0. Introduction

1. Reminder:

E-Dynamics in homogenous media and at interfaces

2. Photonic Crystals

- 2.1 Introduction
- 2.2 1D Photonic Crystals
- 2.3 2D and 3D Photonic Crystals
- 2.4 Numerical Methods
- 2.5 Fabrication
- 2.6 Non-linear optics and Photonic Crystals
- 2.7 Quantumoptics
- 2.8 Chiral Photonic Crystals
- 2.9 Quasicrystals
- 2.10 Photonic Crystal Fibers – „Holey“ Fibers

3. Metamaterials and Plasmonics

- 3.1 Introduction
- 3.2 Background
- 3.2 Fabrication
- 3.3 Experiments

Bibliography

- “Optik“, E. Hecht, Addison-Wesley
  (just as a reminder)
- “Nanophotonics“, P.N. Prasad, John Wiley & Sons (2004)
  (recent comprehensive overview, nothing in depth,
  good for finding further references and original work)
- “Photonic Crystals“, J.D. Joannopoulos, R.D. Meade, J.N. Winn,
  Princeton University Press
  (nice textbook introduction into the theory, mostly 2D)
- “Photonic Crystals“, K. Busch et al., eds.,
  Wiley-VCH (2004)
  (collection of recent review papers, incl. experimental ones)
- “Optical Properties of Photonic Crystals”, K. Sakoda, Springer (2001)
  (advanced theory, mostly 2D, good introduction into symmetry properties)

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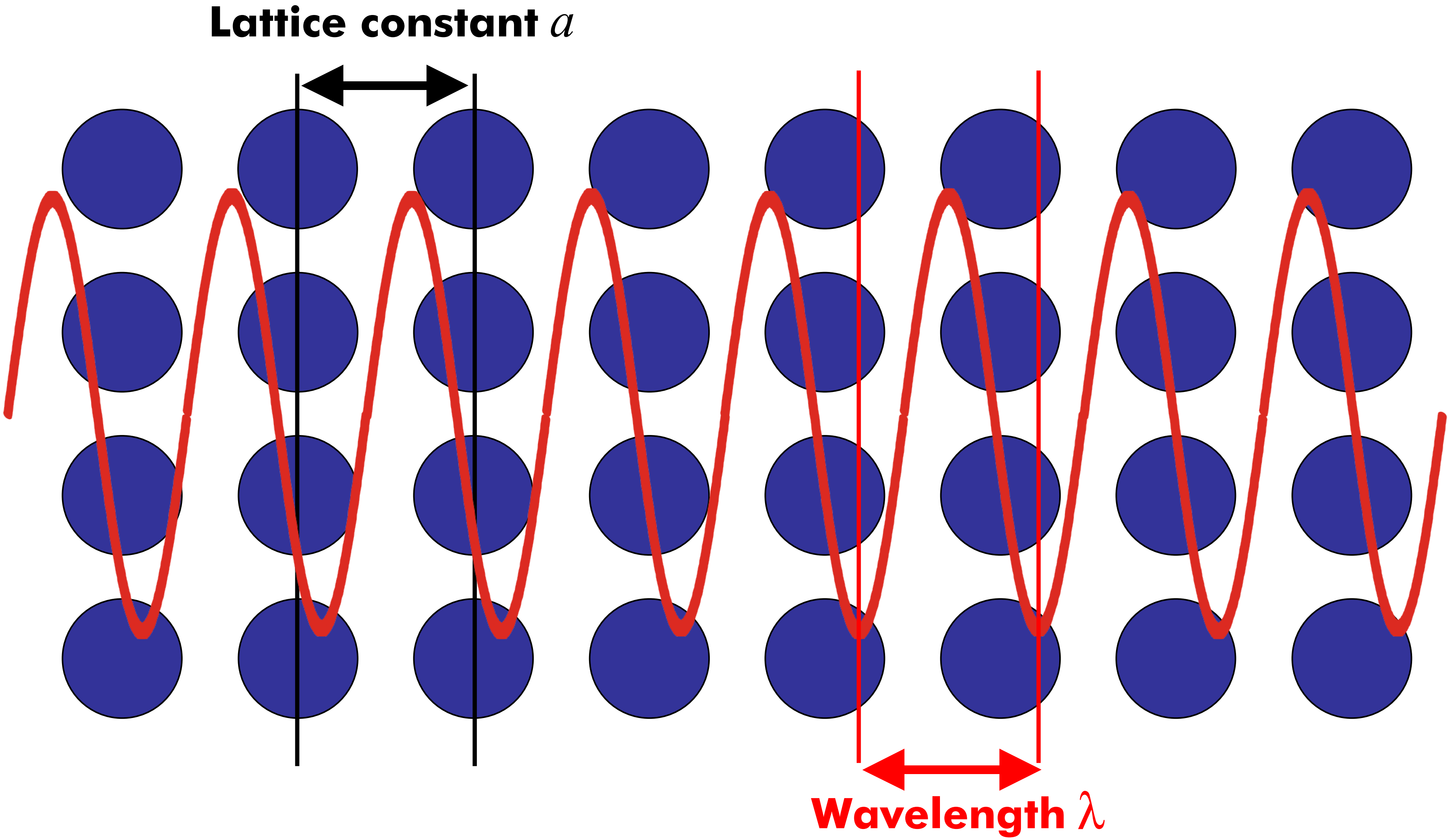
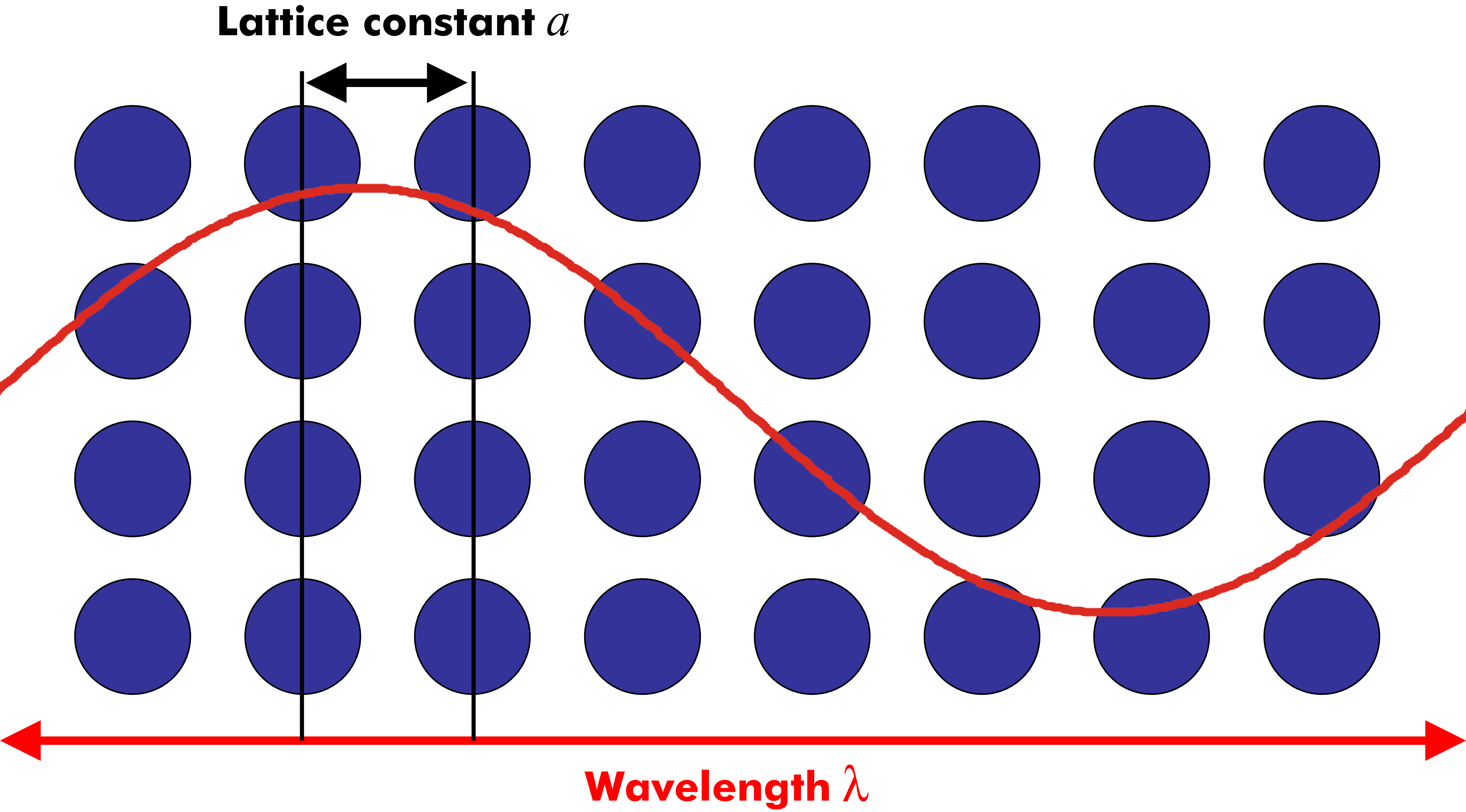
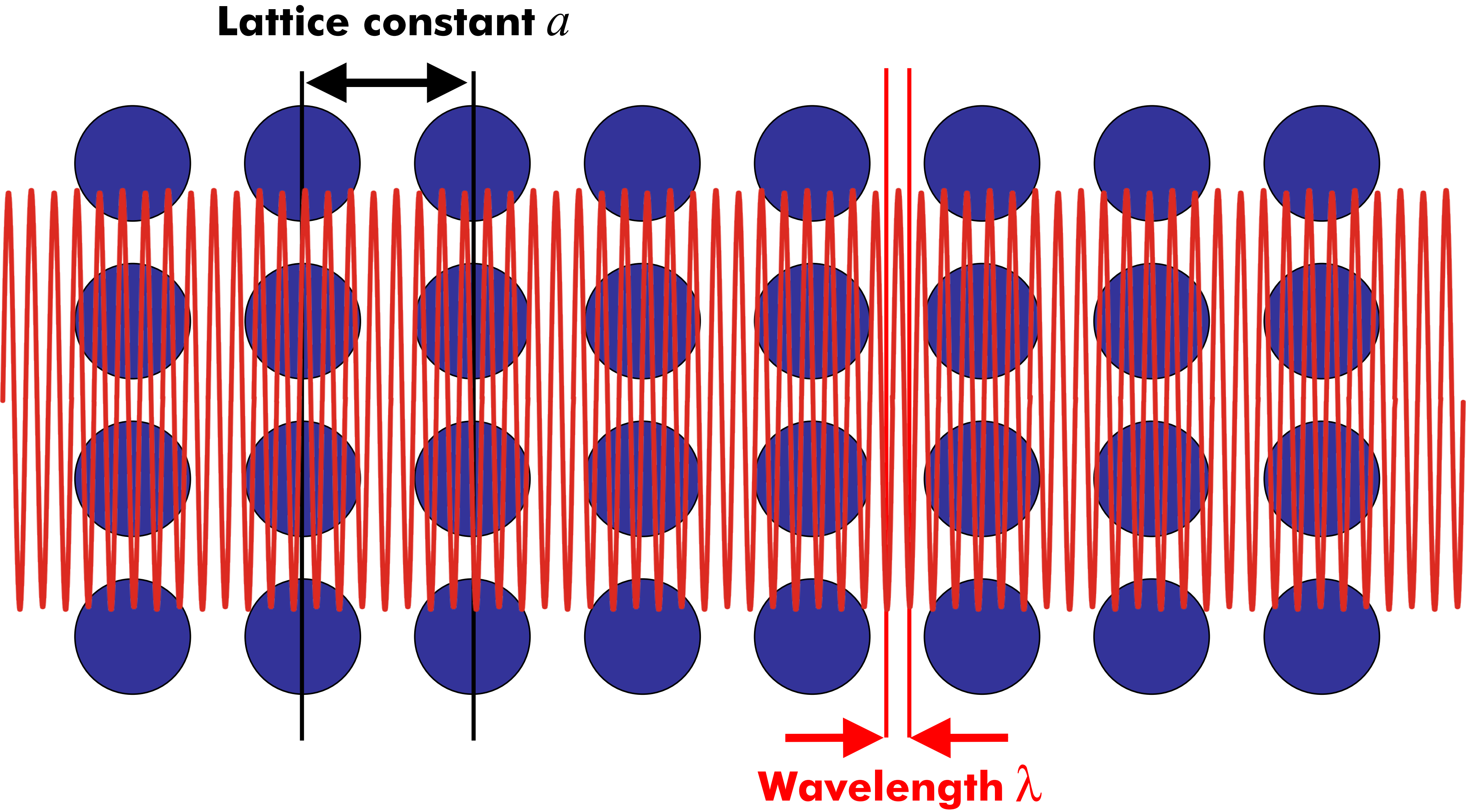
Optical properties of periodic structures



