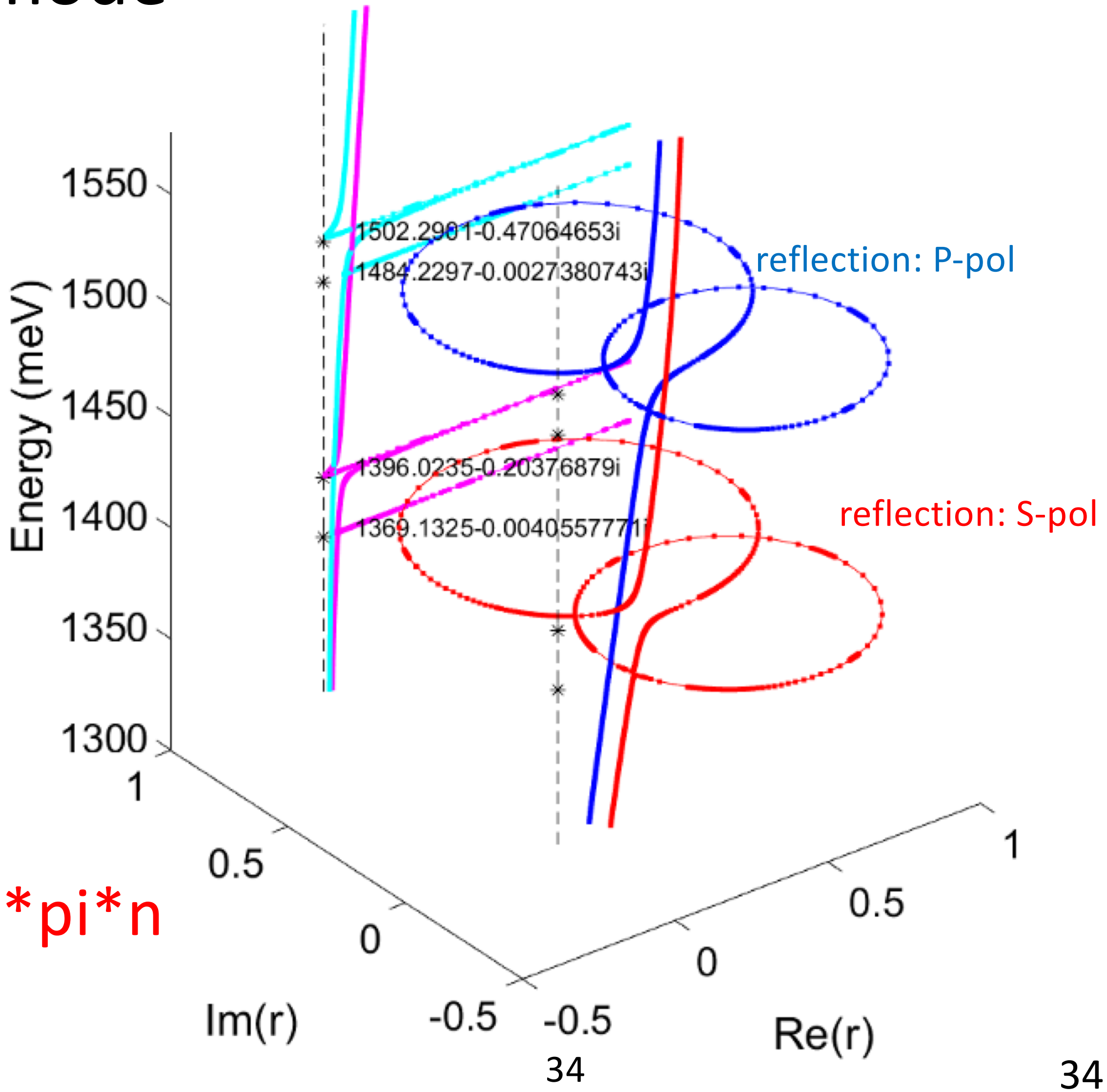


$^2\smile^2(E,\mathbf{k})\,_2\frown_2(E,\mathbf{k})$ = 1. Resonanance $\Phi(k_0, k_{||})$ = 2*pi*n

