5.4.1 Summary to: 5.1 Optics

- Know your numbers and relations for visible light!
  - Wavelengths: $\lambda \approx$ **400 nm - 800 nm.**

    $\lambda_{mat} = \lambda_0 / n$.
  - Frequency: $\nu \approx$ **10^{15} Hz**.
  - Index of refraction: $n = \epsilon_r^{1/2} \approx$ **1,5 - 2,5**
  - Energy $E \approx$ **1,8 eV - 3,2 eV**.
  - Dispersion relation: $c_0 = \nu \lambda_0 = 3 \cdot 10^8$ m/s

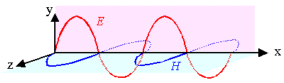
    $c_{Mat} = \nu \lambda_0 / n(\lambda)$

For the *propagation* of light:
use the *wave model*
For the *generation* and disappearance (= *absorption*) of light:
use the *photon model*

Snellius law:
$n = \sin\alpha / \sin\beta$ with α, β the angle of incidence or propagation, resp.

- Know yout basic equations and terminology

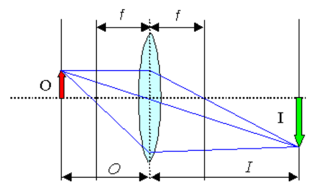
$$\begin{pmatrix} \underline{E}(\underline{r},t) \\ \underline{H}(\underline{r},t) \end{pmatrix} = \begin{pmatrix} \underline{E}_0 \\ \underline{H}_0 \end{pmatrix} \cdot \exp\{i(\underline{k}\underline{r} - \omega t)\}$$



Coherent monochromatic plane wave
E and ***H*** perpendicular and in phase

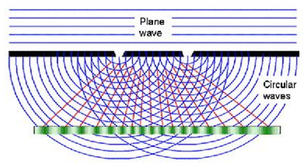
  - **Reflection** always with "angle in" = "angle out".
  - **Refraction** is the sudden "***bending***" or "flexing" of light beams at the interface
  - **Diffraction** is the continous "***bending***" of light beams around corners; interference effects.

- **Geometric optics**
  Key paramters
  - Focal length ***f*** and numerical aperture **NA** of lenses, mirrors.
  - Image formation by simple geometric constration
  - Various aberrations (spherical. chromatic, astigmatism, coma, ...) limit performance.



- **Wave optics**
  Huygens principle: and interference
  - Ultimate limit to resolution

$$d_{min} \approx \frac{\lambda}{2NA}$$



- Know your basic types of waves:
  - (Running, coherent, monochromatic) *plane wave*.
  - *Standing waves* = superposition of plane waves.
  - Incoherent, multichromatic *real* waves

- Relation s between electrical field $\underline{\boldsymbol{E}}$, magnetic field $\underline{\boldsymbol{H}}$ and **Poynting vector** (energy flow vector) $\underline{\boldsymbol{S}} = \underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}$

$$\langle S \rangle = \frac{E_0 H_0}{2} = \frac{E_0{}^2}{Z_W}$$

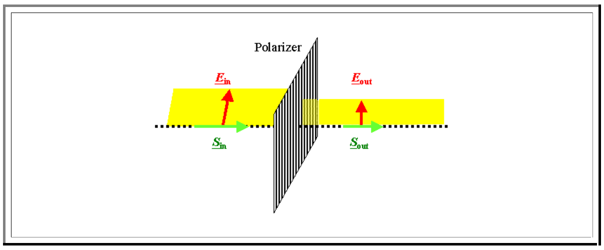
$$W_{elect} = \frac{\epsilon_0 \cdot E^2}{2} \qquad W_{mag} = \frac{\mu_0 \cdot H^2}{2}$$

$$[W_{elect;\ magn}] = [\mathrm{Ws\ m^{-3}}]$$

$$E_0 = \left(\frac{\mu_r \mu_0}{\epsilon_r \epsilon_0}\right)^{1/2} \cdot H_0 = Z_W \cdot H_0$$