Optical properties of periodic structures

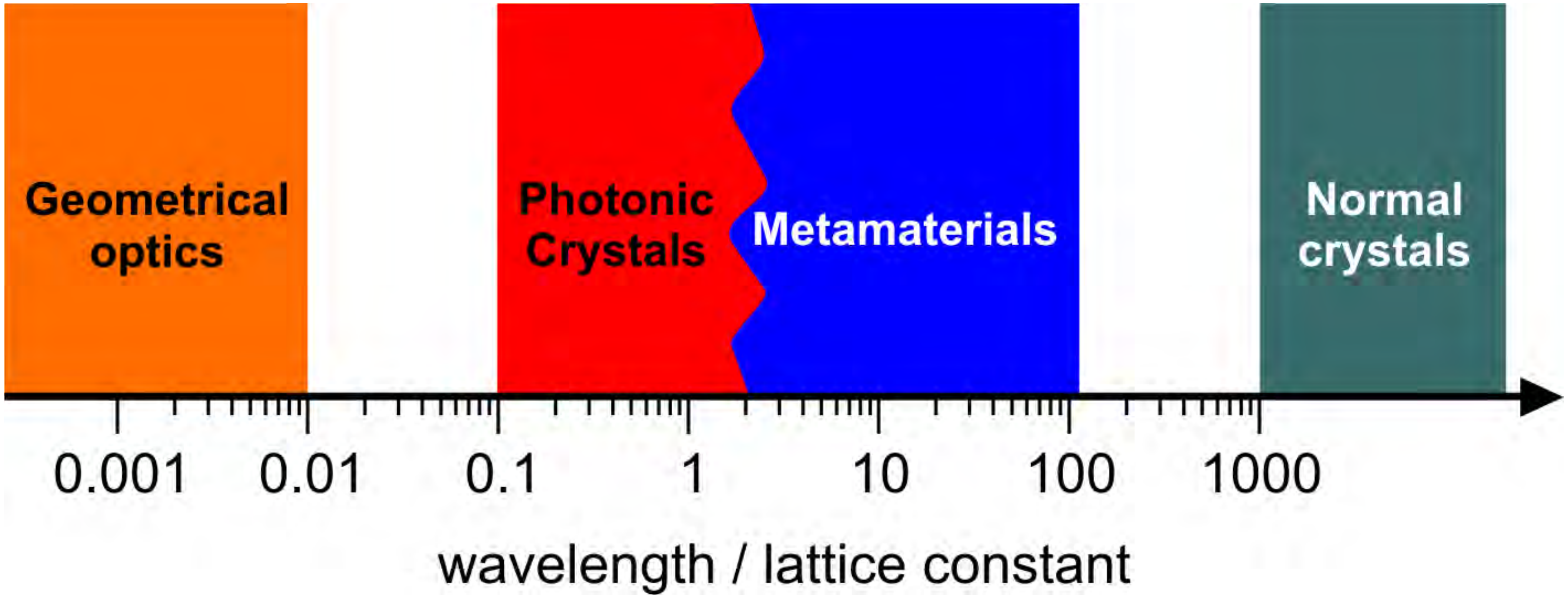


Optical properties of periodic structures

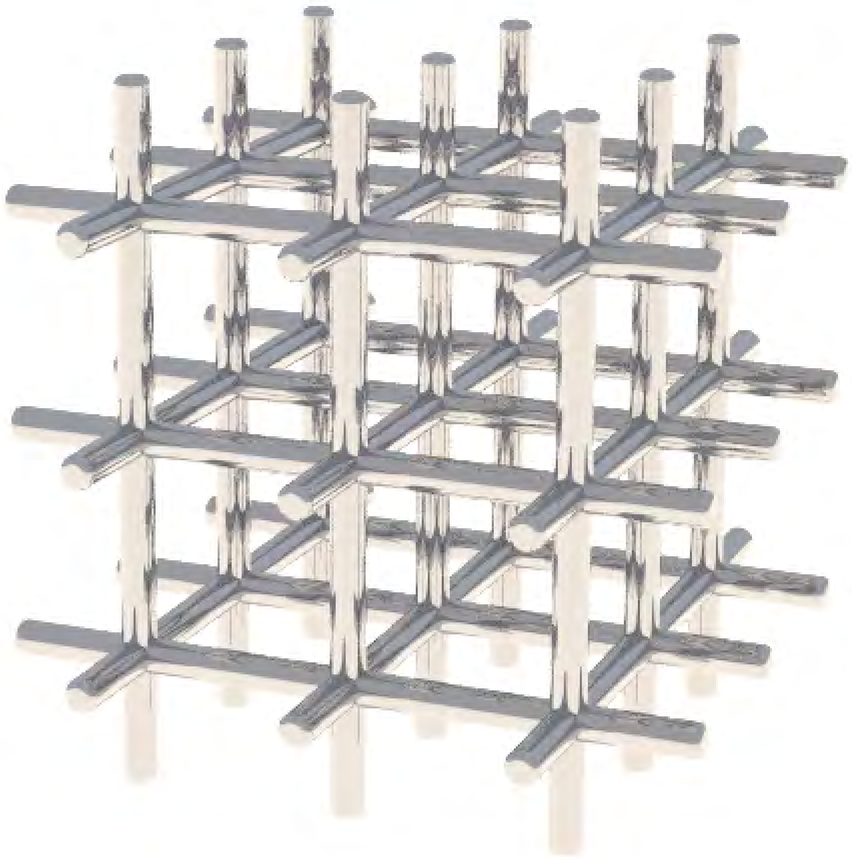


Theoretical framework

Relevant parameter: wavelength λ / lattice constant a



Geometrical optics ...



... is only valid in the limit
$\lambda / a << 1.$

... neglects wave effects
(diffraction, interference).

... treats light propagation
in terms of rays.

... is employed, e.g., in
raytracing programs.

"Normal" crystals ...

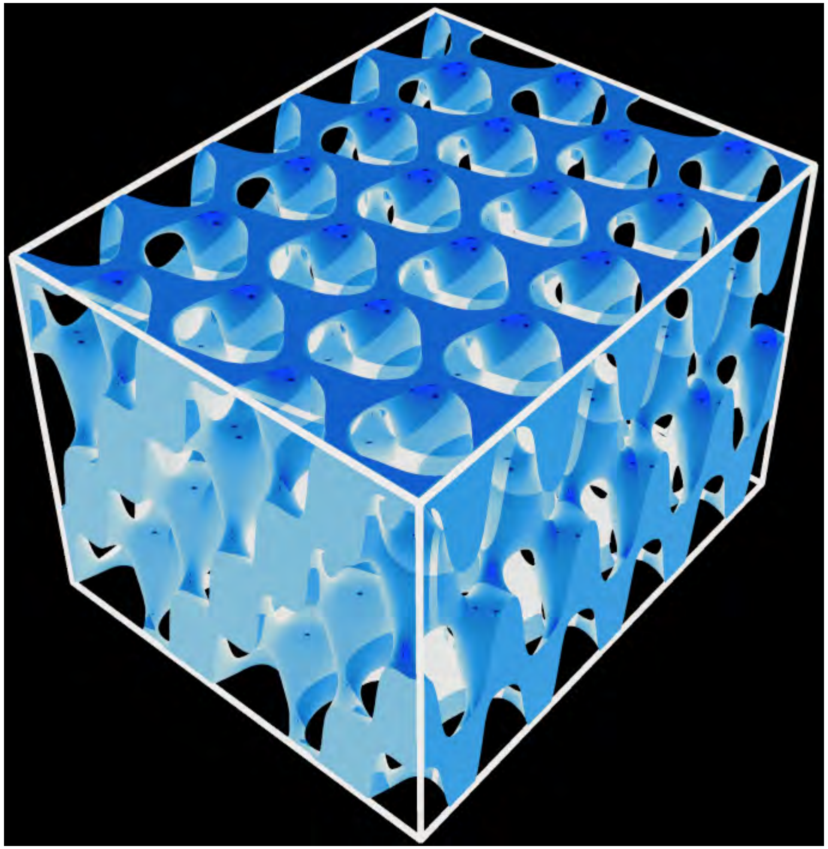
... have lattice constants much smaller than the wavelength of light ($\lambda / a \;>>\; 1$).

... can be treated as homogeneous media (Q.M. $\rightarrow \varepsilon,\mu,n,Z$).

... are common optical materials.

... have a refractive index $n > 0$.

Photonic crystals ...



... have lattice constants **comparable** to the wavelength of light ($\lambda / a \approx 1$).

... are (in most cases) artificial materials.

... exhibit a photonic band structure (Maxwell).

... can have a complete photonic bandgap.

Metamaterials ...


Structure made at UCSD by David Smith

... have lattice constants **smaller** than the wavelength of light ($\lambda / a > 1$).

... are artificial materials.

... can be treated as homogeneous media (Maxwell $\rightarrow \varepsilon, \mu, n, Z$).

... can have a negative index of refraction $n < 0$.

Photonics

"Photonics is the science and technology of generating and controlling photons, particularly in the visible and near infra-red light spectrum.

The science of photonics includes the emission, transmission, amplification, detection, modulation, and switching of light. Photonic devices include optoelectronic devices such as lasers and photodetectors, as well as optical fibers, photonic crystals, planar waveguides and other passive optical elements."

http://en.wikipedia.org/wiki/Photonics

Example I

- **DWDM (*Dense Wavelength Division Multiplexing*)**

Can we fabricate these devices on a micron scale?

see Photonic Crystals

Example II

- Conventional optical fibers guide the light inside a glass core, thus showing dispersion. After a certain travel distance, information sent in the form of short laser pulses, smears out. Therefore, repeaters and amplifiers are needed.

Can we transmit light without dispersion?

see Photonic Crystal fibres

Example III

- With the further downscaling of conventional electronic components, quantum effects become important.

What can we expect from photonic structures on a wavelength or even smaller scales?

see Photonic Crystals, Quantumoptics

Example IV

- All known natural materials exhibit a positive index of refraction.

Can we design and fabricate artificial materials with a negative index of refraction?

see Metamaterials

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All of macroscopic electromagnetism can be described within the framework of the macroscopic Maxwell equations:

$$\vec{\nabla}\cdot\vec{D}=\rho$$

$$\vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\cdot\vec{B}=0$$

$$\vec{\nabla}\times\vec{H}=\vec{j}+\frac{\partial\vec{D}}{\partial t}$$

with

$$\vec{D}=\varepsilon_0\vec{E}+\vec{P}$$

$$\vec{B}=\mu_0\vec{H}+\vec{M}$$

$\vec{E}$: **electric field**

$\vec{D}$: **dielectric displacement**

$\vec{P}$: **polarization**

ρ : **free charge density**

$\vec{B}$: **magnetic induction**

$\vec{H}$: **magnetic field**

$\vec{M}$: **magnetization**

$\vec{j}$: **free current density**

The material properties enter via the constitutive relations.

For low light intensities, one usually finds a linear relationship between the polarization and the electric field as well as between the magnetization and magnetic field:

$$\vec{P}(t,\vec{r}) = \varepsilon_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \overleftrightarrow{\chi}_e(t,t',\vec{r},\vec{r}')\,\vec{E}(t',\vec{r}')\,dt'\,d\vec{r}'$$

$$\vec{M}(t,\vec{r}) = \mu_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \overleftrightarrow{\chi}_m(t,t',\vec{r},\vec{r}')\,\vec{H}(t',\vec{r}')\,dt'\,d\vec{r}'$$

Tensors!

Here, we consider only isotropic materials with a local response:

$$\chi_e(t,t',\vec{r},\vec{r}') = \chi_e(t,t')\,\delta(\vec{r}-\vec{r}')$$

$$\chi_m(t,t',\vec{r},\vec{r}') = \chi_m(t,t')\,\delta(\vec{r}-\vec{r}')$$

The response functions must be causal and do not explicitly depend on time (homogeneity in time):

$$\chi_e(t,t') = \chi_e(t-t')\,\Theta(t-t')$$

$$\chi_m(t,t') = \chi_m(t-t')\,\Theta(t-t')$$

$$\Rightarrow \boxed{\begin{aligned} \vec{P}(t) &= \varepsilon_0 \int_{-\infty}^{t} \chi_e(t-t')\,\vec{E}(t')\,dt' \\ \vec{M}(t) &= \mu_0 \int_{-\infty}^{t} \chi_m(t-t')\,\vec{H}(t')\,dt' \end{aligned}}$$

In the frequency domain, we get:

$$\vec{P}(t) = \varepsilon_0 \int_{-\infty}^{t} \chi_e(t - t')\,\vec{E}(t')\,dt' \xrightarrow{\text{F.T.}} \vec{P}(\omega) = \varepsilon_0 \chi_e(\omega)\,\vec{E}(\omega)$$

$$\vec{M}(t) = \mu_0 \int_{-\infty}^{t} \chi_m(t - t')\,\vec{H}(t')\,dt' \xrightarrow{\text{F.T.}} \vec{M}(\omega) = \varepsilon_0 \chi_m(\omega)\,\vec{H}(\omega)$$

Electric permittivity

This finally leads to

$$\boxed{\begin{aligned} \vec{D}(\omega) &= \varepsilon_0\left(1 + \chi_e(\omega)\right)\vec{E}(\omega) = \varepsilon_0\,\varepsilon(\omega)\,\vec{E}(\omega) \\ \vec{B}(\omega) &= \mu_0\left(1 + \chi_m(\omega)\right)\vec{H}(\omega) = \mu_0\,\mu(\omega)\,\vec{H}(\omega) \end{aligned}}$$

Magnetic permeability

Electromagnetic waves in homogenous media without dispersion, free charges and free currents ($\varepsilon = \text{const}, \mu = \text{const}, \rho = 0, j = 0$):

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \xrightarrow[\partial/\partial t]{\vec{B} = \mu_0 \mu \vec{H}} \frac{\partial}{\partial t} \vec{\nabla} \times \vec{E} = -\mu_0 \mu \frac{\partial^2}{\partial t^2} \vec{H}$$

$$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} \xrightarrow[\vec{\nabla} \times]{\vec{D} = \varepsilon_0 \varepsilon \vec{E}} \vec{\nabla} \times \vec{\nabla} \times \vec{H} = \varepsilon_0 \varepsilon \frac{\partial}{\partial t} \vec{\nabla} \times \vec{E}$$

With $\vec{\nabla} \times \vec{\nabla} \times = \vec{\nabla}\left(\vec{\nabla} \cdot\right) - \Delta$ **and** $\vec{\nabla} \cdot \vec{B} = 0$ **we obtain the wave equation:**

$$\Delta \vec{H}(t, \vec{r}) - \varepsilon_0 \mu_0 \varepsilon \mu \frac{\partial^2}{\partial t^2} \vec{H}(t, \vec{r}) = 0$$

see "Physik II" and "THEORIE D"

Electromagnetic waves in homogenous media without dispersion, free charges and free currents ($\varepsilon = \text{const}, \mu = \text{const}, \rho = 0, j = 0$):

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \xrightarrow[\vec{\nabla}\times]{\vec{B} = \mu_0 \mu \vec{H}} \vec{\nabla} \times \vec{\nabla} \times \vec{E} = -\mu_0 \mu \frac{\partial}{\partial t} \vec{\nabla} \times \vec{H}$$

$$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} \xrightarrow[\partial / \partial t]{\vec{D} = \varepsilon_0 \varepsilon \vec{E}} \frac{\partial}{\partial t} \vec{\nabla} \times \vec{H} = \varepsilon_0 \varepsilon \frac{\partial^2}{\partial t^2} \vec{E}$$

With $\vec{\nabla} \times \vec{\nabla} \times = \vec{\nabla}\left(\vec{\nabla} \cdot\right) - \Delta$ **and** $\vec{\nabla} \cdot \vec{E} = 0$ **we obtain the wave equation:**

$$\Delta \vec{E}(t, \vec{r}) - \varepsilon_0 \mu_0 \varepsilon \mu \frac{\partial^2}{\partial t^2} \vec{E}(t, \vec{r}) = 0$$

see “Physik II“ and “THEORIE D“

With the complex ansatz for E and H ...

$$\vec{E}(t,\vec{r}) = \vec{E}_0 \exp\left[i\left(\vec{k}\cdot\vec{r} - \omega t\right)\right]$$

$$\vec{H}(t,\vec{r}) = \vec{H}_0 \exp\left[i\left(\vec{k}\cdot\vec{r} - \omega t\right)\right]$$

The physical electric and magnetic fields are obtained by taking the real parts of the complex quantities!

