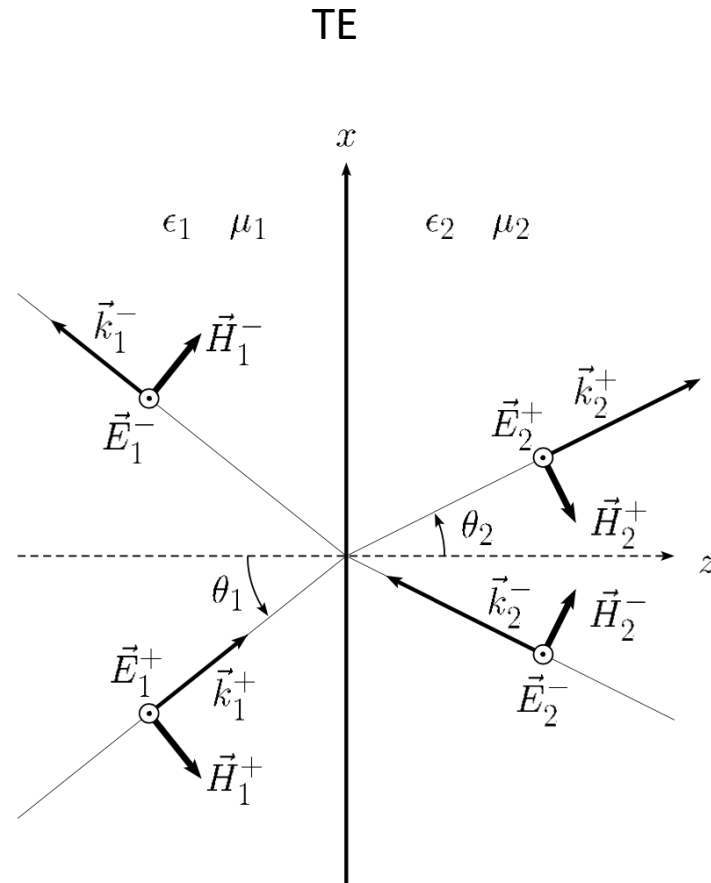
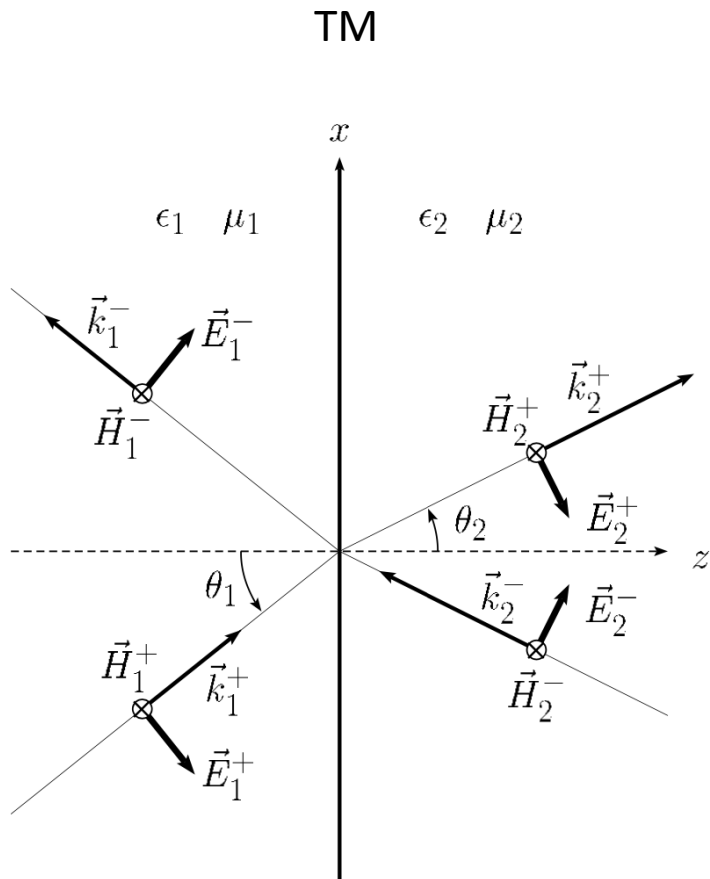


אופטיקה של חומרים דו-מימדיים - שיעור מס. 3

- The Transfer-Matrix-Method
- מבוא לפולריטונים
- Surface-plasmon-polaritons

מעבר גלים בין שתי שכבות



$$\hat{n} \cdot (\vec{B}_2 - \vec{B}_1) = 0 \Rightarrow B_{1\perp} = B_{2\perp}$$

$$\hat{n} \times (\vec{E}_2 - \vec{E}_1) = 0 \Rightarrow \vec{E}_{1\parallel} = \vec{E}_{2\parallel}$$

$$\hat{n} \cdot (\vec{D}_2 - \vec{D}_1) = \sigma \Rightarrow D_{2\perp} - D_{1\perp} = \sigma$$

(σ = surface charge density)

$$\hat{n} \times (\vec{H}_2 - \vec{H}_1) = \vec{K} \Rightarrow \vec{H}_{2\parallel} - \vec{H}_{1\parallel} = \vec{K}$$

(\vec{K} = surface current density)

מעבר גלים בין שתי שכבות-TM

$$\vec{H} = (0, H, 0)$$

$$\vec{E} = (E_x, 0, E_z)$$

$$H_1^+ + H_1^- = H_2^+ + H_2^-$$

מתנאי השפה נדרוש:

$$E_{1x}^+ + E_{1x}^- = E_{2x}^+ + E_{2x}^-$$

$$\vec{k} \times \vec{H} = -\frac{\epsilon\omega}{c} \vec{E},$$

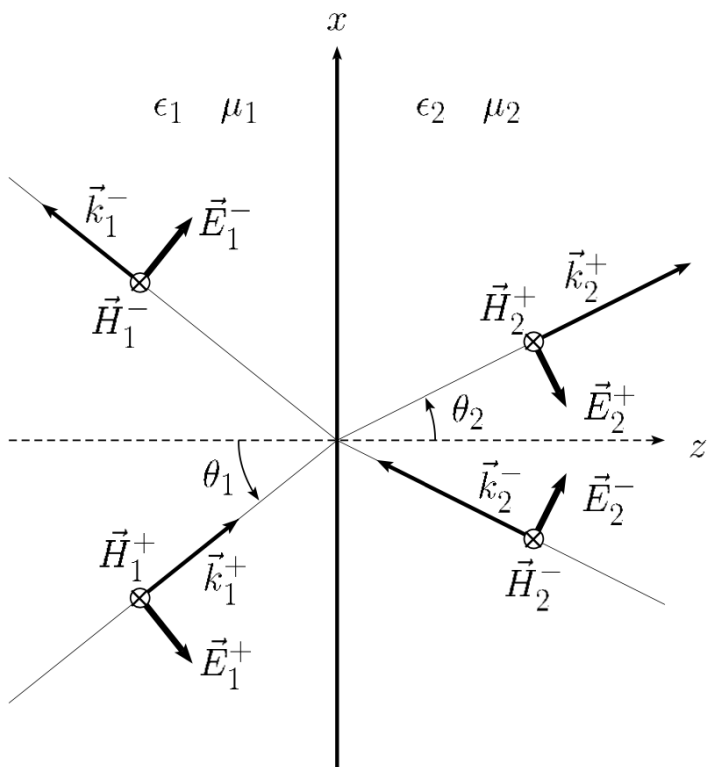
$$\frac{\epsilon_1\omega}{c} E_{1x}^+ = k_{1z} H_1^+ \quad \text{and} \quad \frac{\epsilon_1\omega}{c} E_{1x}^- = -k_{1z} H_1^-$$

$$\begin{pmatrix} 1 & 1 \\ \frac{k_{1z}}{\epsilon_1} & -\frac{k_{1z}}{\epsilon_1} \end{pmatrix} \begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ -\frac{k_{2z}}{\epsilon_2} & +\frac{k_{2z}}{\epsilon_2} \end{pmatrix} \begin{pmatrix} H_2^+ \\ H_2^- \end{pmatrix}$$

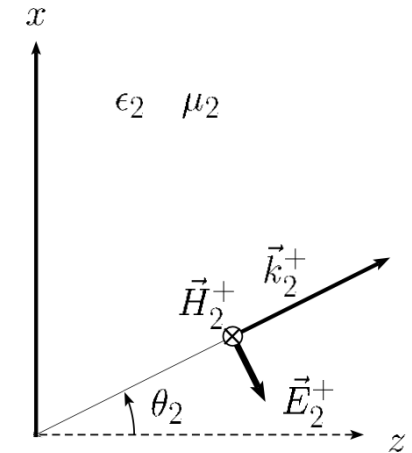
$$\begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} = \tilde{M}^{(p)} \begin{pmatrix} H_2^+ \\ H_2^- \end{pmatrix} = \begin{pmatrix} M_{11} H_2^+ + M_{12} H_2^- \\ M_{21} H_2^+ + M_{22} H_2^- \end{pmatrix}$$

$$\tilde{M}^{(p)} = \frac{1}{2} \begin{pmatrix} 1 + \frac{\epsilon_1 k_{2z}}{\epsilon_2 k_{1z}} & 1 - \frac{\epsilon_1 k_{2z}}{\epsilon_2 k_{1z}} \\ 1 - \frac{\epsilon_1 k_{2z}}{\epsilon_2 k_{1z}} & 1 + \frac{\epsilon_1 k_{2z}}{\epsilon_2 k_{1z}} \end{pmatrix} \quad r = \frac{M_{21}}{M_{11}} \quad t = \frac{1}{M_{11}}$$

