Fano Resonances in Hyperbolic metamaterial-based cavities

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Overview

- Introduction to hyperbolic metamaterials (HMMs)
- Some properties
- Hyperbolic cavities with Fano resonances

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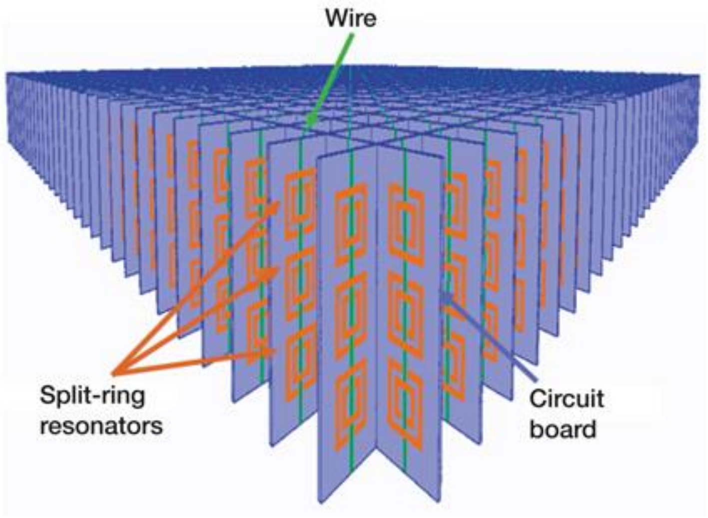
Metamaterials

Metamaterials: « material engineered to have a property that is not found in nature »

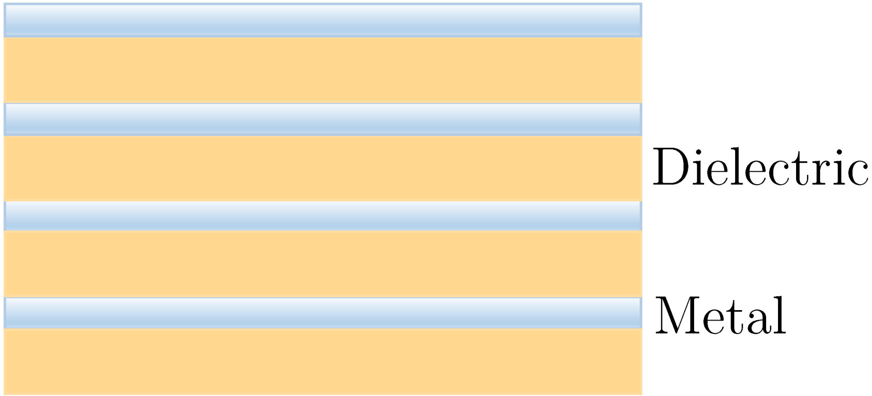


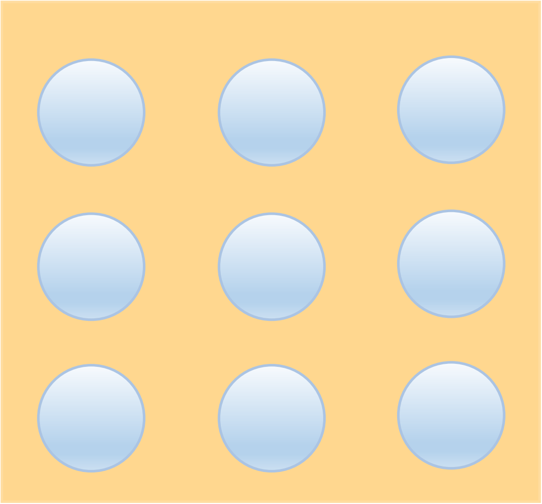
Building blocks : subwavelength « meta-atoms »

Optical properties from design rather than base materials

Applications: negative refractive index, invisibility cloak,
epsilon-near-zero metamaterials, epsilon-near-pole metamaterials, hyperlens, …

Hyperbolic metamaterial : anisotropic media





Standard effective medium theory (Bruggeman):

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_\parallel & 0 & 0 \\ 0 & \varepsilon_\parallel & 0 \\ 0 & 0 & \varepsilon_\perp \end{bmatrix}$$

$$\varepsilon_\parallel = f\varepsilon_m + (1-f)\varepsilon_d$$

$$\varepsilon_\perp = \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m(1-f) + \varepsilon_d f}$$

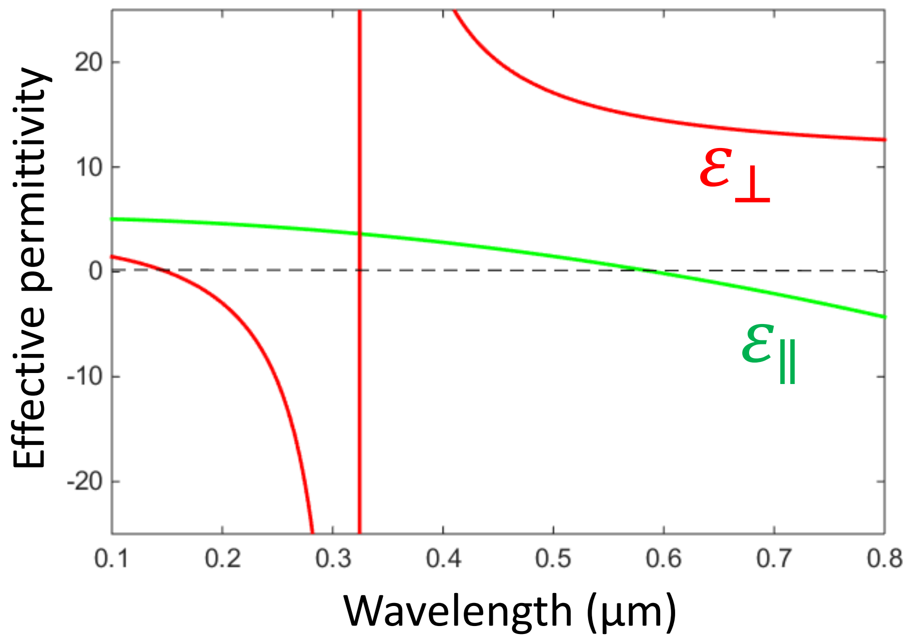
Metal fill factor ← (f)

$$\frac{k_\parallel^2}{\varepsilon_\perp} + \frac{k_\perp^2}{\varepsilon_\parallel} = k_0^2$$

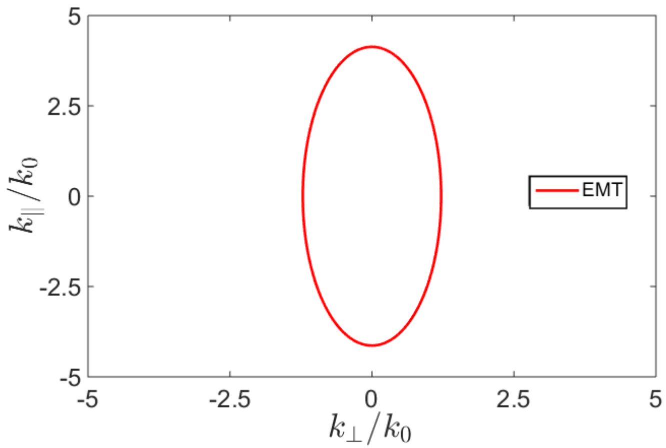
TM or p-polarization

Example with Ag and TiO_2

f = 1/3
d_{Ag} = 10 nm
d_{TiO2} = 20 nm



λ = 500 nm - elliptic



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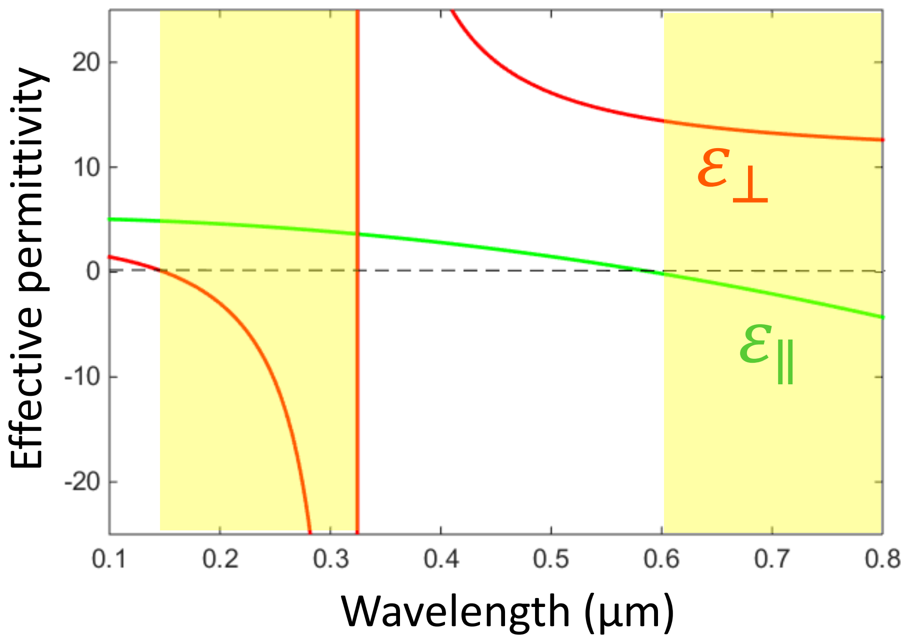
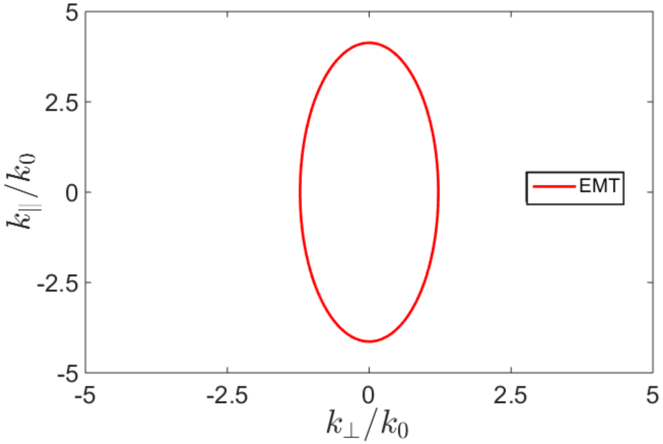


$\varepsilon_\parallel . \varepsilon_\perp < 0$ possible

$$\frac{k_\parallel^2}{\varepsilon_\perp} + \frac{k_\perp^2}{\varepsilon_\parallel} = \frac{\omega^2}{c^2}$$

Hyperbolic isofrequency curve!

λ = 500 nm - elliptic



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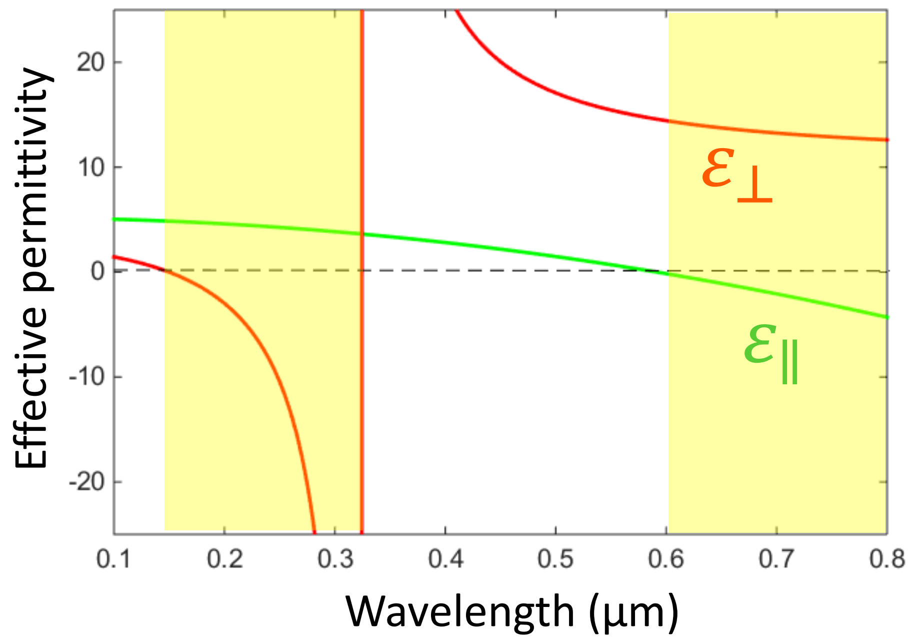

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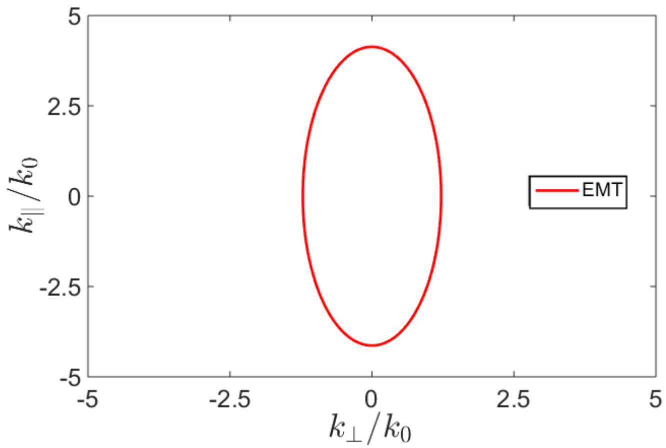
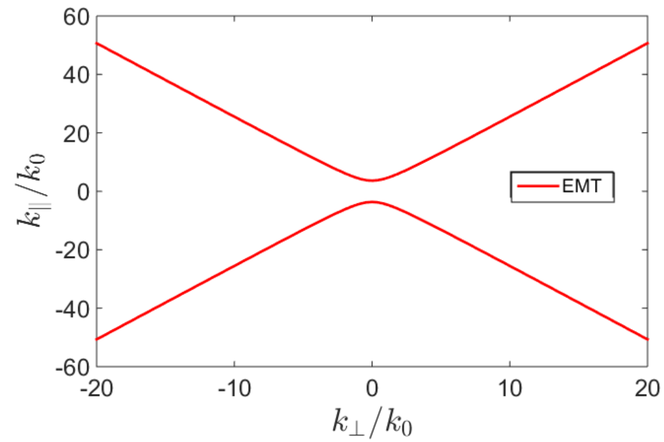
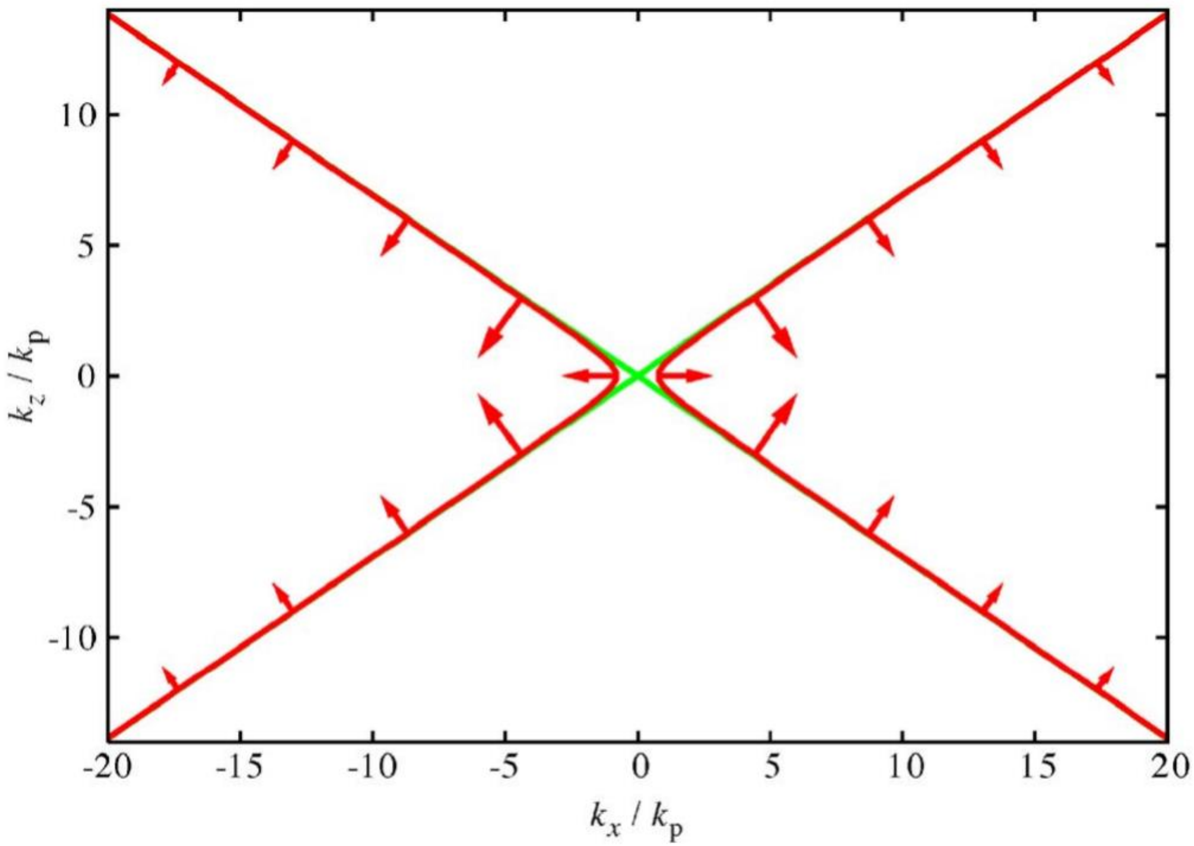


λ = 700 nm - hyperbolic



Group velocity



B. Wood, J. B. Pendry, and D. P. Tsai
Phys. Rev. B, vol. 74, 115116. (2006)

Preferred direction of propagation along a cone!

