Lecture 2 – EM Waves Part I

EECS 598-002 Winter 2006
Nanophotonics and Nano-scale Fabrication
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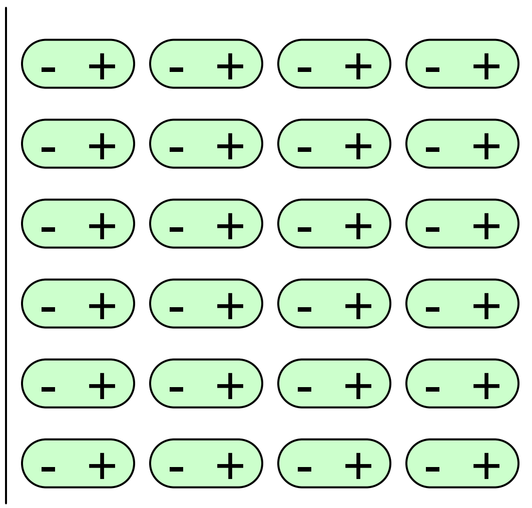
Lecture 2-4 EM waves in nanoscale

- Interaction of EM waves with macroscopic media
  - Derivation of macroscopic Maxwell's equations
  - Boundary conditions
  - Basic properties of EM waves
- Examples of interaction between EM waves and macroscopic media
  - Interface phenomena
  - Evanescent waves
- Generation of EM waves
  - Antenna basics
  - Dipole antenna
  - Near field and far field
- More on the interaction between EM waves and macroscopic media
  - Diffraction and scattering
  - Wave guiding
- Scaling and symmetry in EM waves

Illustrations of polarization and magnetization

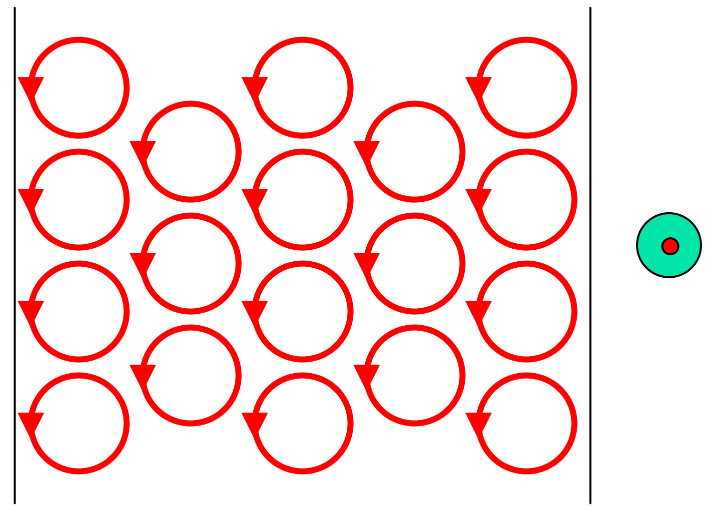
Polarization P



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

2^{nd} rank tensor

Magnetization M



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

Examples of different macroscopic media

Linear media

Isotropic media

$$\vec{D} = \varepsilon \vec{E} + \xi \vec{H}$$

$$\vec{B} = \mu \vec{H} + \zeta \vec{E}$$

Dielectric media

$$\vec{D} = \boldsymbol{\varepsilon} \vec{E}$$

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

Magnetic media

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

$$\vec{B} = \boldsymbol{\mu} \vec{H}$$

Nonlinear media

$$D_i = \varepsilon_0 E_i + 2\chi_{ijk}^{(2)} E_j E_k + 4\chi_{ijkl}^{(3)} E_j E_k E_l + \cdots$$

$$\vec{B} = \mu_0 \vec{H} + \mathbf{g}(H^2, H^3, \cdots)$$

Chiral media

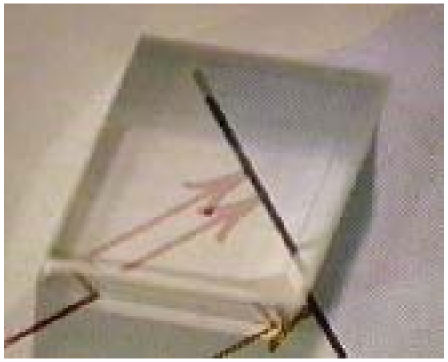
$$\vec{D} = \varepsilon \vec{E} - \chi \frac{\partial \vec{H}}{\partial t}$$

$$\vec{B} = \mu \vec{H} + \chi \frac{\partial \vec{E}}{\partial t}$$

Linear dielectric materials

- Isotropic media
  - Most of the materials can be regarded as isotropic dielectric materials. Another useful physical parameter refractive index *n* is defined as $n = \sqrt{\varepsilon}$
- Anisotropic media
  - For example, in calcite:

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix}$$



Because of two different refractive indices in different propagation directions, they are called “birefringent.”

Magnetic materials

For examples, check http://www.irm.umn.edu/hg2m/hg2m_b/hg2m_b.html

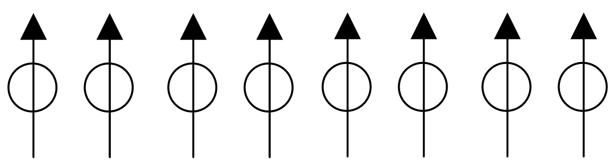
- Diamagnetic

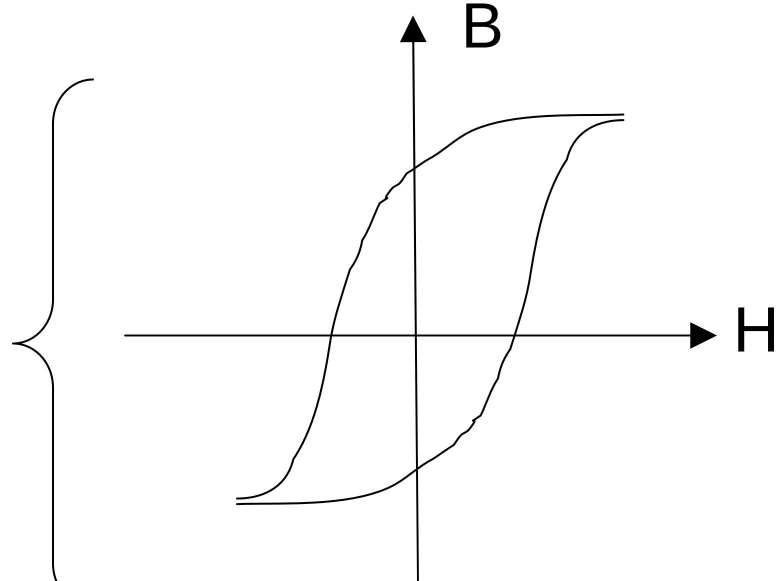
  $$\mu < \mu_0$$

- Paramagnetic

  $$\mu > \mu_0$$

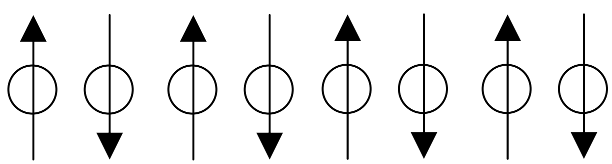
- Ferromagnetic





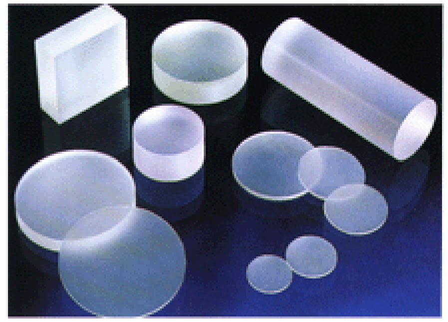
hysteresis

- Antiferromagnetic



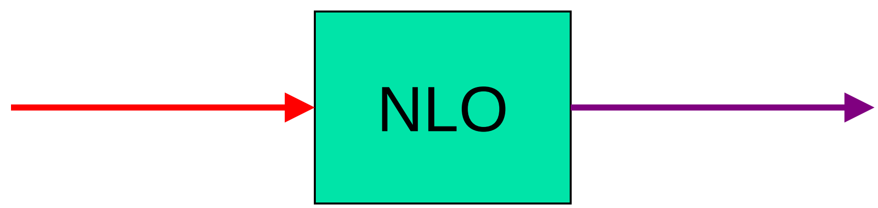
Nonlinear optical (NLO) crystals