Transmission Matrix



התקדמות גלים בתוך שכבה:

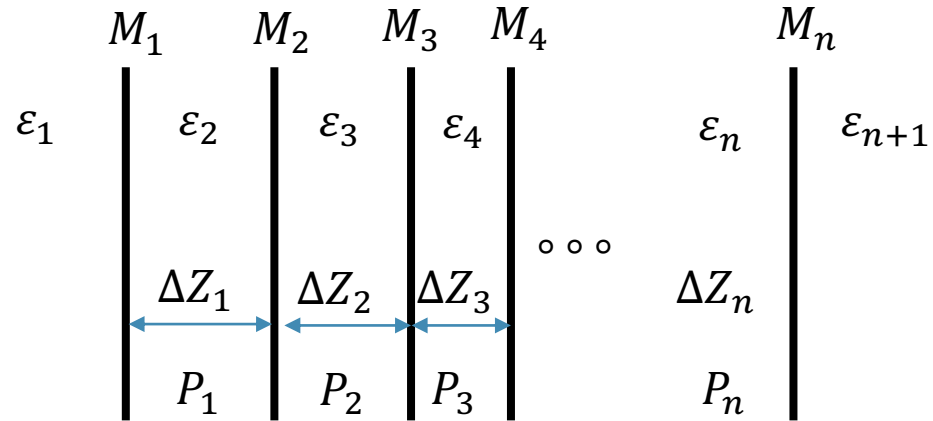


$$\begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} = P(\Delta z) \begin{pmatrix} H_2^+ \\ H_2^- \end{pmatrix}$$

$$P(\Delta z) = \begin{bmatrix} e^{-ik_z \Delta z} & 0 \\ 0 & e^{ik_z \Delta z} \end{bmatrix}$$

Propagation Matrix

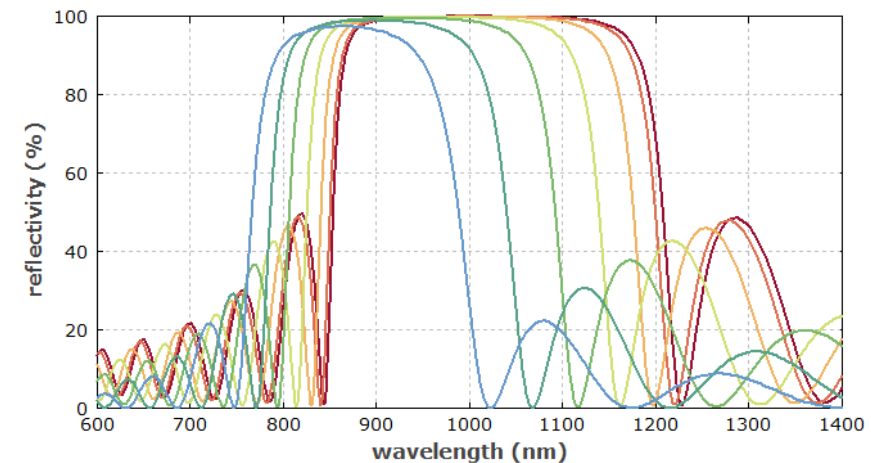
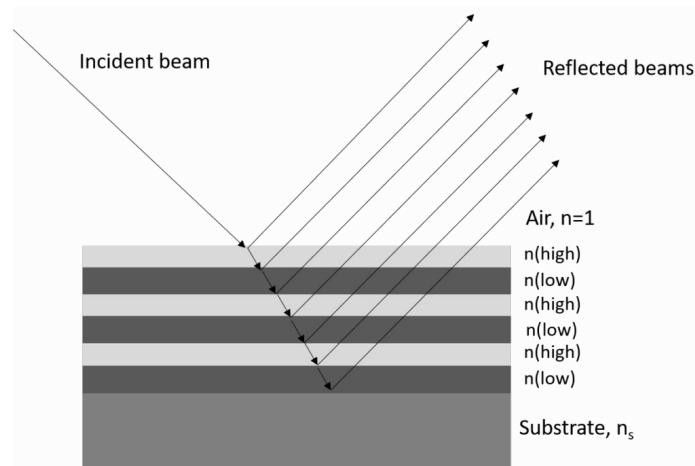
Transfer-Matrix-Method



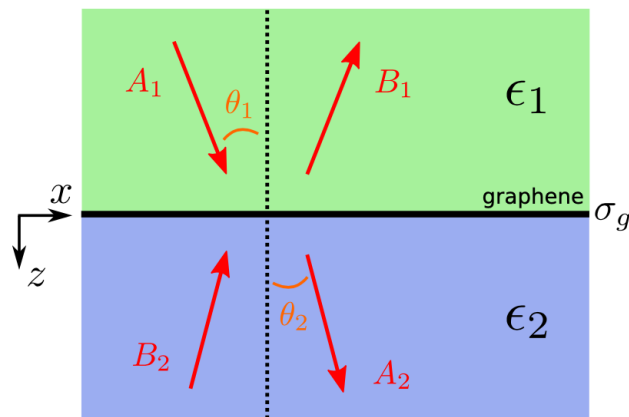
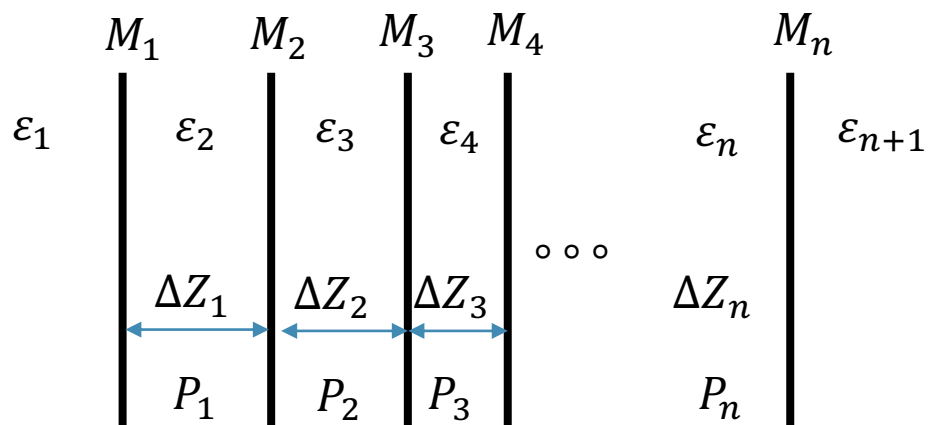
$$\begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} = TM \begin{pmatrix} H_2^+ \\ H_2^- \end{pmatrix}$$