... we obtain from the wave equations:

$$\boxed{k^2 = \varepsilon_0 \mu_0 \varepsilon \mu \, \omega^2}$$

Case 1: Plane waves

$$\varepsilon\mu > 0 \Rightarrow k_i \in \Re \,, i \in \{x, y, z\}$$

Case 2: Evanescent modes

$$\varepsilon\mu < 0 \Rightarrow k_i \in \Im \,, i \in \{x, y, z\}$$

Plane waves ...

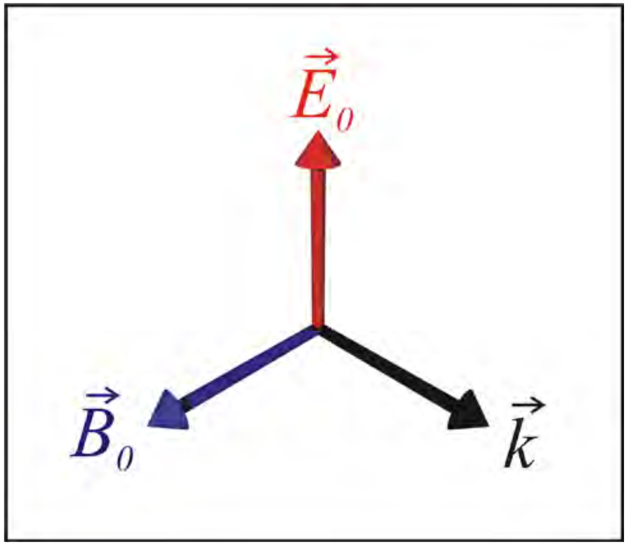
$$\vec{E}(t,\vec{r}) = \vec{E}_0 \exp\left[i\left(\vec{k}\cdot\vec{r} - \omega t\right)\right]$$

$$\vec{B}(t,\vec{r}) = \vec{B}_0 \exp\left[i\left(\vec{k}\cdot\vec{r} - \omega t\right)\right]$$

... are transversal:

$$\vec{\nabla} \times \vec{E} = \begin{pmatrix} ik_y E_z - ik_z E_y \\ ik_x E_z - ik_z E_x \\ ik_x E_y - ik_y E_x \end{pmatrix} = i\vec{k} \times \vec{E} \overset{!}{=} - i\omega \vec{B}$$

$$\vec{\nabla} \cdot \vec{B} = i\left(k_x B_x + k_y B_y + k_z B_z\right) = i\vec{k}\cdot\vec{B} \overset{!}{=} 0$$



Moreover, E and B are in phase.

The planes of constant phase propagate with the phase velocity c :

$$c^2 = \frac{\omega^2}{k^2} = \frac{1}{\varepsilon_0 \varepsilon \mu_0 \mu} = \frac{c_0^2}{\varepsilon \mu} = \frac{c_0^2}{n^2}$$

The material properties enter via the refractive index ...

$$n^2 = \varepsilon \mu \quad \Rightarrow \quad n = \pm \sqrt{\varepsilon \mu} \quad \longrightarrow$$

Dielectric materials: $n = \sqrt{\varepsilon \mu}$

$$(\varepsilon, \mu > 0)$$

... and the impedance

$$Z = \sqrt{\frac{\mu_0 \mu}{\varepsilon_0 \varepsilon}} \qquad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 376.7\,\Omega$$

see Metamaterials

The energy density w of an electromagnetic wave in a nondispersiv medium is given by

$$w = \frac{1}{4}\Re\left(\vec{E}_0 \cdot \vec{D}_0^{\,*} + \vec{H}_0 \cdot \vec{B}_0^{\,*}\right) \quad \longleftarrow$$

This formula is valid only for nondispersive media!

The corresponding time averaged energy flux density is given by the Poynting vector

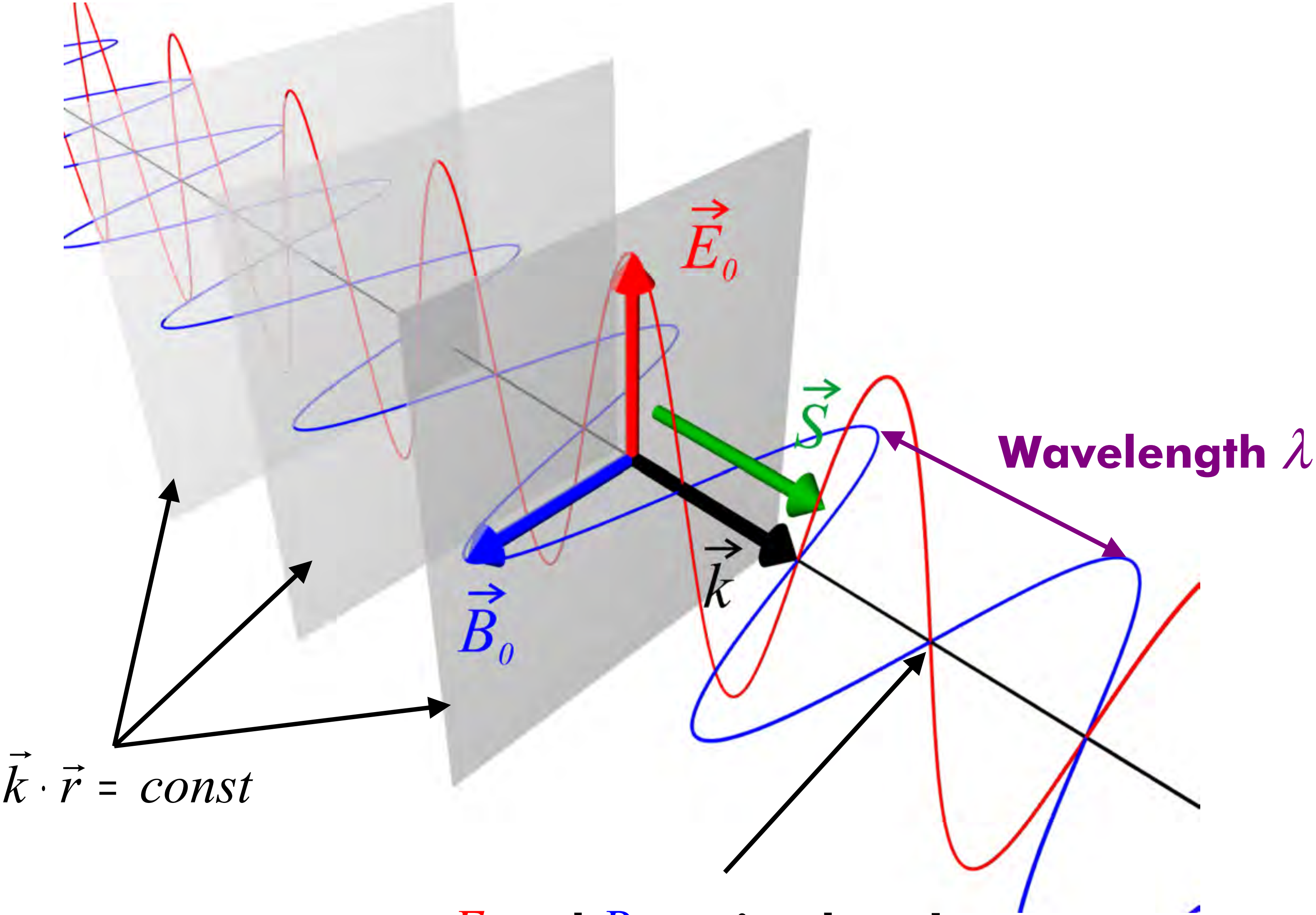
$$\vec{S} = \frac{1}{2}\Re\left(\vec{E}_0 \times \vec{H}_0^{\,*}\right) \qquad \longleftarrow \qquad \mu > 0 \Rightarrow \vec{S} \parallel \vec{k}$$

The magnitude of $\vec{S}$ denotes the intensity of the electromagnetic field:

$$I = \left|\vec{S}\right| = \frac{1}{2}\varepsilon_0 \varepsilon\, c \left|\vec{E}_0\right|^2$$

These quantities are spatially constant for plane waves.

Plane waves …



$\vec{k} \cdot \vec{r} = const$

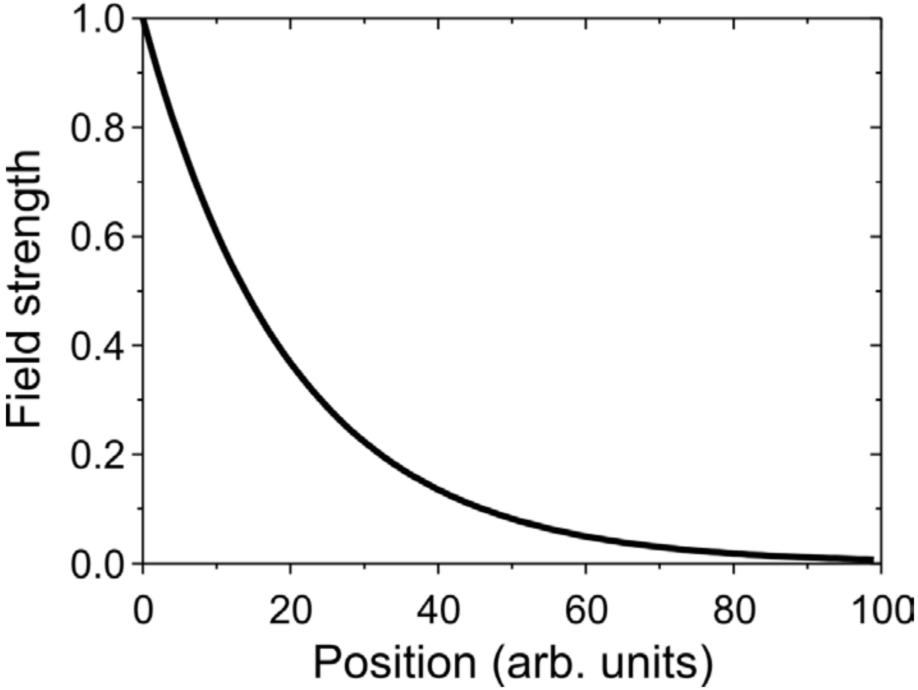
E **and** B **are in phase!**

Evanescent modes ...

$$\vec{E}(t,\vec{r}) = \vec{E}_0 \exp\left[- \,|\vec{k}|\,\vec{e}_k \cdot \vec{r}\right] \exp\left[- i\omega\, t\right]$$

$$\vec{B}(t,\vec{r}) = \vec{B}_0 \exp\left[- \,|\vec{k}|\,\vec{e}_k \cdot \vec{r}\right] \exp\left[- i\omega\, t\right]$$

... exhibit exponentially decaying field strengths (E and B).



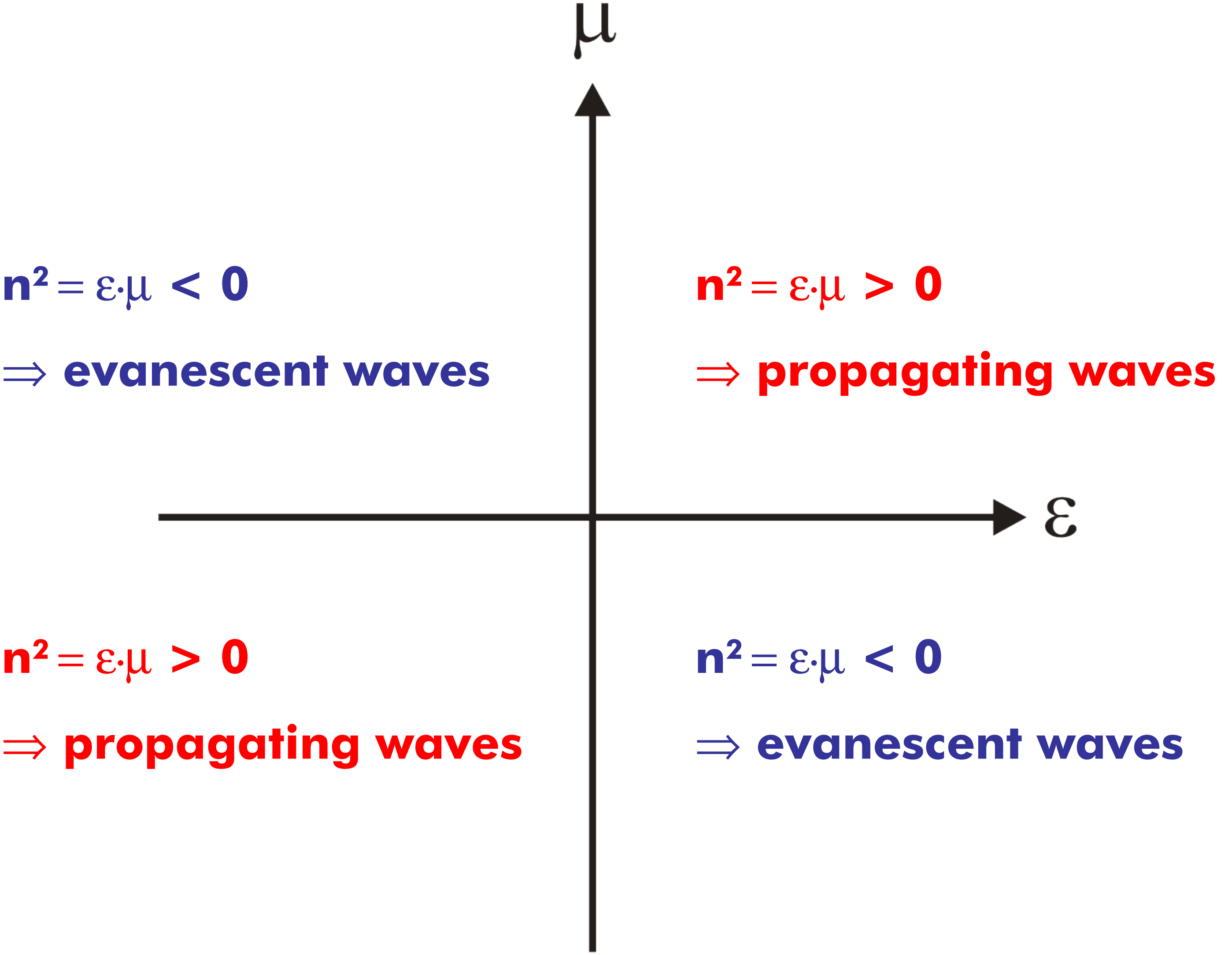
Evanescent modes …

… do not transport energy since the time-averaged normal component of the Poynting vector vanishes :

$$\vec{S}_{\vec{e}_k} = \frac{1}{2}\Re\left(\vec{e}_k\cdot\left[\vec{E}_0\times\vec{H}_0^{\,*}\right]\right) = \frac{1}{2\omega\mu_0\mu}\Re\left(\vec{e}_k\cdot\underbrace{\left[\vec{E}_0\times(\boxed{\vec{k}}\times\vec{E}_0)^{*}\right]}_{\textbf{Purely imaginary!}}\right) = 0$$

Therefore, evanescent modes do only have a noticeable field strength at interfaces.

