FACULTY OF ENGINEERING
AND ARCHITECTURE

ELECTRONICS AND INFORMATION SYSTEMS DEPARTMENT
LIQUID CRYSTALS AND PHOTONICS RESEARCH GROUP

LIQUID CRYSTALS AND LIGHT EMITTING MATERIALS FOR PHOTONIC APPLICATIONS

Kristiaan Neyts April 2018 Lecture series at WAT in Warsaw

GHENT UNIVERSITY

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nb-photonics
Center for Nano- and Biophotonics
Ghent University

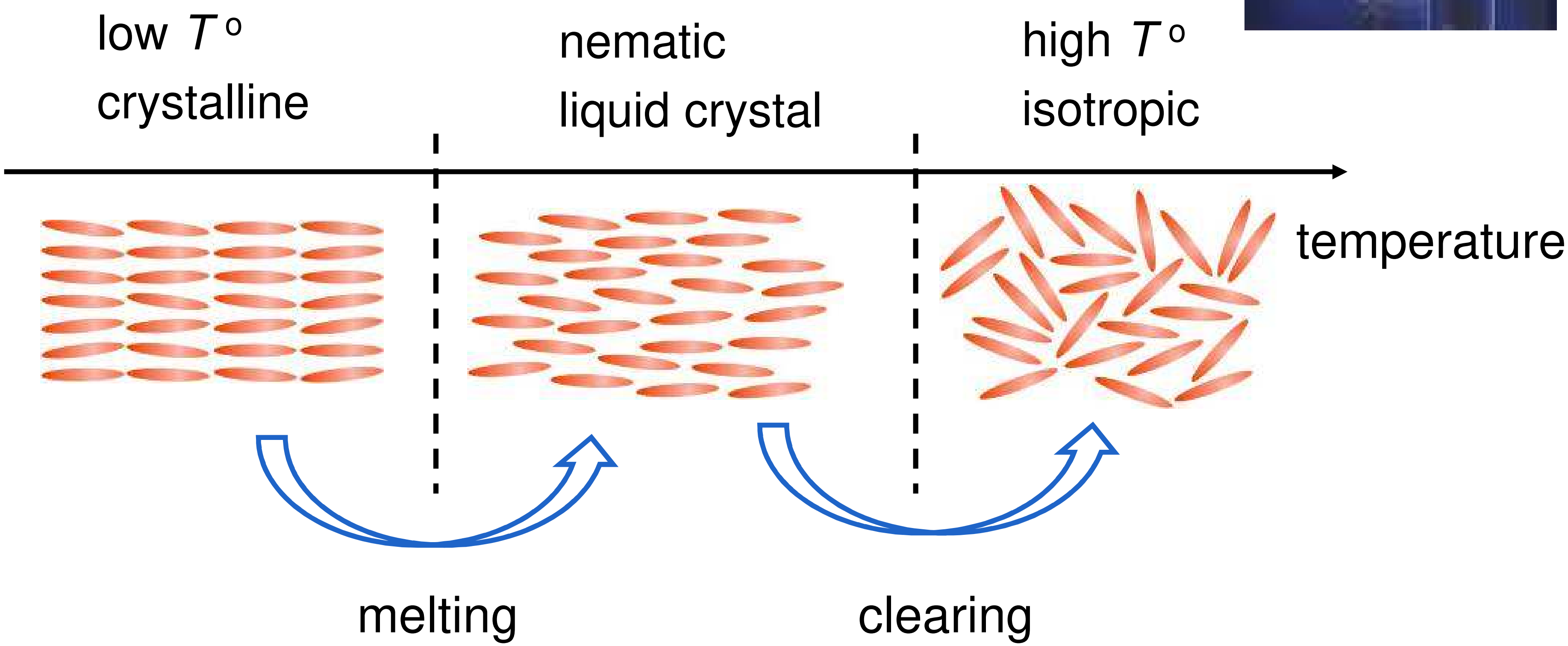
Liquid Crystals and Photonics

OVERVIEW

- Introduction (2h)
- Electrical and optical properties of materials (6h)
- Liquid crystal properties (10h)
- Display applications (6h)
- Photonic applications (6h)

LIQUID CRYSTALS

Introduction: the fourth state of matter



Liquid Crystals and Photonics

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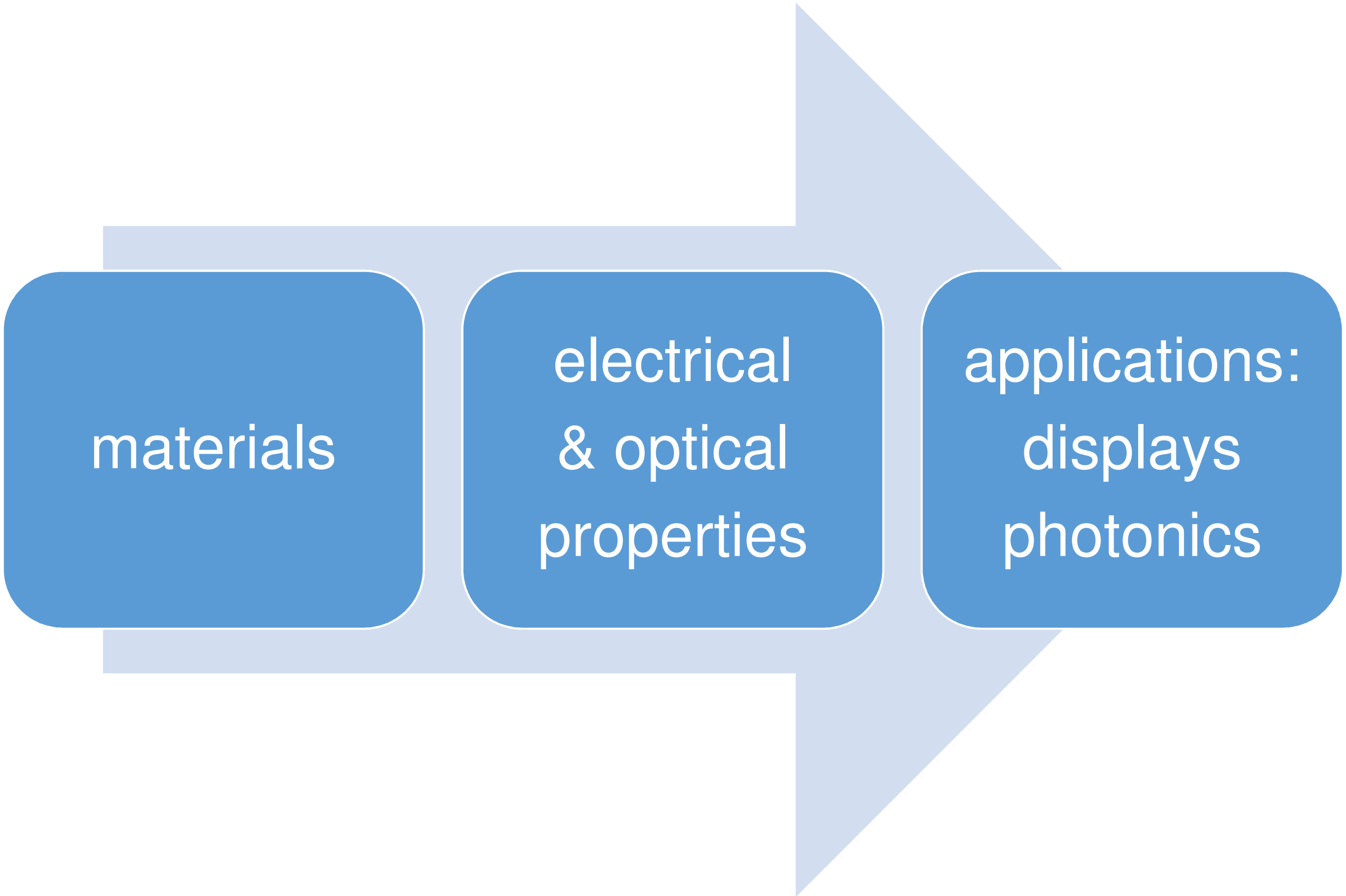
OVERVIEW