$$TM = M_1 P_1 M_2 P_2 \cdots M_{n+1}$$

Bragg mirrors



חומרים דו-מימדיים

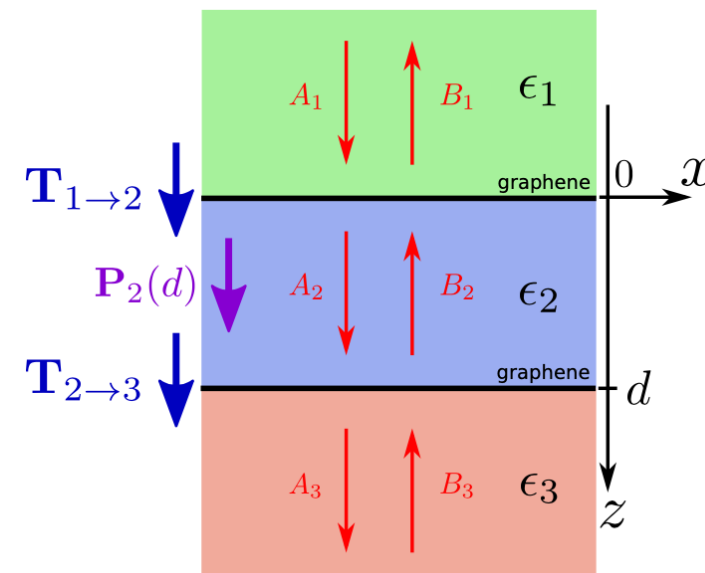


$$E_{1,x}(x, z)|_{z=0} = E_{2,x}(x, z)|_{z=0} ,$$

$$B_{1,y}(x, z)|_{z=0} - B_{2,y}(x, z)|_{z=0} = 0$$

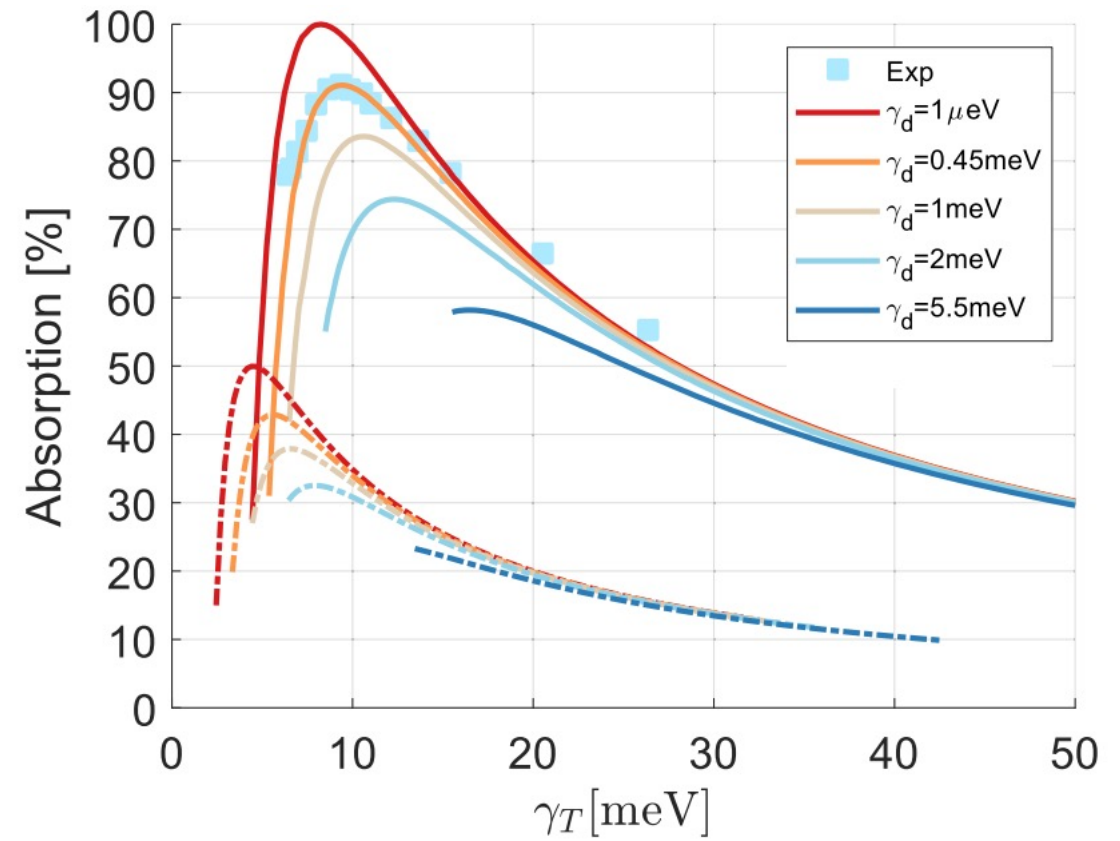
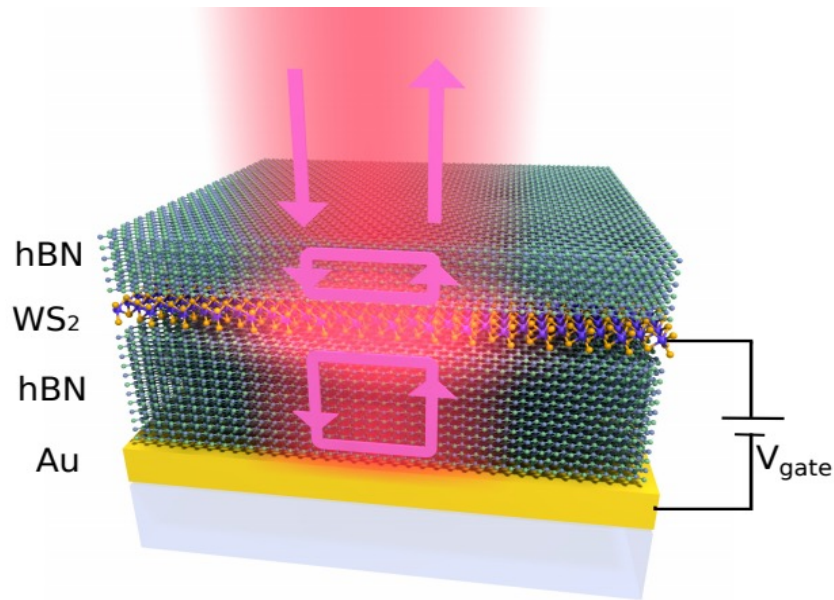
$$E_{1,x}(x, z)|_{z=0} = E_{2,x}(x, z)|_{z=0} ,$$

$$B_{1,y}(x, z)|_{z=0} - B_{2,y}(x, z)|_{z=0} = \mu_0 J_x(x) = \mu_0 \sigma_{xx} E_{2,x}(x, z)|_{z=0}$$



חומרים דו-מימדיים

דוגמה: 100% בליעה בשכבה אטומית של מוליך למחצה



Introduction to Polaritons

Polaritons = coupled to a photon

Matter excitation

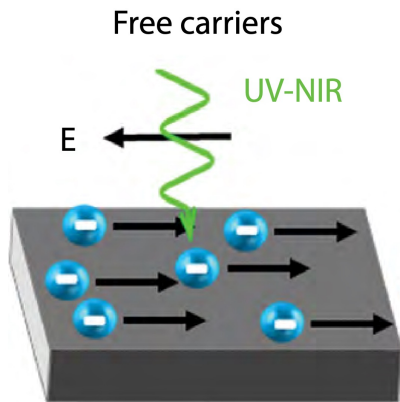
Light

Electric dipole oscillations

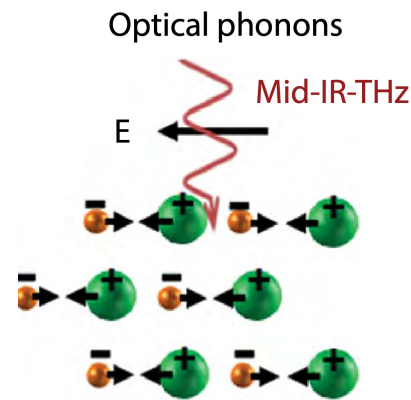


Electromagnetic field oscillations

Caldwell et al, Nanophotonics 4, 44 (2015)