Classification of electromagnetic modes



$n^2 = \varepsilon \cdot \mu < 0$

⇒ **evanescent waves**

$n^2 = \varepsilon \cdot \mu > 0$

⇒ **propagating waves**

$n^2 = \varepsilon \cdot \mu > 0$

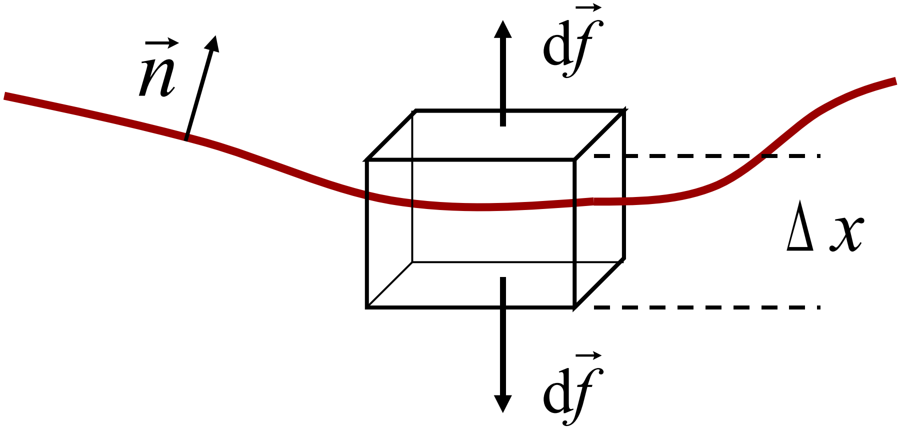
⇒ **propagating waves**

$n^2 = \varepsilon \cdot \mu < 0$

⇒ **evanescent waves**

Electromagnetic fields at interfaces

- **Use 3rd Maxwell equation**
- **Use Gauss-Theorem**

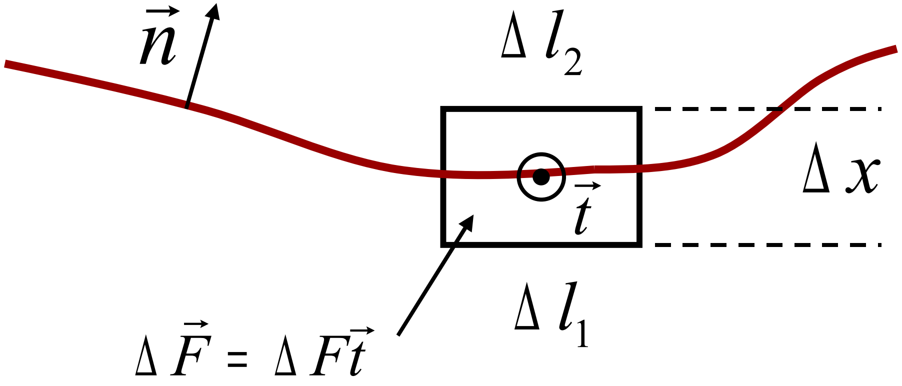


$$0 = \int_{\Delta V} \mathrm{d}^3 r\, \vec{\nabla} \cdot \vec{B} = \int_{S(\Delta V)} \mathrm{d}\vec{f} \cdot \vec{B} \xrightarrow[\Delta x \to 0]{} \left| d\vec{f} \right| \vec{n} \cdot \left(\vec{B}_2 - \vec{B}_1 \right)$$

⇒ Normal component of B must be continous

Electromagnetic fields at interfaces

- **Use 4th Maxwell equation**
- **Use Stokes-Theorem**



$$\left.\begin{aligned}
&\int_{\Delta F} \mathrm{d}\vec f \cdot \vec\nabla \times \vec H = \int_{\Delta F} \mathrm{d}\vec f \cdot \vec j_\mathrm{f} + \frac{\partial}{\partial t}\int_{\Delta F} \mathrm{d}\vec f \cdot \vec D \xrightarrow[\Delta x \to 0]{} \Delta l\left(\vec j_F \cdot \vec t\right)\\
&\int_{\Delta F} \mathrm{d}\vec f \cdot \mathrm{rot}\, \vec H = \int_{\partial \Delta F} \mathrm{d}\vec s \cdot \vec H \xrightarrow[\Delta x \to 0]{} \Delta l\left(\vec t \times \vec n\right) \cdot \left(\vec H_2 - \vec H_1\right)
\end{aligned}\right\}
\begin{aligned}
&\left(\vec t \times \vec n\right) \cdot \left(\vec H_2 - \vec H_1\right)\\
&= \vec j_F \cdot \vec t
\end{aligned}$$

⇒ (no surface current) Tangential component of H must be continous

Electromagnetic fields at interfaces

With a similar derivation for E and D follows:

- **D normal**
- **E tangential**
- **B normal**
- **H tangential**

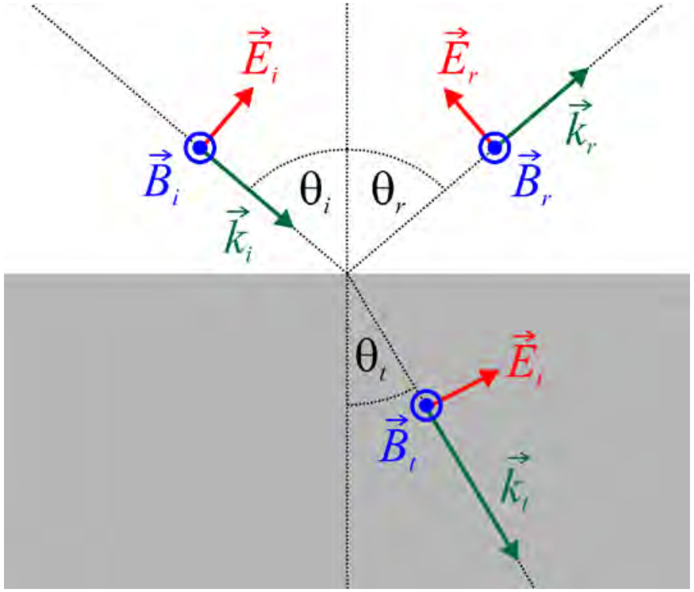
have to be continous across charge- and current-free interfaces.

We obtain for the other field components:

$$D_{2t} = \frac{\varepsilon_2}{\varepsilon_1} D_{1t} \qquad E_{2n} = \frac{\varepsilon_1}{\varepsilon_2} E_{1n} \qquad B_{2t} = \frac{\mu_2}{\mu_1} B_{1t} \qquad H_{2n} = \frac{\mu_1}{\mu_2} H_{1n}$$

Refraction at an interface – Fresnel formulas

p-polarization



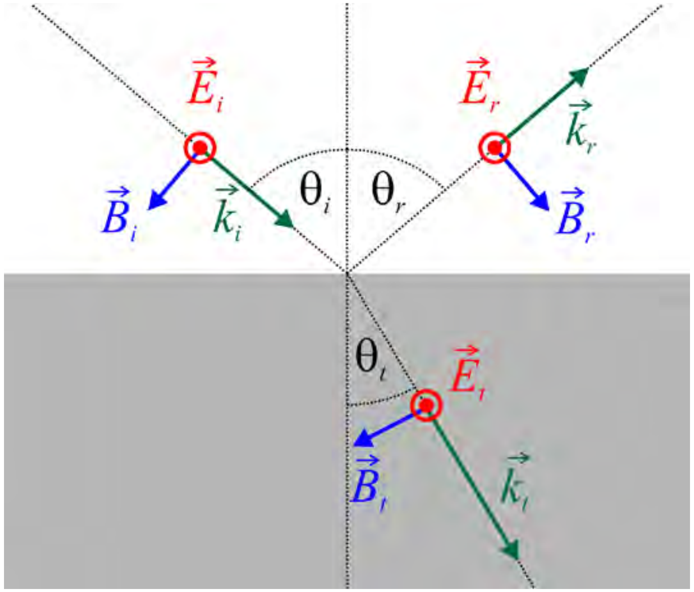
$$\Theta_i = \Theta_r \qquad n_i \sin(\Theta_i) = n_t \sin(\Theta_t)$$

$$r_p = \left(\frac{E_r}{E_i}\right)_p = \frac{(n_t/\mu_t)\cos(\Theta_i) - (n_i/\mu_i)\cos(\Theta_t)}{(n_i/\mu_i)\cos(\Theta_t) + (n_t/\mu_t)\cos(\Theta_i)}$$

$$t_p = \left(\frac{E_t}{E_i}\right)_p = \frac{2(n_i/\mu_i)\cos(\Theta_i)}{(n_i/\mu_i)\cos(\Theta_t) + (n_t/\mu_t)\cos(\Theta_i)}$$

Refraction at an interface – Fresnel formulas

s-polarization

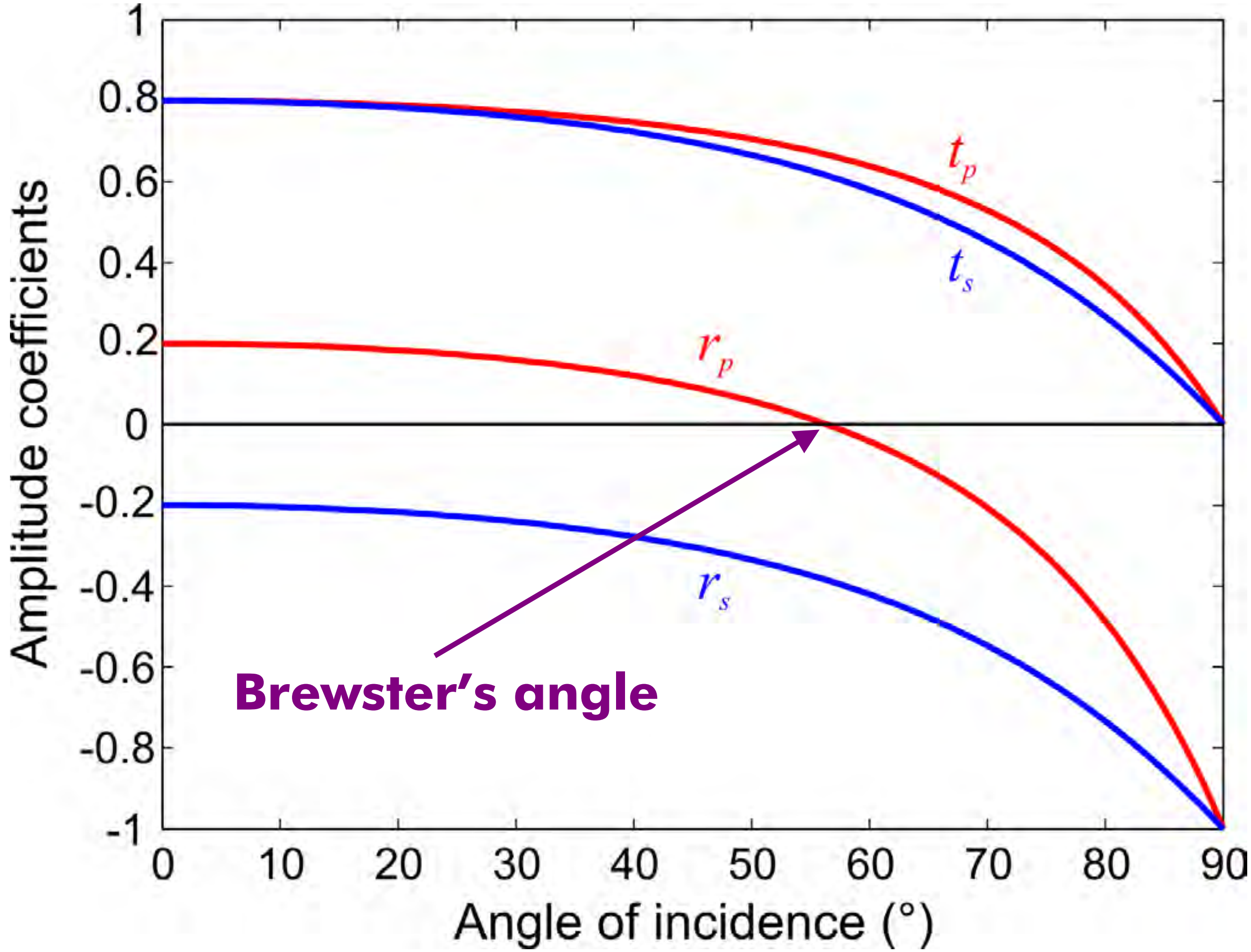


$$\Theta_i = \Theta_r \qquad n_i \sin(\Theta_i) = n_t \sin(\Theta_t)$$

$$r_s = \left(\frac{E_r}{E_i}\right)_s = \frac{(n_i/\mu_i)\cos(\Theta_i) - (n_t/\mu_t)\cos(\Theta_t)}{(n_i/\mu_i)\cos(\Theta_i) + (n_t/\mu_t)\cos(\Theta_t)}$$

$$t_s = \left(\frac{E_t}{E_i}\right)_s = \frac{2(n_i/\mu_i)\cos(\Theta_i)}{(n_i/\mu_i)\cos(\Theta_i) + (n_t/\mu_t)\cos(\Theta_t)}$$