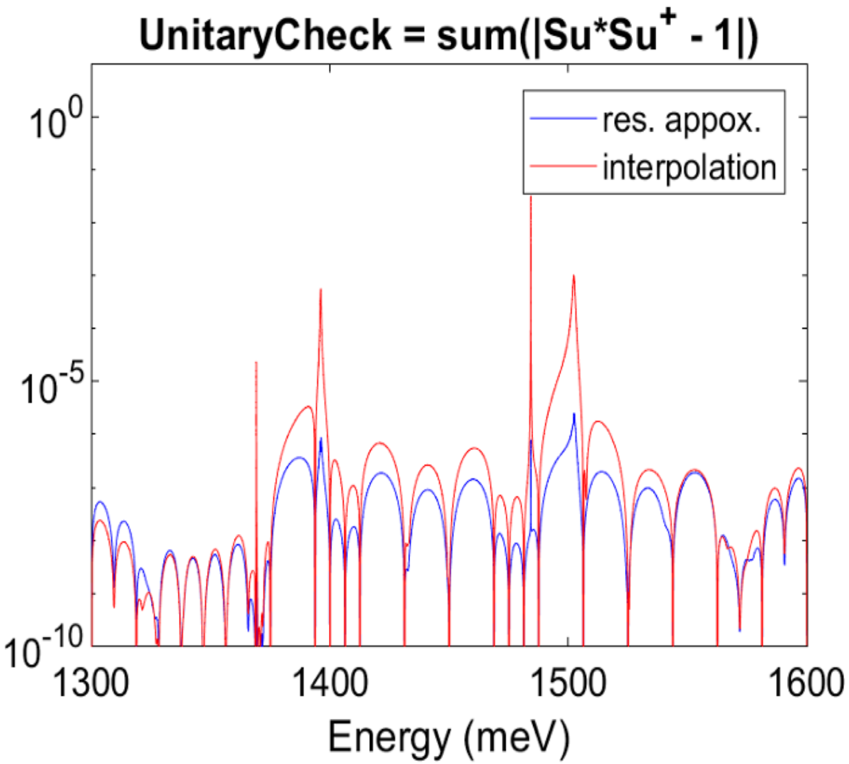
Roundtrip phase of resonant mode is smooth function of energy