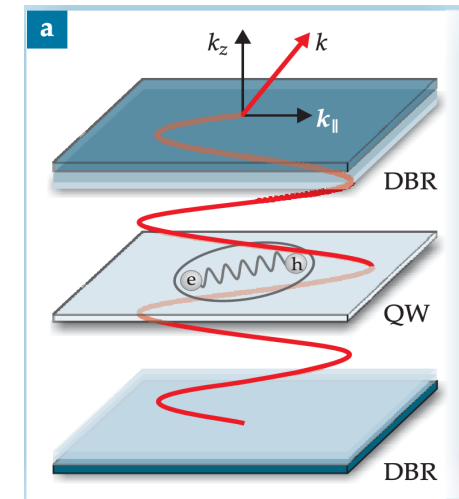


Surface-plasmon-polaritons

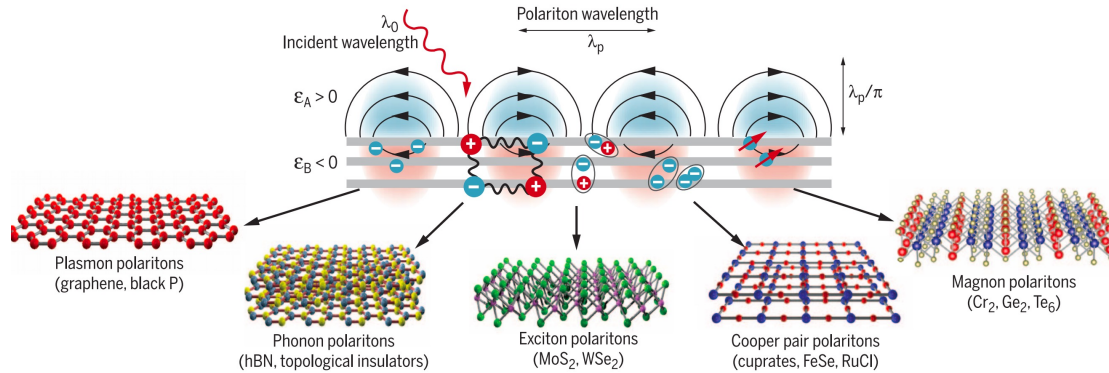


Surface-phonon-polaritons

Exciton-polaritons



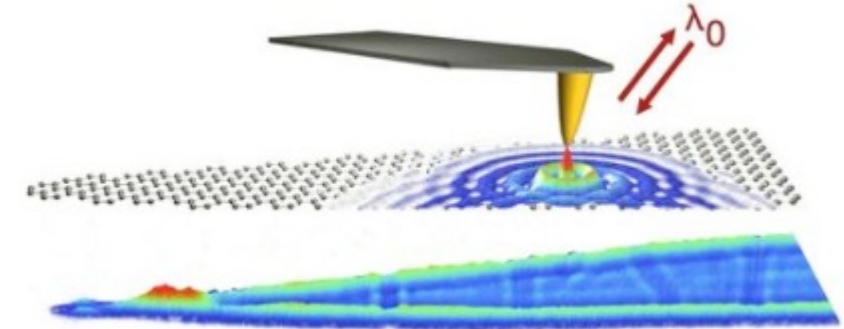
Polaritons in 2D materials



D. N. Basov, M. M. Fogler, F. J. García de Abajo, *Science* 354, 6309(2016)

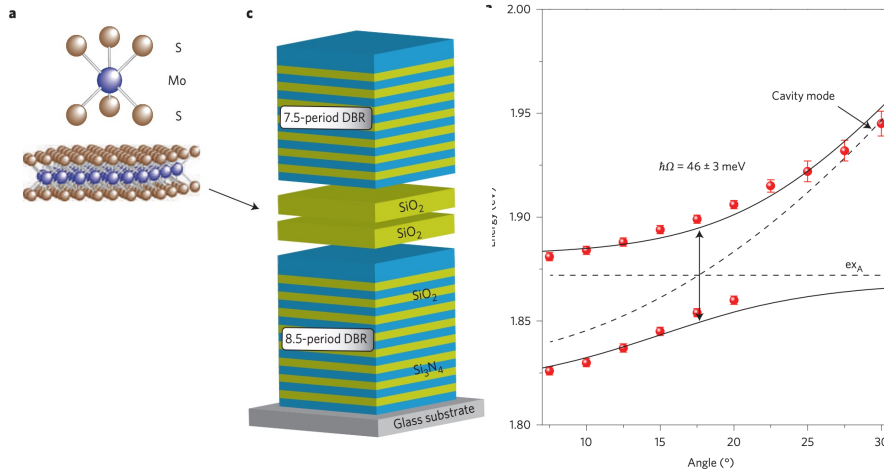
Low, T. et al, *Nat. Mater.* 16, 182–194 (2017).

D. N. Basov et al, *Nanophotonics* 10, 549-577(2021).

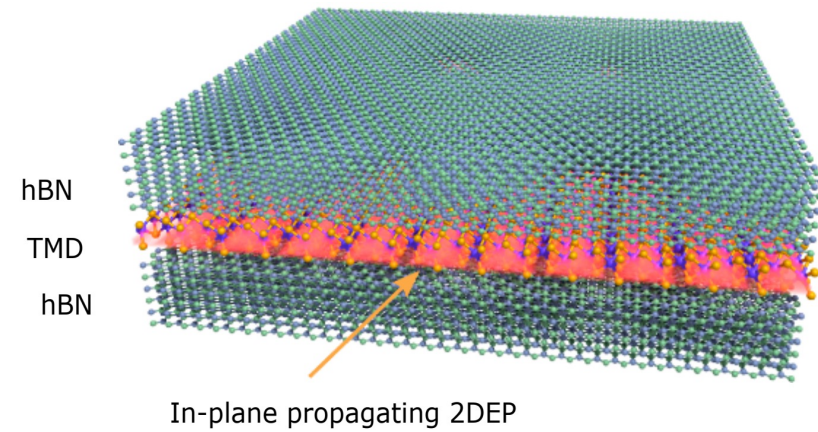


Fei, Z. et al, *Nature* 487, 82–85 (2012).

Chen, J. et al, *Nature* 487, 77–81 (2012).



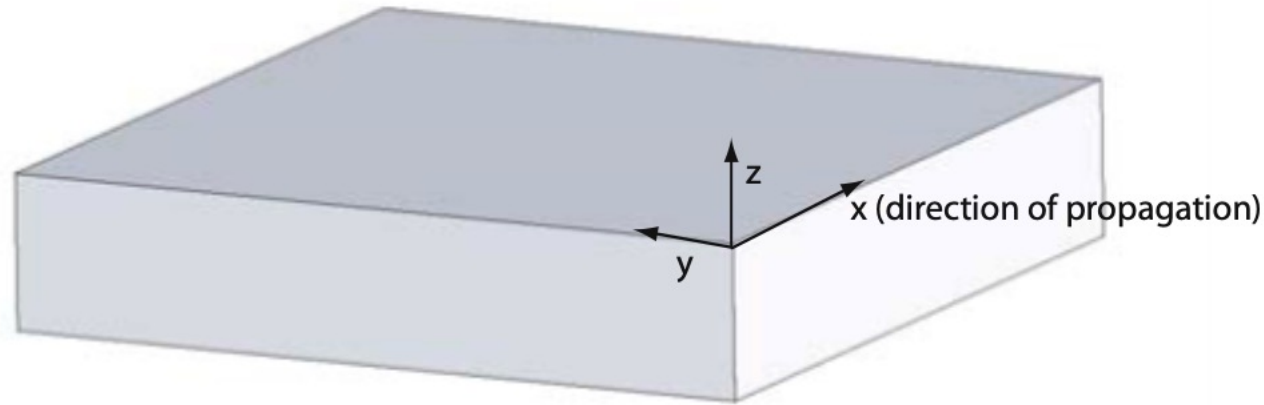
Liu, X., Galfsky, T., Sun, Z. et al. *Nat. Phot.* 9, 30–34 (2015).



I. Epstein et al, *2D Materials* 7, 035031 (2020)

Surface-plasmon-polaritons (SPPs)

- S.A. Maier- “plasmonics: fundamentals and applications”



$$\nabla^2 \mathbf{E} + k_0^2 \epsilon \mathbf{E} = 0$$

$$\mathbf{E}(x, y, z) = \mathbf{E}(z)e^{i\beta x}$$

$$\frac{\partial^2 \mathbf{E}(z)}{\partial z^2} + (k_0^2 \epsilon - \beta^2) \mathbf{E} = 0$$

$$\cancel{\frac{\partial E_z}{\partial y}} - \frac{\partial E_y}{\partial z} = i\omega\mu_0 H_x$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = i\omega\mu_0 H_y$$

$$\frac{\partial E_y}{\partial x} - \cancel{\frac{\partial E_x}{\partial y}} = i\omega\mu_0 H_z$$

$$\cancel{\frac{\partial H_z}{\partial y}} - \frac{\partial H_y}{\partial z} = -i\omega\epsilon_0 \epsilon E_x$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = -i\omega\epsilon_0 \epsilon E_y$$

$$\frac{\partial H_y}{\partial x} - \cancel{\frac{\partial H_x}{\partial y}} = -i\omega\epsilon_0 \epsilon E_z$$

Surface-plasmon-polaritons

$$\begin{aligned}\frac{\partial E_y}{\partial z} &= -i\omega\mu_0 H_x \\ \frac{\partial E_x}{\partial z} - i\beta E_z &= i\omega\mu_0 H_y \\ i\beta E_y &= i\omega\mu_0 H_z \\ \frac{\partial H_y}{\partial z} &= i\omega\varepsilon_0\varepsilon E_x \\ \frac{\partial H_x}{\partial z} - i\beta H_z &= -i\omega\varepsilon_0\varepsilon E_y \\ i\beta H_y &= -i\omega\varepsilon_0\varepsilon E_z.\end{aligned}$$

For TM:

E_x , E_z and H_y are nonzero

$$\begin{aligned}E_x &= -i\frac{1}{\omega\varepsilon_0\varepsilon}\frac{\partial H_y}{\partial z} \\ E_z &= -\frac{\beta}{\omega\varepsilon_0\varepsilon}H_y,\end{aligned}$$

wave equation for TM modes is

$$\frac{\partial^2 H_y}{\partial z^2} + (k_0^2\varepsilon - \beta^2) H_y = 0.$$

For a bound mode at the interface:

for $z > 0$ $k_i \equiv k_{z,i}$ ($i = 1, 2$)

$$H_y(z) = A_2 e^{i\beta x} e^{-k_2 z} \quad \text{Re}(K) > 0$$

$$E_x(z) = iA_2 \frac{1}{\omega\varepsilon_0\varepsilon_2} k_2 e^{i\beta x} e^{-k_2 z}$$

$$E_z(z) = -A_1 \frac{\beta}{\omega\varepsilon_0\varepsilon_2} e^{i\beta x} e^{-k_2 z}$$

for $z < 0$

$$H_y(z) = A_1 e^{i\beta x} e^{k_1 z}$$

$$E_x(z) = -iA_1 \frac{1}{\omega\varepsilon_0\varepsilon_1} k_1 e^{i\beta x} e^{k_1 z}$$

$$E_z(z) = -A_1 \frac{\beta}{\omega\varepsilon_0\varepsilon_1} e^{i\beta x} e^{k_1 z}$$