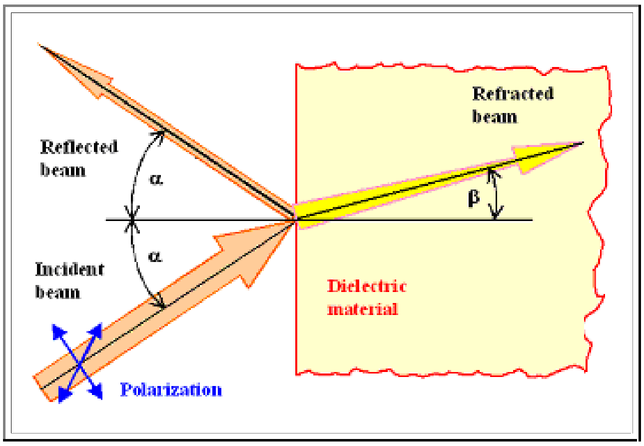
  This equation links *energy flow* (easy in photon picture) to *field strength* in wave picture.
  - Z_W = **wave impedance** of the medium.
    Z_W(vacuum) = 376,7 Ω

- **Polarization** = key to "advanced" optics.
  Simple case: **linear polarization**.
  - Plane of polarization contains $\underline{\boldsymbol{E}}$-vector and $\underline{\boldsymbol{S}}$ ($\underline{\boldsymbol{k}}$) vector.
  - Any (coherent) wave is polarized but *net polarization* of many waves with random polarization is zero!
  - Light *intensity* ($\propto \underline{\boldsymbol{E}}^2$) between polarizers at angle α scales with $(\cos\alpha)^2$.



- General case: *elliptical* polarization; important are the two extremes: *linear* and **circular** polarization.
  - For circular polarizaiton the $\underline{\boldsymbol{E}}$-vector rotates on a circle while moving "forward". This results from a superposition of two plane waves with $\underline{\boldsymbol{E}}$-vectors ar right angles and a *phase difference* of **π/2**.
  - Technically important (3-dim Cinema; Lab optics)

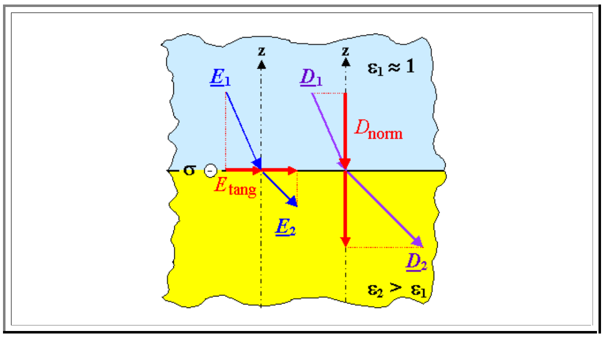
- **The task:**
  Calculate and understand intensities, angles, phases, polarization and attenuation (damping) of the various light beams shown from the materials properties
  - Still assuming a perfectly flat surface



- First step: Decompose impinging light into two waves with polarization in he interface plane (**TE** case) or at right angles (**TM** case)
  - Energy conservation yields for the intensities:

$$I_{tr}(z = 0) = I_{in} - I_{re}$$

- Boundary conditions as shown in the figure involve the "dielectric constant ϵ and thus the so far only relevant material property.
  - Considering energy (proportional to $\boldsymbol{E}^2$) and momentum (proportional to $\underline{\boldsymbol{k}}^2$") conservation for the TE and TM case separately yields the **Fresnel equations** that provide the answers to the questions above
  - A wealth of insights and relations follow, e.g. or field strength $\boldsymbol{E}$ or intensities I:



$$\frac{E_{ref}}{E_{in}} = -\frac{n-1}{n+1}$$

$$\frac{I_{ref}}{I_{in}} = \left(\frac{n-1}{n+1}\right)^2$$

- one consequence as example for the power of these equations: ***n* = 2** means that almost **10 %** of the intensity will be reflected, implying that for optical instruments you *must* provide some "anti-reflection" coating.

Using the complex (and frequency dependent "dielectric constant $\epsilon(\omega) = \epsilon' + i\epsilon''$" yields the **complex index of refraction**

$$n^*(\omega) = n + i\,\kappa$$

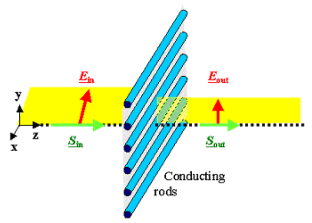
- The imaginary part κ describes the attenuation (damping) of the transmitted wave in the material.

$$n^2 = \frac{1}{2}\left(\left(\epsilon'^2 + \epsilon''^2\right)^{½} + \epsilon'\right)$$

$$\kappa^2 = \frac{1}{2}\left(\left(\epsilon'^2 + \epsilon''^2\right)^{½} - \epsilon'\right)$$