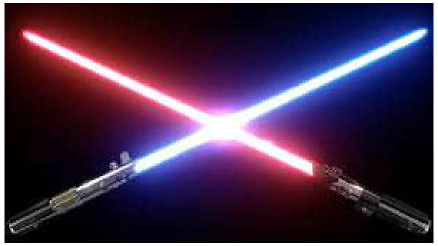

materials
electrical & optical properties
applications: displays photonics

OVERVIEW FOR NEXT LECTURES

Electrical and optical properties of materials (6h)

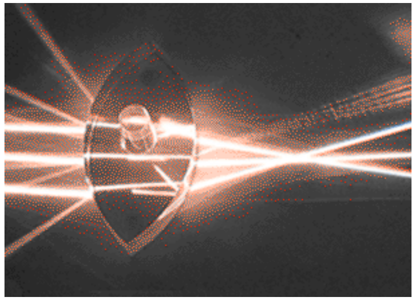
Polarizability of dielectric materials
Conductors and semiconductors
Light propagation
Light propagation in anisotropic media
Polarized light
Spontaneous and stimulated emission

LIGHT MATTER INTERACTION



"Changing the properties of light"

in vacuum light behaves according to the laws of Maxwell: no manipulation possible (homogeneous equations, superposition)



materials are influenced by light
light is influenced by materials
→ study of optical materials

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MAXWELL'S EQUATIONS

Maxwell's Equations with charges and currents

$$\nabla \cdot \vec{E} = \frac{1}{\varepsilon_0} \rho_a$$

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

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

$$\nabla \times \vec{B} = \mu_0 \vec{J}_a + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

source terms (a : all)

Charge density ρ_a

Current density $\vec{J}_a$

https://en.wikipedia.org/wiki/Maxwell's_equations

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MAXWELL'S EQUATIONS

total charge density $$\rho_a = \rho + \rho_p$$

- separate charges:

  electrons, ions $\boxed{\rho}$ $\quad q$

- couples of opposite charges forming a dipole

  - electron around an atom
  - polar molecule
  - displaced ion

  $\boxed{\rho_p}$ $\quad -q \quad q \quad \vec{d}$

$$\rho_P = -\nabla \cdot \vec{P}$$

dipole moment $$\boxed{\vec{p} = q\vec{d}}$$

MAXWELL'S EQUATIONS

current density $\vec{J}_a = \vec{J} + \vec{J}_P + \vec{J}_M$

- current of single charges: $\vec{J}$

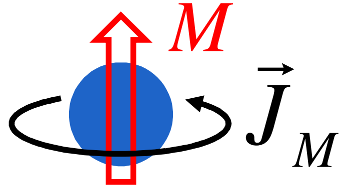
  electrons, atoms, ions

- variation of dipoles: $\vec{J}_p$ $\qquad \vec{J}_P = \dfrac{\partial \vec{P}}{\partial t}$

  rotation, stretching, displacement

- magnetization current: $\vec{J}_M$

  magnetic moment *m*, spin & orbit



$$\vec{J}_M = \nabla \times \vec{M}$$

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MAXWELL'S EQUATIONS

$$\nabla \cdot \vec{E} = \frac{1}{\varepsilon_0}\left(\rho - \nabla \cdot \vec{P}\right)$$

$$\rho_P = -\nabla \cdot \vec{P}$$

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

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

$$\nabla \times \vec{B} = \mu_0\left(\vec{J} + \frac{\partial \vec{P}}{\partial t} + \nabla \times \vec{M}\right) + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

$$\vec{J}_P = \frac{\partial \vec{P}}{\partial t}$$

$$\vec{J}_M = \nabla \times \vec{M}$$

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Maxwell's Equations

Rearranging the source terms in Maxwell's equations

$$\nabla\cdot\vec{E}=\frac{1}{\varepsilon_0}\left(\rho-\nabla\cdot\vec{P}\right)$$

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

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

$$\nabla\times\vec{B}=\mu_0\left(\vec{J}+\frac{\partial\vec{P}}{\partial t}+\nabla\times\vec{M}\right)+\varepsilon_0\mu_0\frac{\partial\vec{E}}{\partial t}$$

$$\nabla\cdot\left(\varepsilon_0\vec{E}+\vec{P}\right)=\rho$$

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

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

$$\nabla\times\left(\frac{\vec{B}}{\mu_0}-\vec{M}\right)=\vec{J}+\frac{\partial\left(\varepsilon_0\vec{E}+\vec{P}\right)}{\partial t}$$

MAXWELL'S EQUATIONS REVISITED

substitution of source terms ρ_a, J_a

$$\nabla\cdot\left(\varepsilon_0\vec{E}+\vec{P}\right)=\rho$$

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

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

$$\nabla\times\left(\frac{\vec{B}}{\mu_0}-\vec{M}\right)=\vec{J}+\frac{\partial\left(\varepsilon_0\vec{E}+\vec{P}\right)}{\partial t}$$

⇒

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

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

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

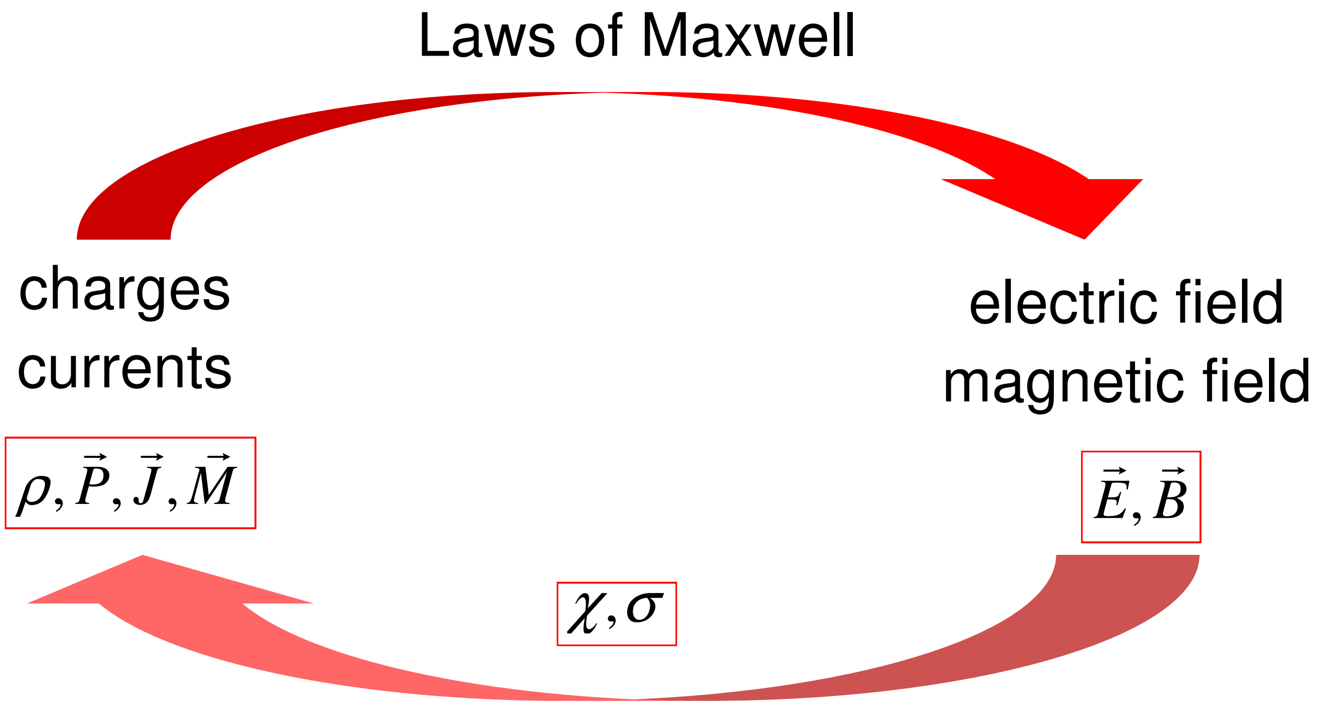
$$\nabla\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}$$