Limits of EMT

$$\frac{k_{\parallel}^2}{\varepsilon_{\perp}} + \frac{k_{\perp}^2}{\varepsilon_{\parallel}} = \frac{\omega^2}{c^2}$$

Limits of EMT

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Origin of hyperbolic properties: plasmonic
→ Nonlocality

Limits of effective medium theory

$$\cos\left(k_y D\right) = \frac{\left(\kappa_d \varepsilon_m + \kappa_m \varepsilon_d\right)^2}{4\kappa_d \kappa_m \varepsilon_d \varepsilon_m} \cosh\left(\kappa_d d_d + \kappa_m d_m\right) - \frac{\left(\kappa_d \varepsilon_m - \kappa_m \varepsilon_d\right)^2}{4\kappa_d \kappa_m \varepsilon_d \varepsilon_m} \cosh\left(\kappa_d d_d - \kappa_m d_m\right)$$

$$\kappa_{m,d} = \sqrt{k_x^2 - \varepsilon_{m,d} k_0^2}$$

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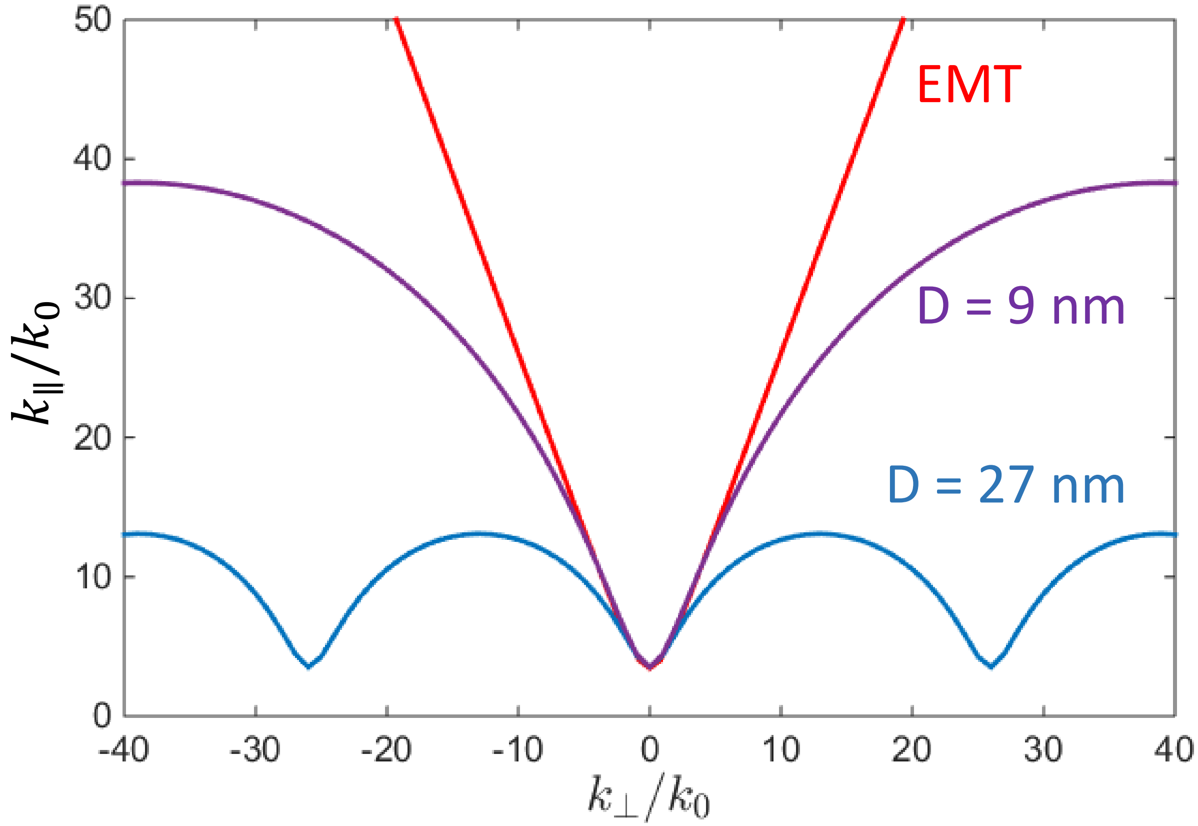
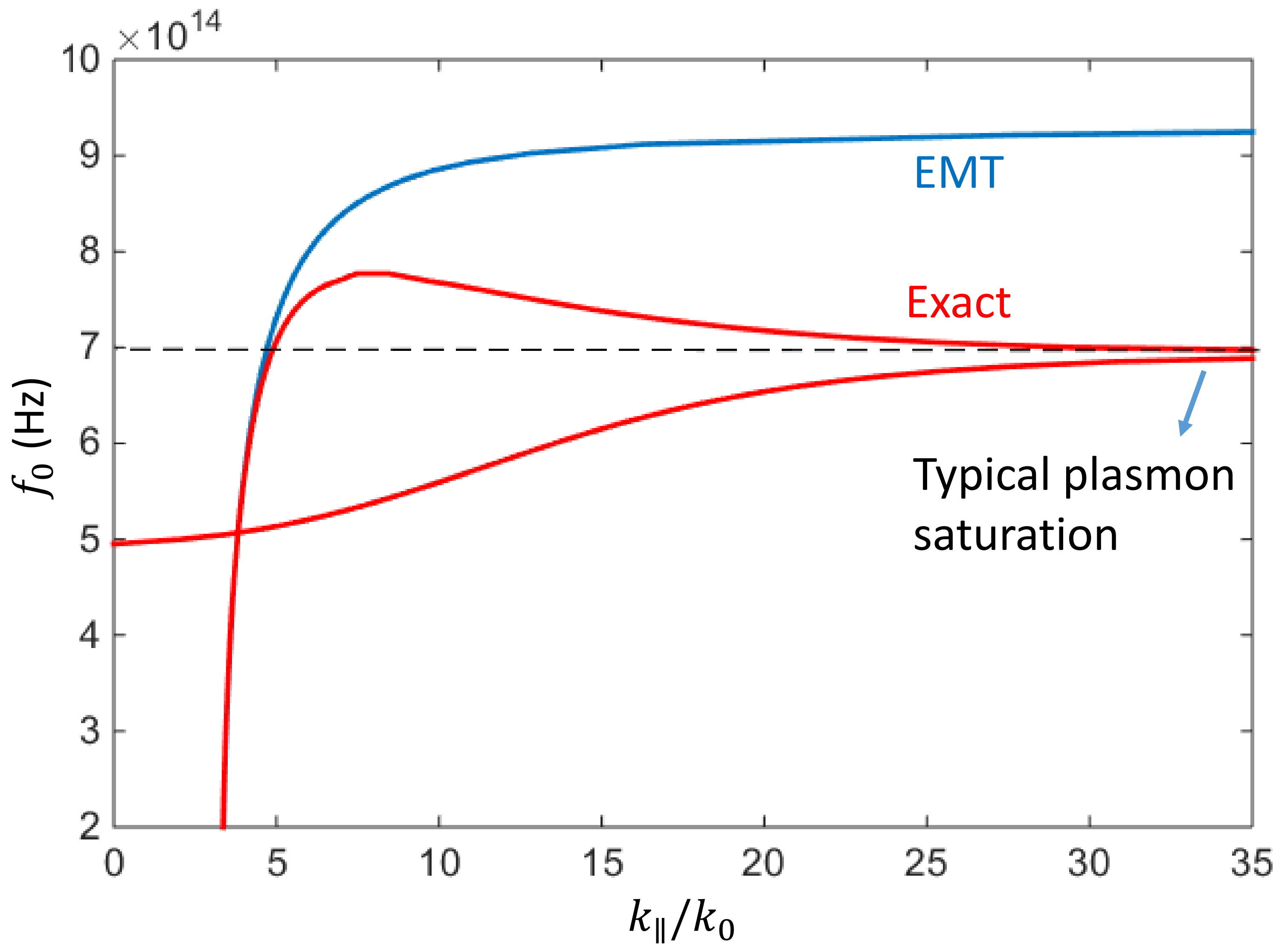


Limited inside Brillouin zone: $\frac{\pi}{D}$

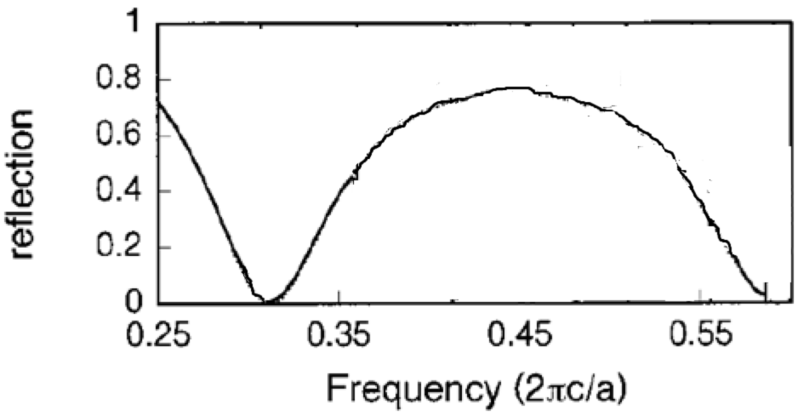
Standard effective medium approach (EMT) not valid in many case



×10^14
10
9
8
7
6
5
4
3
2
0
5
10
15
20
25
30
35
f_0 (Hz)
$k_{\|}/k_0$
EMT
Exact
Typical plasmon saturation

Fano resonances

Slowly varying background



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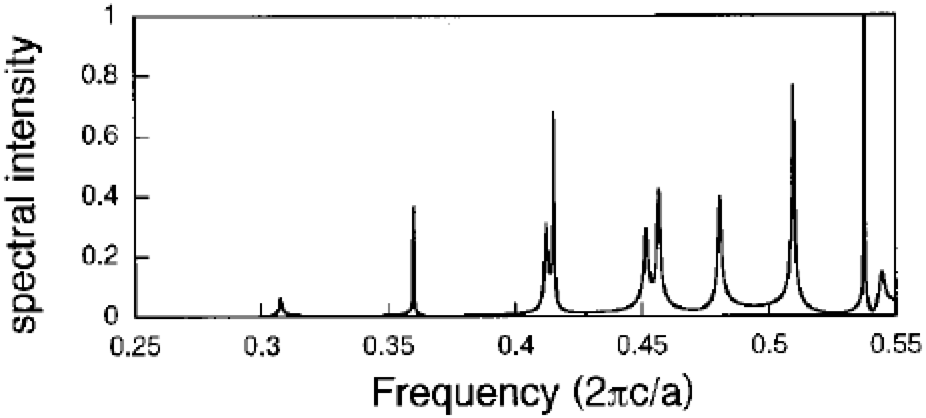
Narrow resonances



Fano resonances

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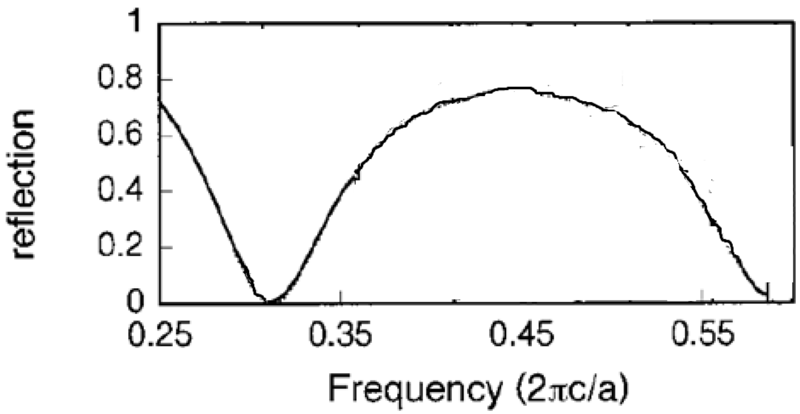

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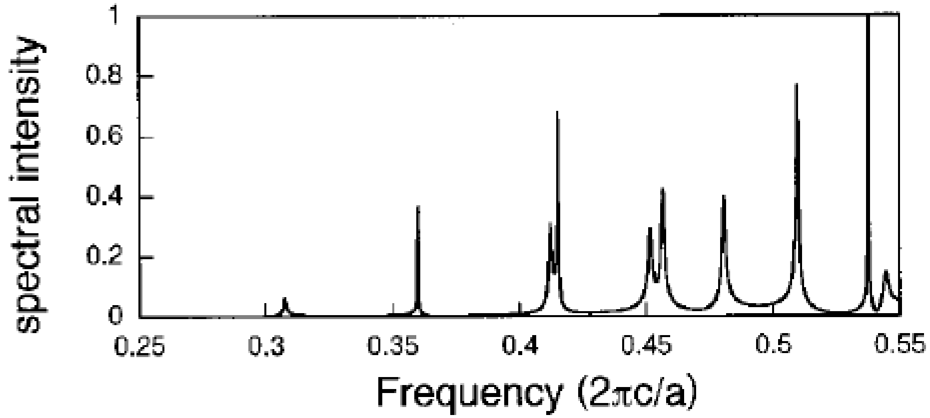

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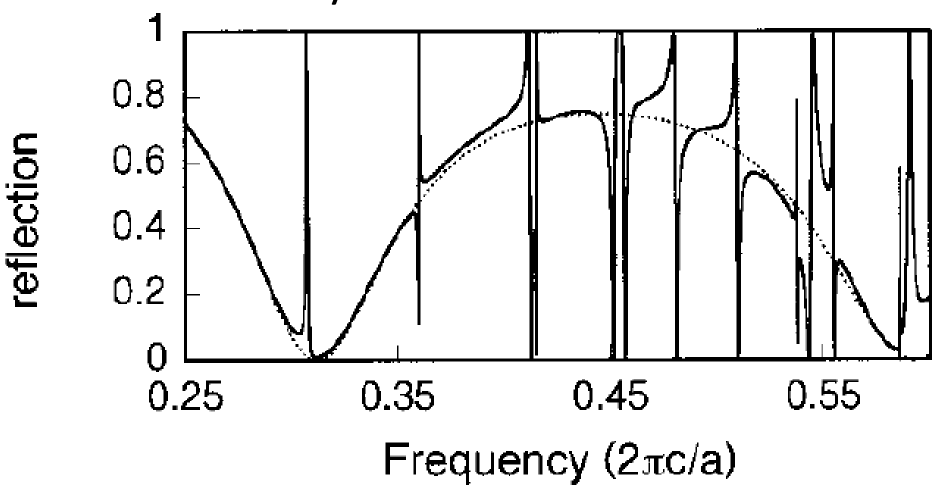
Asymmetric Fano resonances



S. Fan and J.D. Joannopoulos, Phys. Rev. B, vol. 65, 235112. (2002)

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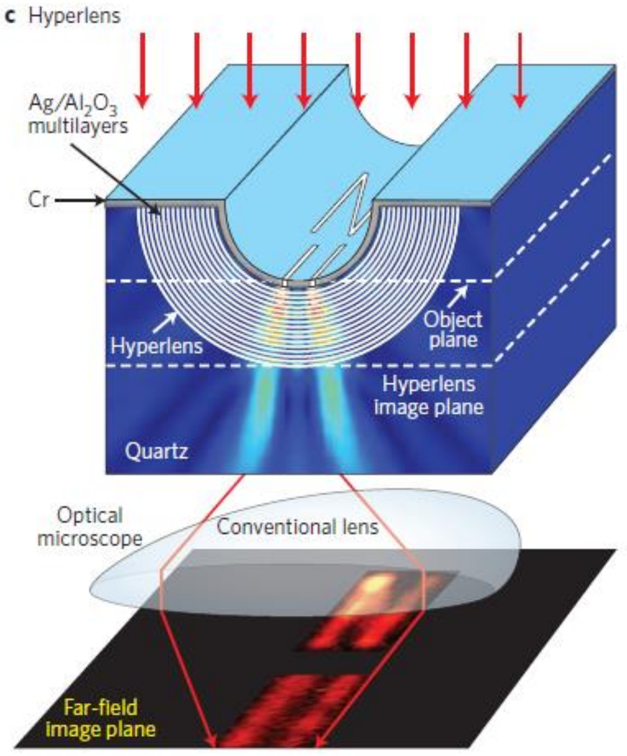
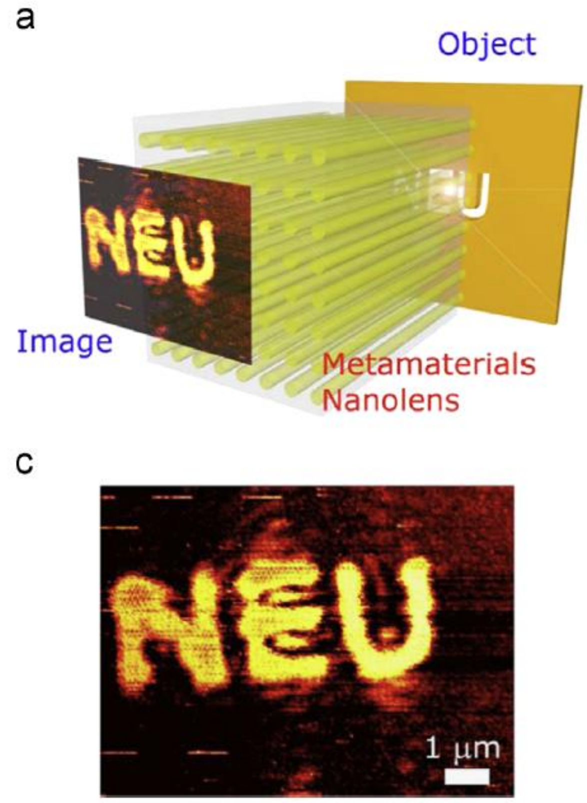
High-k propagating waves

High-k waves can propagates inside HMM → Possibility to overcome diffraction limit