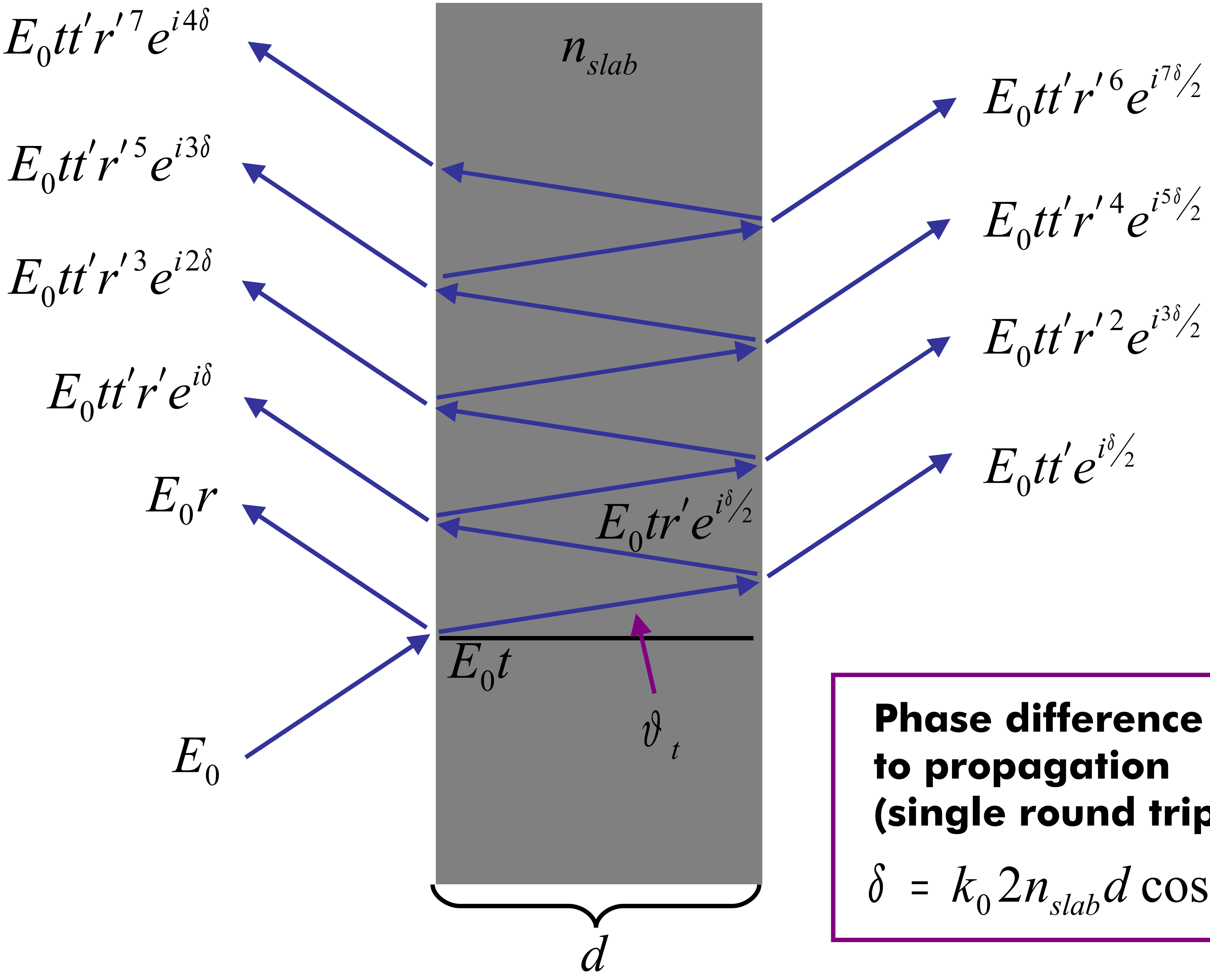
Refraction at an interface – Fresnel formulas



Brewster's angle

Parameters: ε_1=1.0, μ_1=1.0, ε_2=2.25, μ_2=1.0

A slab of matter: Fabry-Perot modes



Phase difference due to propagation (single round trip):

$$\delta = k_0 2 n_{slab} d \cos(\vartheta_t)$$

A slab of matter: Fabry-Perot modes

The total transmitted electric field is given by the superposition of all partially transmitted electric fields:

$$E_t = E_0 tt' e^{i\delta/2} + E_0 tt' r'^2 e^{i3\delta/2} + E_0 tt' r'^4 e^{i5\delta/2} + E_0 tt' r'^6 e^{i7\delta/2} + \ldots$$

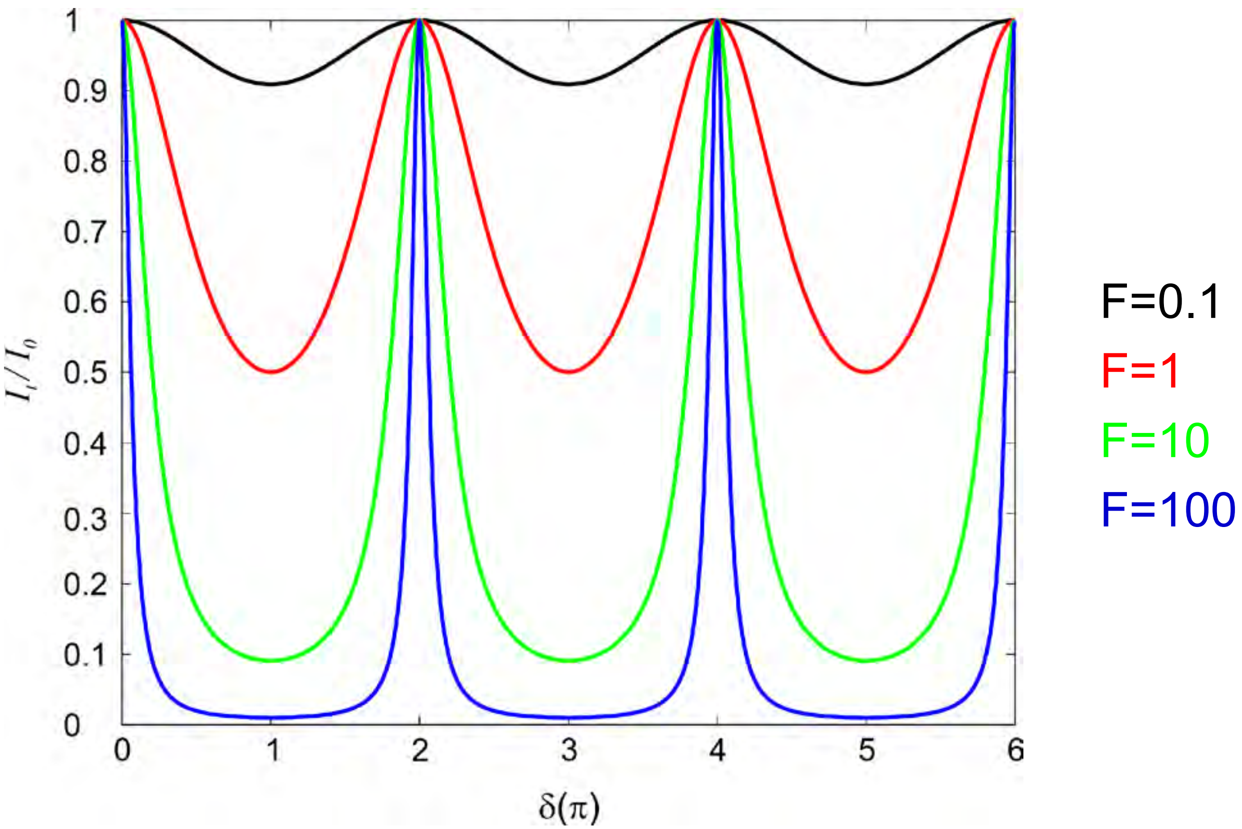
After a little bit of algebra we obtain the intensity of the total transmitted electromagnetic field (for lossless media)

$$I_t = I_0 \frac{1}{1 + F \sin^2(\delta\ /2)}$$

with the finesse factor $F = \left(\frac{2r}{1 - r^2} \right)^2$

See, e.g., "Optik", E. Hecht, Addison-Wesley

A slab of matter: Fabry-Perot modes



The transcribed transmittance is maximal for $\delta = 2m\pi \;,\; m \in \{0,1,2,...\}$

since all partial waves are in phase:

$$E_t = E_0 t t' e^{i\delta/2}(1 + r'^2 + r'^4 + r'^6 + ...)$$

A slab of matter: Fabry-Perot modes

The total reflected electric field is given by the superposition of all partially reflected electric fields:

$$E_r = E_0 r + E_0 t t' r' e^{i\delta} + E_0 t t' r'^3 e^{i2\delta} + E_0 t t' r'^5 e^{i3\delta} + \dots$$

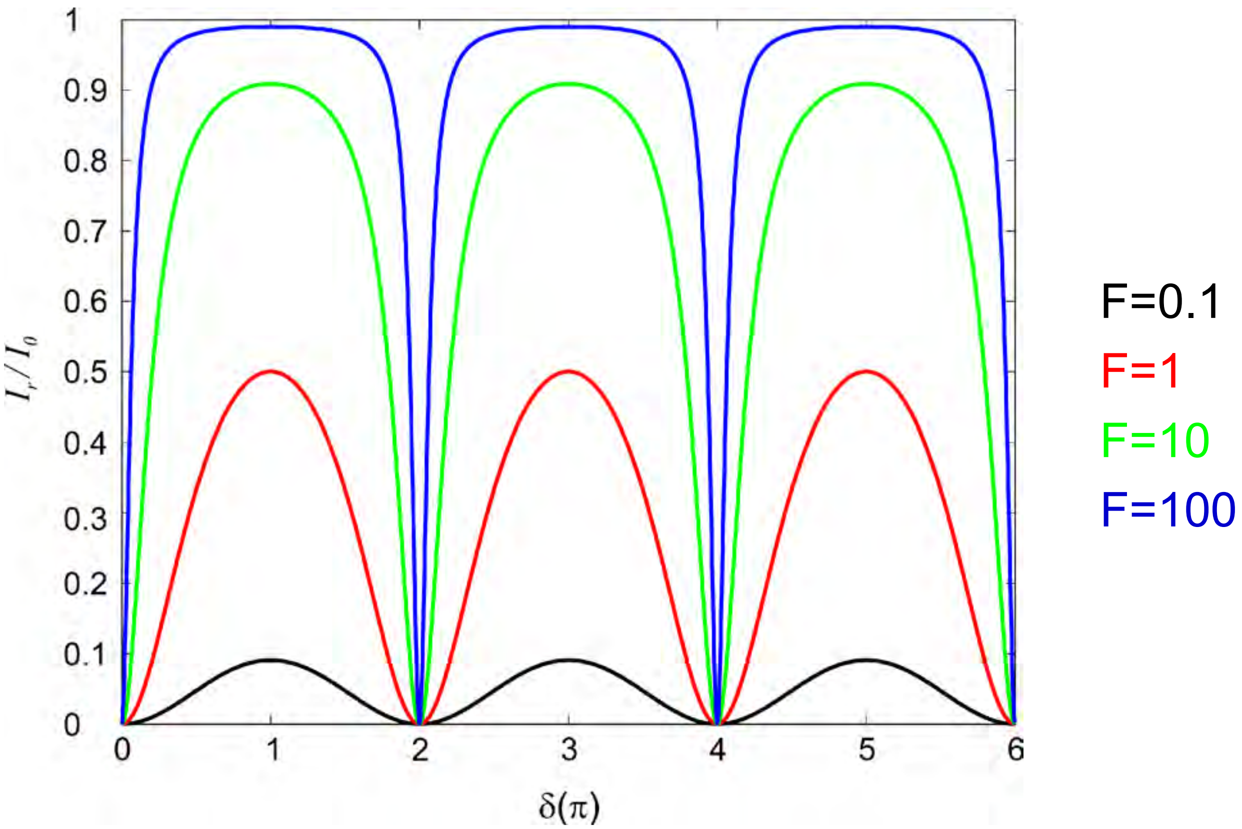
After a little bit of algebra we obtain the intensity of the total reflected electromagnetic field (for lossless media)

$$I_r = I_0 \frac{F \sin^2(\delta / 2)}{1 + F \sin^2(\delta / 2)}$$

with the finesse factor $F = \left(\frac{2r}{1 - r^2} \right)^2$

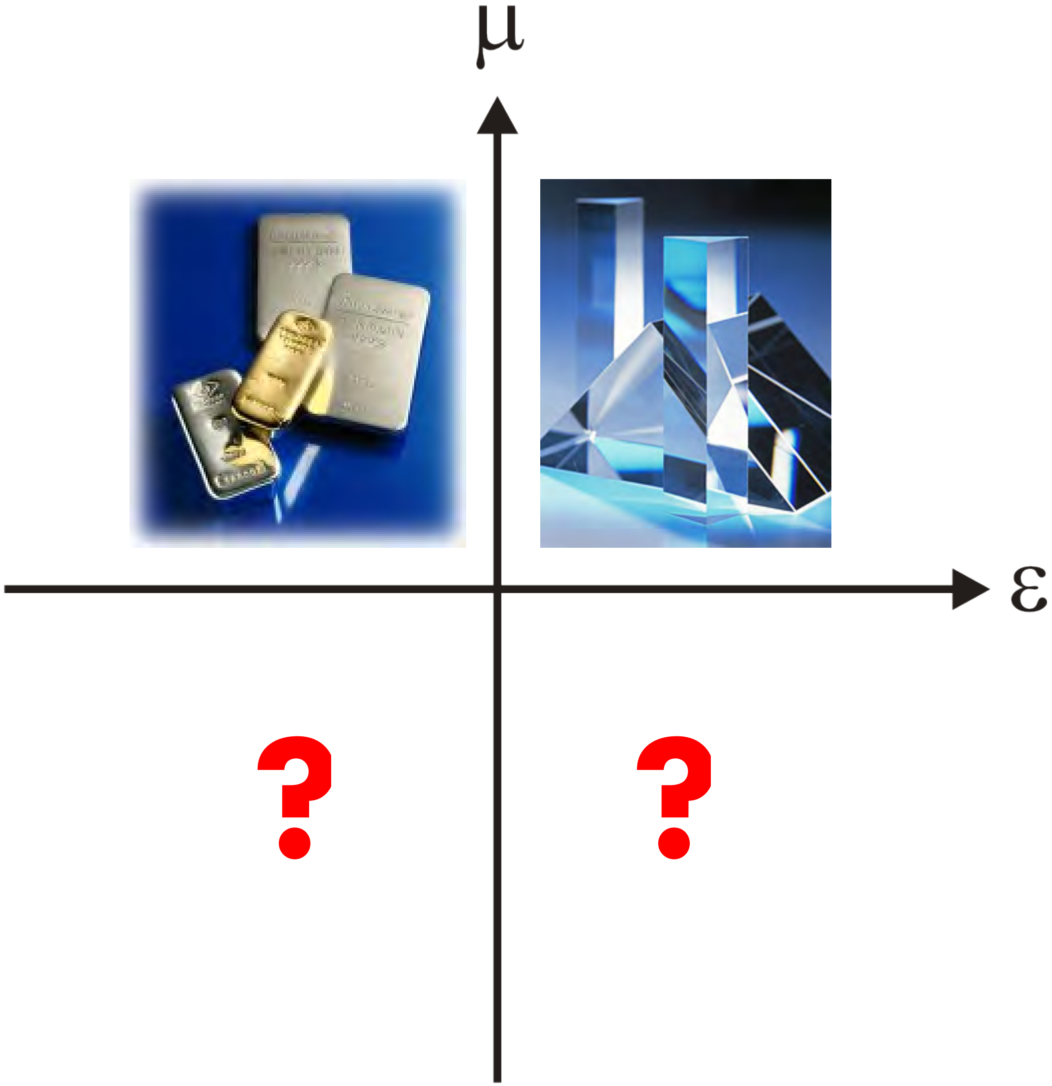
See, e.g., "Optik", E. Hecht, Addison-Wesley