introduction of *D* and *H* fields:

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

$$\vec{H}=\frac{\vec{B}}{\mu_0}-\vec{M}$$

CONSTITUTIVE EQUATIONS



Constitutive equations

electrical properties, optical properties, absorption

MICROSCOPIC THEORY OF LINEAR ISOTROPIC MATERIALS

Microscopic Theory for Dielectrics

origin of electric susceptibility? $\vec{P} = \varepsilon_0 \chi \vec{E}$

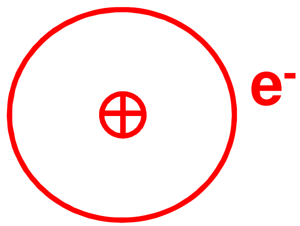
Static Electronic Polarization

shape of the electron cloud in a material

is influenced by the electric field

mass m_e (9.11 x 10^{-31} kg)

charge e (1.602 x 10^{-19} C)



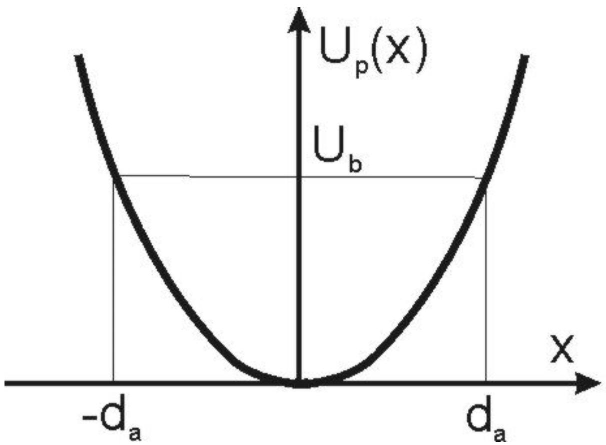
STATIC ELECTRONIC POLARIZATION

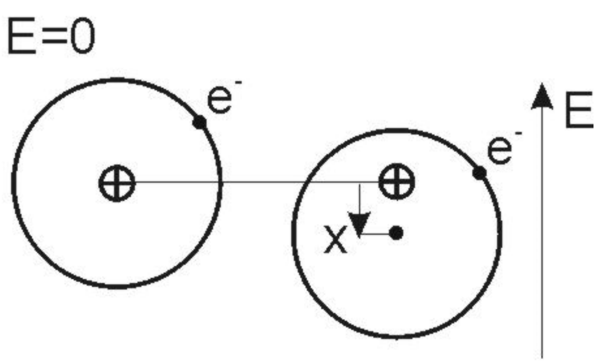
force on the electron due to electric field

$$\vec{F}_E = -e\vec{E}$$

force on the electron due to potential well U_p

$$U_p(x) = \frac{a}{2}x^2 \qquad F_p(x) = -\frac{dU_p}{dx} = -ax$$





STATIC ELECTRONIC POLARIZATION

static: equilibrium of forces: $F_{tot}=0$

dipole moment

$$\left.\begin{aligned}\vec{F}_E &= -e\vec{E} \\ \vec{F}_p(x) &= -a\vec{x}\end{aligned}\right\} \qquad \vec{x} = -\frac{e}{a}\vec{E} \qquad \vec{p} = -e\vec{x} = \frac{e^2}{a}\vec{E}$$

$$\vec{p} = \alpha\varepsilon_0\vec{E} \qquad \alpha_{e,s} = \frac{Ze^2}{\varepsilon_0 a}$$

polarizability
of an atom with Z e

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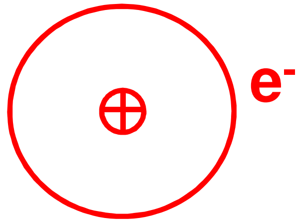
DYNAMIC ELECTRONIC POLARIZATION

differential equation of motion: *m.a=ΣF*



$$m_e \frac{d^2 x}{dt^2} = -eE - ax - 2m_e \gamma \frac{dx}{dt}$$

E-field

restoring force

damping force

resonance frequency: $\omega_0^2 = \frac{a}{m_e}$

periodic regime

$$\frac{\partial}{\partial t} \to i\omega$$

$$x = -\frac{eE}{m_e(\omega_0^2 - \omega^2 + i2\gamma\omega)}$$

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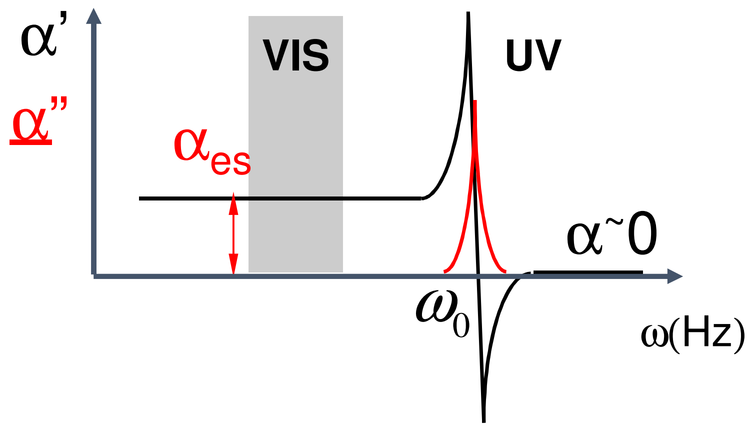
DYNAMIC ELECTRONIC POLARIZATION

atomic polarizability

$$\alpha_e = \frac{Ze^2}{\varepsilon_0 m_e} \frac{1}{\omega_0^2 - \omega^2 + i2\gamma\omega}$$