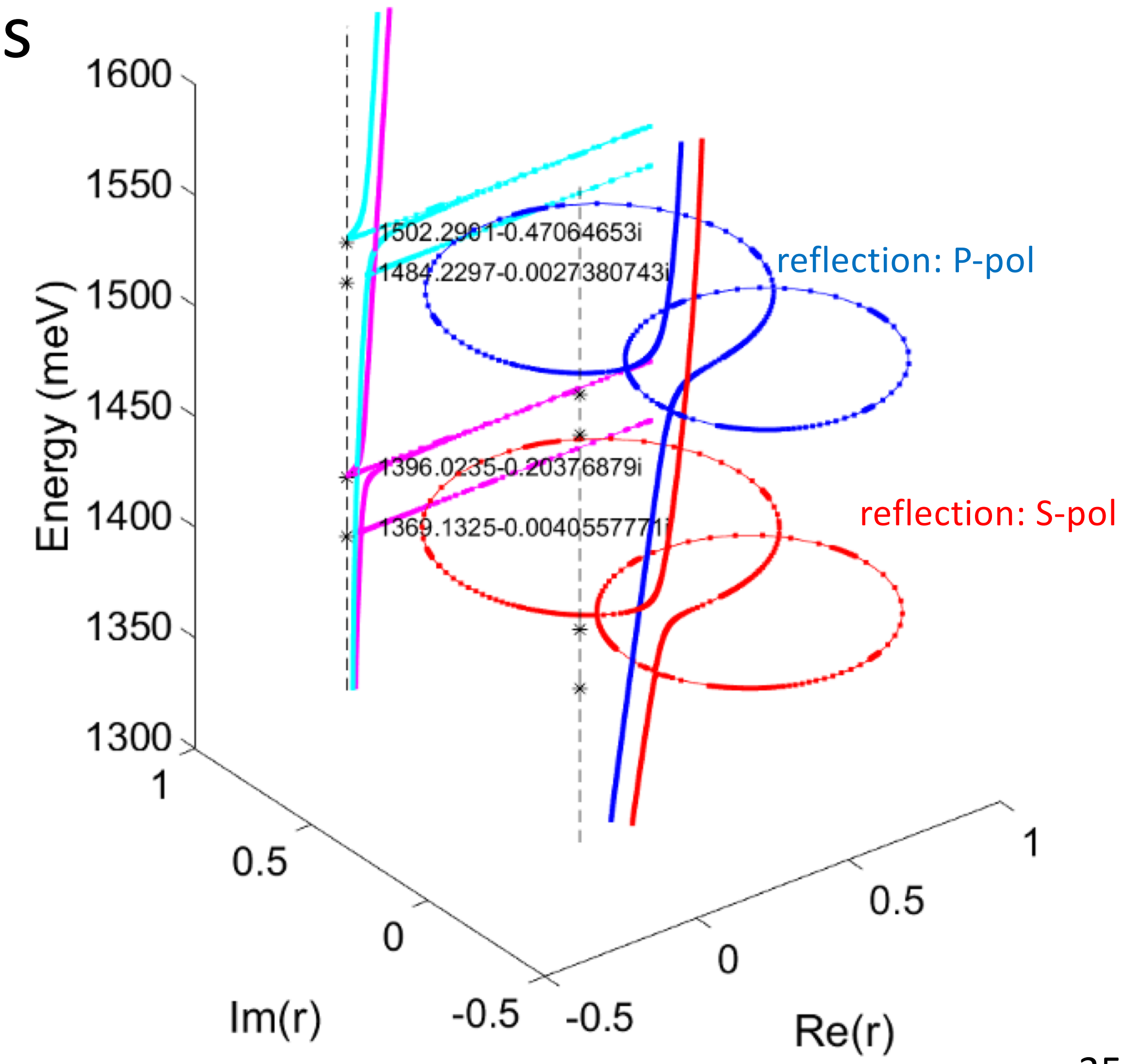


Resonanance : Phase = 2*pi*n

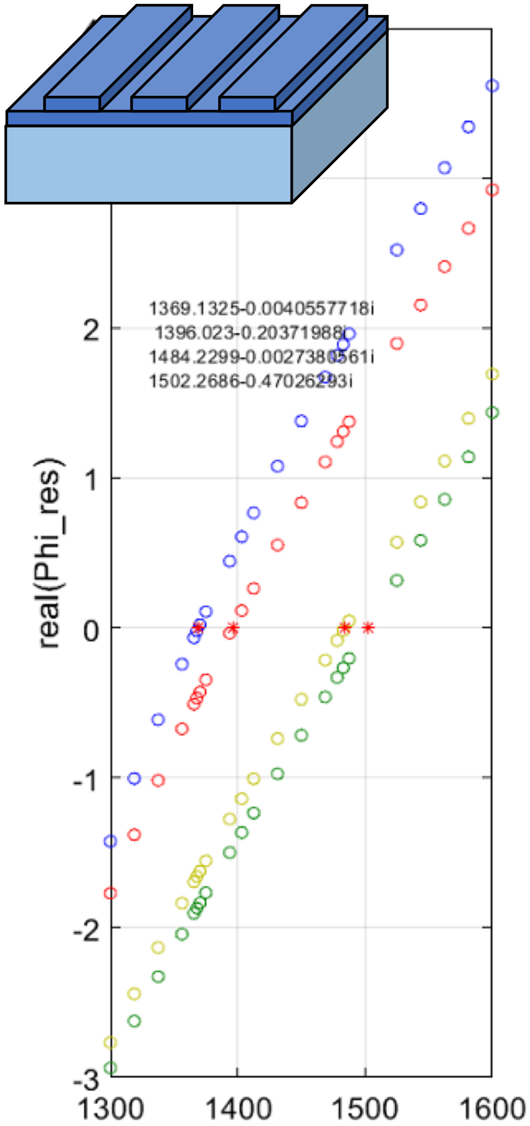