Application: hyperlens



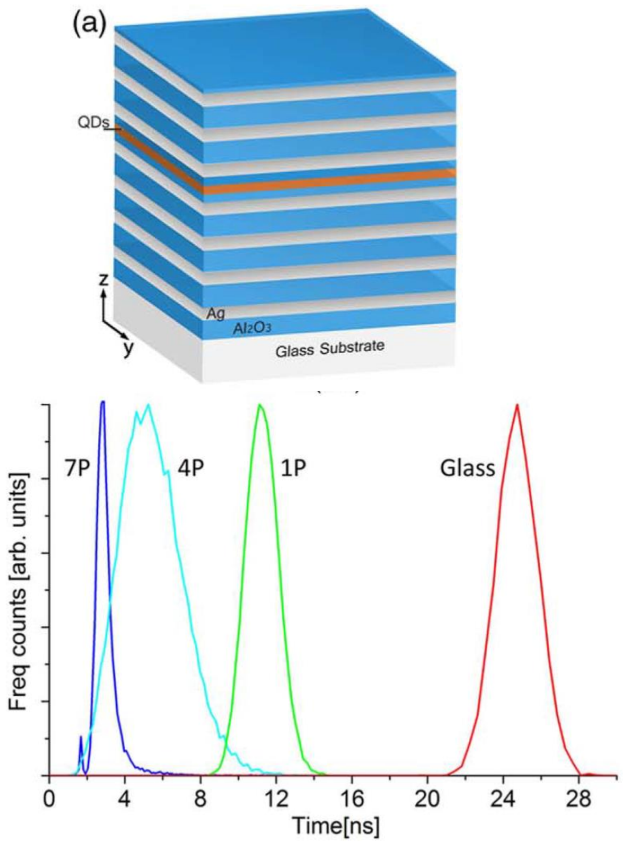


Liu, Z. et al., Science, vol. 315, 1686. (2007)

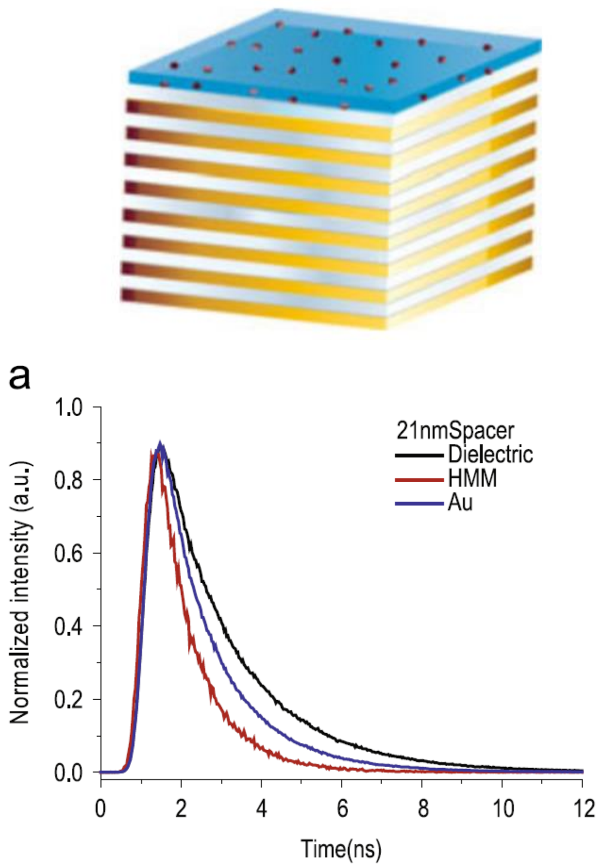
B. D. F. Casse et al., Appl. Phys. Lett., vol. 96, 023114 (2010)

Extremely high PDOS

Nonresonant phenomena → Broadband extremely high PDOS
Spontaneous emission engineering possible

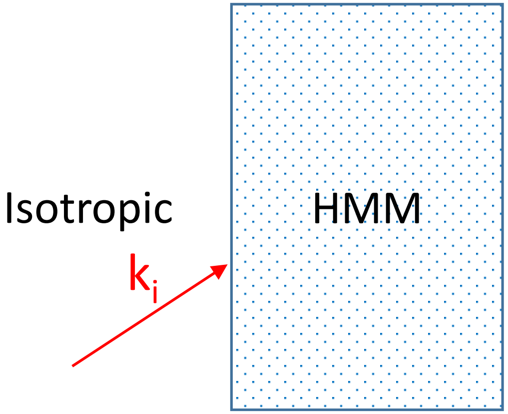


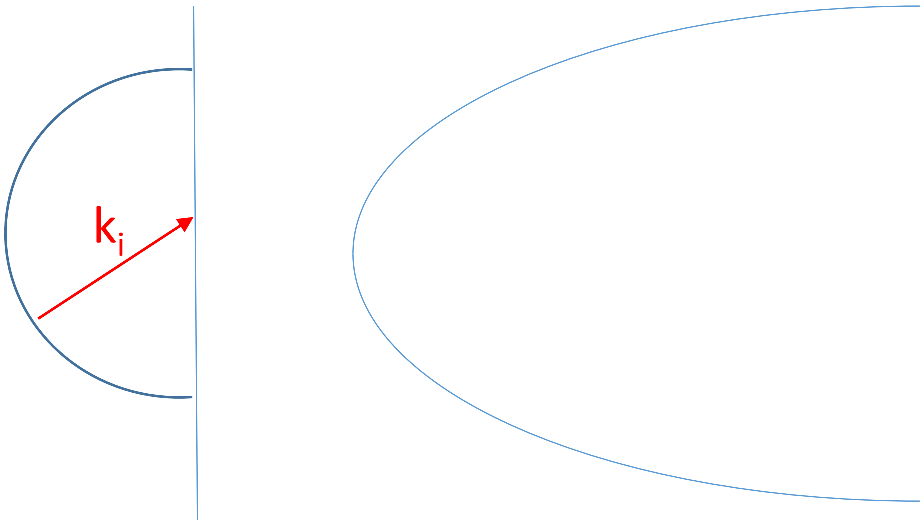
Galfsky, T. et al., Optica, vol. 2, 62-65. (2015)



Z. Jacob et al, Applied Physics B, vol. 100, 215. (2010)

Negative refraction





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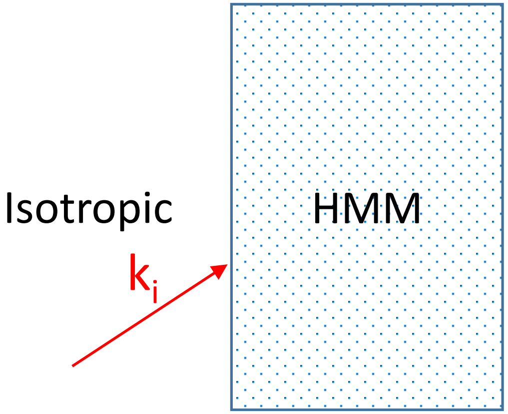

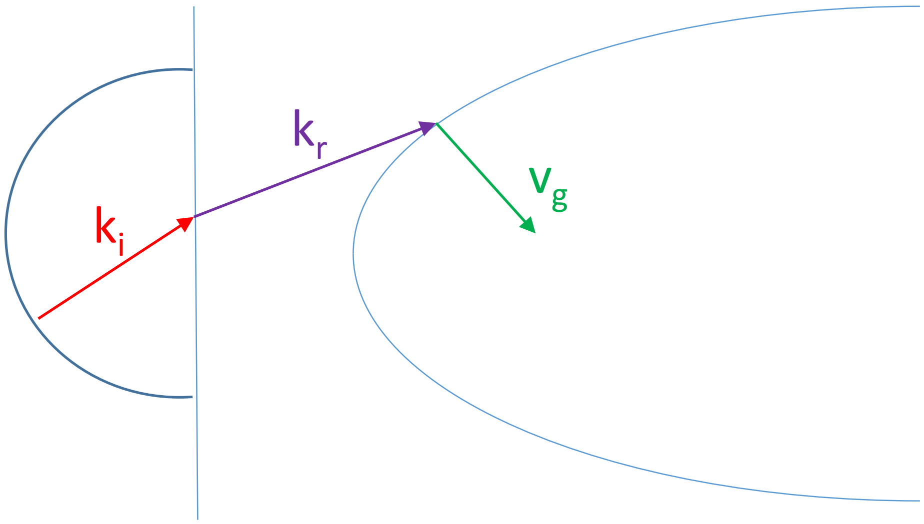

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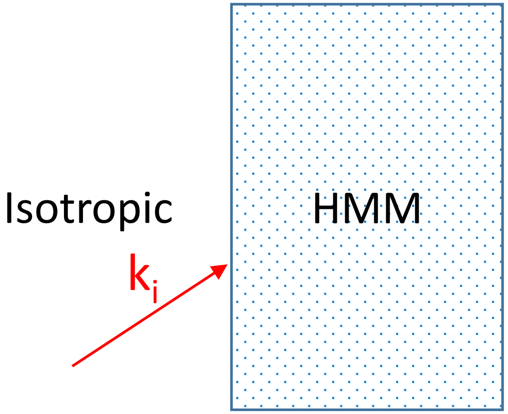
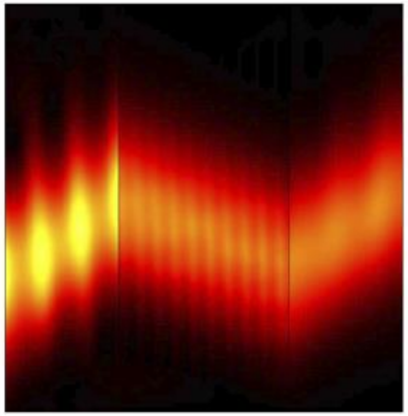
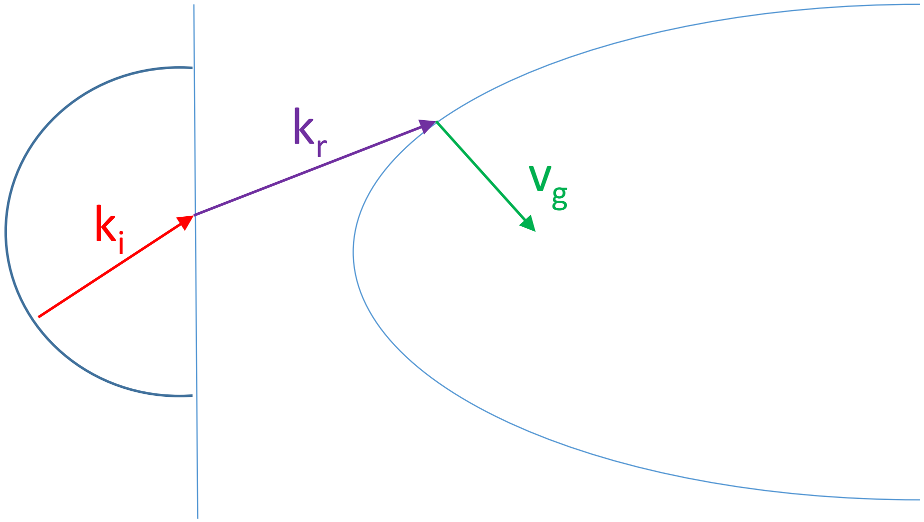
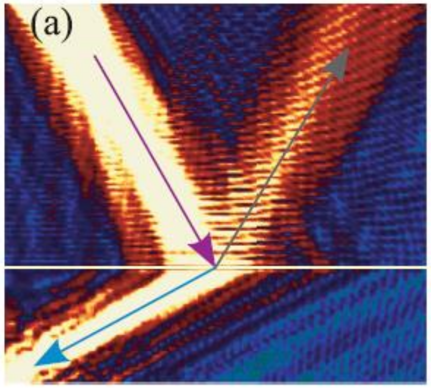




Y. Liu et al, Optics Express, vol. 16, 15439. (2008)





A. Orlov et al, Physical Review B, vol. 84, 045424 (2011)

Overview

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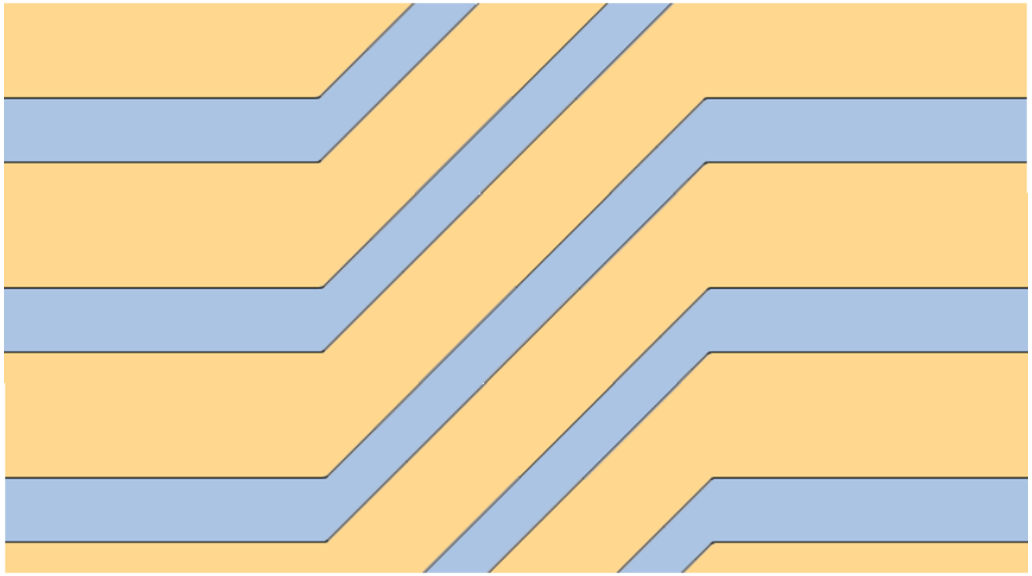
Reflection and transmission in slanted cavities



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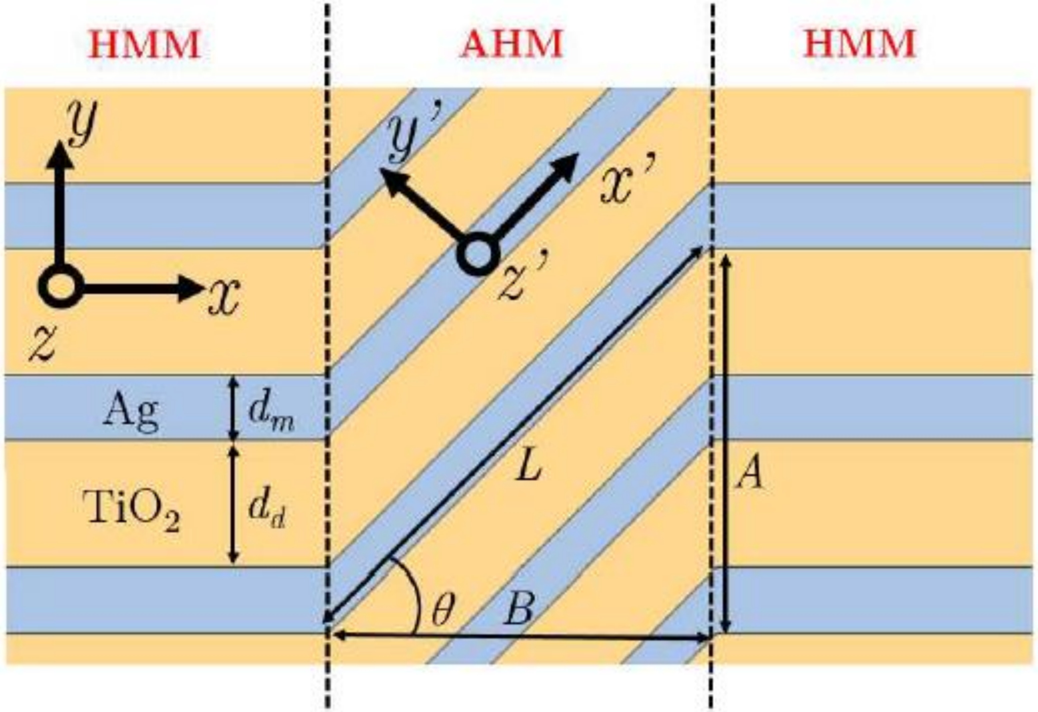
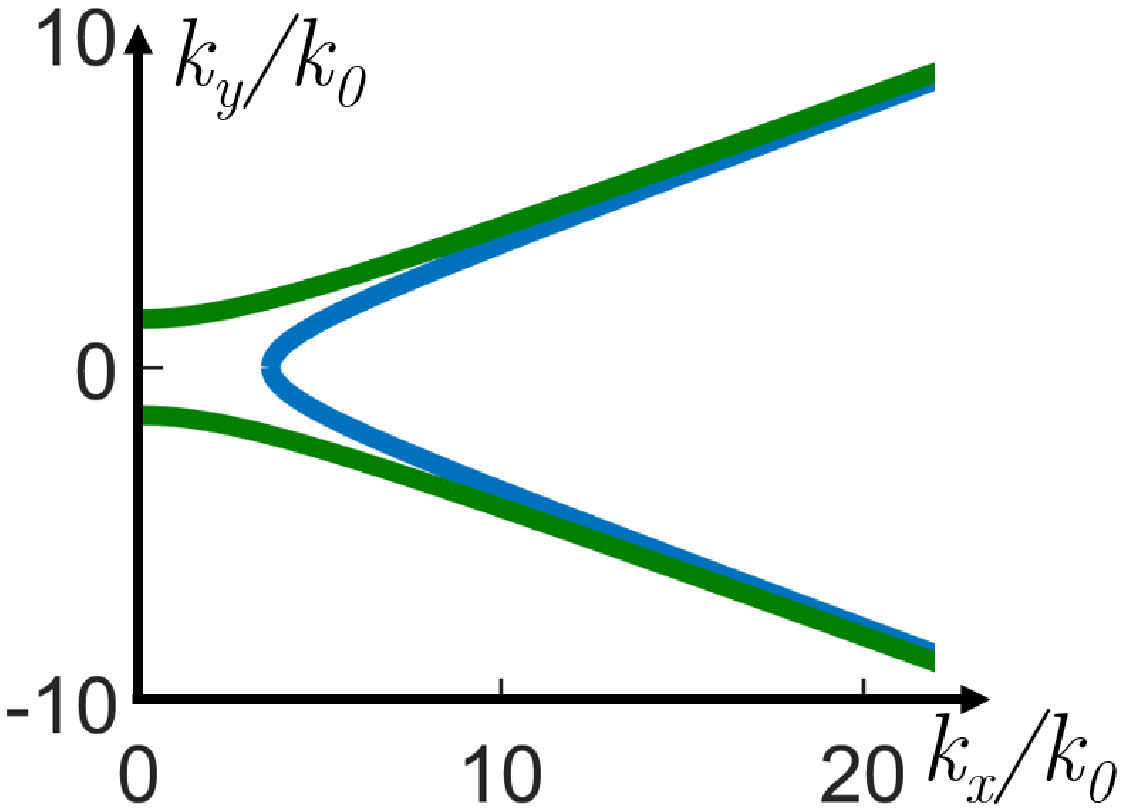