A slab of matter: Fabry-Perot modes

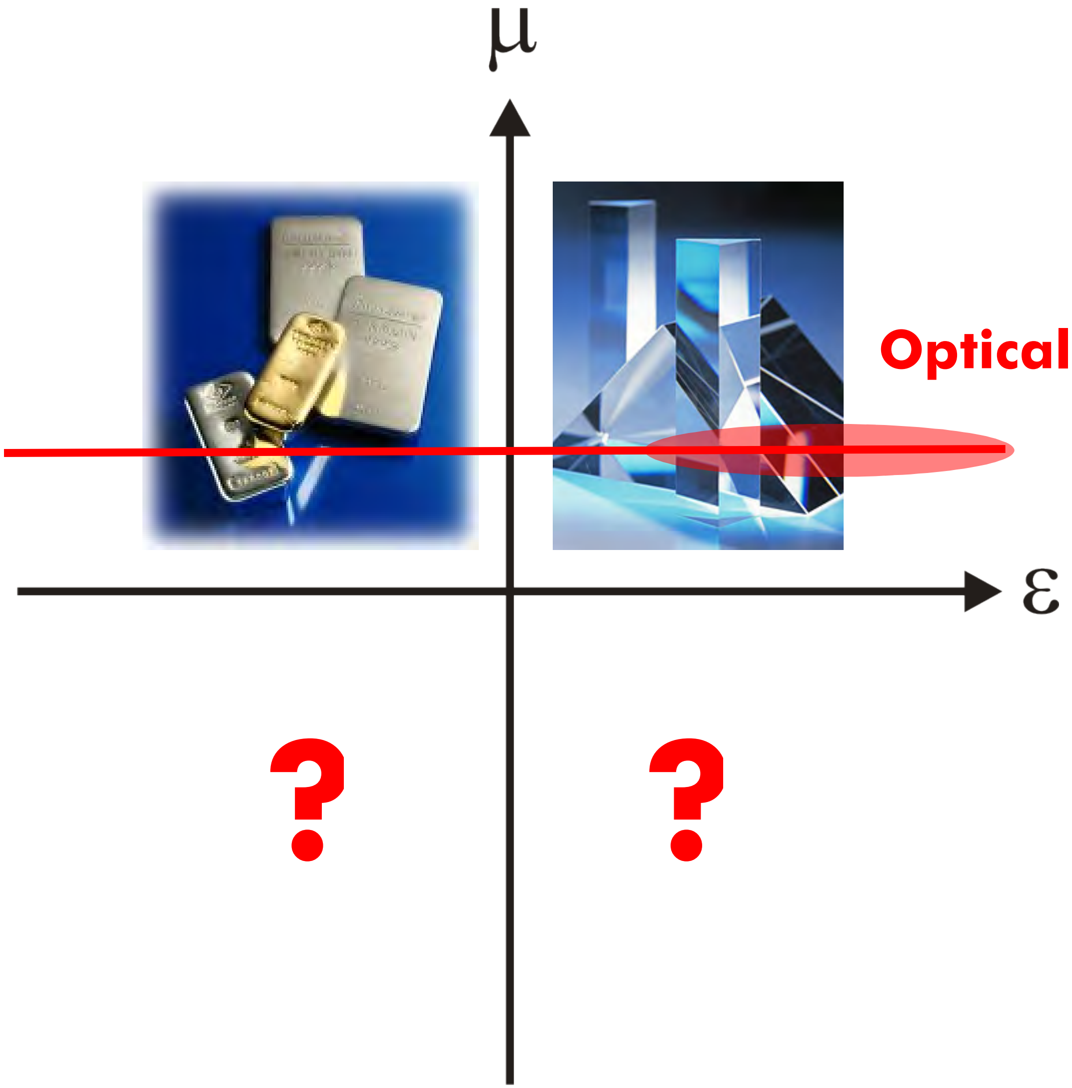


The reflectance is maximal for $\delta = (2m+1)\pi \;,\; m \in \{0,1,2,...\}$

Classification of optical materials



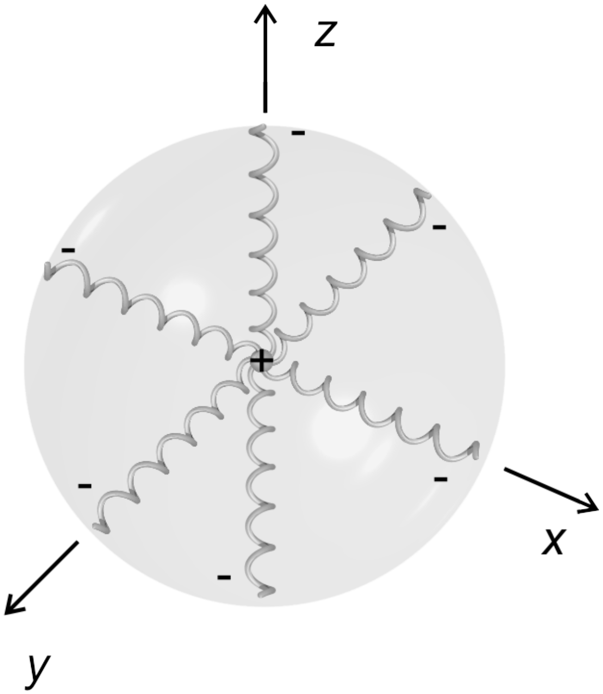
Classification of optical materials



Optical frequencies:

$\mu = 1$

Lorentz Oscillator modell



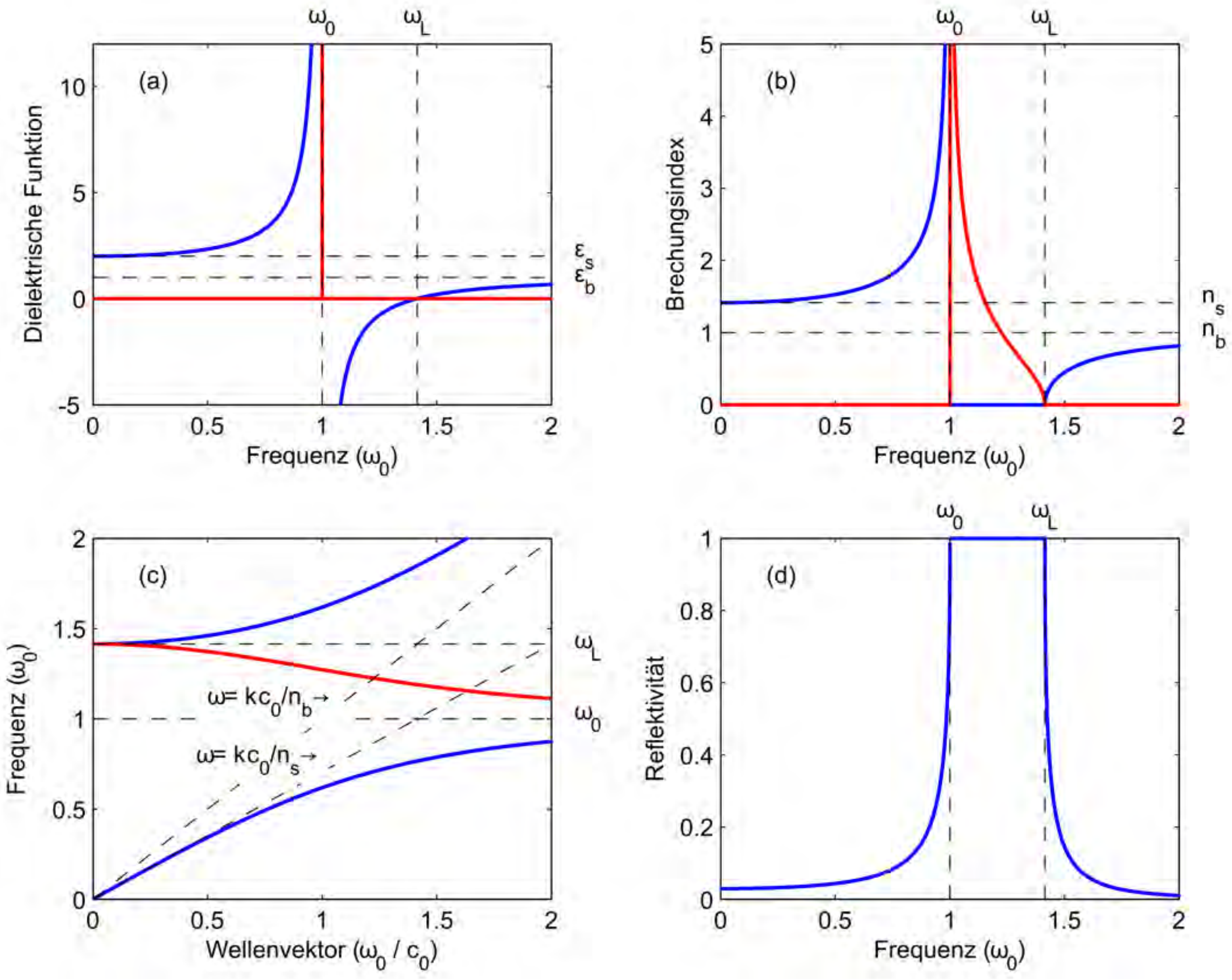
Equation of motion:

$$m\frac{d^2x}{dt^2} + m\gamma_0\frac{dx}{dt} + m\omega_0^2 x = -qE_0 e^{-i\omega t}$$

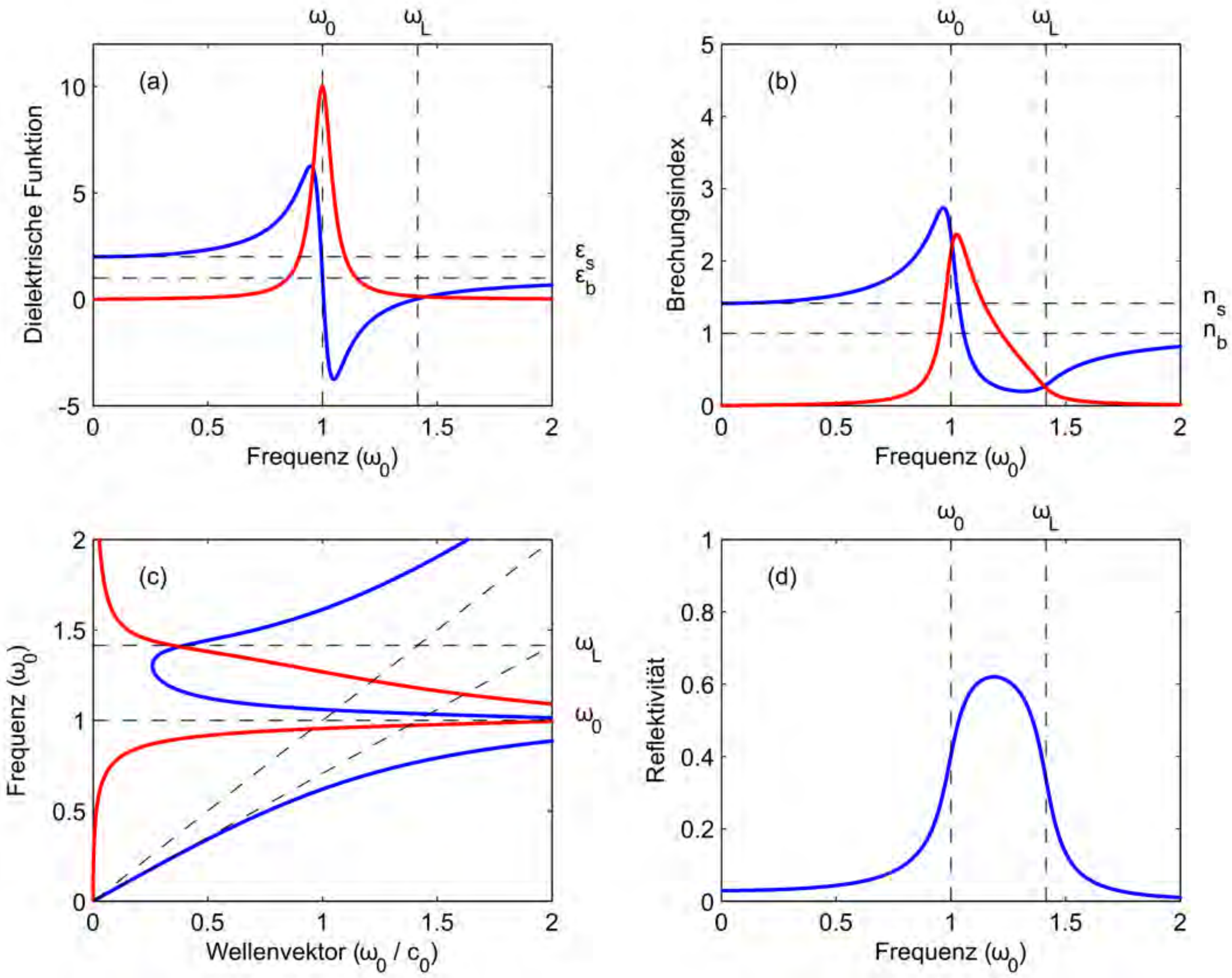
Lorentz dielectric function:

$$\varepsilon(\omega) = 1 + \frac{Nq^2}{m\varepsilon_0}\frac{1}{\omega_0^2 - \omega^2 - i\omega\gamma_0}$$