Surface-plasmon-polaritons

Continuity at the interface:

$$A_1 = A_2$$

$$\frac{k_2}{k_1} = -\frac{\epsilon_2}{\epsilon_1}$$



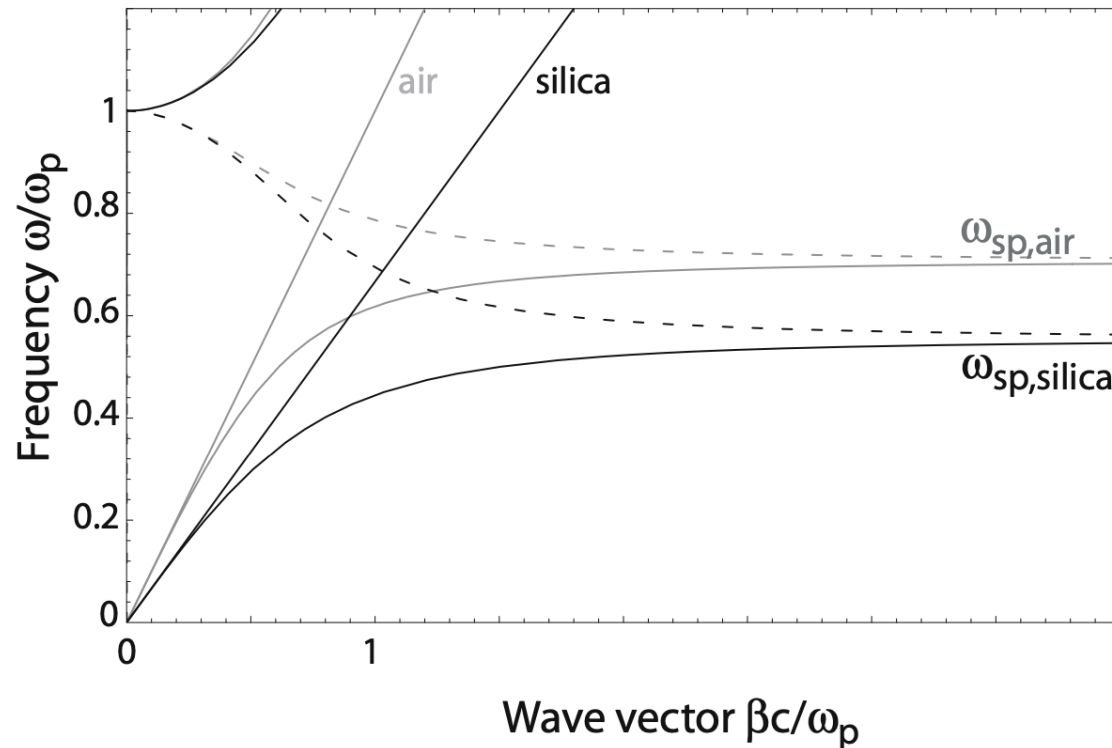
From the wave equation:

$$k_1^2 = \beta^2 - k_0^2 \epsilon_1$$

$$k_2^2 = \beta^2 - k_0^2 \epsilon_2$$

Dispersion relation:

$$\beta = k_0 \sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}}.$$



Surface-plasmon-polaritons

Dispersion relation
with real metals:

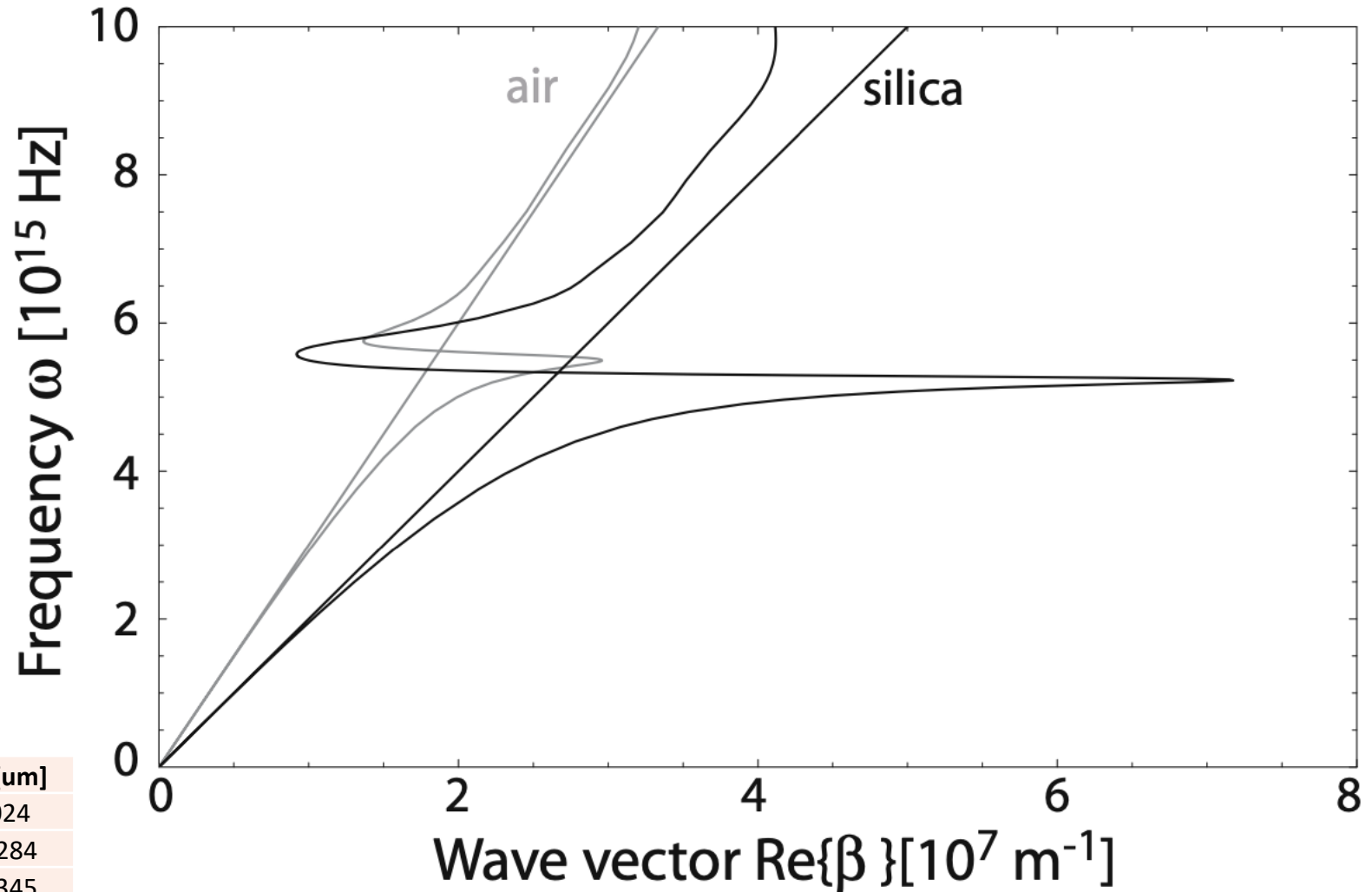
$$\beta = k_0 \sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}}$$

$$\lambda_{\text{sp}} = 2\pi / \text{Re}[\beta]$$

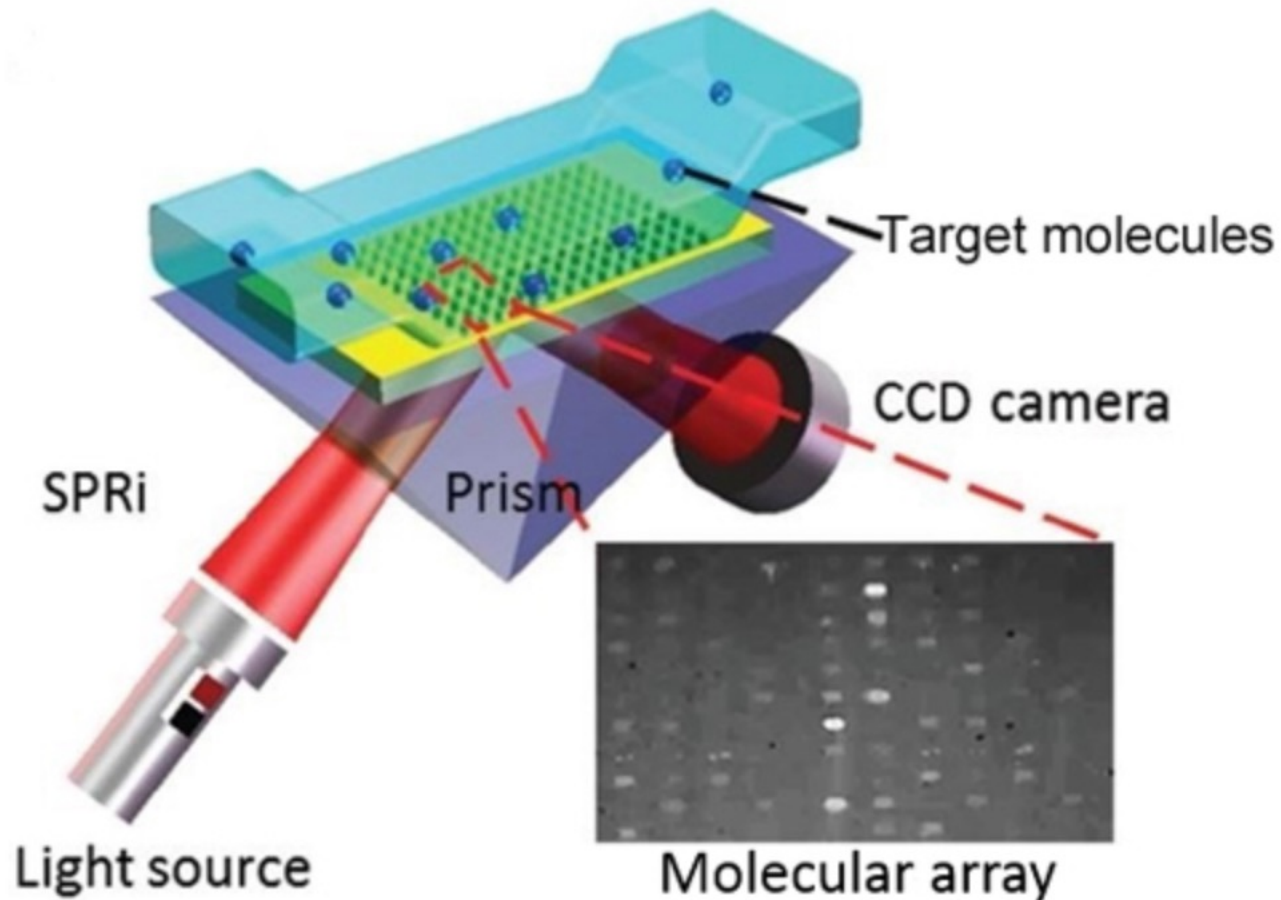
$$L = (2\text{Im}[\beta])^{-1}$$

$$\hat{z} = 1/|k_z|$$

lam0 [um]	lamSP [um]	L [um]	Zd [um]	Zm [um]
1.064	1.053	108	1.2	0.024
0.623	0.595	8.11	0.32	0.0284
0.45	0.442	0.4	0.22	0.0345