Right and left: simple multilayer HMM

Centre: « asymmetric hyperbolic metamaterial » (tilted optical axis)

1st model: EMT

$$\frac{k_{\parallel}^2}{\varepsilon_{\perp}} + \frac{k_{\perp}^2}{\varepsilon_{\parallel}} = k_0^2$$



- Propagative mode
- Evanescent mode

EMT of the asymmetric HMM

$$\overline{\overline{\varepsilon}} = \mathcal{R}(\theta)\,\overline{\overline{\varepsilon'}}\,\mathcal{R}(\theta)^T = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{xy} & \varepsilon_{yy} \end{pmatrix}$$

$$k_x^{(1,2)} = \frac{k_y \varepsilon_{xy} \pm \sqrt{\left(\varepsilon_{xy}^2 - \varepsilon_{xx}\varepsilon_{yy}\right)\left(k_y^2 - k_0^2 \varepsilon_{xx}\right)}}{\varepsilon_{xx}}$$

EMT of the asymmetric HMM

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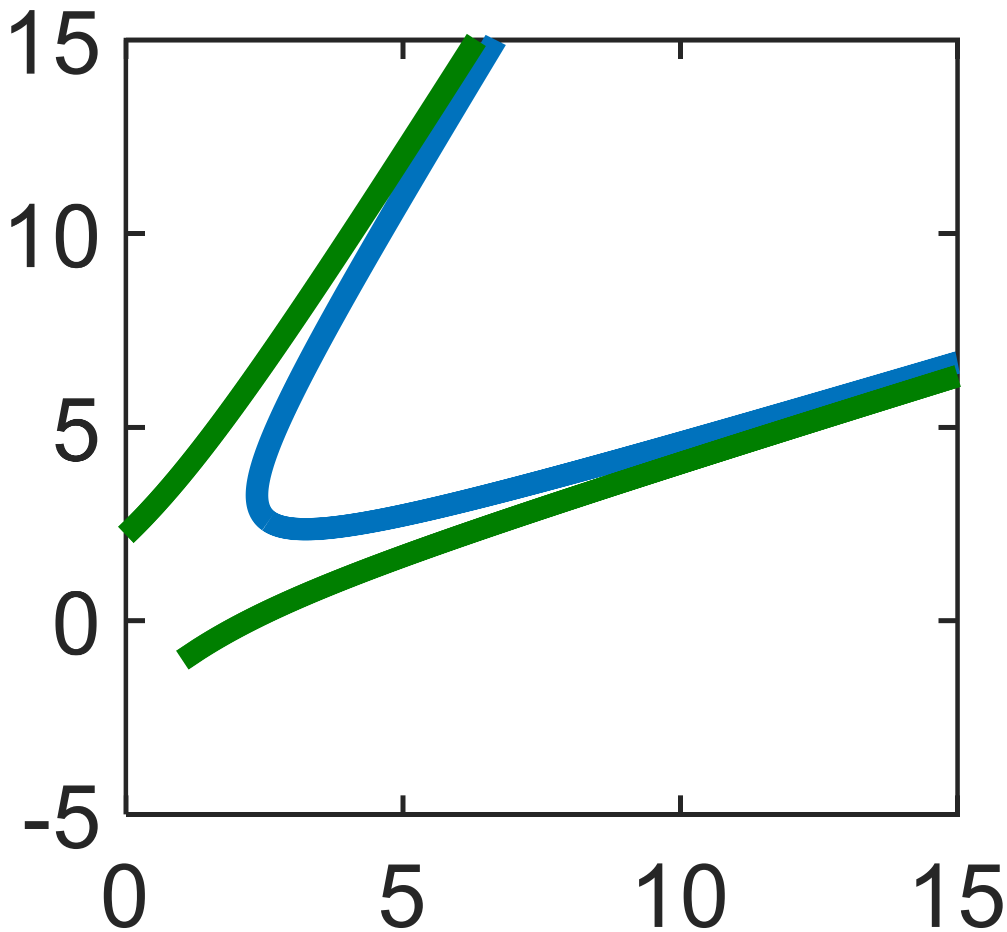
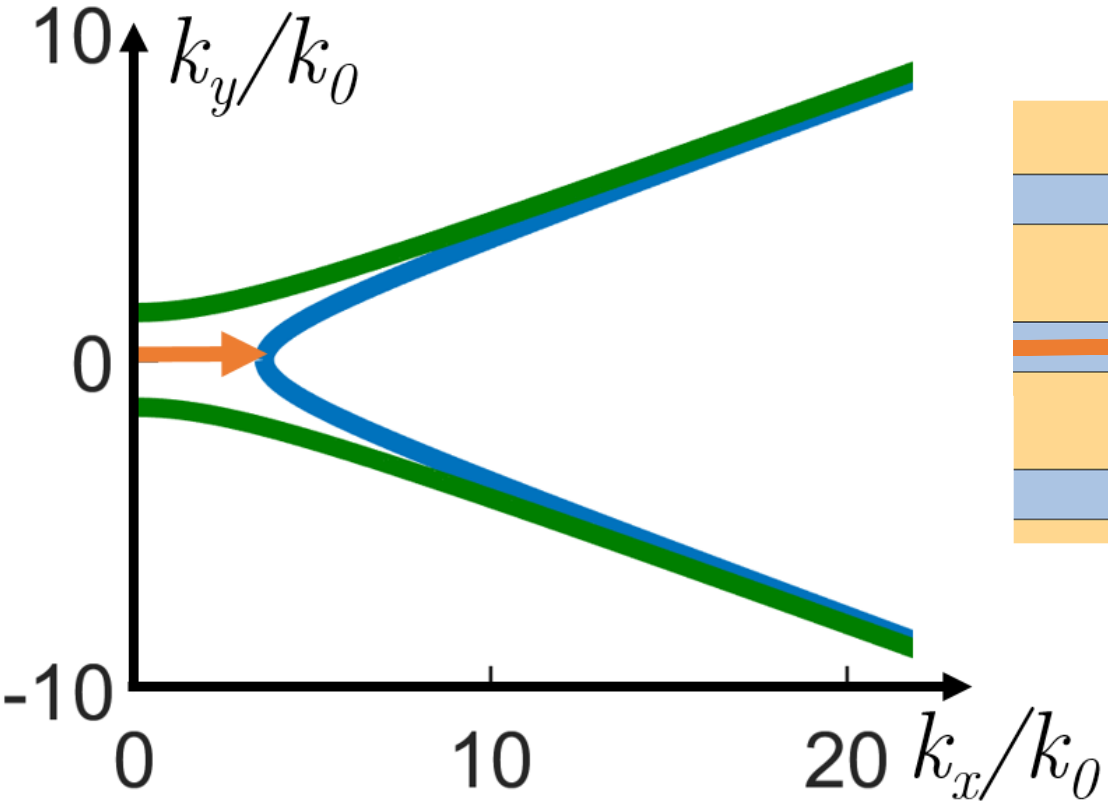
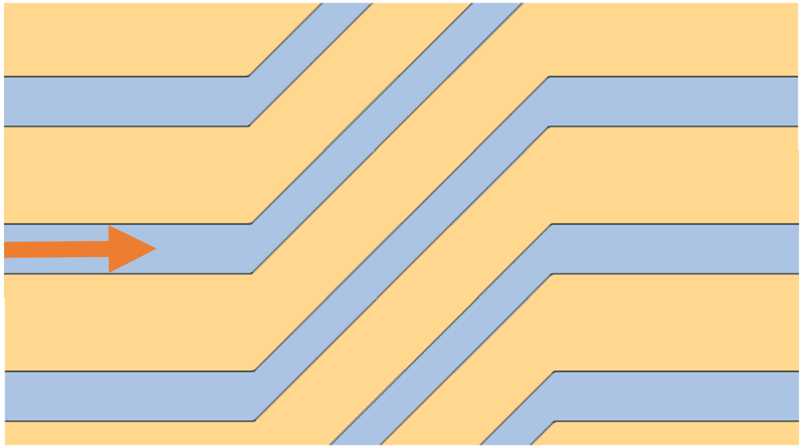


Transverse momentum conservation





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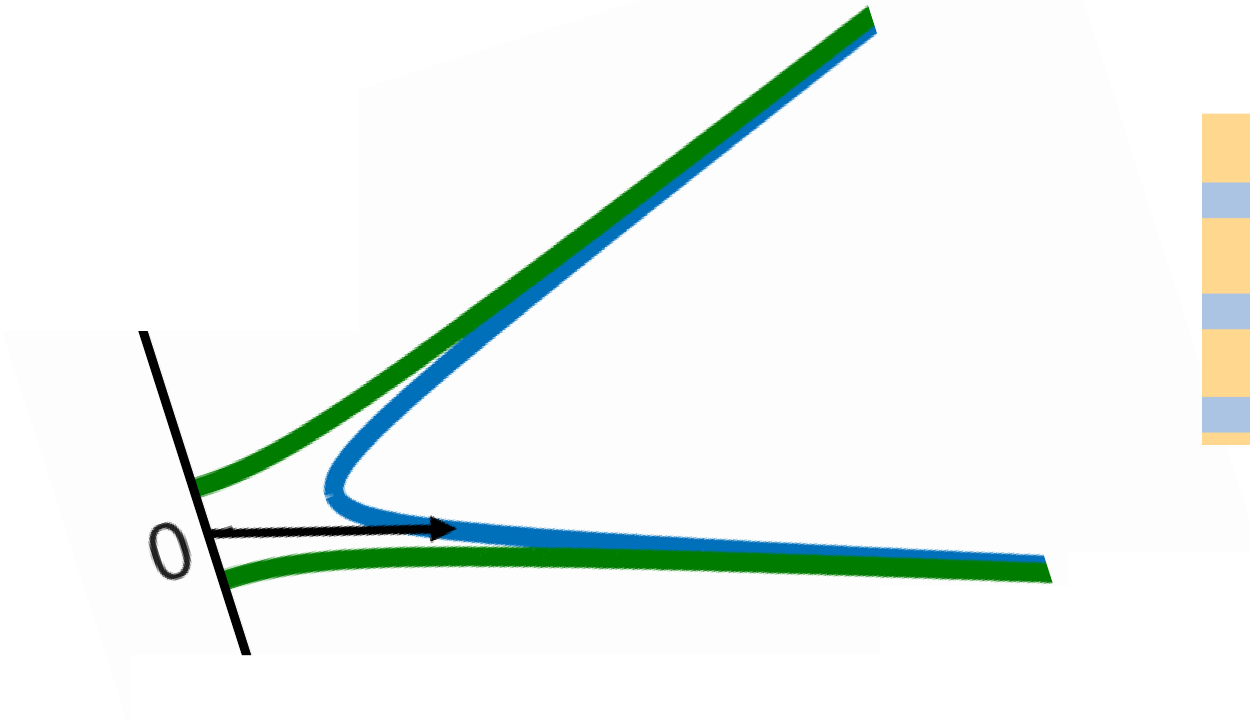
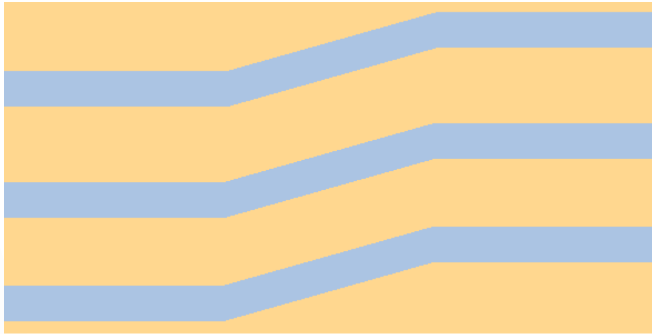
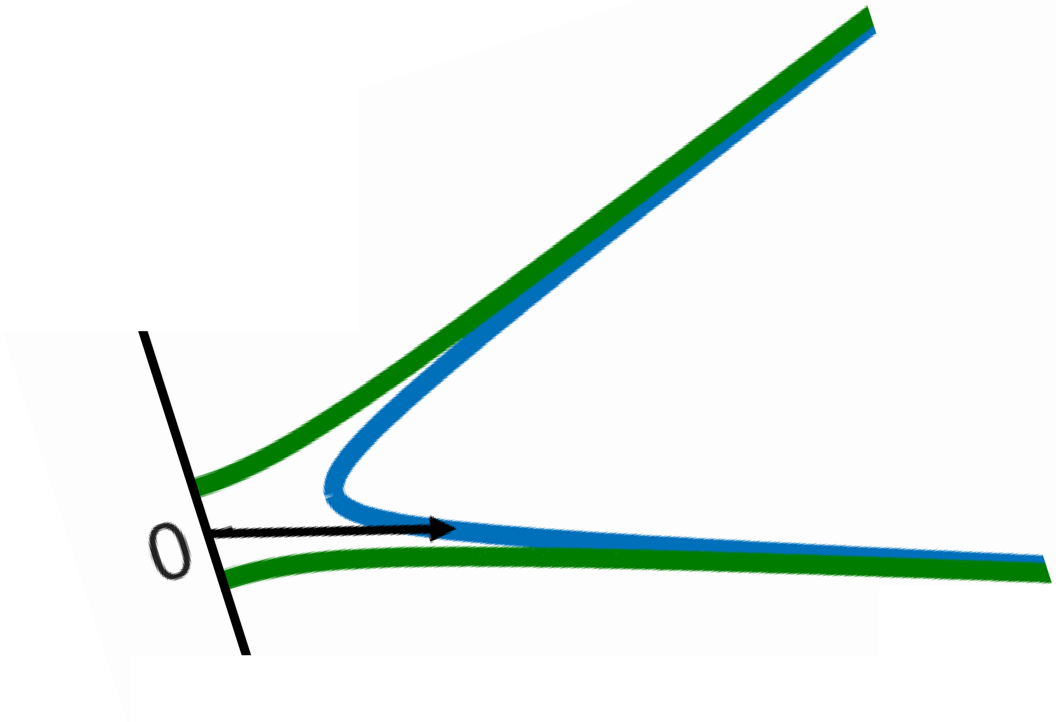
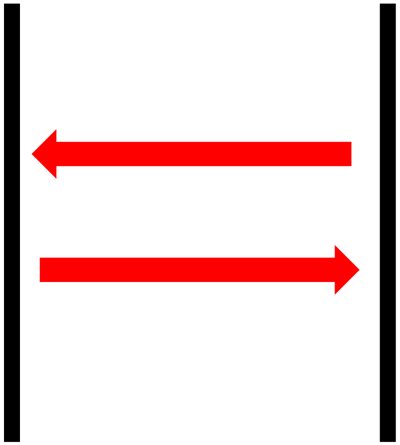