Resonance phenomenon

$$\alpha_e = \alpha' - i\alpha''$$



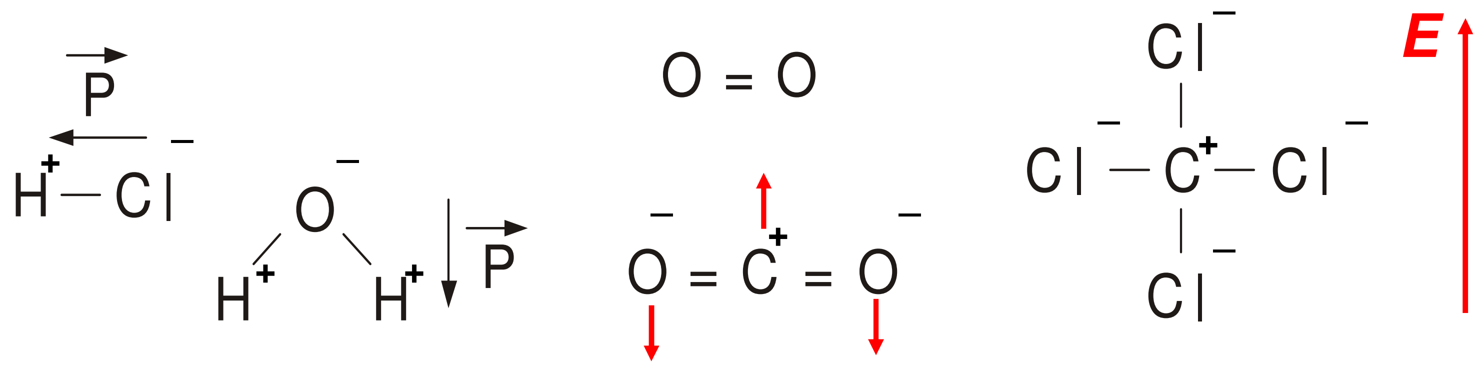
$$\alpha_{e,s} = \frac{Ze^2}{\varepsilon_0 m_e \omega_0^2}$$

IONIC POLARIZATION

Materials with partially ionized atoms

- permanent dipole moment (at *E*=0)

- ions are displaced due to the local field



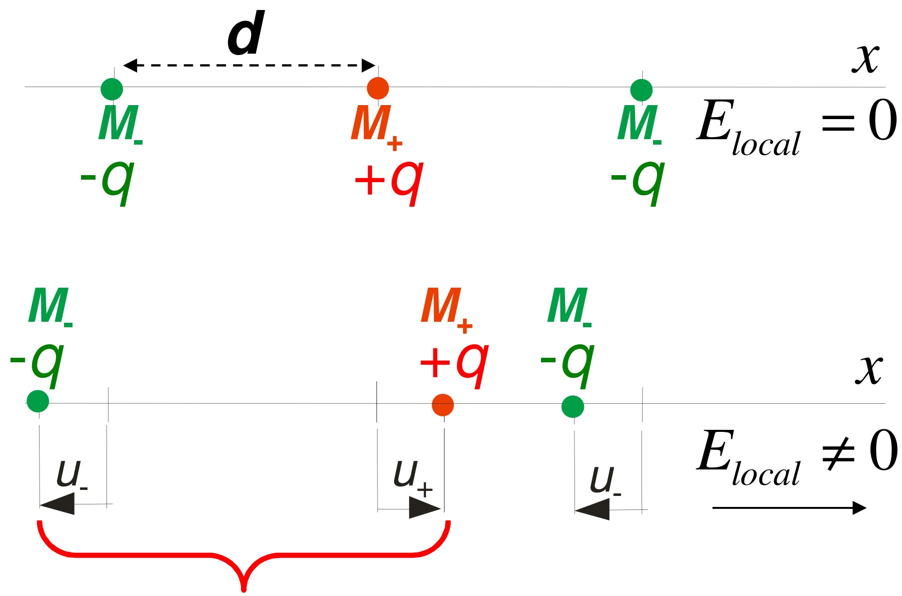
=> induced dipole moment

IONIC POLARIZATION

Solid state: ions move with respect to a grid

equilibrium situation:
ions at distance *d*

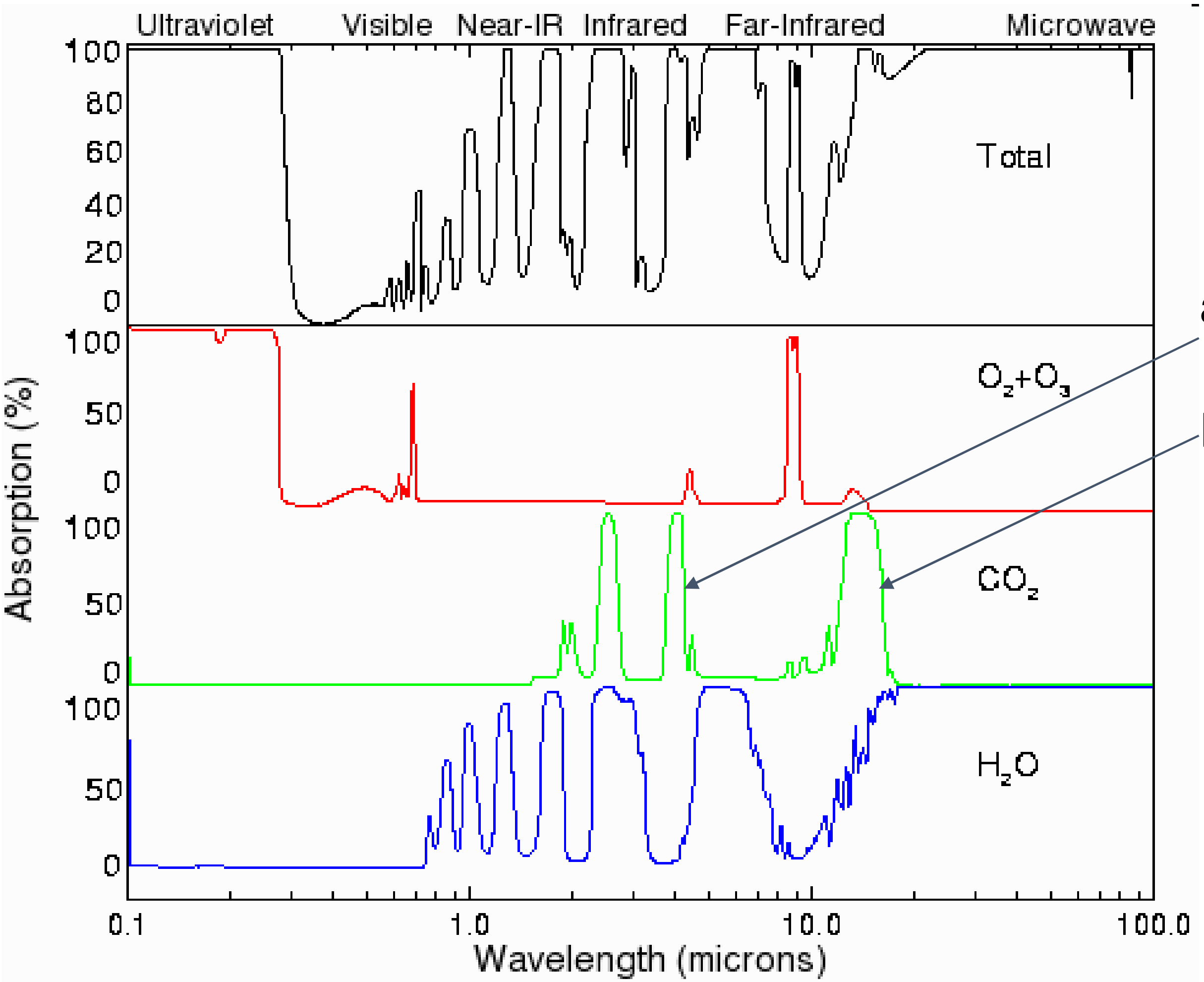
out of equilibrium
M_+ in phase
M_- in phase
deviation *u<<d*