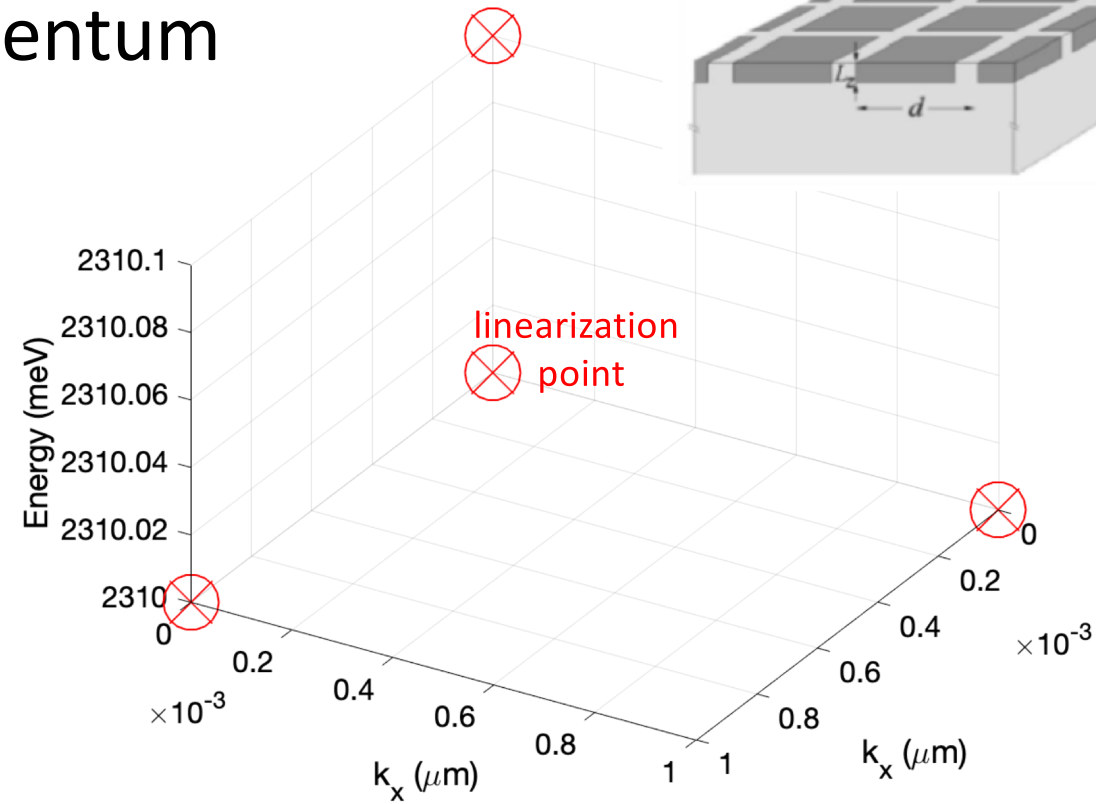
Reflection near resonances is well described