Surface Plasmon Resonance (SPR)



SPR-Pages

SPR Suppliers

- SPRpages home
- SPR Overview
- Kinetics
- Best results
- Sensor chips
- Immobilization
- Experiments
- Troubleshooting
- Data fitting
- Literature

Sensorgrams

SPR Instruments

- SPR Suppliers**
- SPR Services
- SPR Books
- SPR Software
- Downloads
- Science

Contact

- Forum
- Search
- Sitemap
- LogIn

SPR suppliers

On this page some of the main suppliers of SPR machines and s you know some other suppliers and your experience with them. on the logo.

FOX BIOSYSTEMS
Breaking limits in bioanalysis

FOX Biosystems is a dynam the life science and pharr innovative real-time, label success is a novel fiber-op SPR) biosensor which enal cost-effective biomolecular data accurately, fast, and over a wic ready to take its place in your high tech lab.

Creative Biostructure

Creative Biostructure is a structural biology with a t research services for basic coronavirus infection. Cur plasmon resonance (SPR) associated with coronavirus research and support the developr

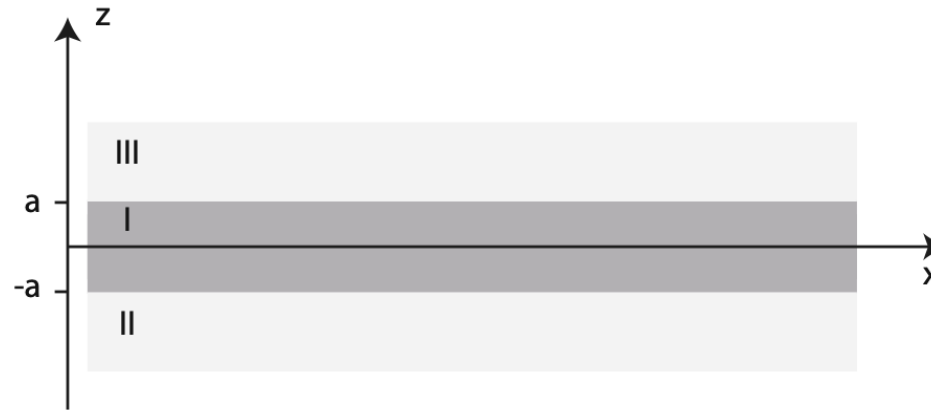
Affinité INSTRUMENTS

At Affinité we believe that fast, r accessible anywhere you need it and chemical innovations center discoveries push the boundaries applied to analytical chemistry, t monitoring.

xantec bioanalytics

Xantec bioanalytics provides lab Surface Plasmon Resonance (SPF technologies. Not only do we fea coatings and chemistries in the v number of different instruments

Surface-plasmon-polaritons - slab geometry



For $z > a$

$$H_y = A e^{i\beta x} e^{-k_3 z}$$

$$E_x = i A \frac{1}{\omega \epsilon_0 \epsilon_3} k_3 e^{i\beta x} e^{-k_3 z}$$

$$E_z = -A \frac{\beta}{\omega \epsilon_0 \epsilon_3} e^{i\beta x} e^{-k_3 z},$$

for $z < -a$

$$H_y = B e^{i\beta x} e^{k_2 z}$$

$$E_x = -i B \frac{1}{\omega \epsilon_0 \epsilon_2} k_2 e^{i\beta x} e^{k_2 z}$$

$$E_z = -B \frac{\beta}{\omega \epsilon_0 \epsilon_2} e^{i\beta x} e^{k_2 z}.$$

Surface-plasmon-polaritons - slab geometry

$$-a < z < a$$

$$H_y = Ce^{i\beta x} e^{k_1 z} + De^{i\beta x} e^{-k_1 z}$$

$$E_x = -iC \frac{1}{\omega \epsilon_0 \epsilon_1} k_1 e^{i\beta x} e^{k_1 z} + iD \frac{1}{\omega \epsilon_0 \epsilon_1} k_1 e^{i\beta x} e^{-k_1 z}$$

$$E_z = C \frac{\beta}{\omega \epsilon_0 \epsilon_1} e^{i\beta x} e^{k_1 z} + D \frac{\beta}{\omega \epsilon_0 \epsilon_1} e^{i\beta x} e^{-k_1 z}.$$

The requirement of continuity of H_y and E_x leads to

$$Ae^{-k_3 a} = Ce^{k_1 a} + De^{-k_1 a}$$

$$\frac{A}{\epsilon_3} k_3 e^{-k_3 a} = -\frac{C}{\epsilon_1} k_1 e^{k_1 a} + \frac{D}{\epsilon_1} k_1 e^{-k_1 a}$$

$$k_i^2 = \beta^2 - k_0^2 \epsilon_i$$

at $z = a$ and at $z = -a$

$$e^{-4k_1 a} = \frac{k_1/\epsilon_1 + k_2/\epsilon_2}{k_1/\epsilon_1 - k_2/\epsilon_2} \frac{k_1/\epsilon_1 + k_3/\epsilon_3}{k_1/\epsilon_1 - k_3/\epsilon_3}$$

$$Be^{-k_2 a} = Ce^{-k_1 a} + De^{k_1 a}$$

$$-\frac{B}{\epsilon_2} k_2 e^{-k_2 a} = -\frac{C}{\epsilon_1} k_1 e^{-k_1 a} + \frac{D}{\epsilon_1} k_1 e^{k_1 a}$$

Surface-plasmon-polaritons - slab geometry

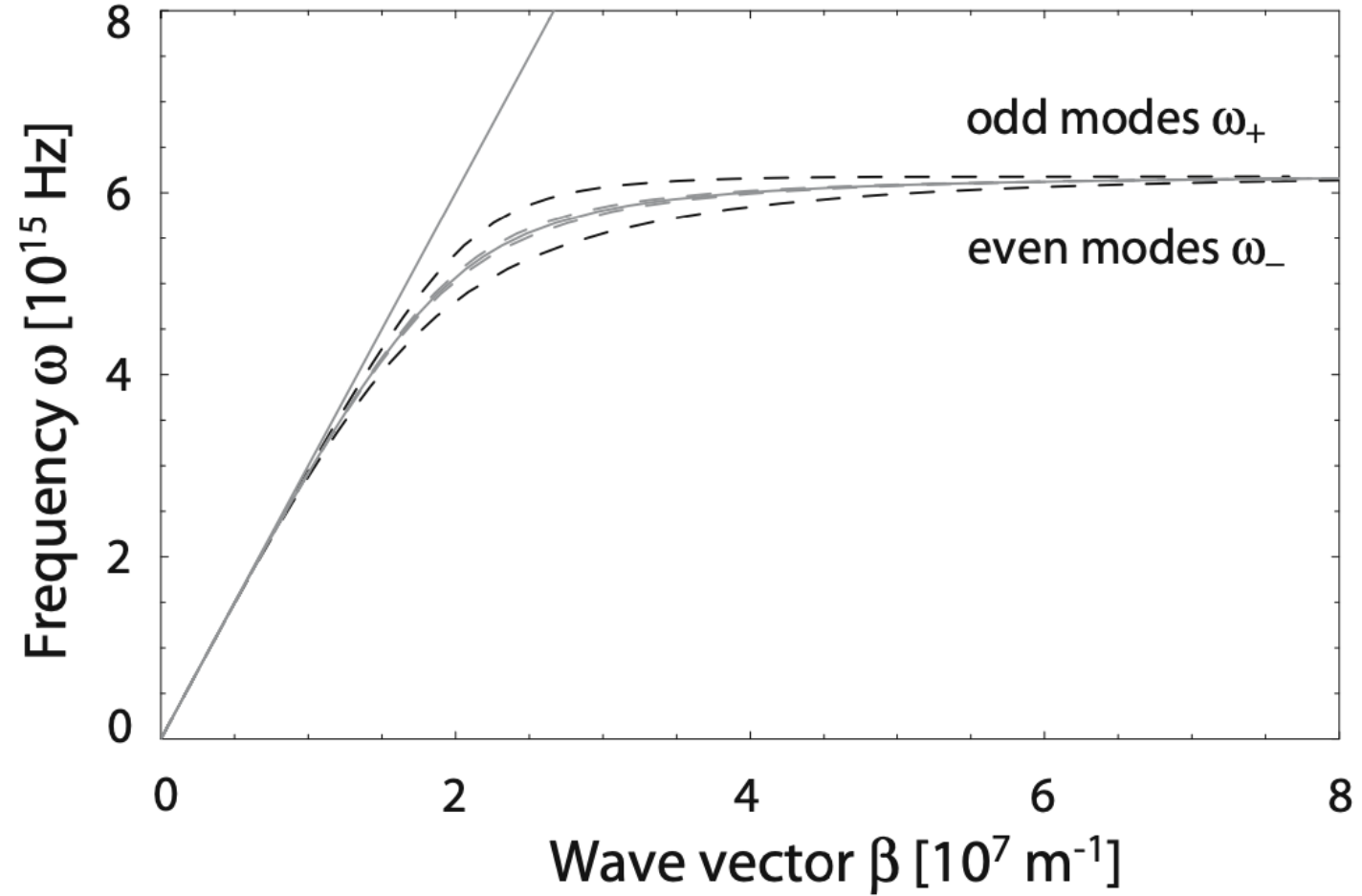
$$e^{-4k_1 a} = \frac{k_1/\varepsilon_1 + k_2/\varepsilon_2}{k_1/\varepsilon_1 - k_2/\varepsilon_2} \frac{k_1/\varepsilon_1 + k_3/\varepsilon_3}{k_1/\varepsilon_1 - k_3/\varepsilon_3}$$