Below θ_t, propagative mode excited

Transverse momentum conservation





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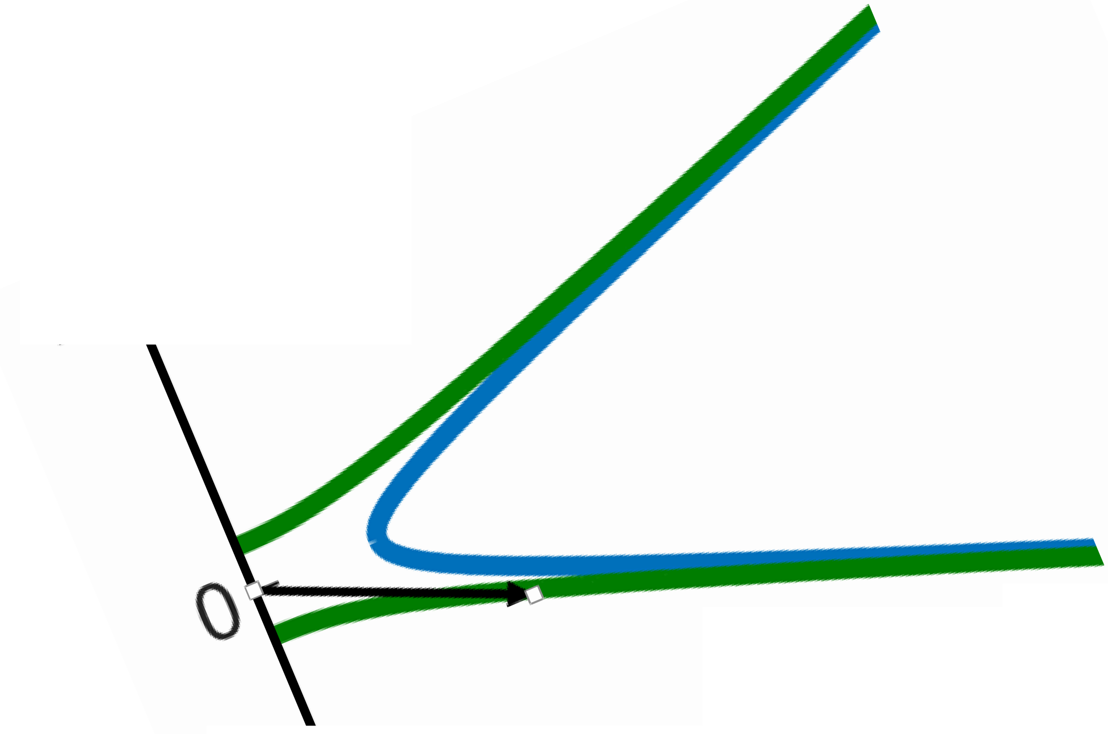
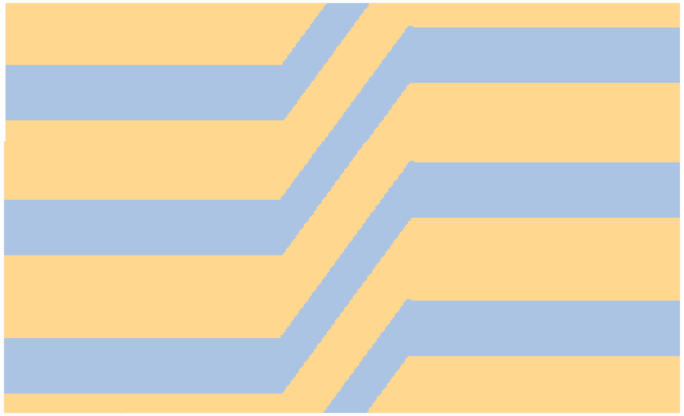
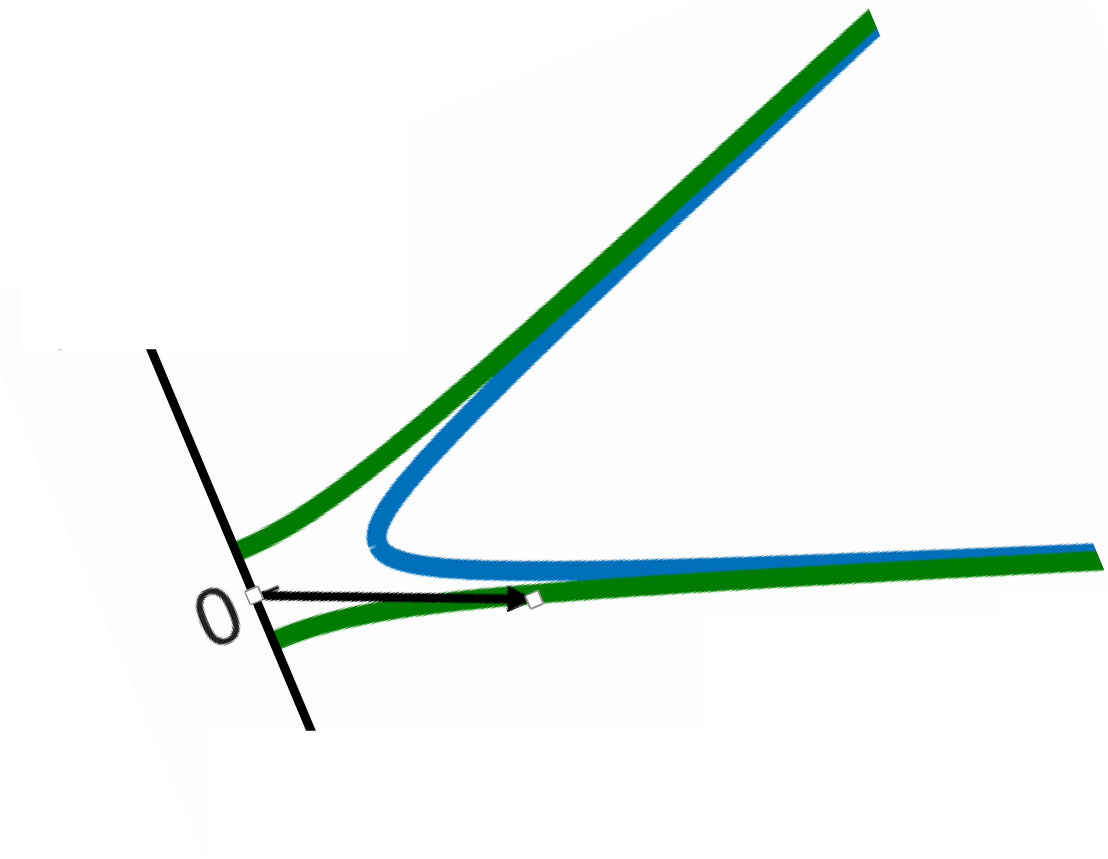


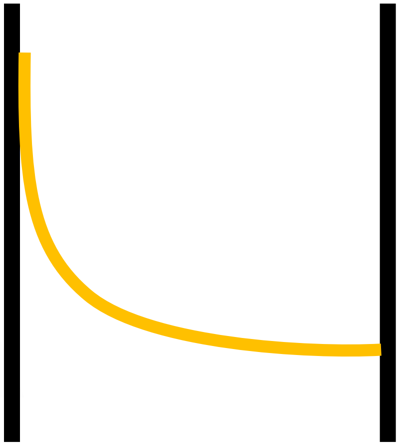


Below θ_t, propagative mode excited

Above θ_t, evanescent mode excited

Transverse momentum conservation

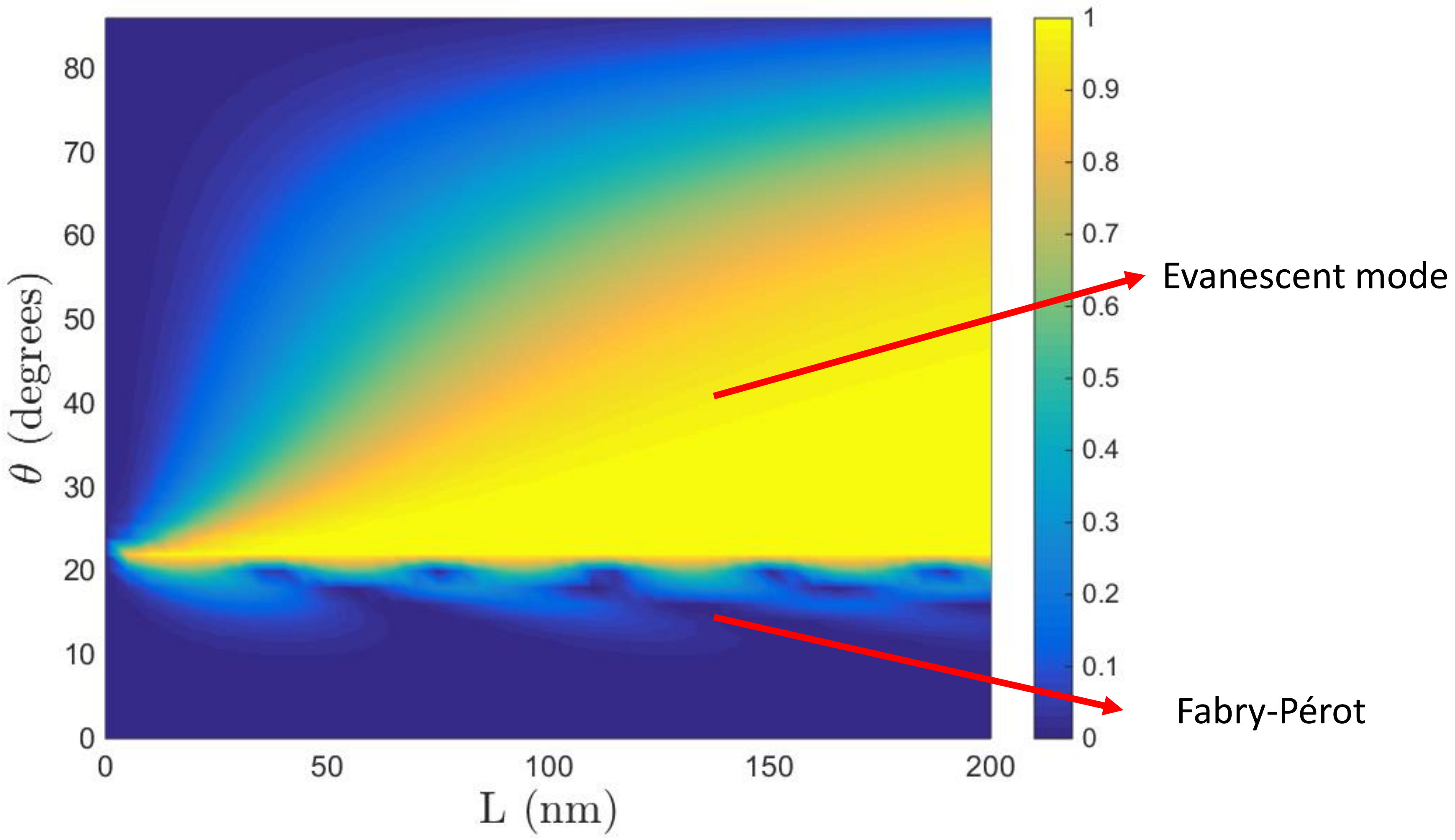




Below θ_t, propagative mode excited

Above θ_t, evanescent mode excited

Reflection map



Exact solution (without losses in metal)

$$\cos\left(k_y D\right) = \frac{\left(\kappa_d \varepsilon_m + \kappa_m \varepsilon_d\right)^2}{4\kappa_d \kappa_m \varepsilon_d \varepsilon_m} \cosh\left(\kappa_d d_d + \kappa_m d_m\right) - \frac{\left(\kappa_d \varepsilon_m - \kappa_m \varepsilon_d\right)^2}{4\kappa_d \kappa_m \varepsilon_d \varepsilon_m} \cosh\left(\kappa_d d_d - \kappa_m d_m\right)$$

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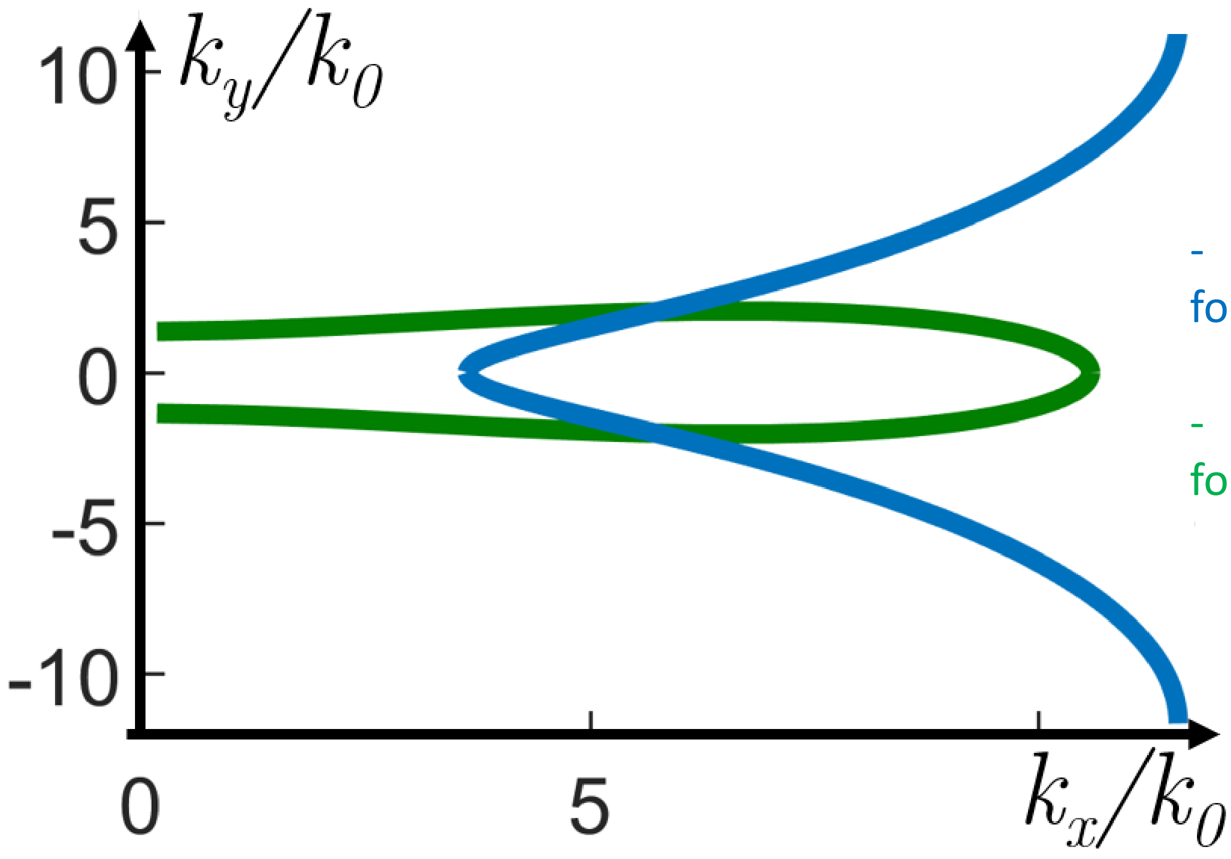
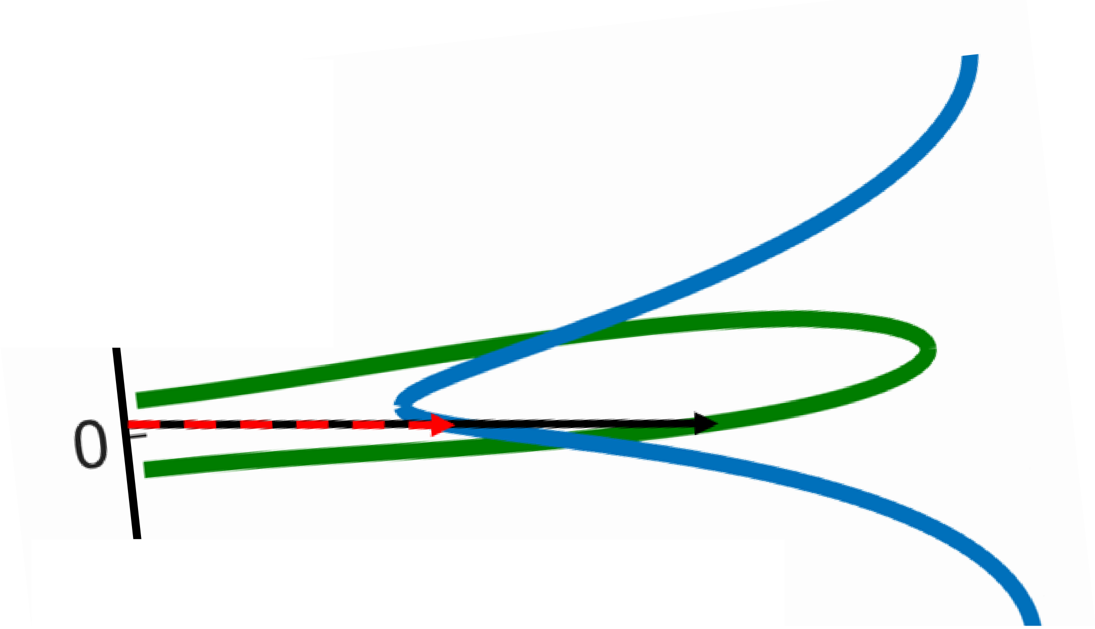
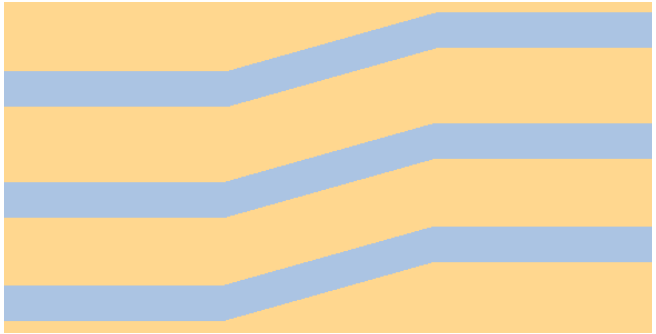


- Periodic isofrequency curve for the propagative mode
- Close isofrequency curve for the evanescent mode

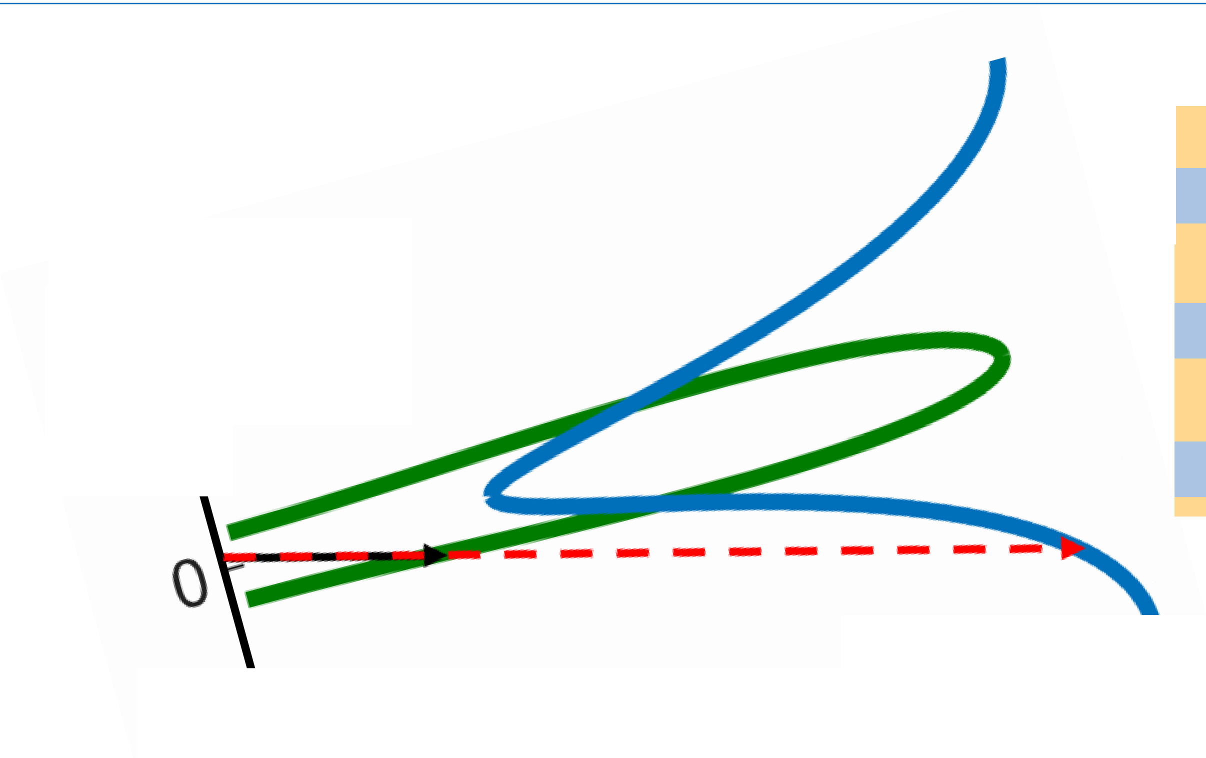
Transverse momentum conservation (k_y = 0)

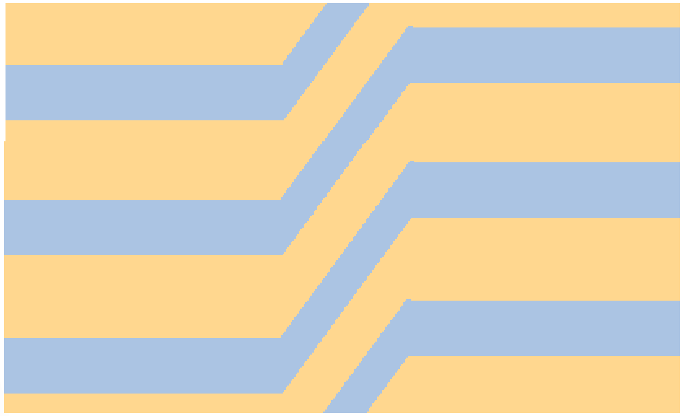




Always a propagative and evanescent mode excited !