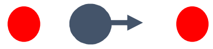


restoring force between two ions:
leads to resonance

$$\alpha(\omega) = \frac{q^2}{\varepsilon_0\left(2C - M\omega^2\right)}$$

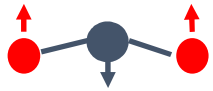
ABSORPTION BY THE ATMOSPHERE





asym. stretch

bend: 15µm



global warming

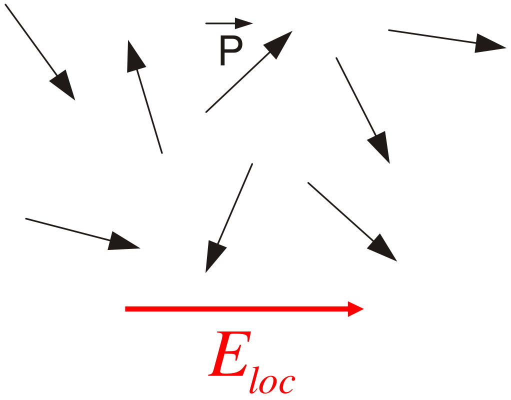
Peixoto, J.P. and Oort, A.H., Physics of Climate Springer, 1992, p. 118.

ORIENTATION POLARIZATION

Permanent dipoles in an electric field

potential energy

$$U = -\vec{p} \cdot \vec{E}_{loc} = -p \cdot E_{loc} \cdot \cos\theta$$



Boltzmann-probability f_B for the potential energy U

more dipoles align with E

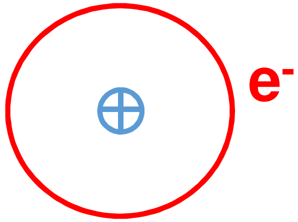
$$f_B = e^{-\frac{U}{kT}} = e^{\frac{p \cdot E_{loc} \cdot \cos\theta}{kT}}$$

MICROSCOPIC THEORY OF LINEAR ISOTROPIC MATERIALS

Microscopic Theory for Dielectrics

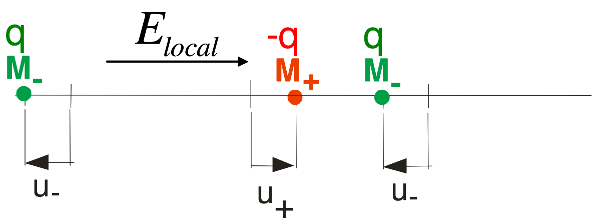
- electronic polarization

  resonance in UV



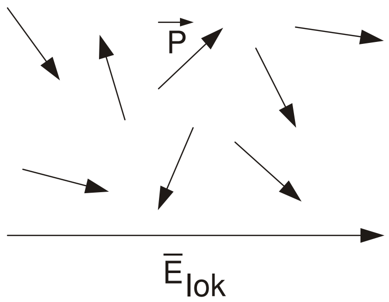
- ionic polarization

  resonance in IR



- orientation polarization

  relaxation or resonance in far IR



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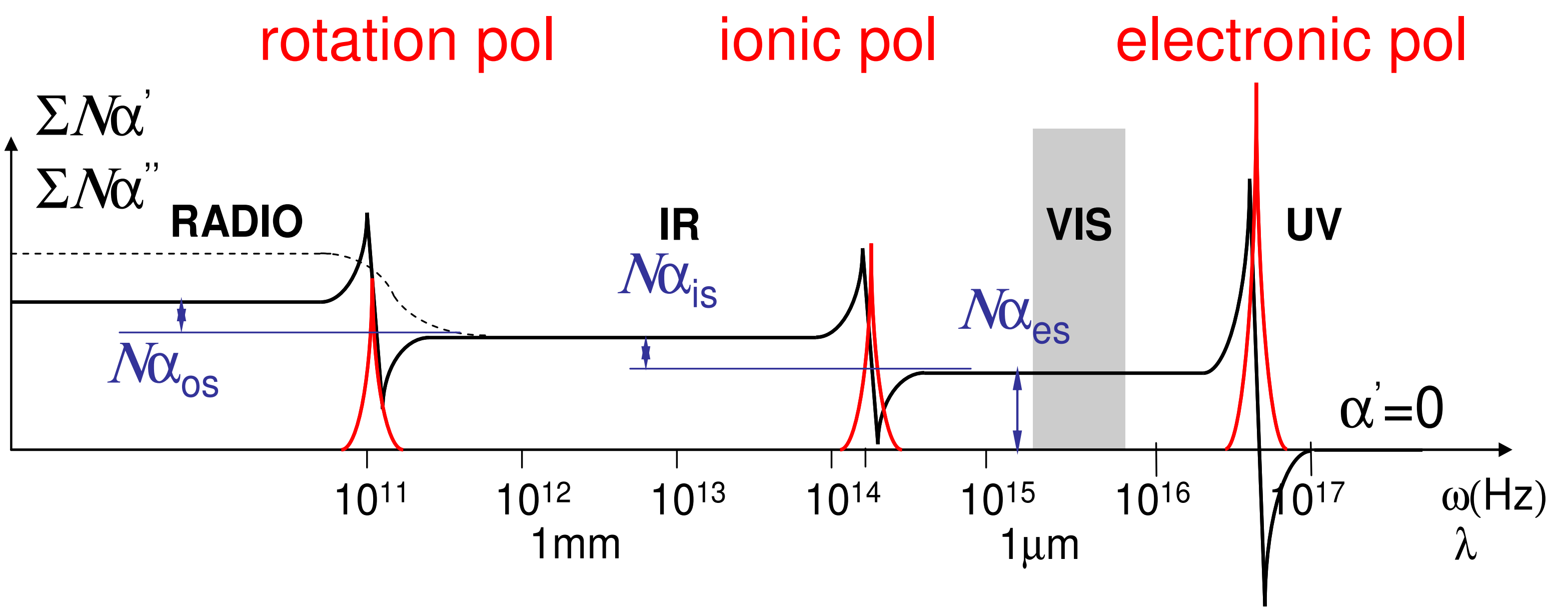
GENERAL DIELECTRIC BEHAVIOR

different resonance/relaxation processes

sum of all polarizabilities per unit volume:



PROPAGATION OF PLANE MONOCHROMATIC WAVES

Maxwell equations in vacuum

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

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

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

$$\nabla \times \vec{B} = \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

wave equation in vacuum

$$\Rightarrow \quad \nabla \times \left(\nabla \times \vec{E} \right) = \nabla \times \left(-\frac{\partial \vec{B}}{\partial t} \right) = -\varepsilon_0 \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

$$\boxed{\nabla^2 \vec{E} - \varepsilon_0 \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2} = 0}$$

solution $\quad \vec{E}_0 \cos\left(\omega t - \vec{k} \cdot \vec{r} \right) = \vec{E}_0 \operatorname{Re}\left[e^{i\left(\omega t - \vec{k} \cdot \vec{r} \right)} \right]$

$$\Rightarrow \quad k^2 - \varepsilon_0 \mu_0 \omega^2 = 0 \qquad\qquad k = \frac{\omega}{c}$$

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LIGHT IS ELECTROMAGNETIC RADIATON