Lorentz Oscillator modell – without losses



Lorentz Oscillator modell – with losses



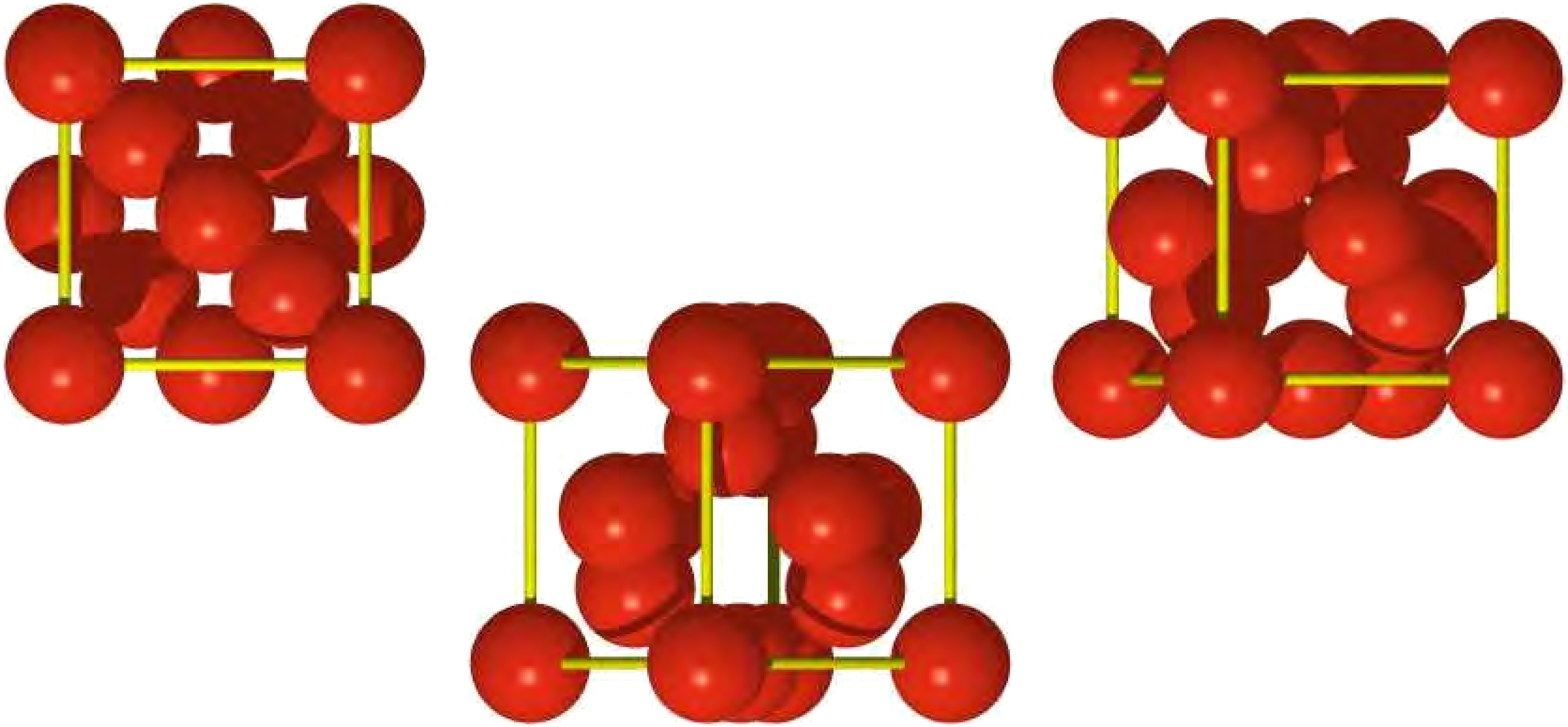
0. Introduction

1. Reminder:
   E-Dynamics in homogenous media and at interfaces

2. Photonic Crystals
   - **2.1 Introduction**
   - 2.2 1D Photonic Crystals
   - 2.3 2D and 3D Photonic Crystals
   - 2.4 Numerical Methods
   - 2.5 Fabrication
   - 2.6 Non-linear optics and Photonic Crystals
   - 2.7 Quantumoptics
   - 2.8 Chiral Photonic Crystals
   - 2.9 Quasicrystals
   - 2.10 Photonic Crystal Fibers – „Holey“ Fibers

3. Metamaterials and Plasmonics
   - 3.1 Introduction
   - 3.2 Background
   - 3.2 Fabrication
   - 3.3 Experiments

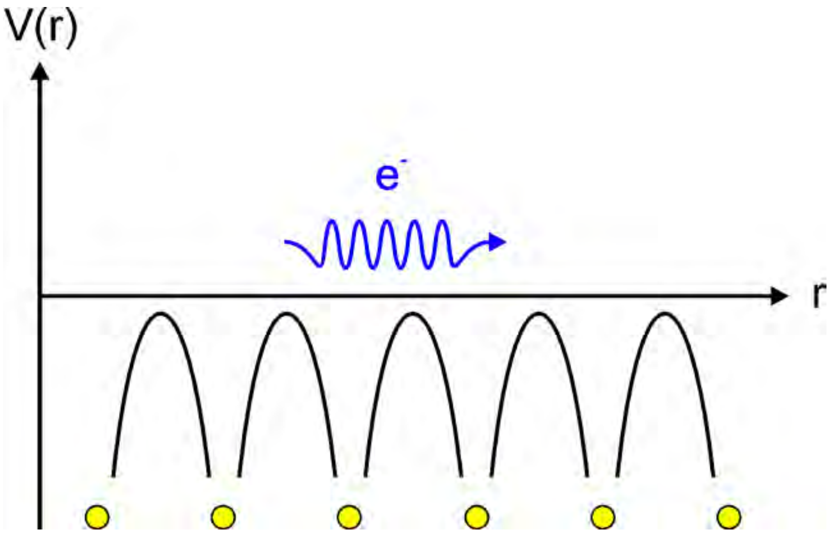
Silicon, a semiconductor crystal



Is there such a thing as a "semiconductor for light" ?

S. John, Phys. Rev. Lett. 58, 2586 (1987)
E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987)

Semiconductors



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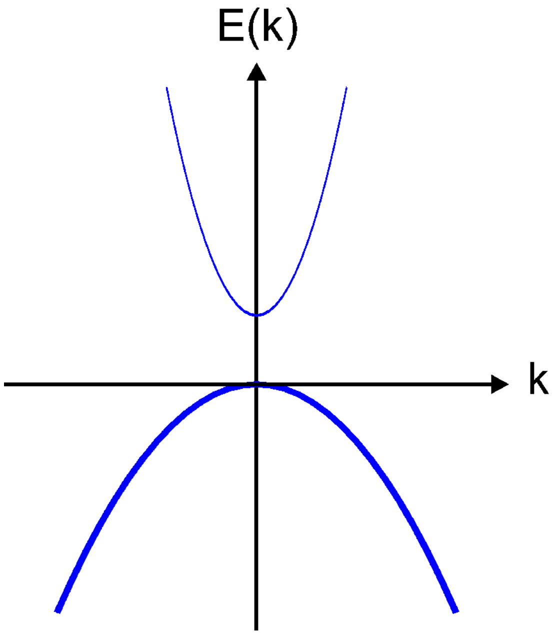
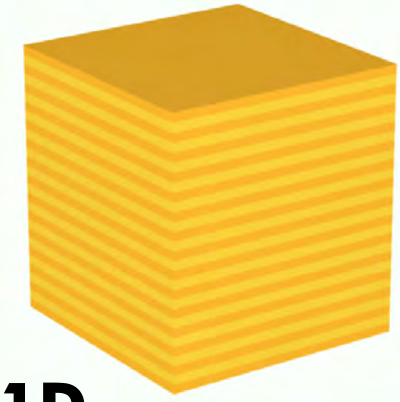


Periodic potential for electrons

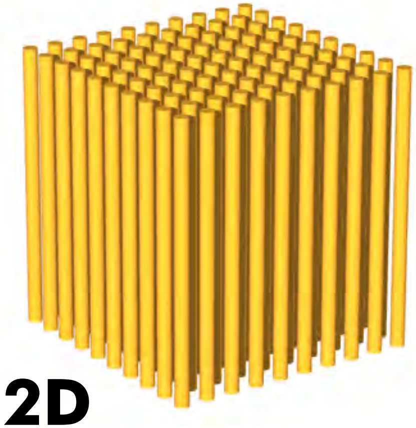
Band structure for electrons

Photonic Crystals

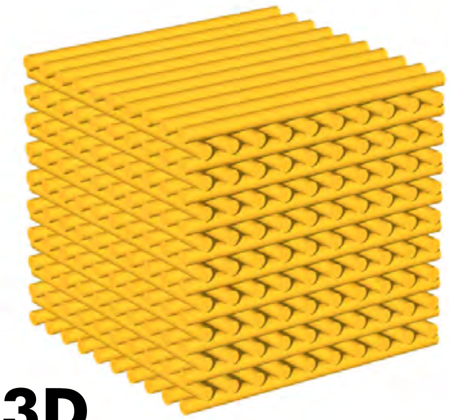
- **Dielectric or metallic materials with a dielectric function $\overleftrightarrow{\varepsilon}(\vec{r},\omega)$ that is periodically modulated along at least one spatial direction:**