$$\varepsilon_2 = \varepsilon_3 \text{ and thus } k_2 = k_3$$

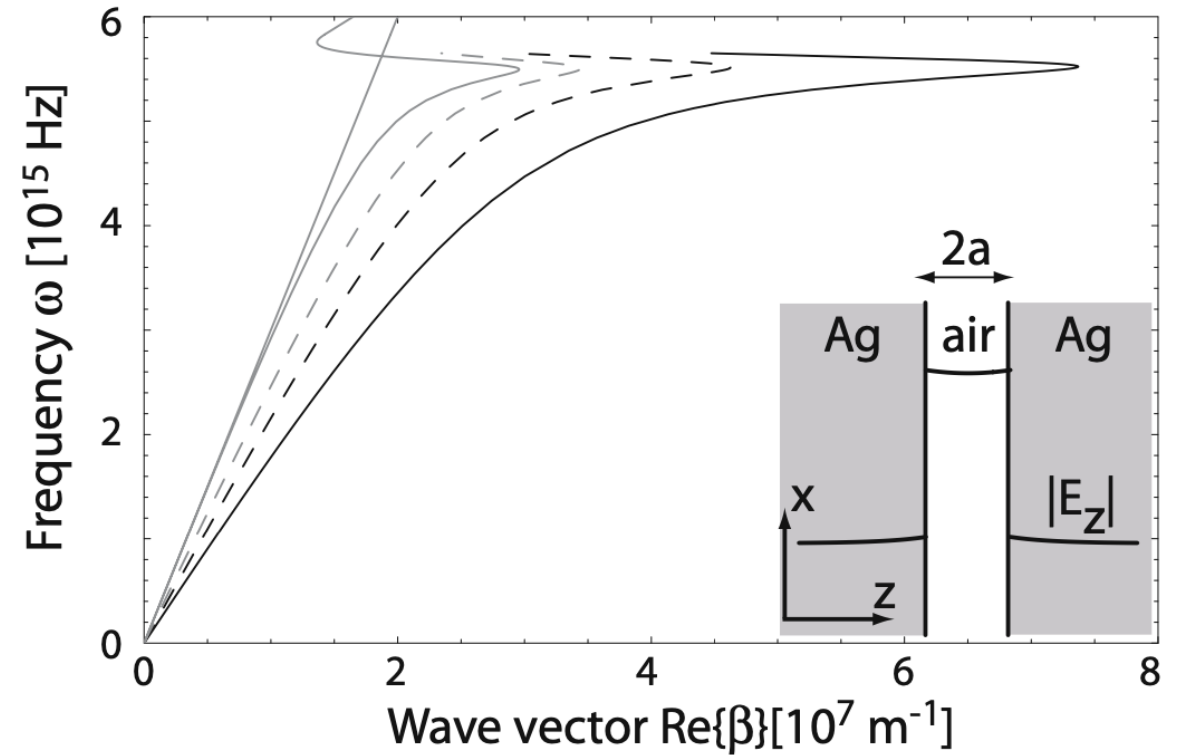
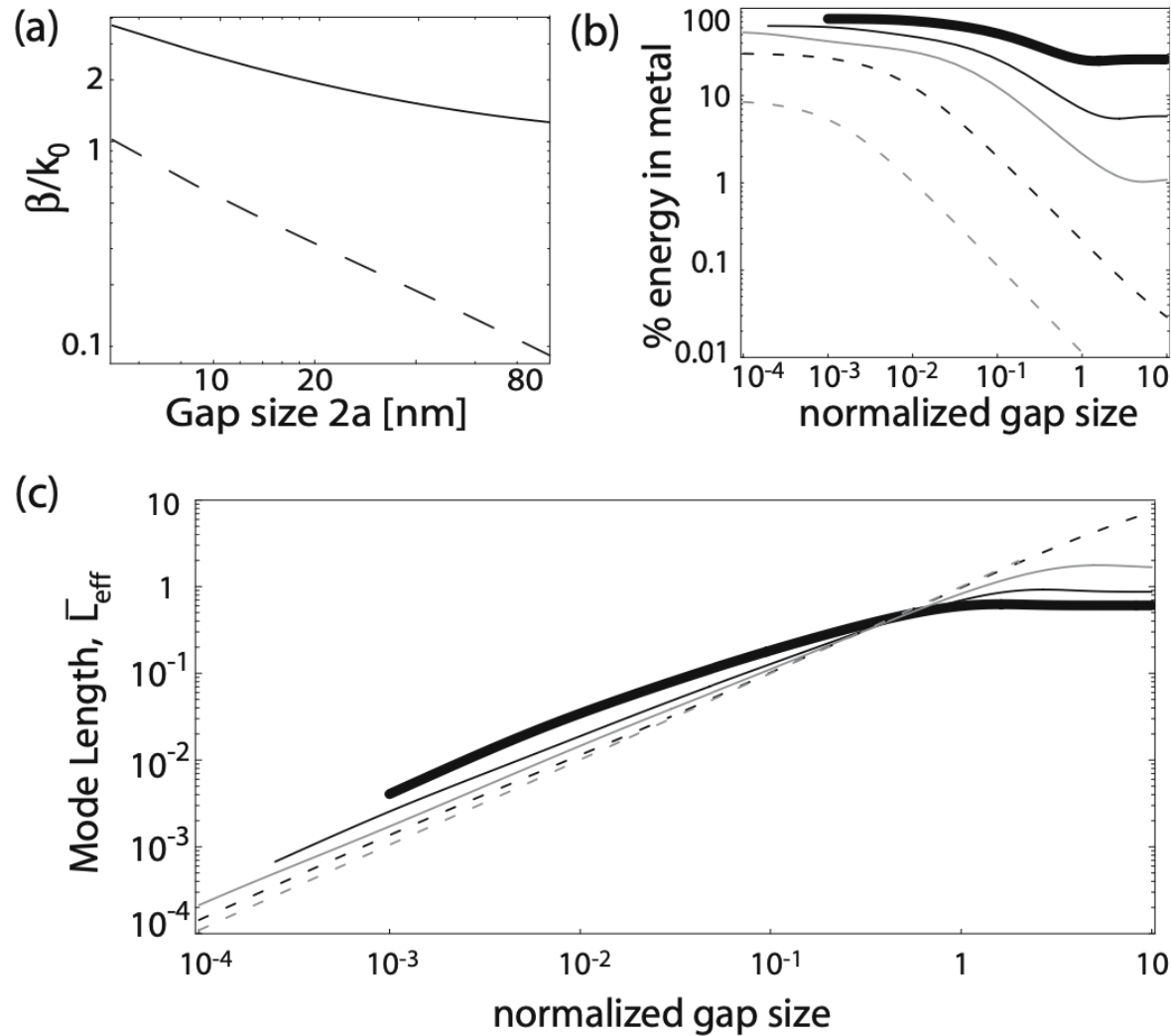
$$\tanh k_1 a = -\frac{k_2 \varepsilon_1}{k_1 \varepsilon_2}$$