Electric field E

Magnetic field B

in vacuum

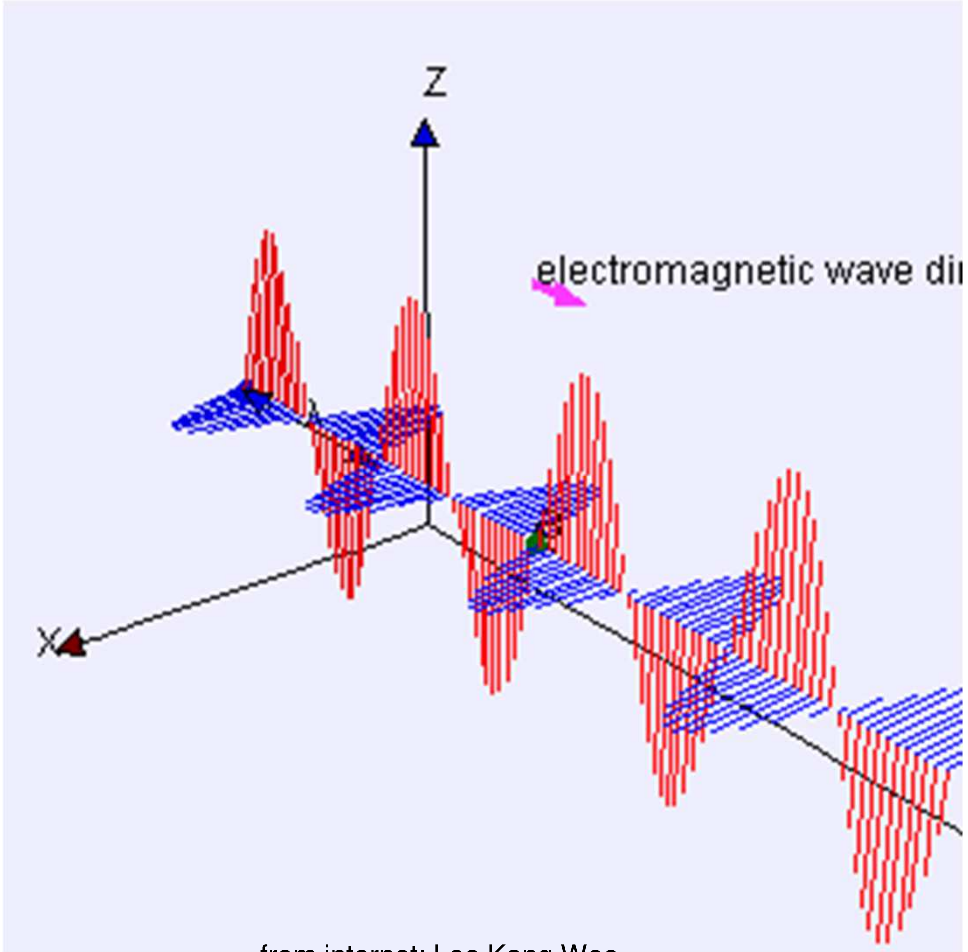
polarization

propagation speed c

frequency *f*

wavelength λ

$$k = \frac{2\pi}{\lambda}$$



from internet: Loo Kang Wee

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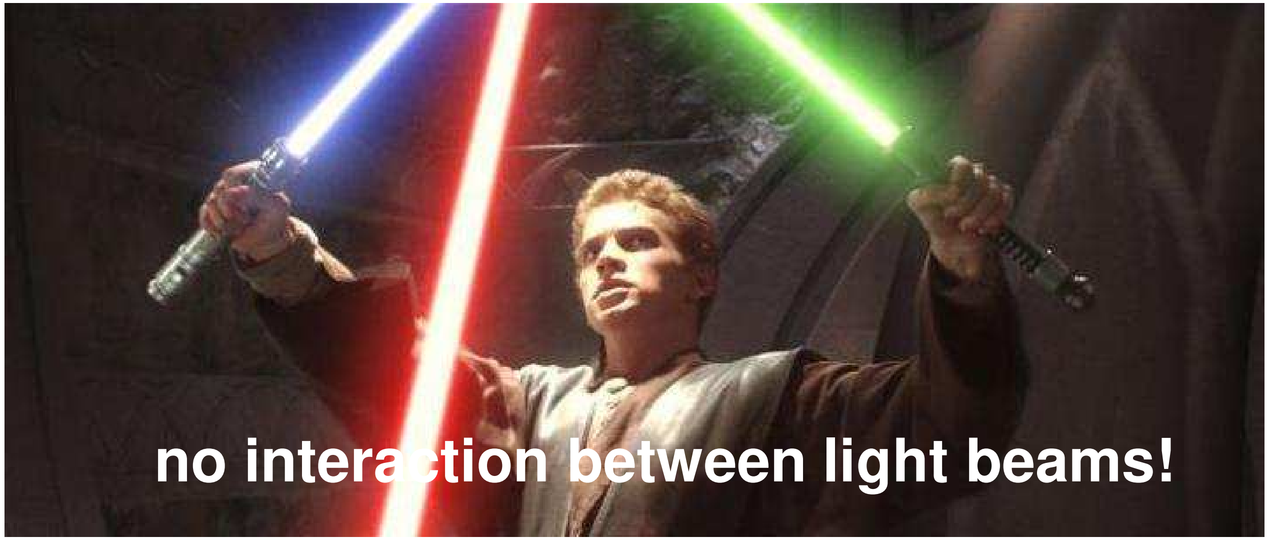
LIGHT IN VACUUM

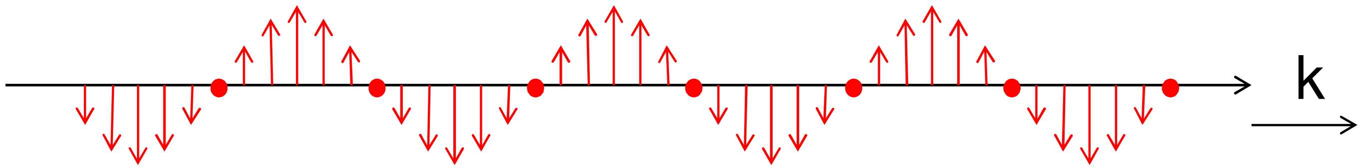
superposition of electric and magnetic fields in vacuum

"light waves, E fields and M fields do not interact"

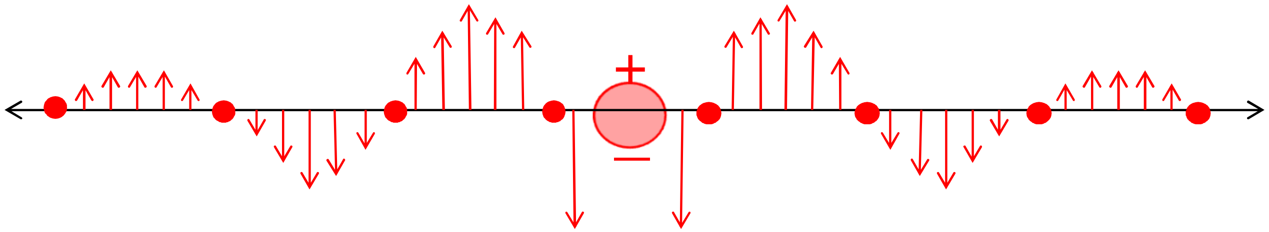


LIGHT SCATTERING BY A MOLECULE

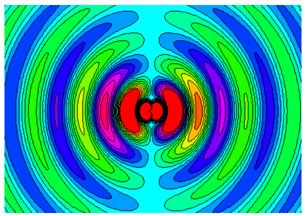
incident plane wave (linearly polarized)