Transverse momentum conservation





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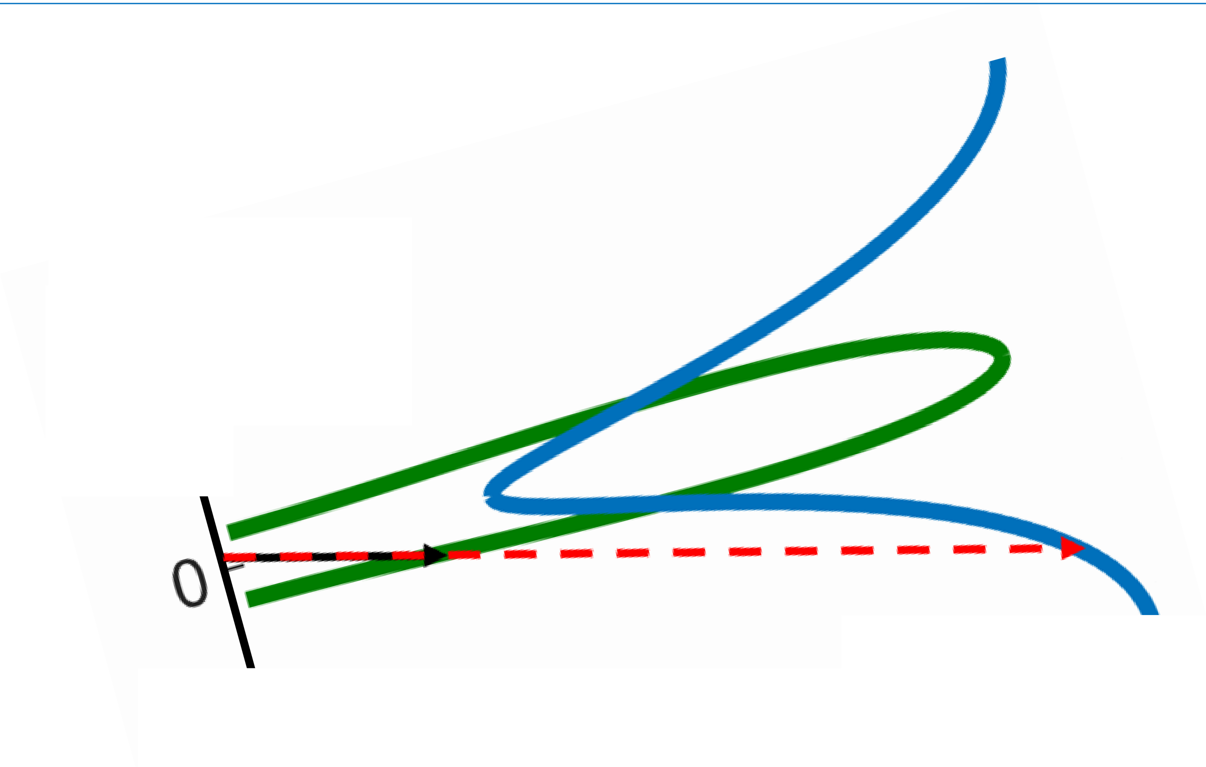
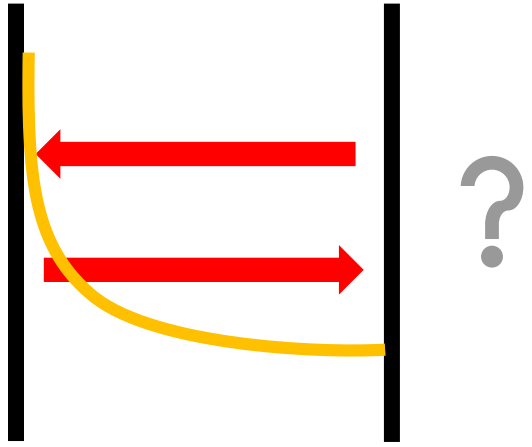
Transverse momentum conservation

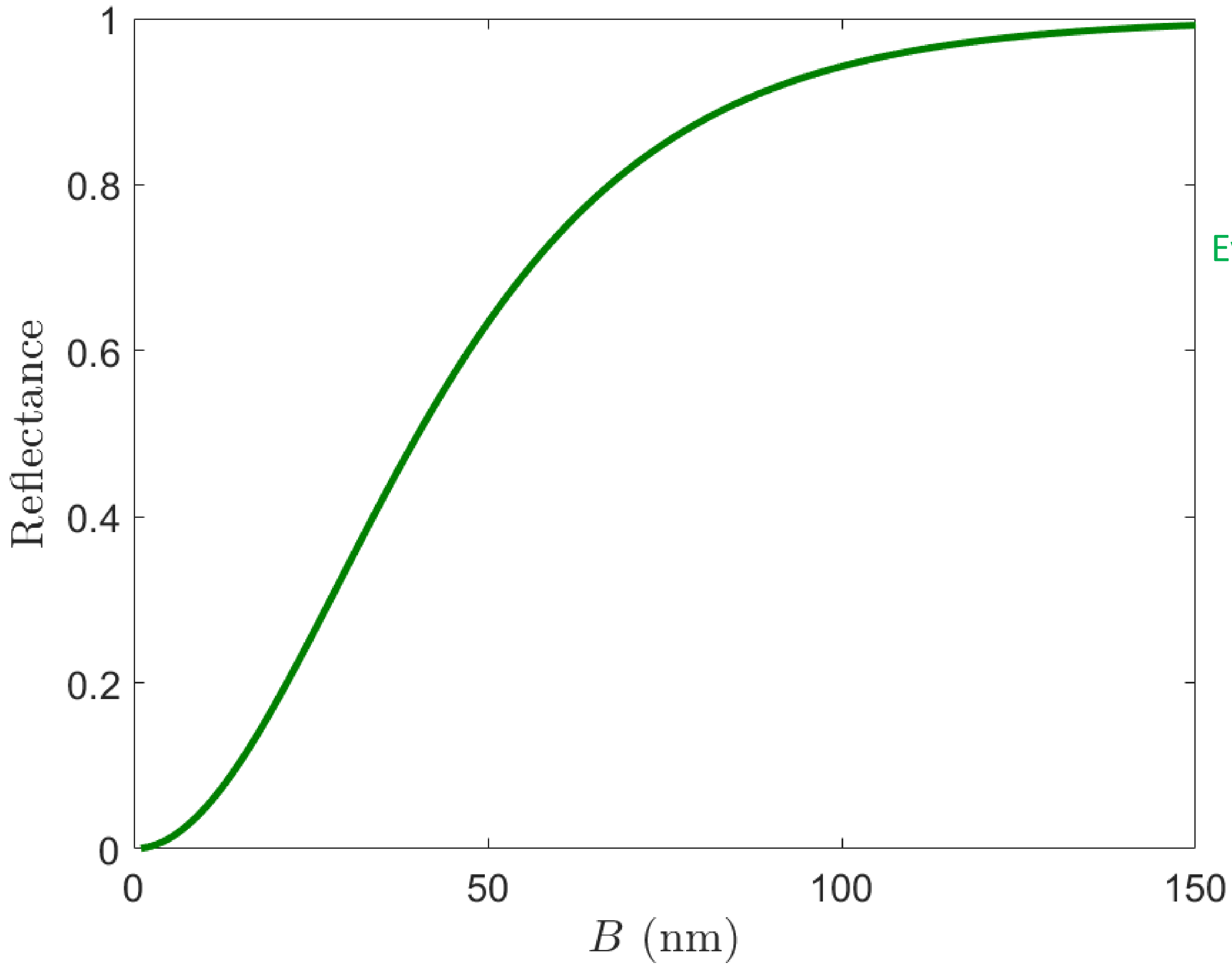




Always a propagative and evanescent mode excited !

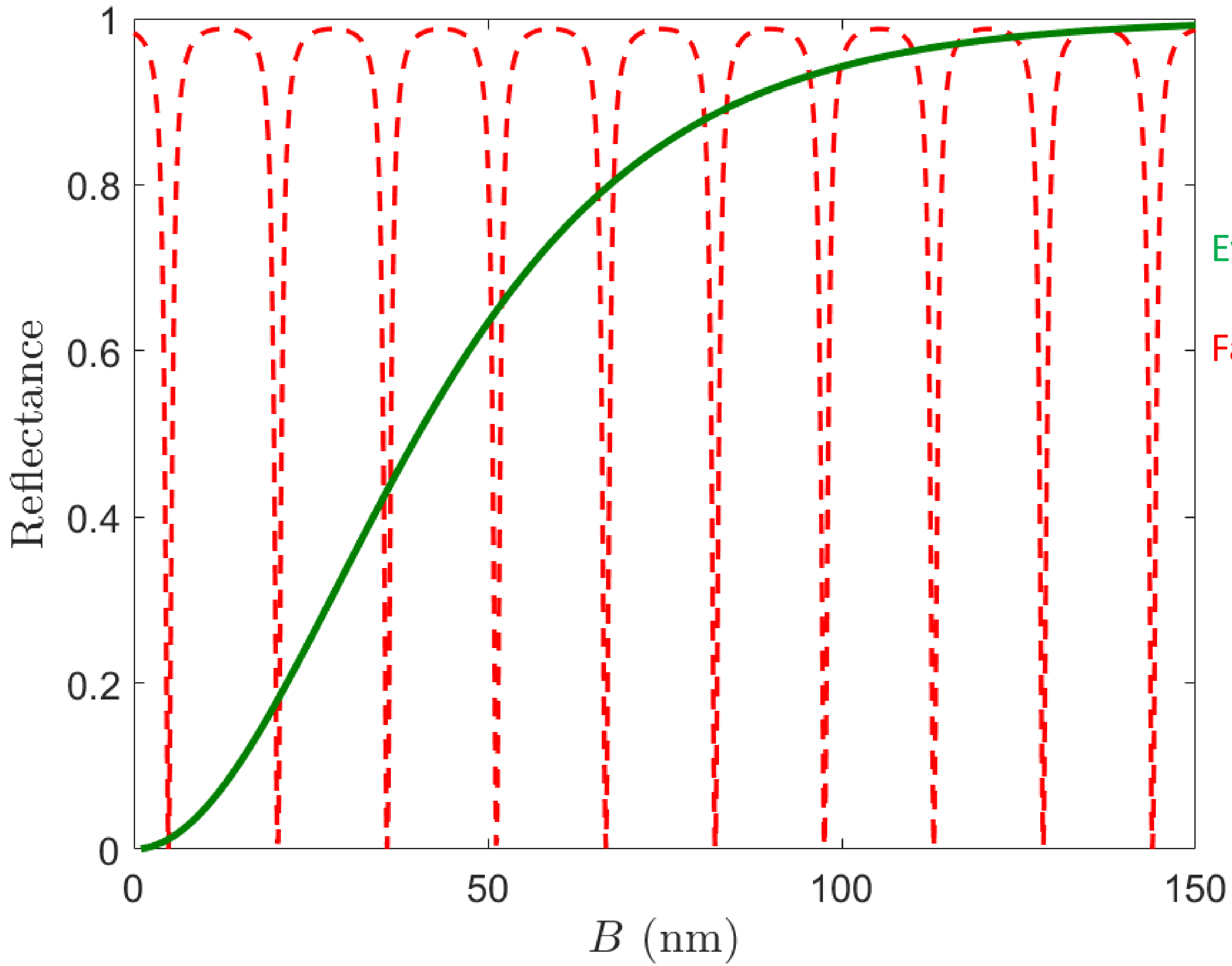
→ Interference at the output

Fano resonances (Θ = 45°)



Evanescent background

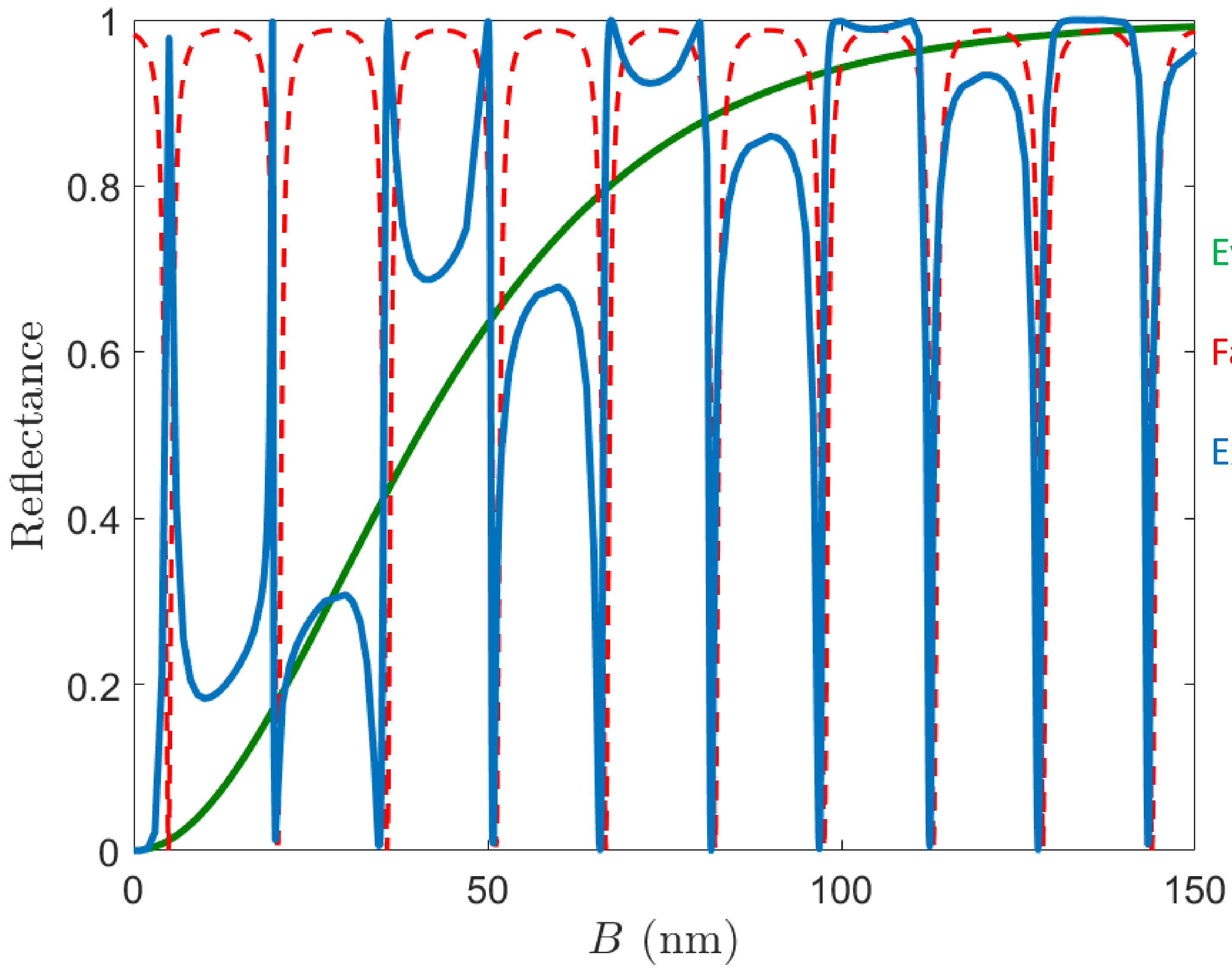
Fano resonances (Θ = 45°)



Evanescent background

Fabry-Pérot

Fano resonances (Θ = 45°)