quartz



BBO

KTP

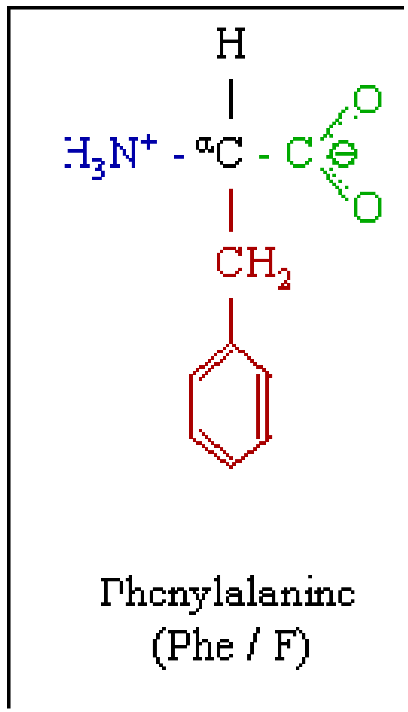


Frequency doubling through NLO.

Chiral materials

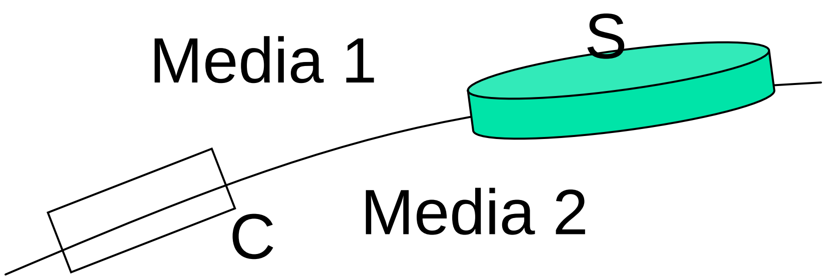
DNA

Amino acid



Sugar solutions

Boundary conditions



C and S are infinitesimal contour and surface.

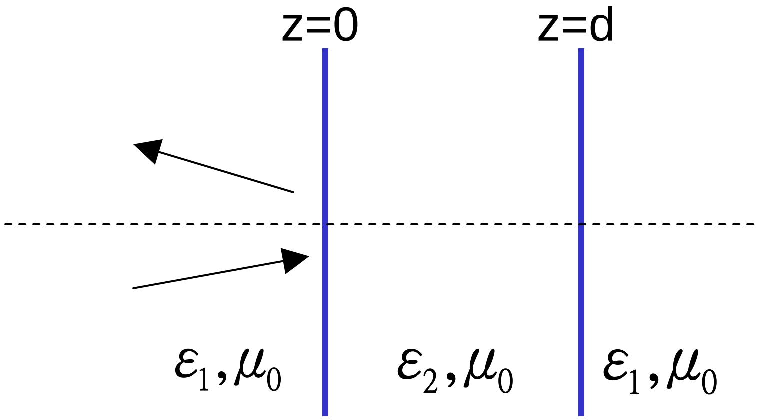
$$\oint_C \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{S} = 0 \Rightarrow E_{1t} = E_{2t}$$

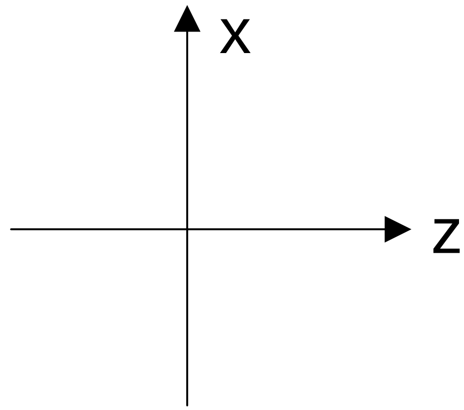
$$\oint_C \vec{H}\cdot d\vec{l} = \int_S \left(\vec{J} + \frac{\partial \vec{D}}{\partial t}\right)\cdot d\vec{s} \Rightarrow \vec{n}_2 \times (\vec{H}_1 - \vec{H}_2) = \vec{J}_S$$