scattered light of a particle with $r \ll \lambda$



backward forward



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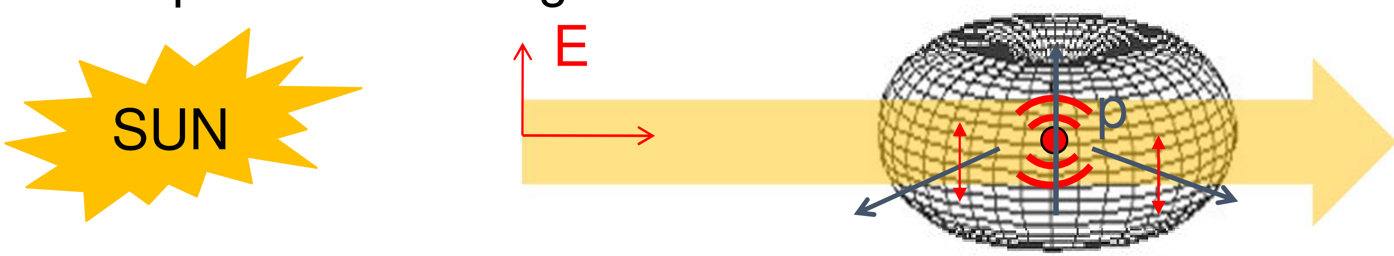
BLUE SKY

Light and a single atom

sunlight incident on N_2 or O_2

makes electrons oscillate

dipole antenna light emission

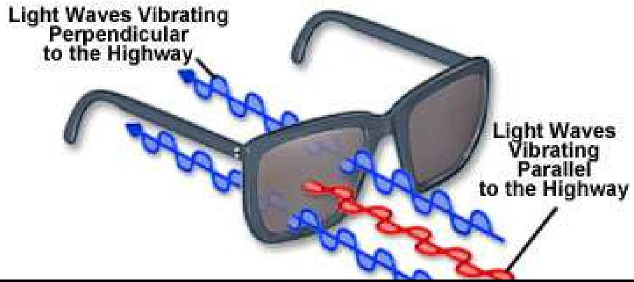


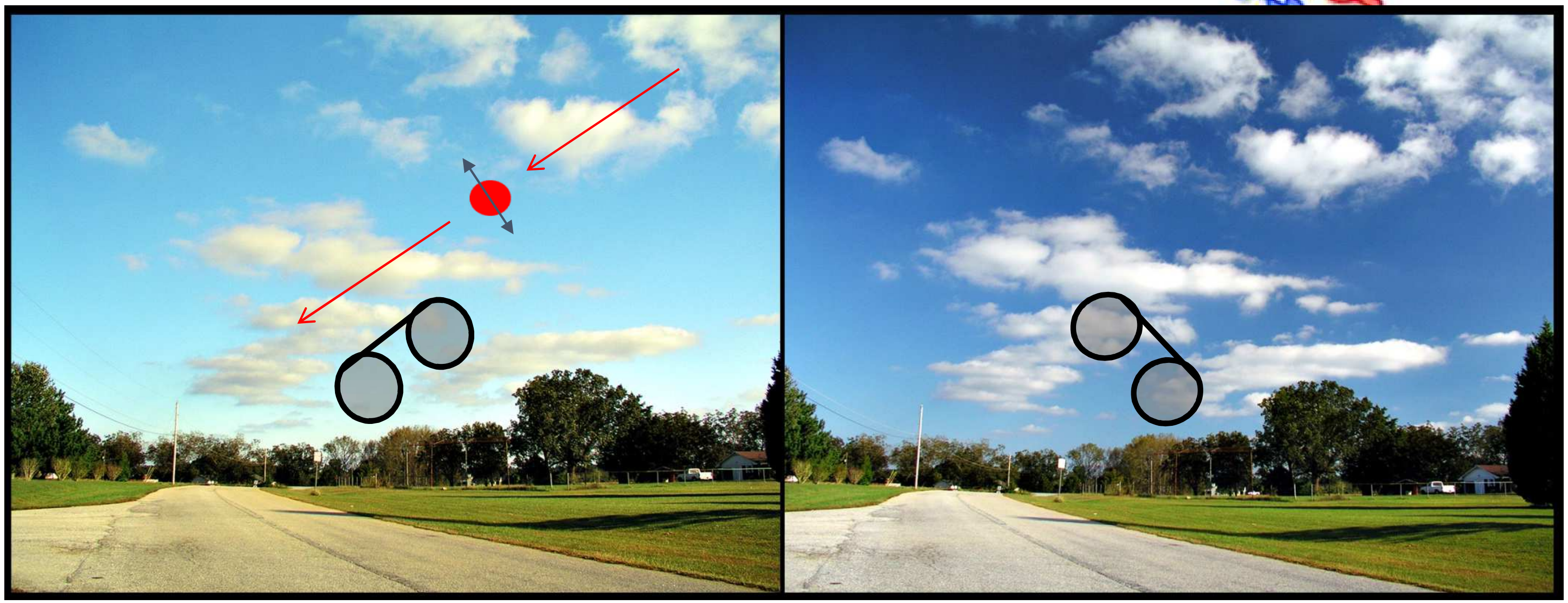
"Rayleigh scattering" in the atmosphere

linearly polarized

more blue than red ~ $(1/\lambda)^4$

BLUE SKY

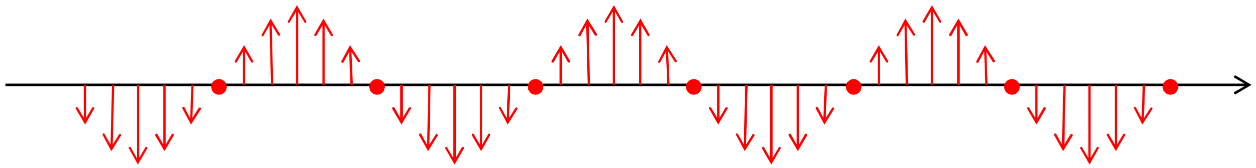




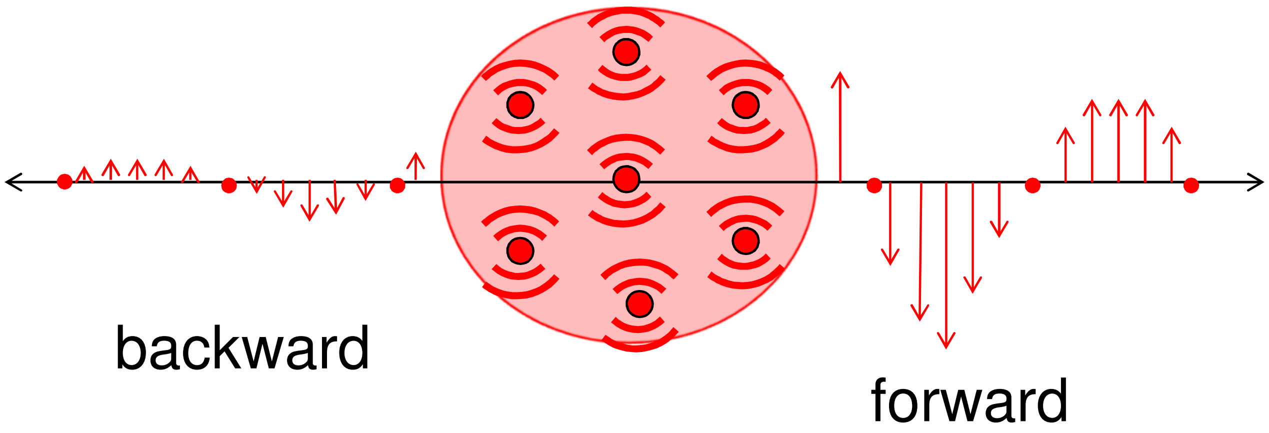
http://district196.org/avhs/dept/science/acc_physics/pages/polarized.html