$$\tanh k_1 a = -\frac{k_1 \varepsilon_2}{k_2 \varepsilon_1}$$

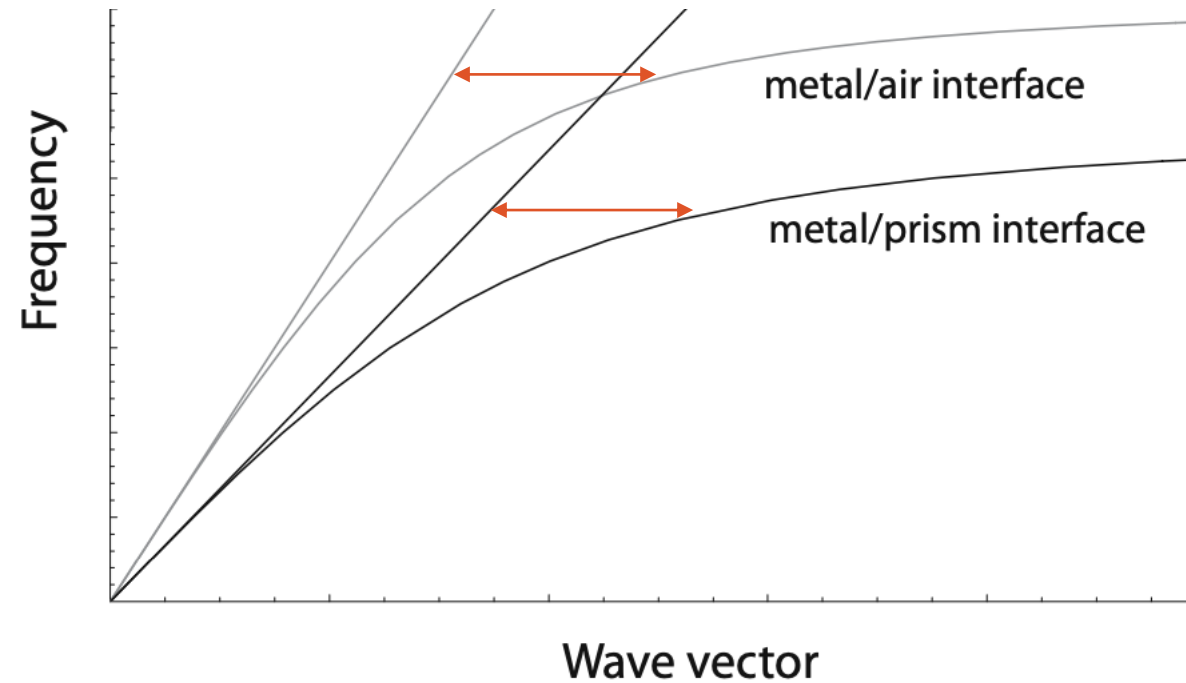
Dispersion relation:



SPPs – confinement and losses

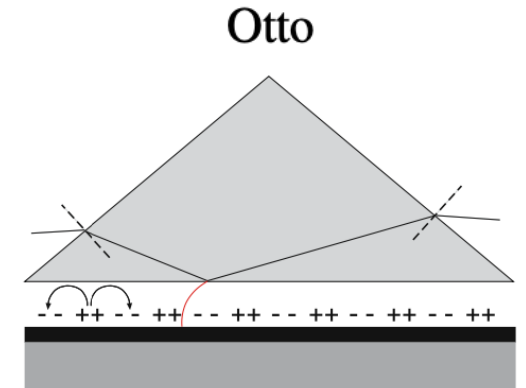
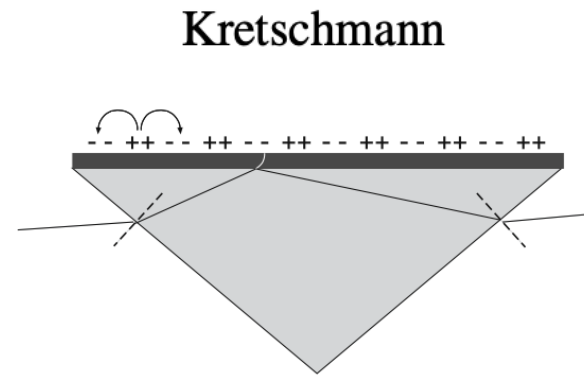
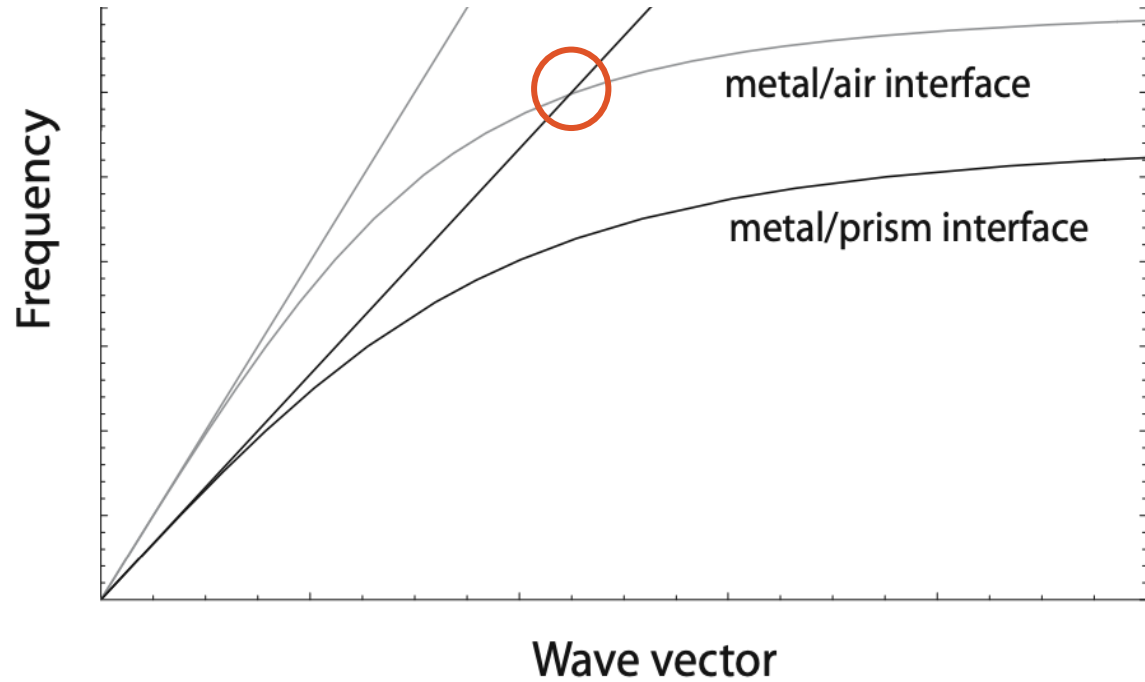


SPPs – excitation

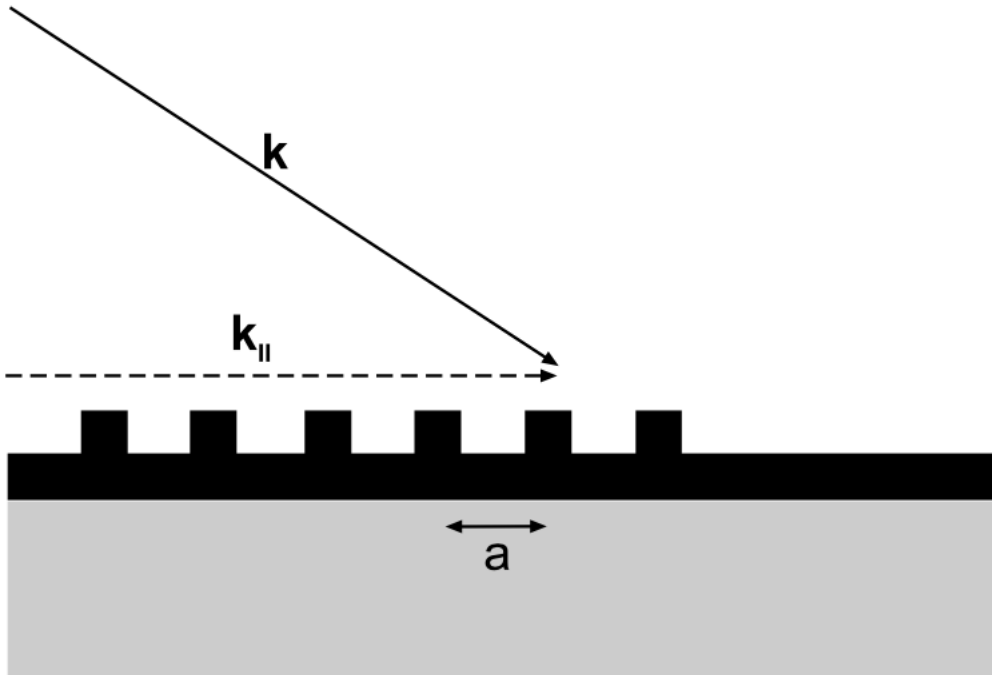


Momentum mismatch – Phase mismatch

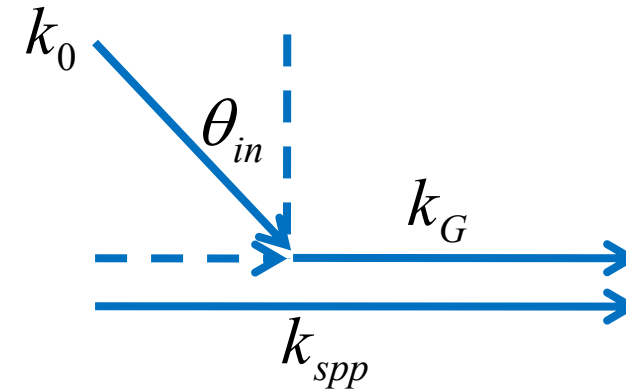
SPPs – prism coupling



SPPs – grating coupling



$$k_G = \frac{2\pi m}{\Lambda}$$



$$k_0 \sin \theta_{in} + m k_G = k_{spp}$$