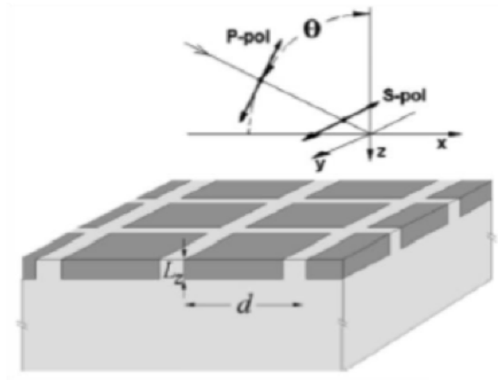


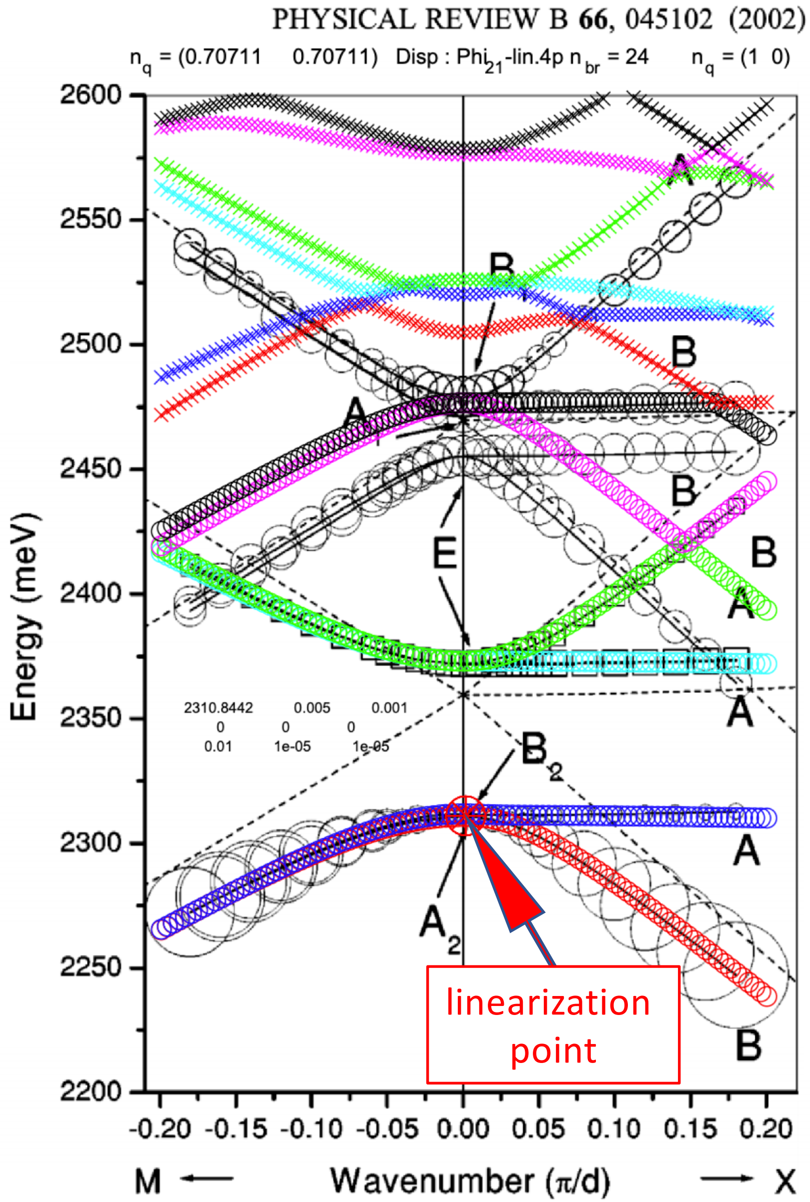


Let's try to linearize the phase in respect to energy and momentum

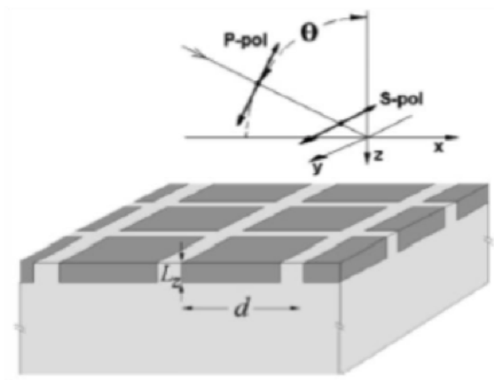


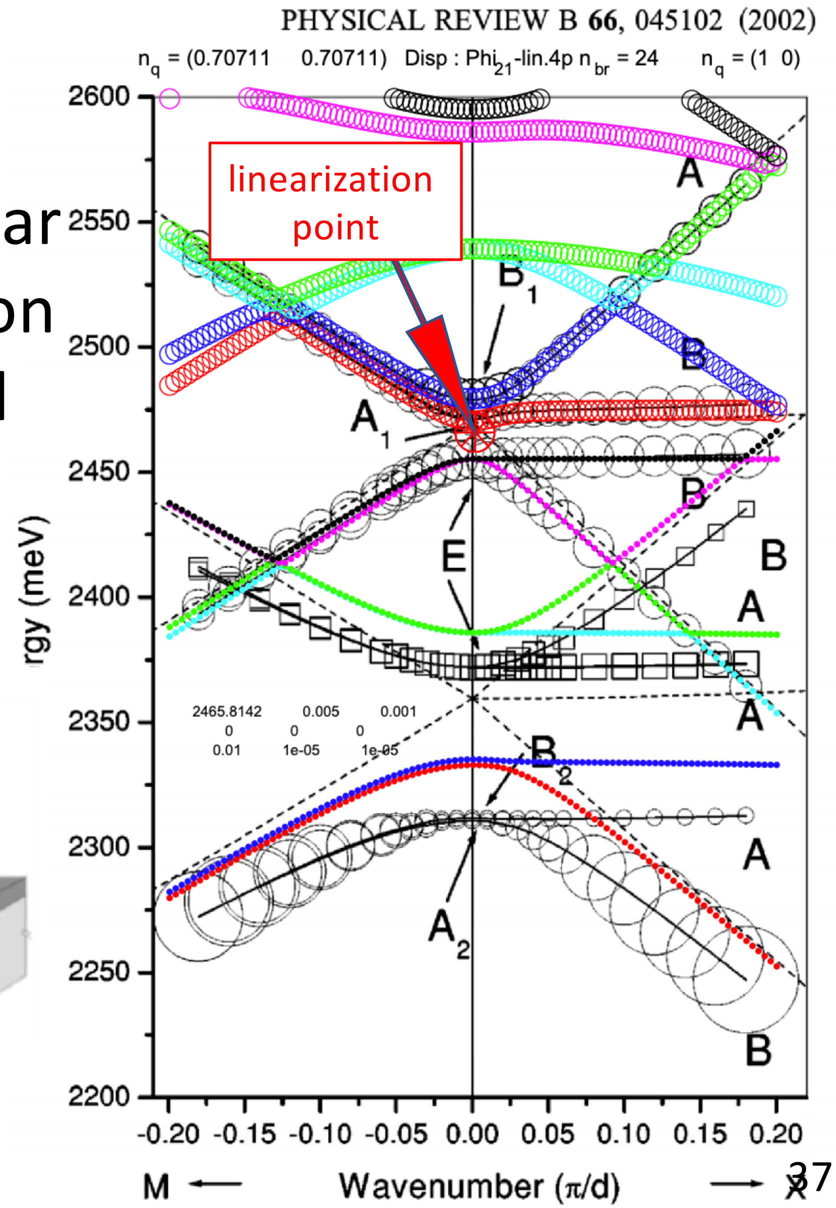






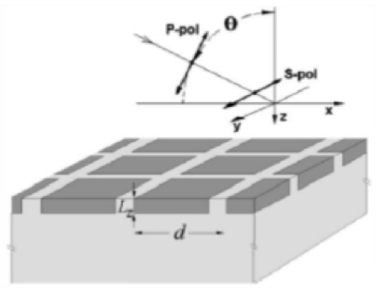
Dispersions of resonances near the linearization points are well described