LIGHT SCATTERING BY A PARTICLE

incident plane wave



scattered light of a particle with r order of λ (Mie scattering)



LIGHT SCATTERING BY A PARTICLE

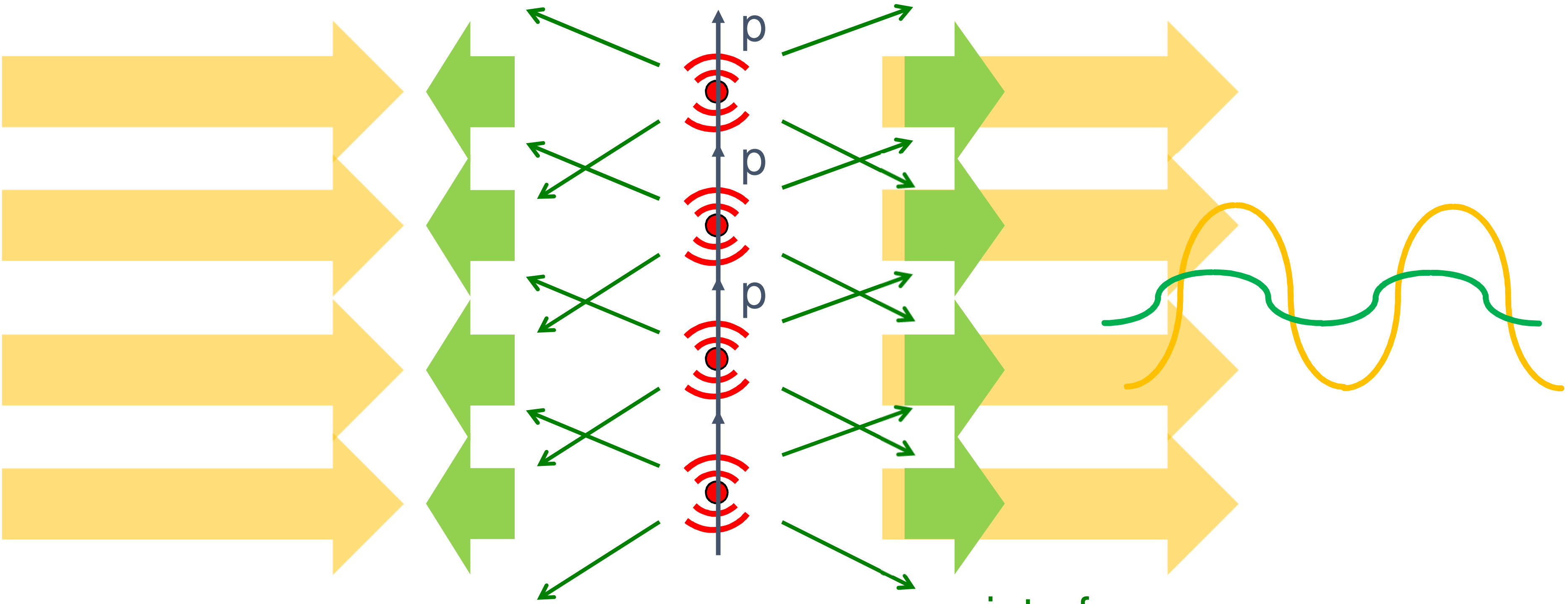
Mie scattering of unpolarized light by spheres $\sim\left(n_2^2 - n_1^2\right)^2$

www.citylab.com

Karl, the SFO fog

LIGHT AND INDUCED DIPOLES

Light and a layer of atoms

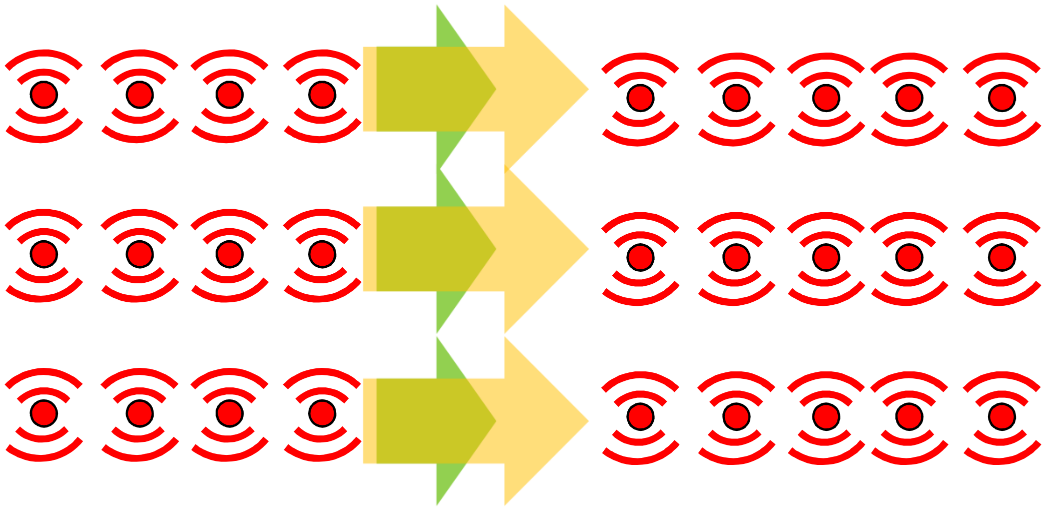


reflection
of a plane wave

interference:
scattering + original
results in a phase delay

LIGHT AND INDUCED DIPOLES

Light and a volume of atoms



Phase delay of the forward scattered light

light has:

... lower speed: c/n

... same frequency *f*

... shorter wavelength λ/n

$$n = \sqrt{1 + \frac{\sum_i N_i \cdot \alpha_i}{1 - \frac{1}{3}\sum_i N_i \cdot \alpha_i}}$$

PROPAGATION OF PLANE MONOCHROMATIC WAVES

Maxwell equations
in a medium

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

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

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

$$\nabla \times \vec{B} = \varepsilon\mu_0 \frac{\partial \vec{E}}{\partial t}$$

⇒

wave equation in vacuum

$$\nabla \times \left(\nabla \times \vec{E}\right) = \nabla \times \left(-\frac{\partial \vec{B}}{\partial t}\right) = -\varepsilon\mu_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

$$\nabla^2 \vec{E} - \varepsilon\mu_0 \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

solution $\vec{E}_0 \cos\left(\omega t - \vec{k} \cdot \vec{r}\right) = \vec{E}_0 \operatorname{Re}\left[e^{i\left(\omega t - \vec{k} \cdot \vec{r}\right)}\right]$

⇒ $k^2 - \varepsilon\mu_0\omega^2 = 0$ $\qquad k = \frac{\omega}{c}\sqrt{\frac{\varepsilon}{\varepsilon_0}} = \frac{\omega}{c} n$

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