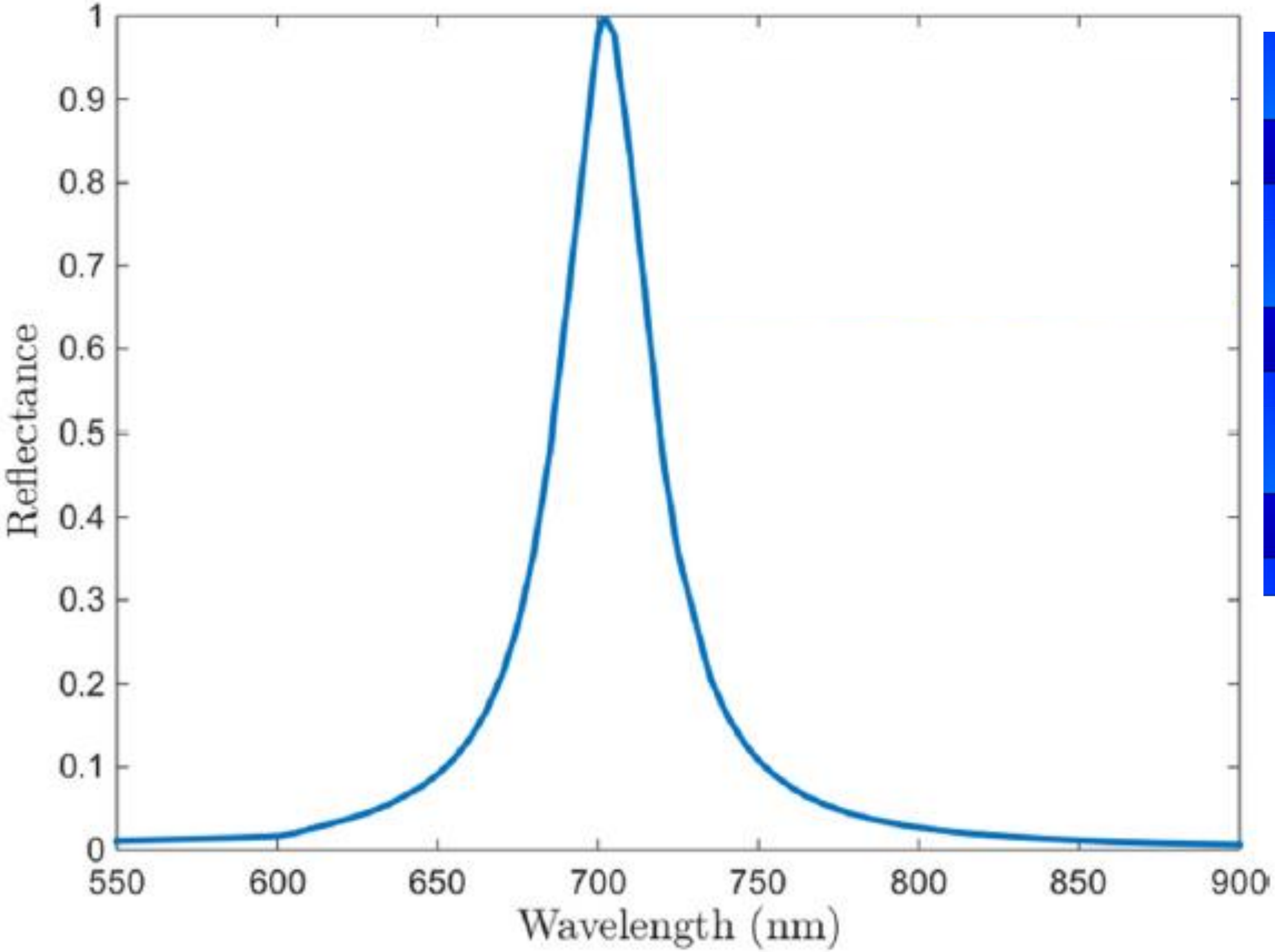


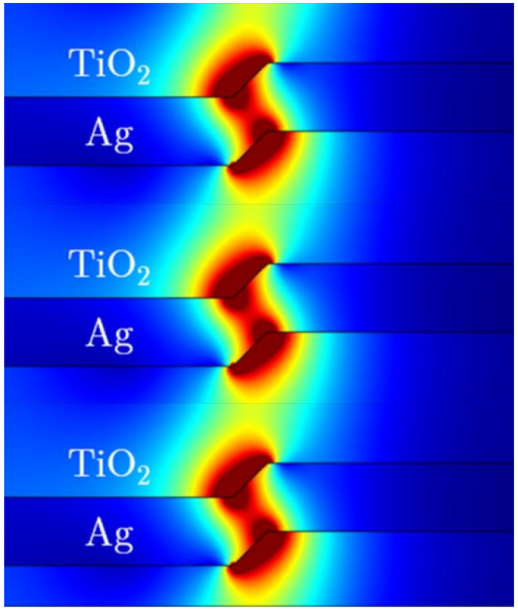
Evanescent background

Fabry-Pérot

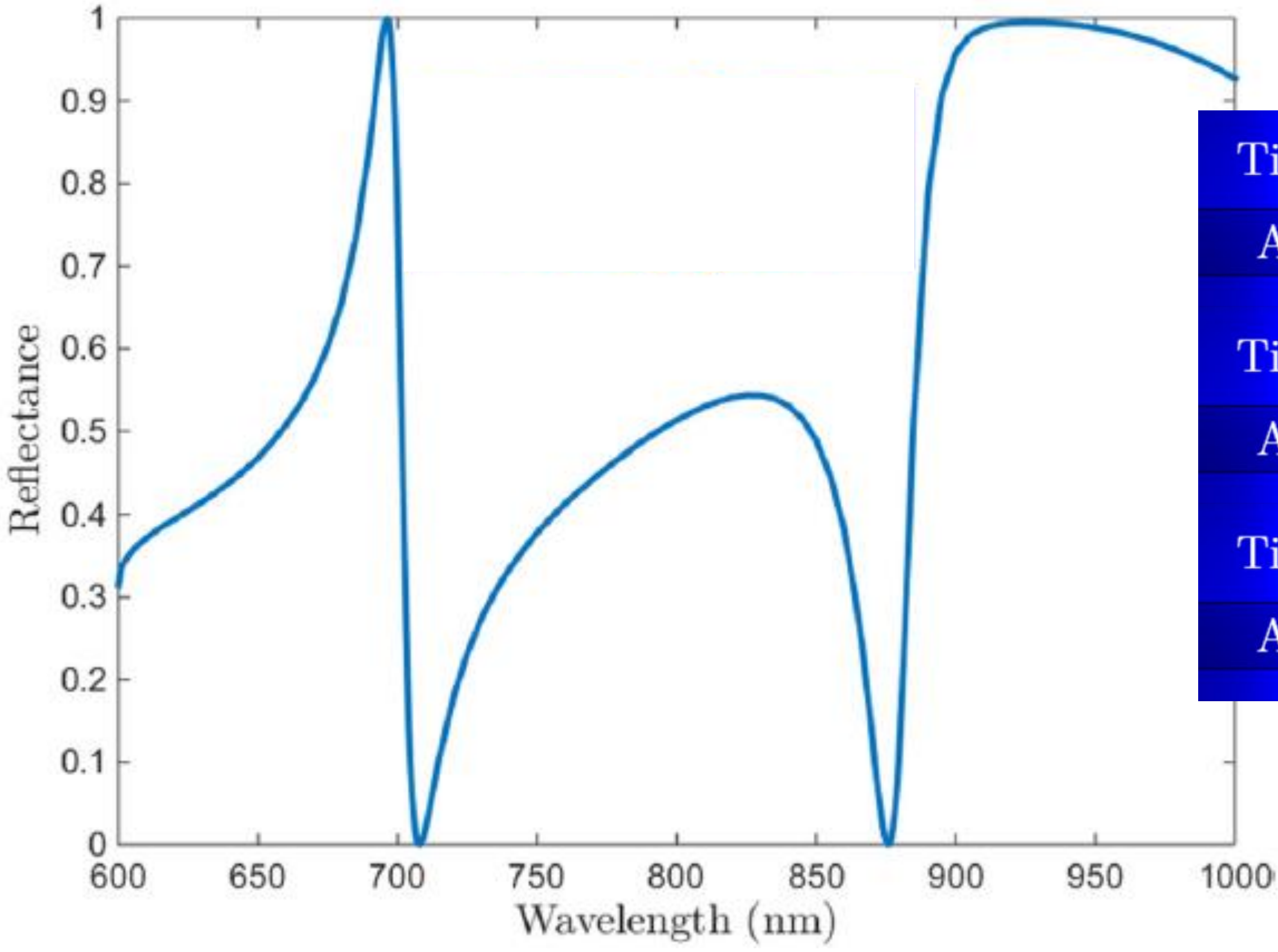
Exact reflection

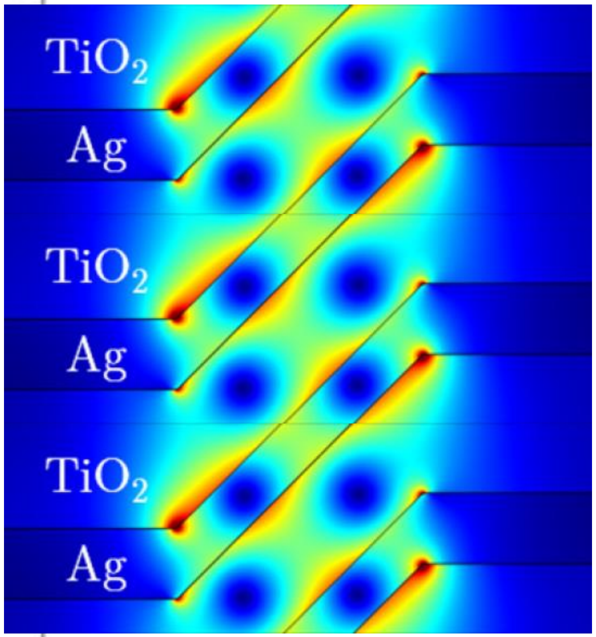
Spectrum for B = 5 nm



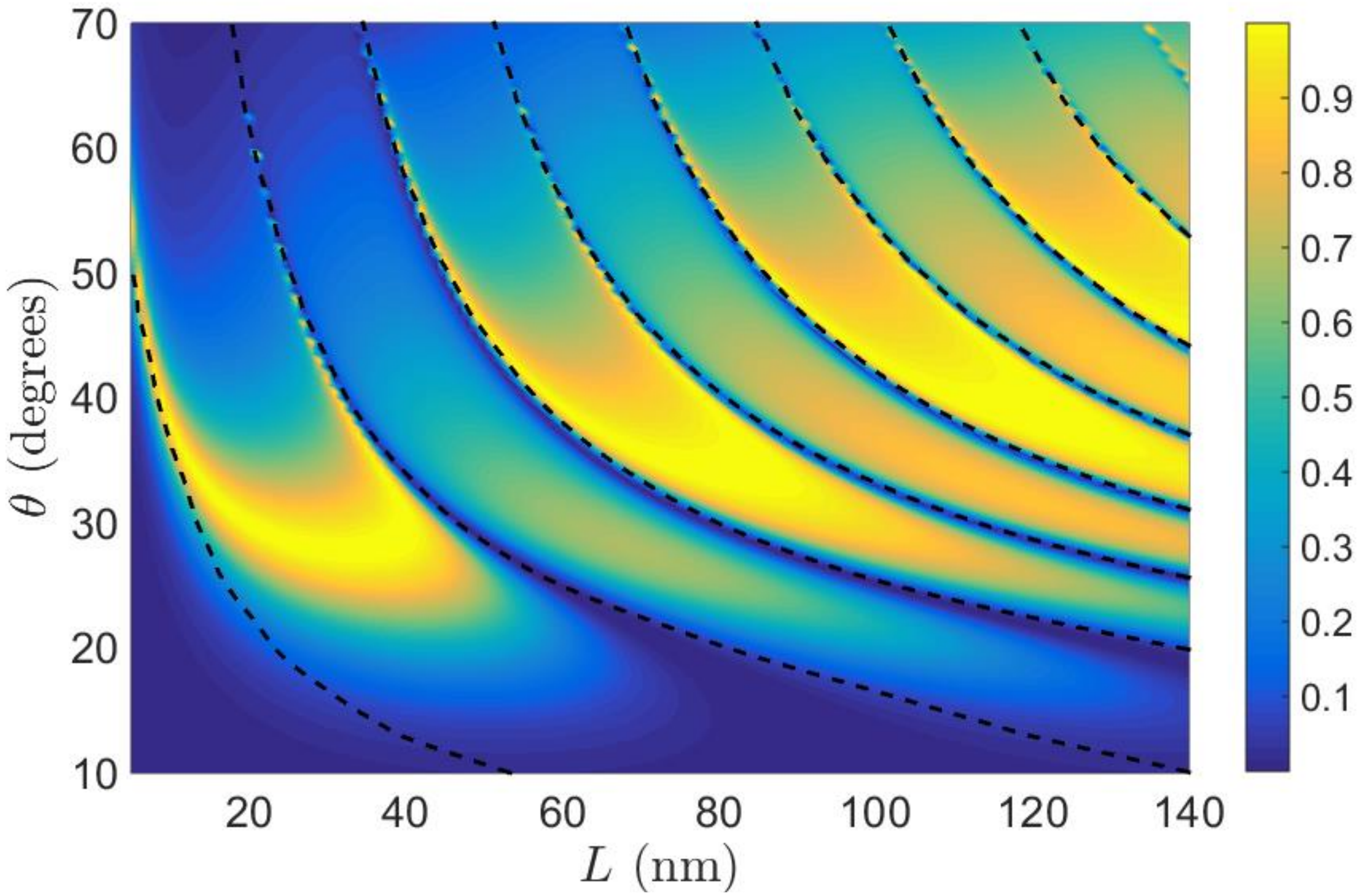


Spectrum for B = 35 nm





Reflection map (without loss)

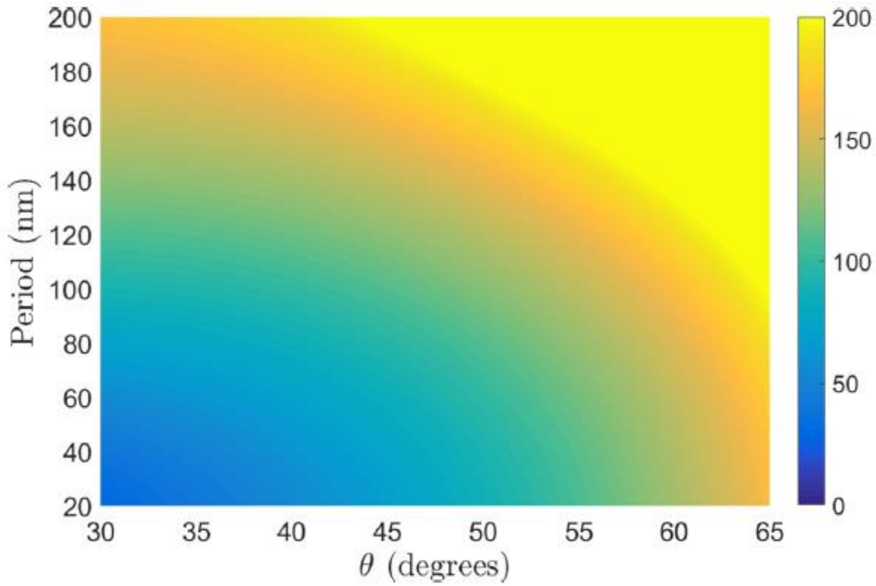


- - - - - - - $2k_x(\theta)B + 2\varphi(\theta) = 2\pi m$ Phase matching

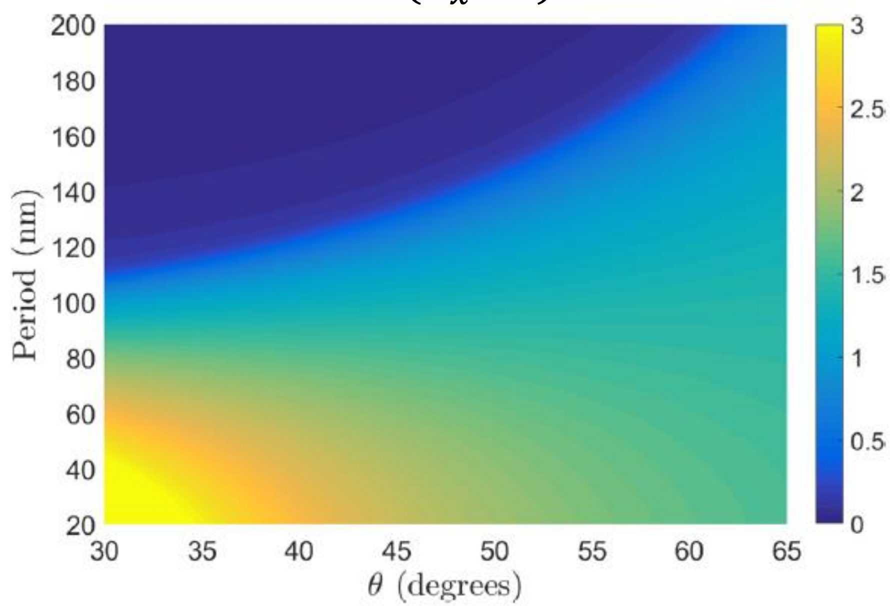
F. Vaianella and B. Maes, Physical Review B, vol. 94, pp 125442. (2016)