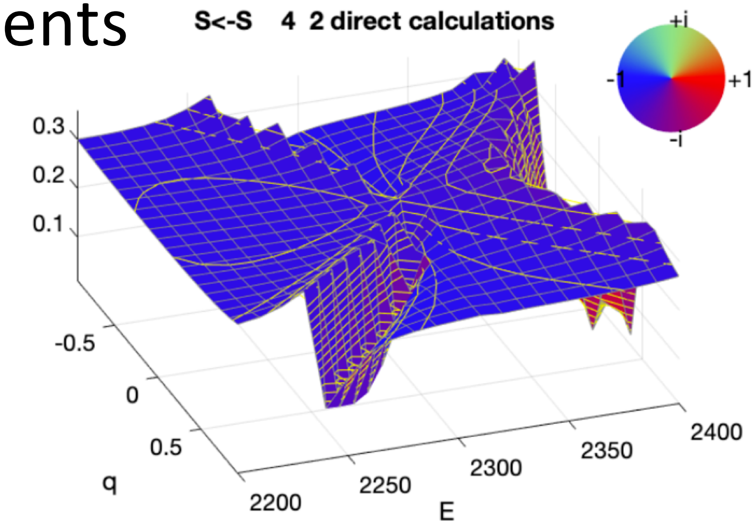


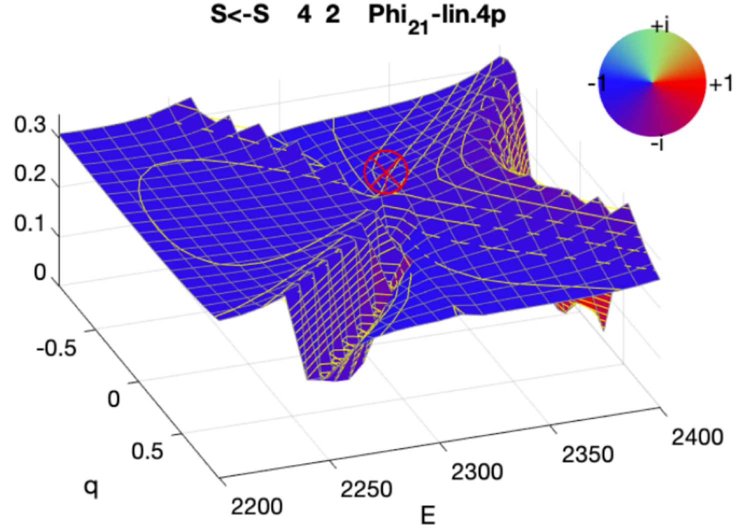
Reflection coefficients

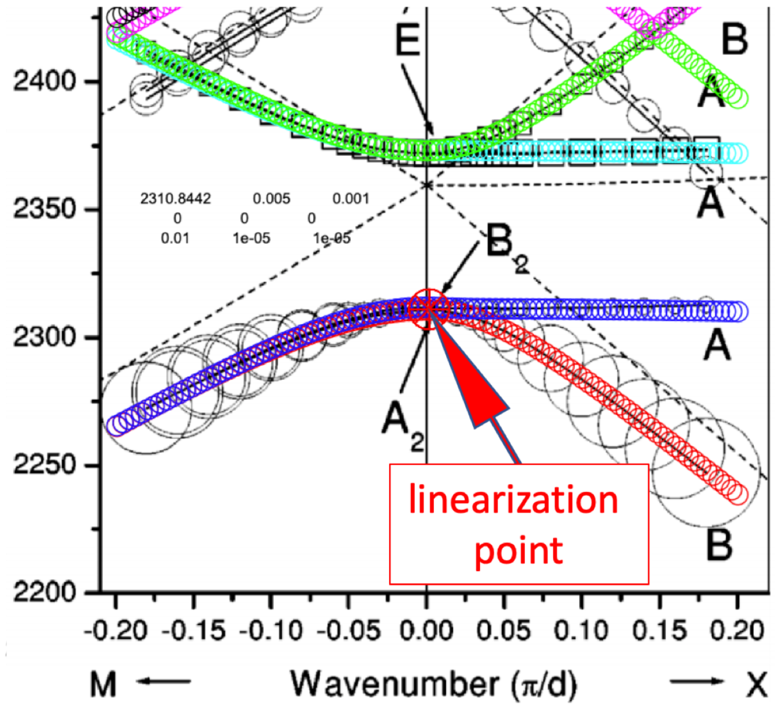
441
S-matrices

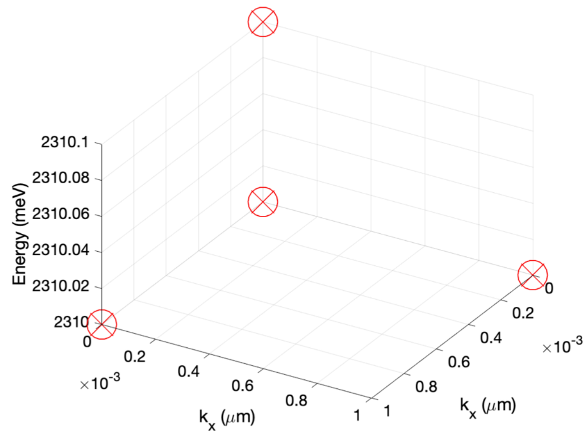


4
S-matrices