$$\oint_S \vec{D}\cdot d\vec{s} = Q \Rightarrow D_{1n} - D_{2n} = \rho_S$$

$$\oint_S \vec{B}\cdot d\vec{s} = 0 \Rightarrow B_{1n} - B_{2n} = 0$$

Thin slab





$$\vec{E}_i = \hat{y}\left(E_i^+ e^{i(k_{ix}x+k_{iz}z)} + E_i^- e^{i(k_{ix}x-k_{iz}z)}\right) \quad i = 1 \cdots 3$$

$$\vec{H}_i = -ik_i\hat{x}\left(E_i^+ e^{i(k_{ix}x+k_{iz}z)} - E_i^- e^{i(k_{ix}x-k_{iz}z)}\right) \quad ; E_3^- = 0$$

(TE polarized)

Applying boundary conditions at each interface, we have:

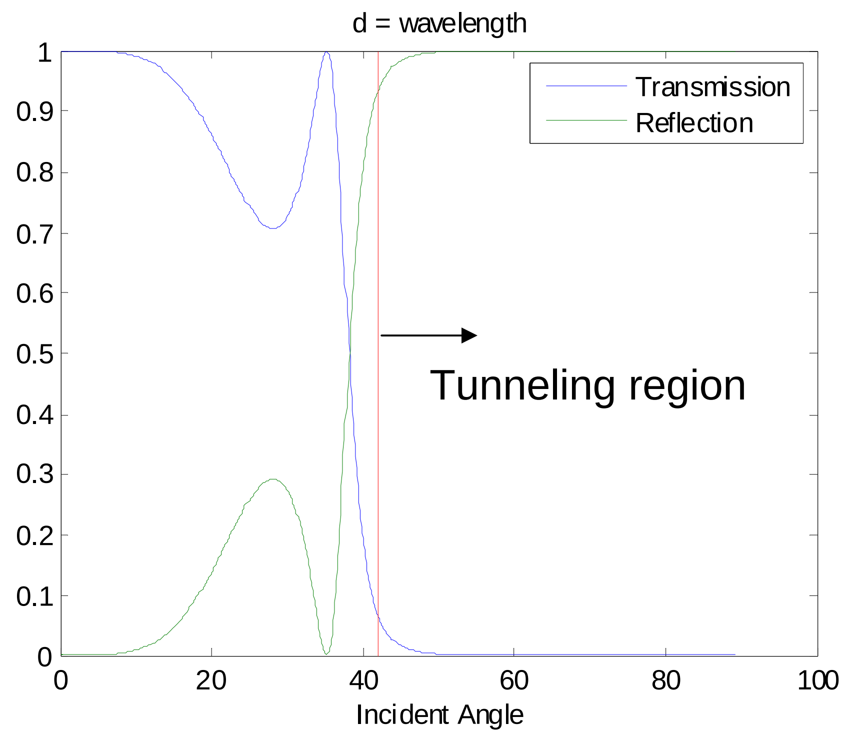
$$k_{1x} = k_{2x} = k_{3x}$$

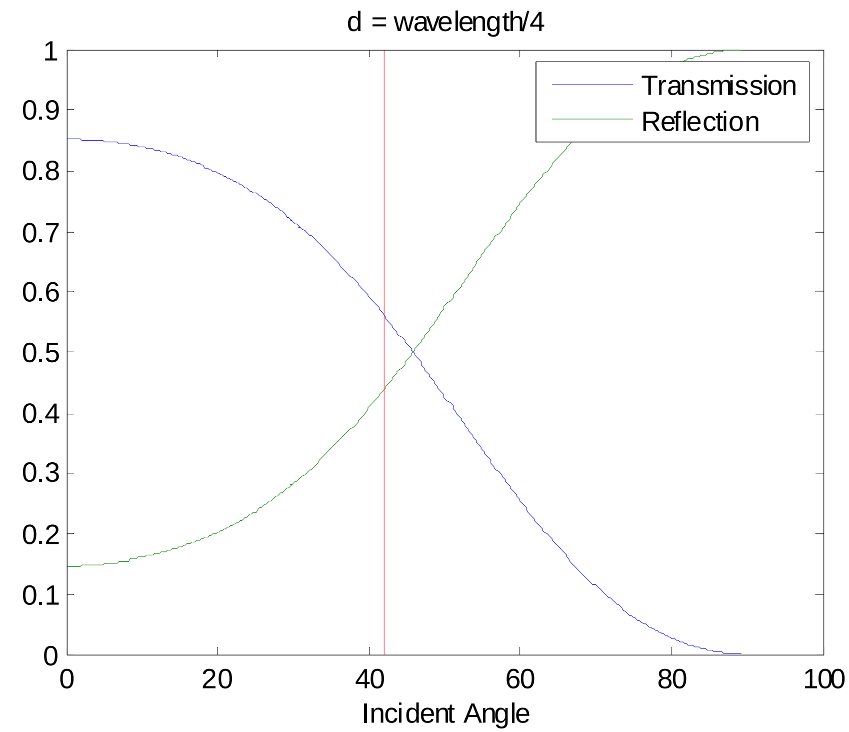
In the case $n_1 > n_2$ and when $k_{1x} > \frac{2\pi n_2}{\lambda}, k_{2z} = \sqrt{\left(\frac{2\pi n_2}{\lambda}\right)^2 - k_{2x}^2}$ is imaginary.