1D

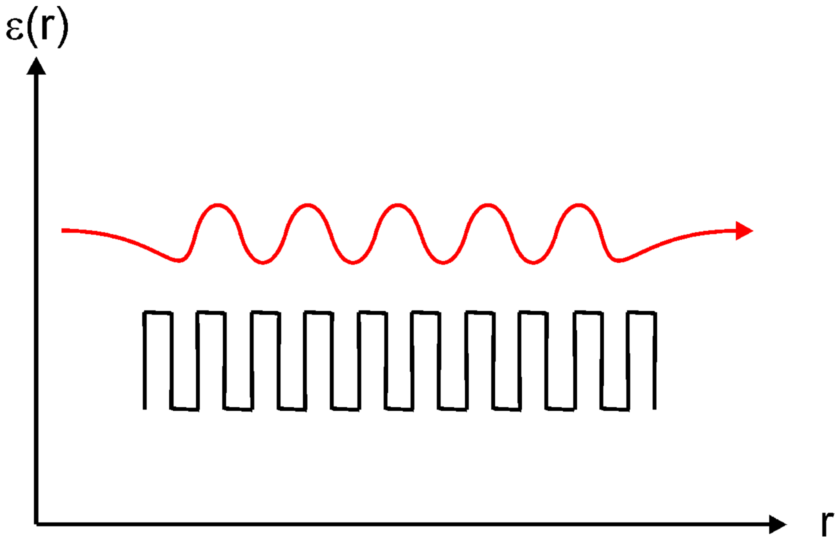


2D



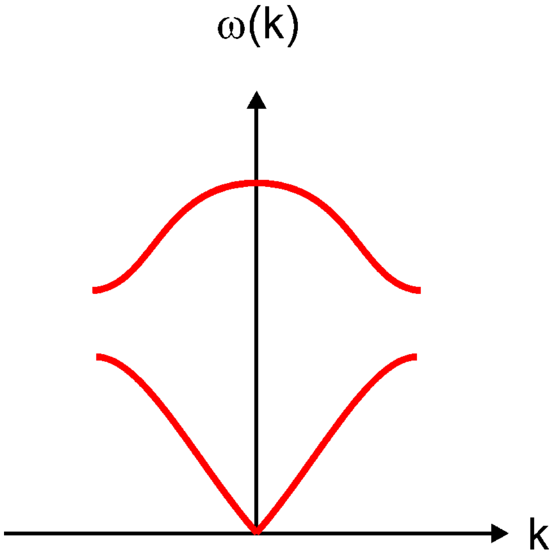
3D

Photonic Crystals



Periodic “potential” for photons

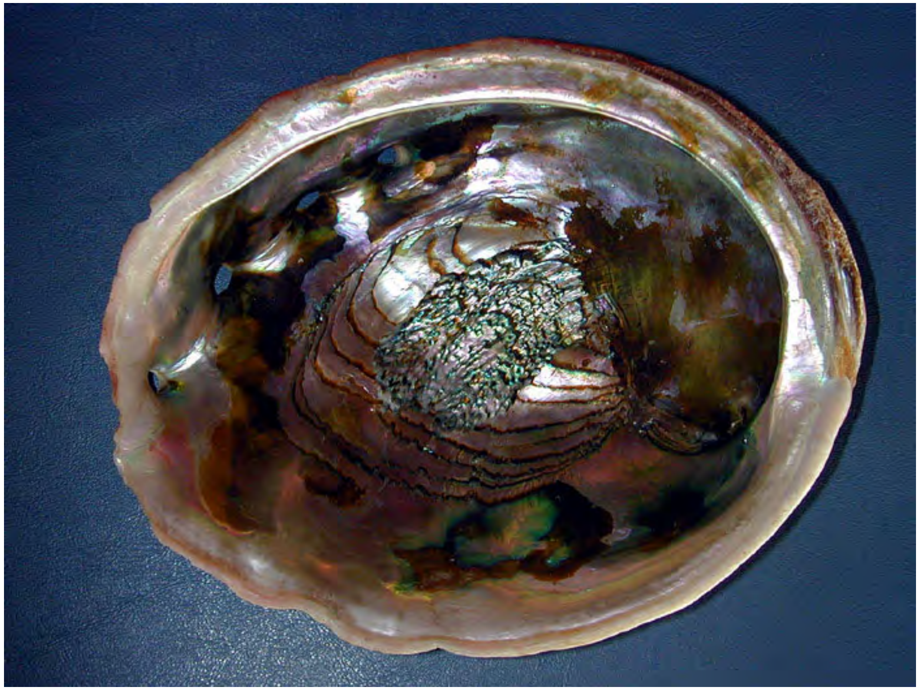
=

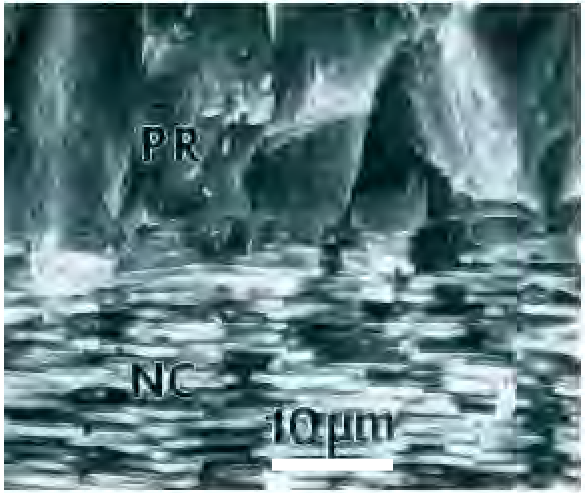


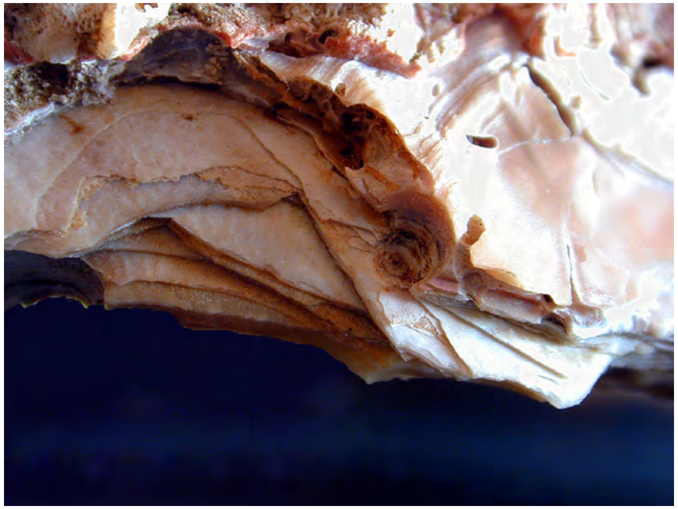
Band structure for photons

1D Photonic Crystals in nature

- **Mother-of-pearl**



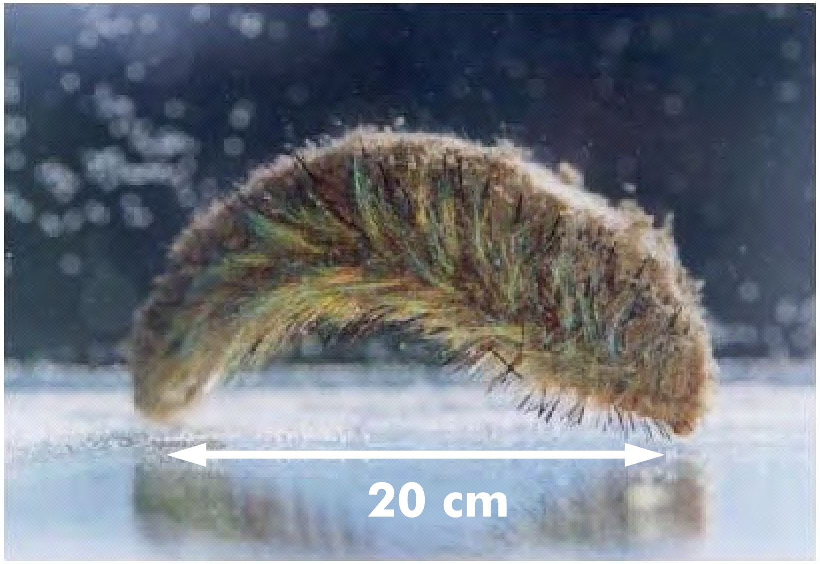


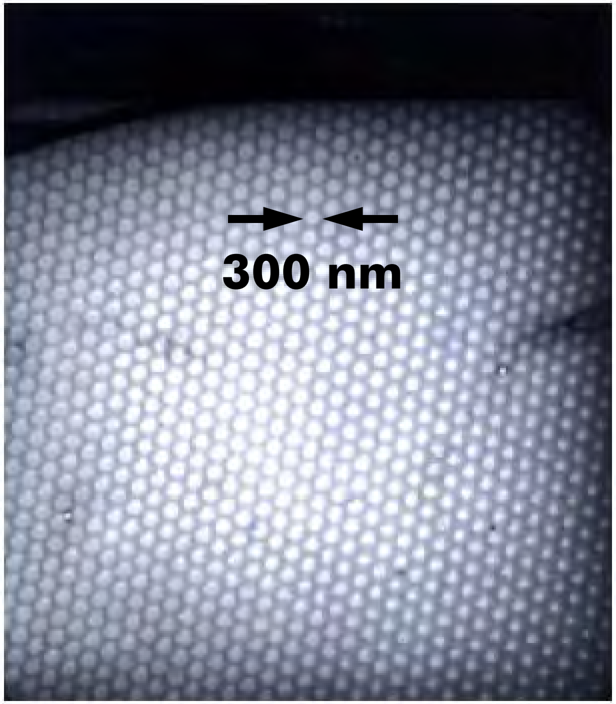


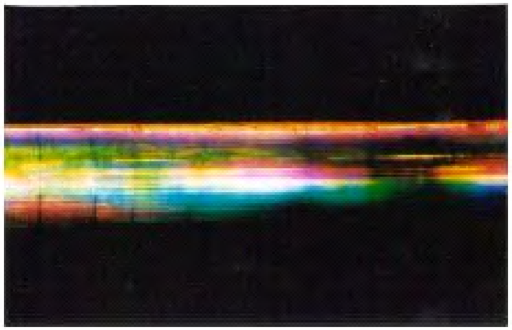
Aragonite [$CaCO_3$] / protein layers

taken from:
http://www.biosbcc.net/ocean/marinesci/06future/abrepro.htm
http://www.solids.bnl.gov/~dimasi/bones/abalone/

2D Photonic Crystals in nature





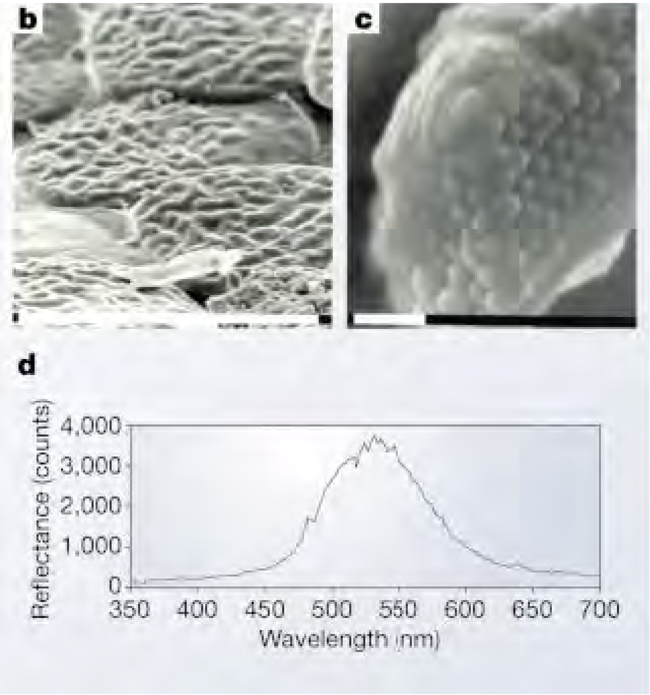


Sea-mouse

Taken from: A.R. Parker et al., Nature 409, 36 (2001)

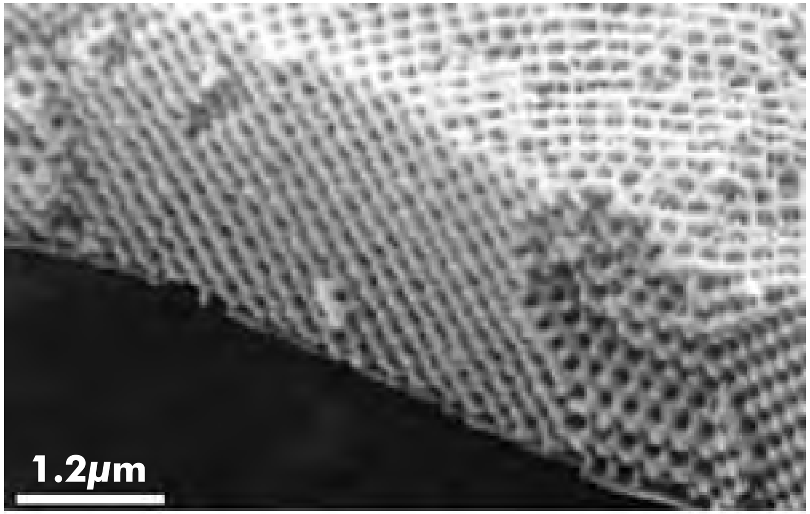
3D Photonic Crystals in nature

- **Pachyrhynchus argus**



Taken from:
- http://www.shgresources.com/nv/symbols/gemstonep
- A. R. Parker et al., Nature 426, 786 (2003)

3D Photonic Crystals in nature



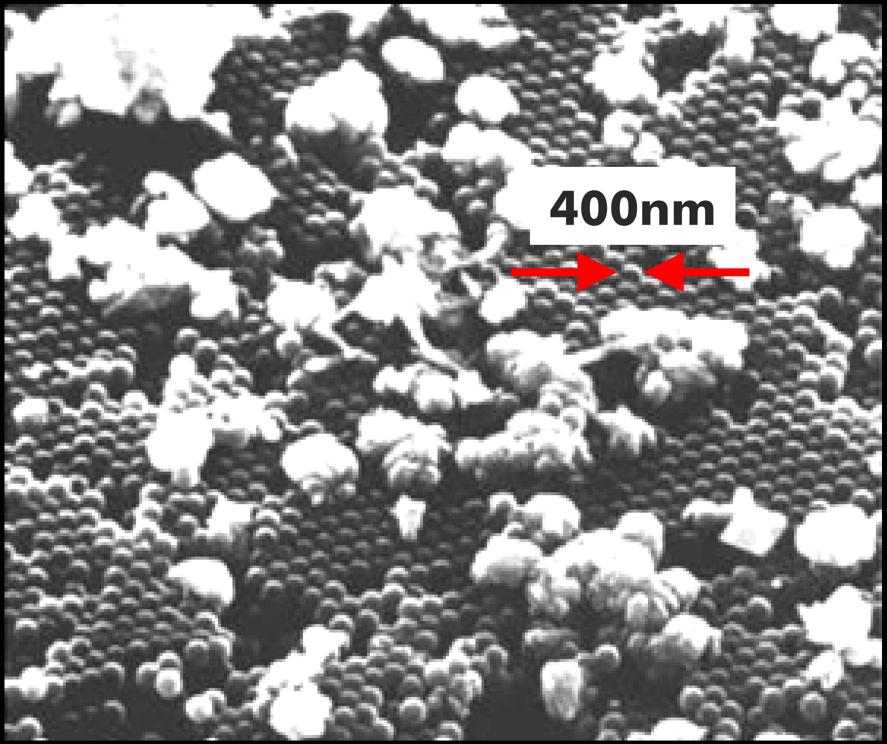
Morpho Rhetenor und Parides Sesostris

Overview: P. Vukusic and J.R. Sambles, Nature 424, 852 (2003)

Opals: 3D Photonic Crystals

Taken from: eBay.com

A closer look at an Opal

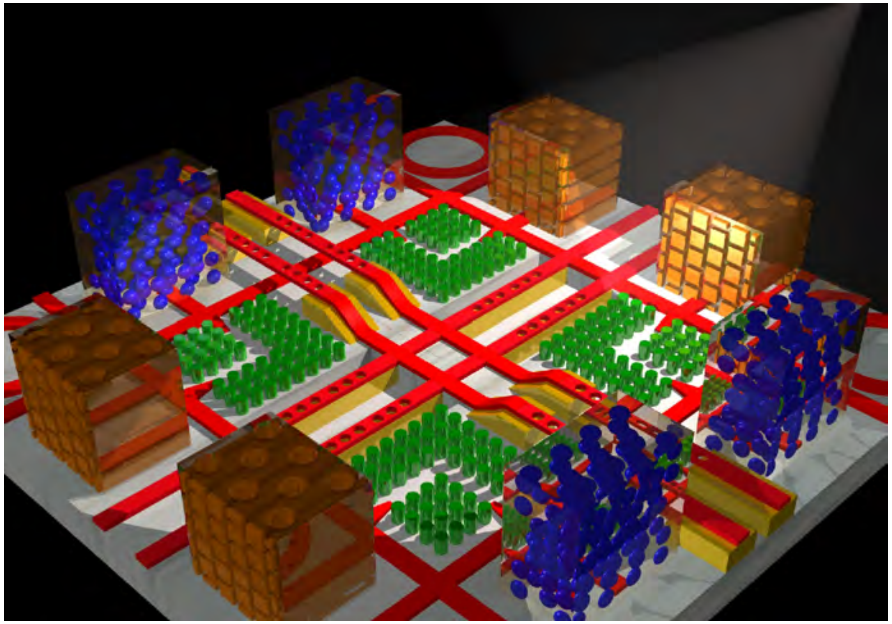


Taken from: J.B. Pendry, Current Science 76, 1311 (1999)

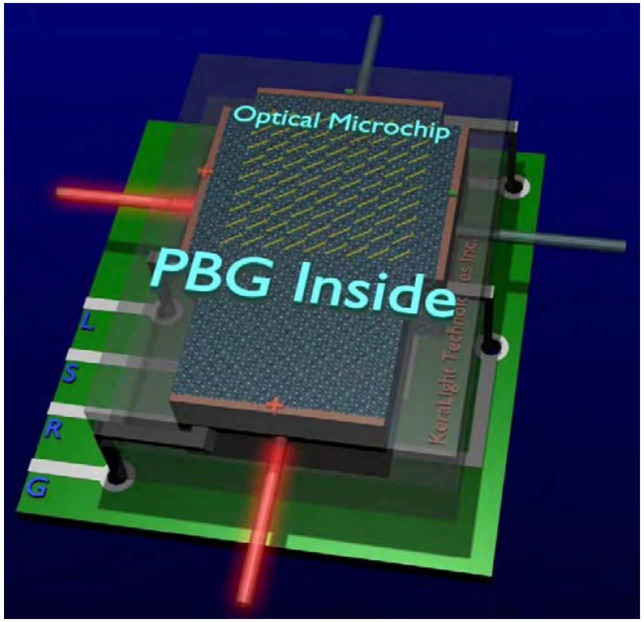
Visions for Photonic Crystals

- Custom designed electromagnetic vacuum
- Control of spontaneous emission
- Zero threshold lasers
- Ultrasmall optical components
- Ultrafast all-optical switching
- Integration of components on many layers

Visions for photonic crystals



‘Photonic Micropolis’
J. Joannopoulos Research Group (MIT)
http://ab-initio.mit.edu/



‘Optical Microchip’
S. John Research Group (Toronto)
http://www.physics.utoronto.ca/~john/