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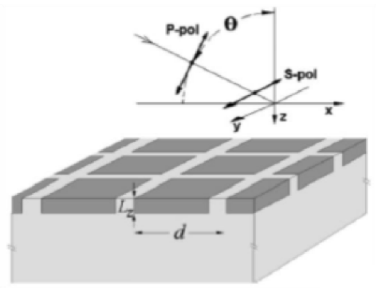
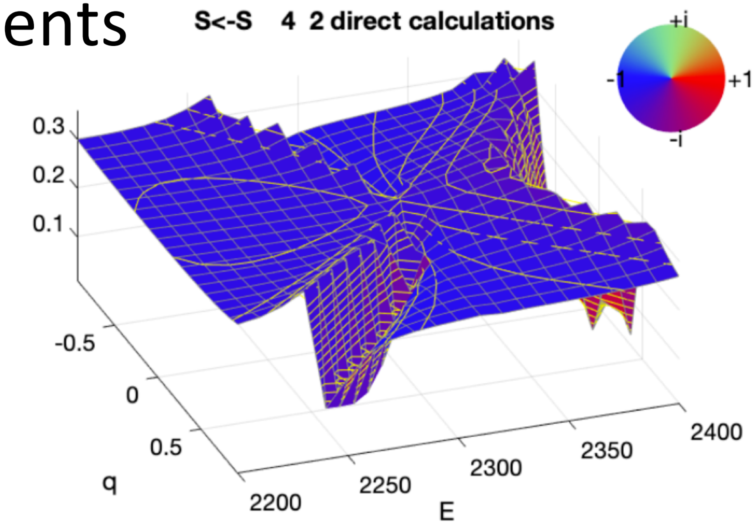
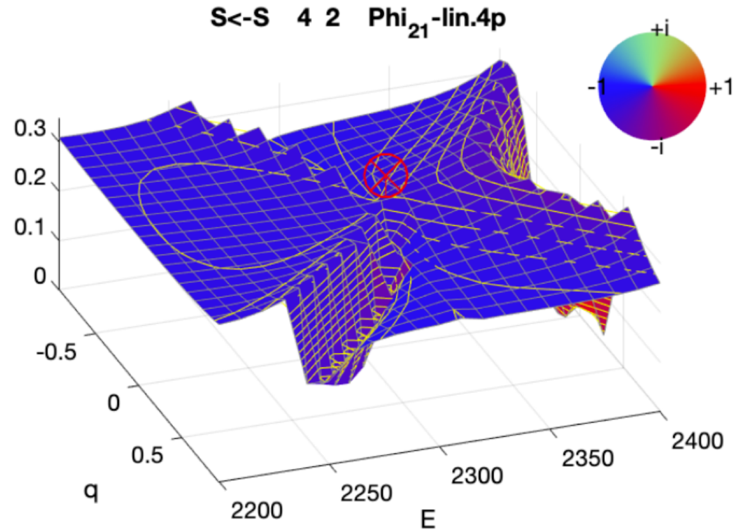
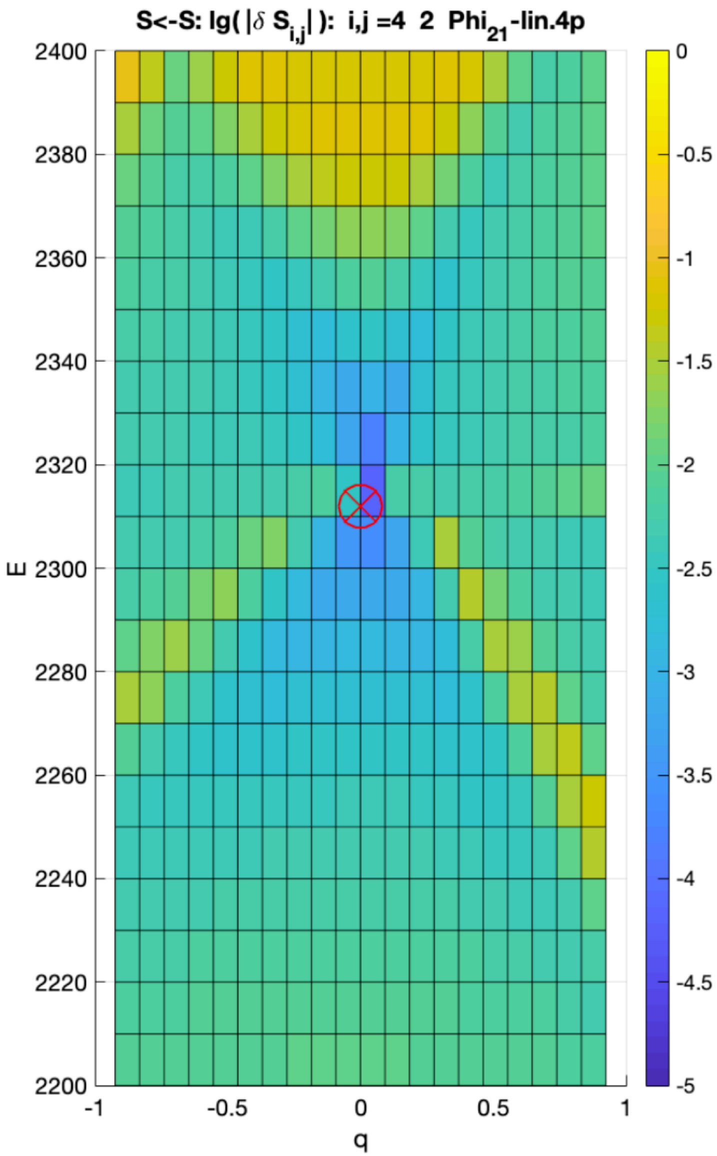