Thin slab (cont.)

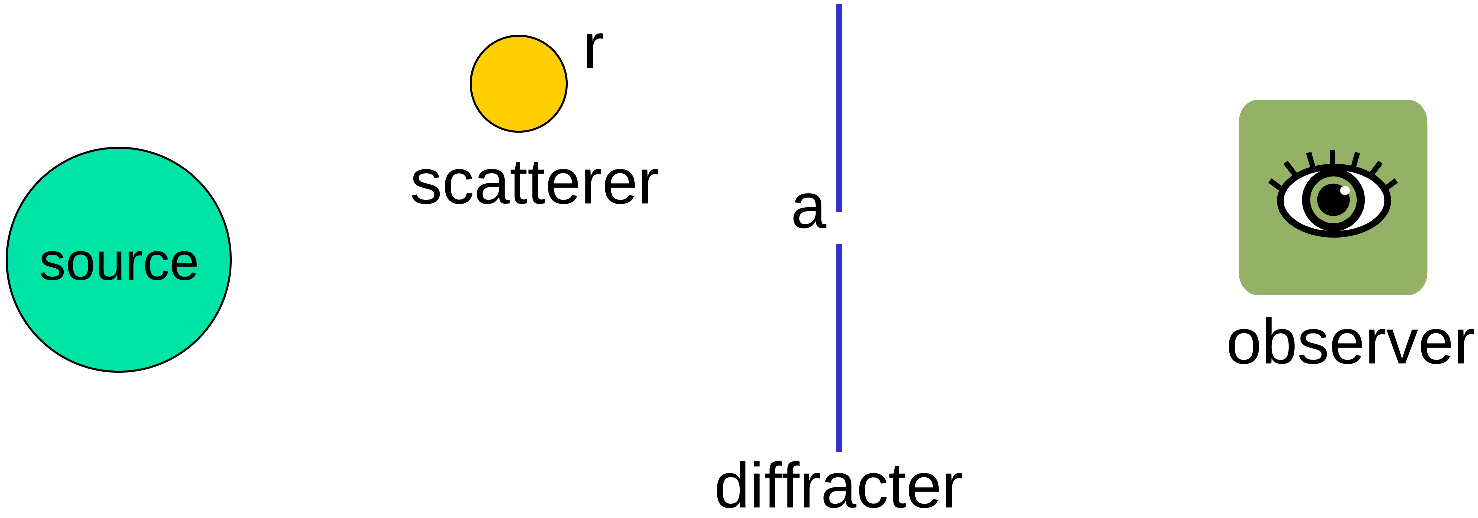
When the incident angle meets the total internal reflection condition at the 1-2 interface, there is no wave propagated in region 2 but there is still a finite transmission through the thin slab. The wave seems to “tunnel” through the slab!

For example, in the following plots, $n_1=1.5$ and $n_2=1$.





Scales



In a general EM problem, we have different length scales:

λ: wavelength
r: size of the scatterer
a: size of the diffracter
R1, R2, …: distances b/w two objects

- Near: R << λ
- Intermediate: R ~ λ
- Far: R >> λ