Lossy metal : condition for Fano resonances

$Re(n_x^{prop})/Im(n_x^{prop})$

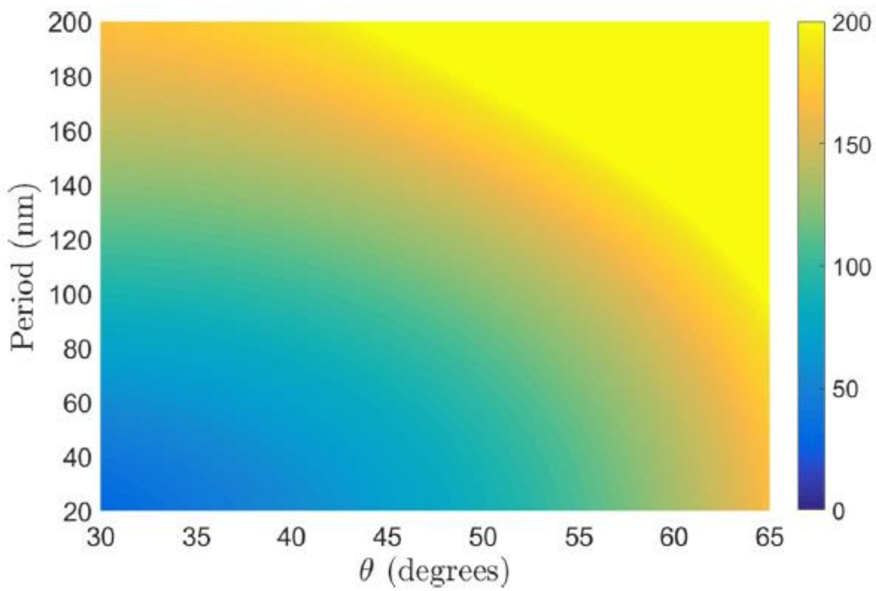


$Im(n_x^{evan})$

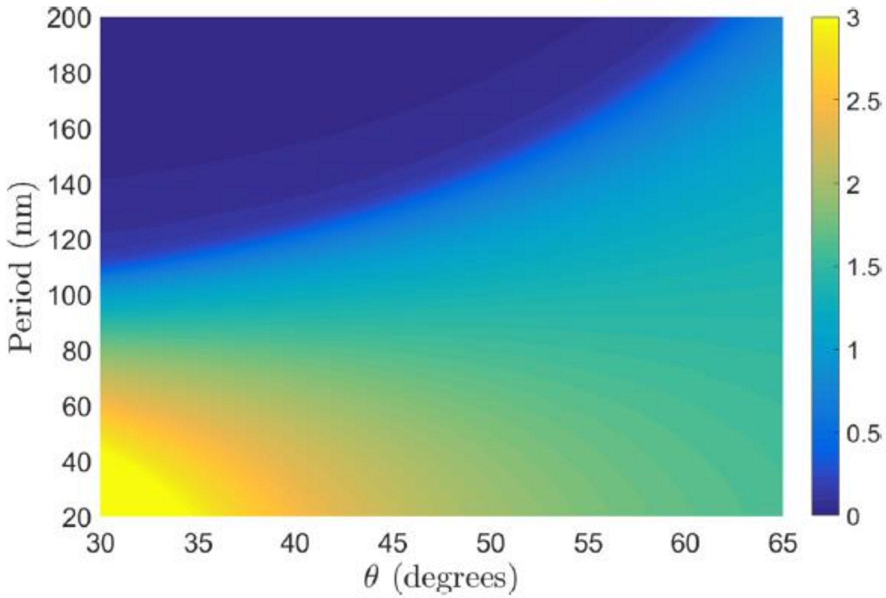


Lossy metal : condition for Fano resonances

$Re(n_x^{prop})/Im(n_x^{prop})$



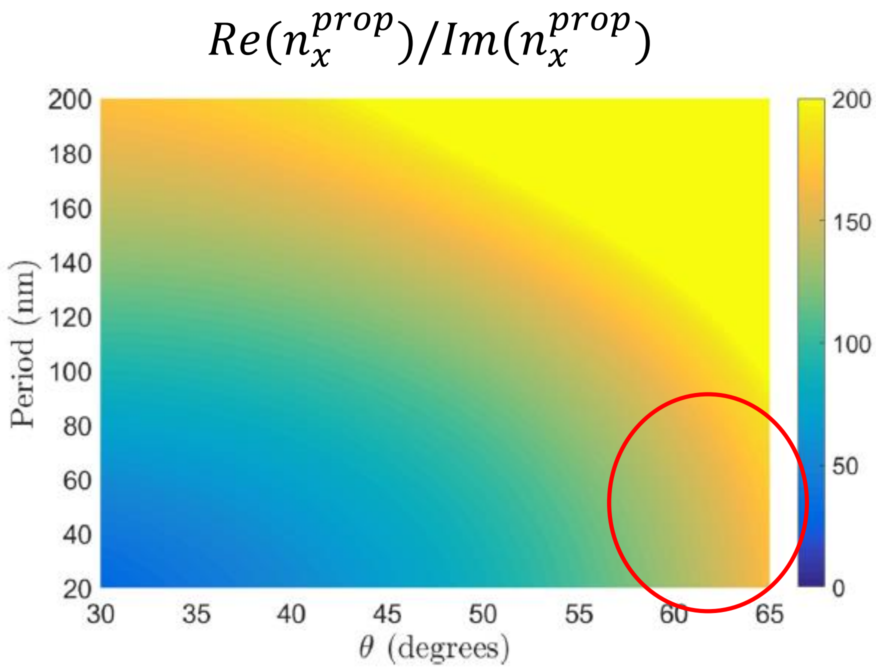
$Im(n_x^{evan})$

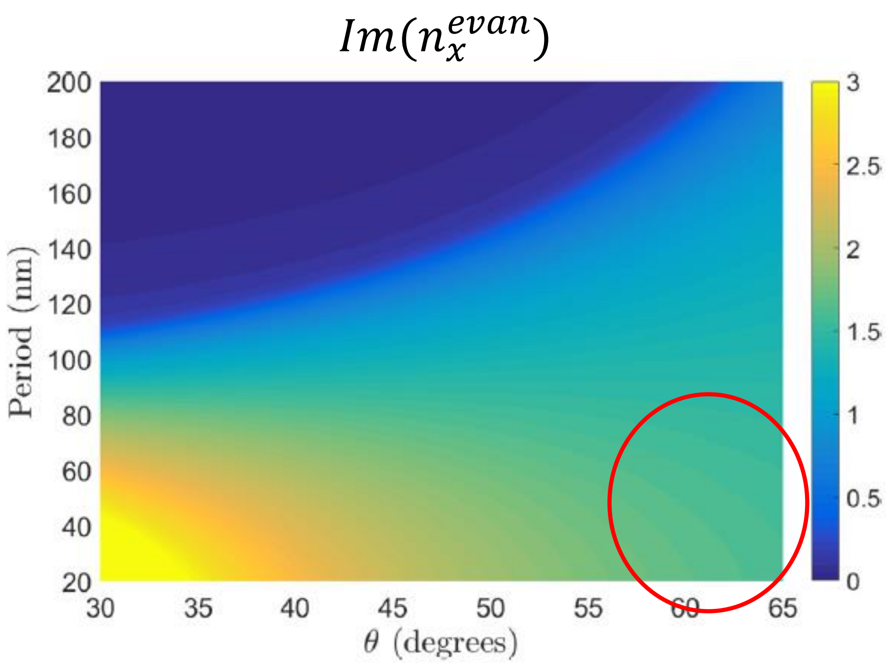


- Propagating mode should have large real part and small imaginary part of refractive effective index

- Evanescent mode should have imaginary part not to high (background would disappear) And not to low (background not efficient)

Lossy metal : conditions for Fano resonances

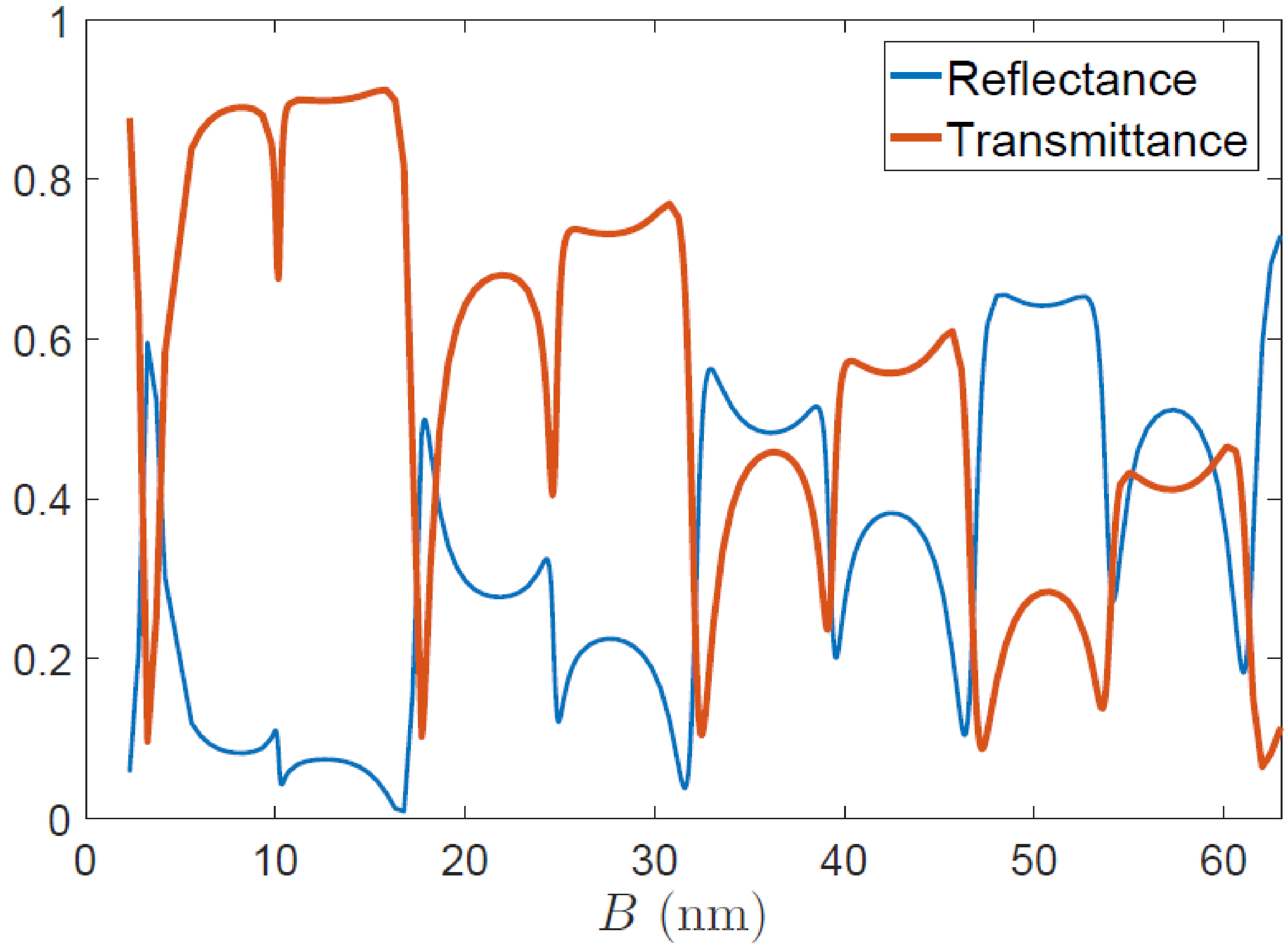




➢ Propagating mode should have large real part and small imaginary part of refractive effective index

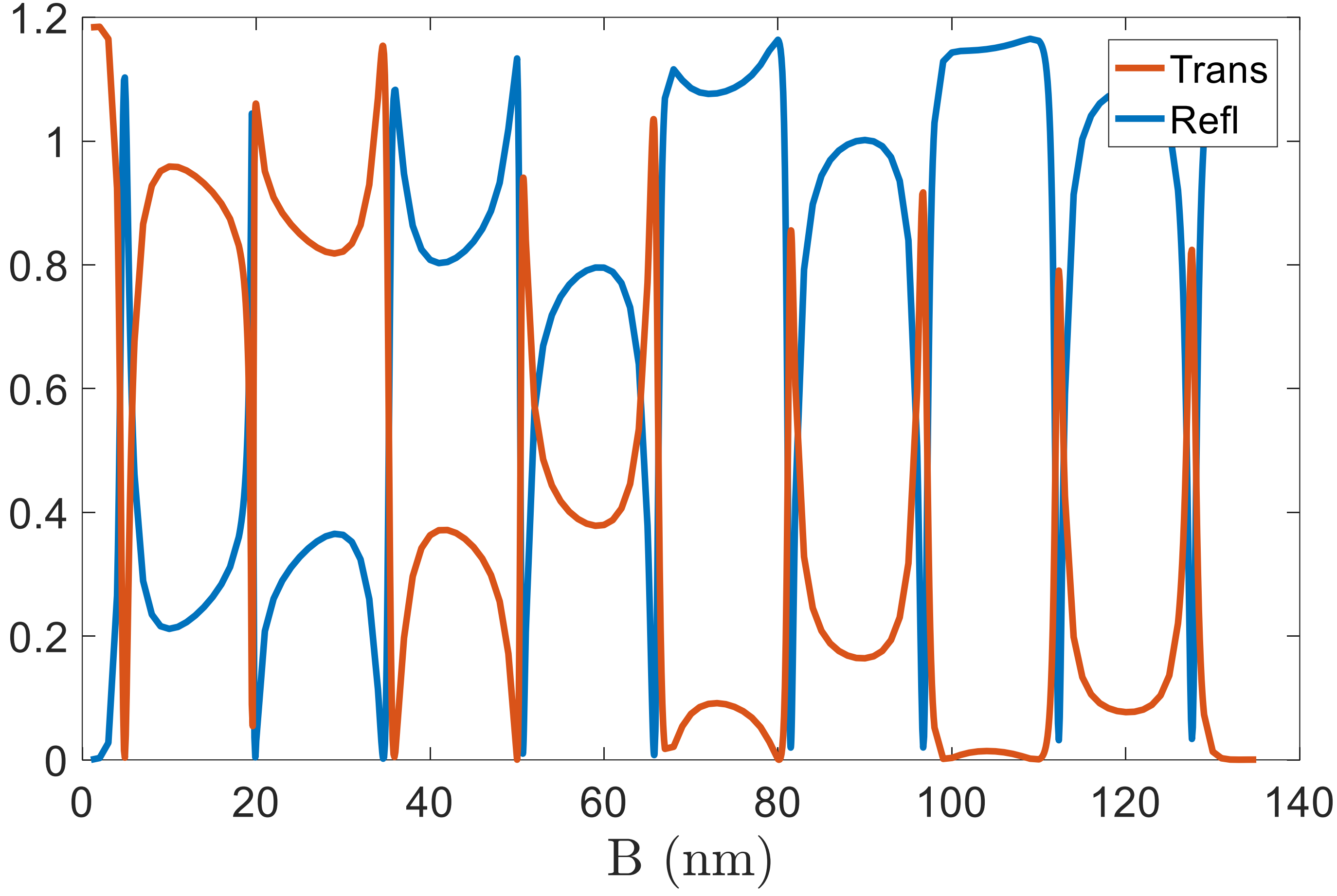
➢ Evanescent mode should have imaginary part not to high (background would disappear) and not to low (background not efficient)

Scattering with losses for $\Theta = 65°$

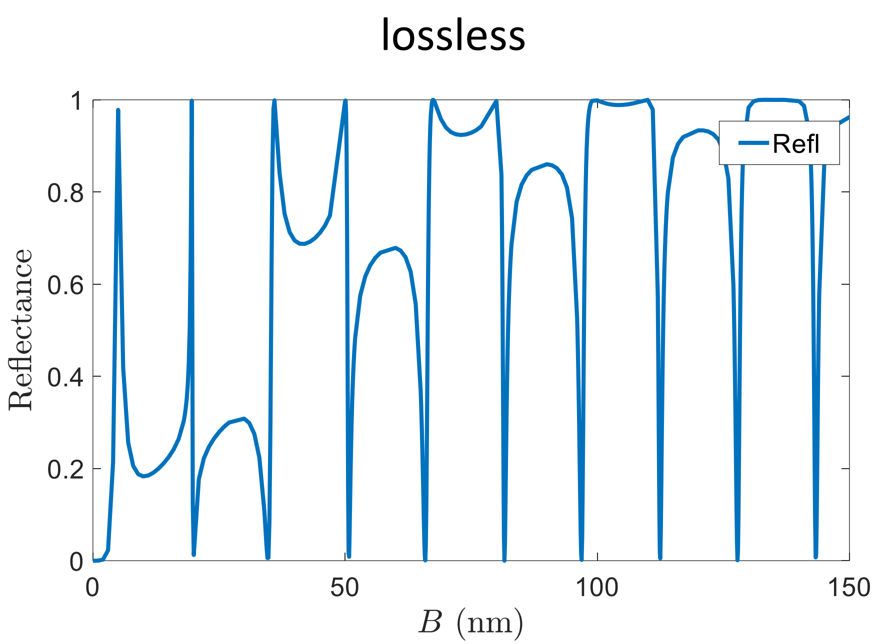


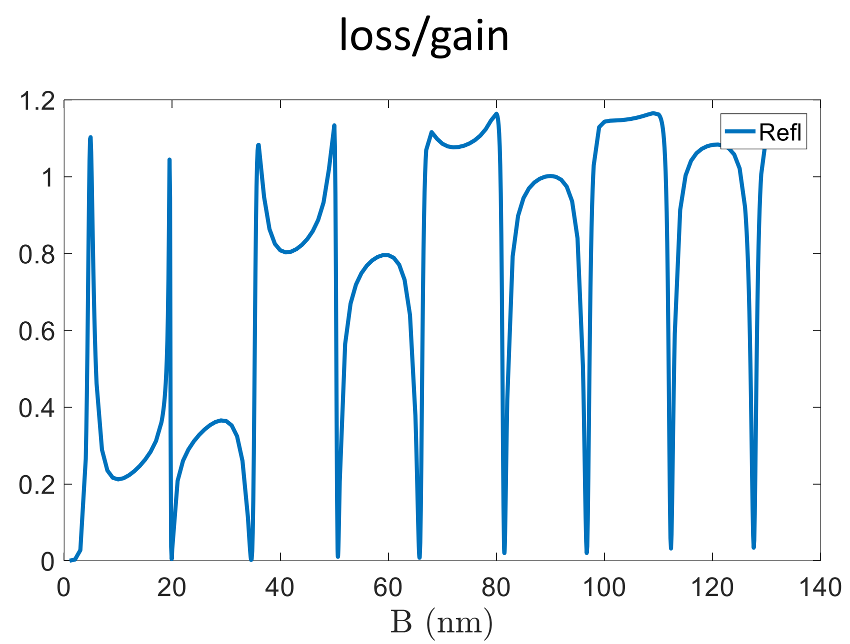
Fano resonances still present but more or less damped

Introduction of gain in the dielectric : $\mathrm{Im}(n_{TiO_2}) = -0,07$



Comparison lossless – gain/loss structures





Introduction of gain allows 100% transmittance-reflectance Fano resonances
Actually difficult to introduce gain in TiO2
Would be easier to work with semiconductors in infrared regime

Conclusions

- Hyperbolic metamaterials are periodic plasmonic structures with positive component of dielectric tensor in one direction and negative in another

- Fano resonances in ultra compact cavities for great control of the reflection and transmission of light

- Effective medium approximation inaccurate for this work. Predicts the excitation of one single mode, no Fano resonances possible

- Other topics: Heat transfer, active HMM, tunable HMM with graphene, homogenization theory, …

Thank you for your attention

This work is financially supported by the F.R.I.A.-F.N.R.S.