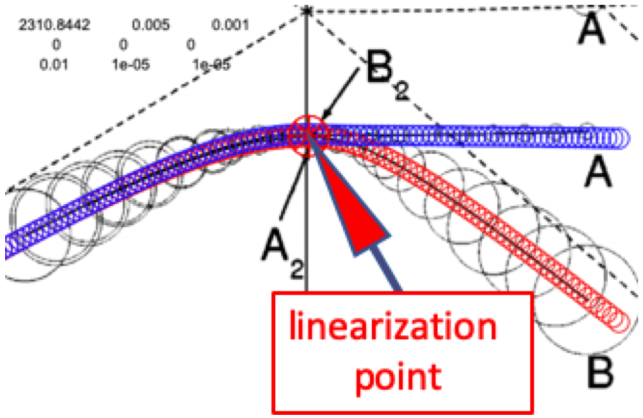
4
S-matrices





Вывод:

Резонансное приближение для составных систем фотоники позволяет эффективно описывать их оптические свойства и значительно увеличивает скорость расчётов



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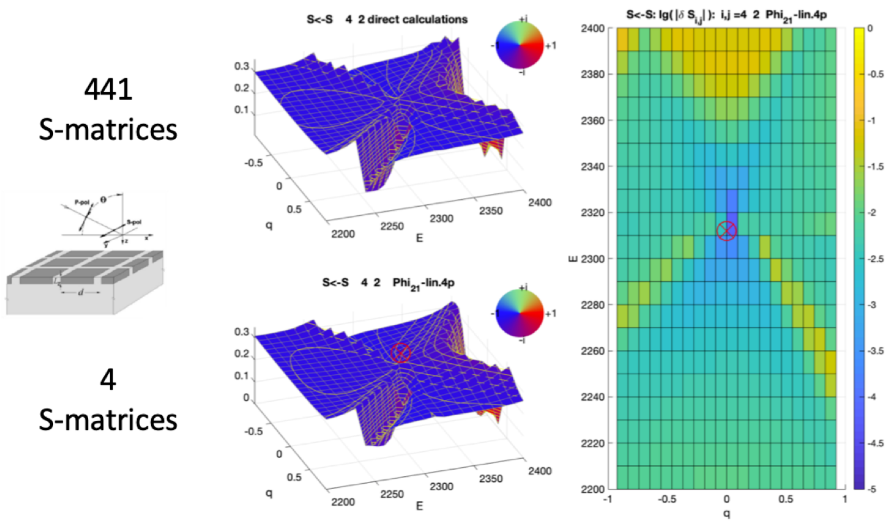

Спасибо за внимание!