Polarization and Material2. How to polarize a light beam

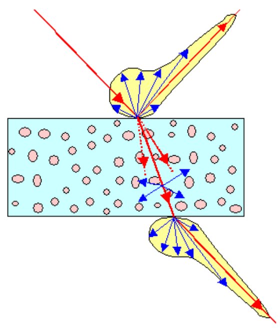
- **1. Geometry**. Use Fresnel equations to produce a polarzed beam under specific angles ("Brewsater angle")
- **1. Polarization foils** = alined conducting rods (of possibly molecular size) "short-circuiting" the electrical field in on direction.
- **3. "Tensor" materials** with optical anisotropy



Theory can an get rather involved; products can be extremely simple and cheap (e.g. circular polarizer in 3-D movie glasses)

Not so perfect materials and properties like specular and diffuse Reflection, transparency, Translucency, Opacity.

- Light is scattered at small things in all directions and the scattering of light is the major topic encountered if we look at not-so-perfect materials
- The picture illustrates:
  Specular and diffuse reflection at the surface.
  Scattering of the transmitted light (running in different directions) at defects or imperfections contained in the material (fat droplets in milk, air bubbles in glass, ...).
  Specular and diffuse reflection at the internal surface the light is coming out off. This is described by a (different) polar diagram characterizing this surface.



Scatter mechanism depend on the size l_{sca} of the scatterer" relative to the wavelength:
$l_{sca} << \lambda$**:** The extreme case would be scattering at single atoms or molecules. Proper **nanoparticles** also belong into this group. This kind of scattering is called **Rayleigh scattering**
$l_{sca} >> \lambda$**:** No problem, we covered that already. Just look at any part of the sample by itself.
$l_{mat} \approx \lambda$**:** Now we have a problem. What will happen in this

case is difficult to deal with and no general rules apply. This kind of scattering is called **Mie scattering**

Generating Light
Two basic cases:

- Light from **hot bodies**. Planck radiation law applies. Efficiency tends to be low

Light from **"cold" bodies** or luminescence

- There are many types of cold light production. Of utmost importance is electroluminescence or, to use another word for essentially the same thing, radiant electron - hole recombination in semiconductors.
  In yet other words: It's the LED, the **light emitting diode**..

Luminescence:	**General name for "cold" light production**
Fluorescence:	**Light production shortly after energy input. Short life time of excited level (< µs)**
Phosphorescence:	**Light production long after energy input. Long life time of excited level (> ms)**

Specialities

- Forget it. The list names some, there are many more.

That's where serious "optics and material" starts. This would need another full lecture course

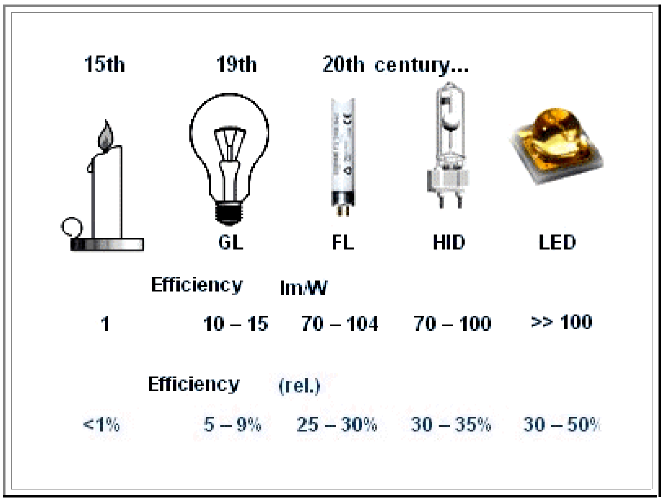
- **Fresnel Lens**
- **Optical Activity**
- **Faraday effect**
- **Kerr Effect**
- **Pockels Effect**

Light Sources
Hot bodies (tungsten filaments) in light bulbs and plasma discharge in fluorescent tubes

- Inefficient light bulbs still dominates when this lecture course started (2010)
- LEDs have taken over when this hyperscript was finalized (2019)

Mot included above is the **Laser**.

- You must learn about the Laser somewhere else



- **Processing light**
  with, for example, conventional lenses, mirrors and prism, anti-reflection coatings

  - Even simple light processors like lenses (and the rest from above) might be extremely complex materials engineering products today. Just look at the picture of a (by now (2019) outdated lens for microelectronic lithography-

- Polarizers, diffraction gratings and filters add another layer of complexity.

  - The list goes on, with, e.g. phase shifters and whatever is needed for doing holgraphy or...

  - Laser "beam forming", modulation, fultr-high speed detection, ...