5. Optics

5.1 Basic Optics

5.1.1 What is Light?

What is **light**? You know the answer, of course. To refresh your memory, here is the definition:

> **Light** is the common name for **electromagnetic waves** with wavelengths just below a micrometer (**400 nm** - **800 nm**).
>
> **Light** is the common name for **photons** with energies just above **1 eV** (**1,8 eV** - **3,2 eV**).

- So we still have the good old ***dichotomy*** between the **wave picture**, championed by **Huygens** and the **particle picture** first championed by **Newton**. As you know, Newton lost the fight but was ***redeemed*** to some extent by **Einstein** in **1905**. More to that in the link.

It is of course **quantum theory** that reconciles the otherwise incompatible viewpoints. Either you have some ideas how this works or you don't. In the latter case you need to do some work on your own. I cannot go into this kind of "details" here.

- In case of doubt think about what you learned about "electron waves". For example the $\psi = \psi_0 \cdot \exp(i\underline{k}\underline{r})$ wavefunction for a free electron that turned a particle into a wave, and the $|\psi|^2$ that turns a wave back into a particle. It's just as easy for photons.
- If you don't get it - tough luck! We're not doing quantum mechanics here. Just accept and follow the simple rule:

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

Now we need to consider a few very basic numbers and relations.

- The key properties and parameters that should come to mind when considering light propagating in vacuum or in some transparent material with dieelectric constant ϵ_r, magnetic permeability μ_r (always $\approx$ **1** for optical frequencies) and index of refraction n are:

Relations concerning light		
	Propagation in vacuum	**Propagation in material with *index of refraction n***
Wavelength	λ_0	λ_0/n
Frequency	ν	ν
Energy	$h\nu = \hbar\omega$	$h\nu = \hbar\omega$
Propagation speed	c_0 = natural constant $= \nu \cdot \lambda$ $= (\epsilon_0 \cdot \mu_0)^{-1/2}$	$c(n) = \dfrac{c_0}{n} = \dfrac{1}{(\epsilon_0\epsilon_r \cdot \mu_0\mu_r)^{1/2}}$ $n = (\epsilon_r \cdot \mu_r)^{1/2} \approx \epsilon_r^{1/2}$
Wave vector	$\lvert\underline{k}\rvert = 2\pi/\lambda_0 = \omega/c_0$	$\lvert\underline{k}\rvert = 2\pi/\lambda = 2\pi n/\lambda_0 = \omega/c$
Momentum	$\underline{p} = \hbar\underline{k} = \hbar\omega/c_0$	$\underline{p} = \hbar\underline{k} = \hbar\omega/c$
Snellius law	$n = \sin\alpha/\sin\beta$ with α, β the angle of incidence or propagation, resp.	

We can actually derive all the materials stuff and Snellius law as given in the last entry very easily by considering energy and momentum conservation. We will do that in a litle exercise.

Exercise 5.1.1
Derivation of Snellius' law

- The following table gives a few basic numbers for these quantities *that you must know* .

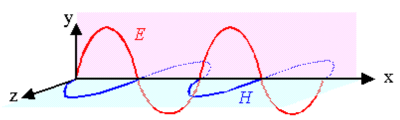
Numbers concerning light		
	Rough order of ten value	**Better value**
Wavelength	**≈ 1 µm**	**500 nm (390 to 750 nm)**
Frequency	**≈ 10^{15} Hz**	**$5 \cdot 10^{15}$ Hz**
Energy	**≈ 1 eV**	**2.5 eV**
c_0 (vacuum)		**300 000 km/s = $3 \cdot 10^8$ m/s**
Momentum ratio	$\dfrac{p(\text{2,5 eV electron})}{p(\text{2,5 eV photon})} \approx 10^3$	

- The momentum entry serves to remind you that photons have very little momentum relative to electrons (and phonons) of the same energy.

At a slightly higher level of sophistication we remember that light is an electromagnetic wave consisting of an interwoven electric and magnetic field; $\underline{E}$ and $\underline{H}$.

- In complex notation (with the understanding that we only use the real part; *in contrast to quantum theory*) a standard **plane wave** with amplitude $\underline{E}$ or $\underline{H}$, wavelength $\lambda = 2\pi/|\underline{k}|$ and circle frequency ω that propagates in $\underline{k}$ direction writes and looks as shown below.

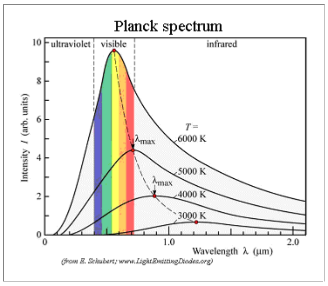
$$\underline{E}(\underline{r},t);\ \underline{H}(\underline{r},t) = \underline{E}_0;\ \underline{H}_0 \cdot \exp\{i(\underline{k}\underline{r} - \omega t)\}$$

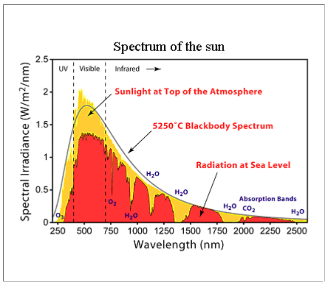


- The electric or magnetic field are *vector* quantities, always perpendicular to each other. Light thus always has a **polarization** vector associated with it, defined as the direction of the electric field vector (always perpendicular to the propagation direction).

Where does light come from? The sun, of course, is a major producer of light and so is any other hot body. **Max Planck**, as you know, first described the spectrum of light emitted by a hot "**black body**" in his famous work that was the beginning of quantum theory. The link gives a short and simple derivation

- What Planck calculated and what the sun actually does is shown in the following pictures.





- The sun comes pretty close to a black-body spectrum and the same is true for a light bulb or any other light source relying on high temperatures.
- It is clear to a Materials Scientist or Engineer that the sun is hot because nuclear fusion going on in its interior delivers the necessary energy, and that the radiation energy flooding the earth is the one and only energy on which life depends.

- Right now (**2011**) we enter the age of massive solar energy harvesting via solar cells and wind or water power. The necessary materials science and engineering for doing this on a large scale will provide work and jobs for many years to come - but that will not concern us here.

Besides hot bodies we also have "cold" light sources like **light emitting diodes** (***LED***s) and *Lasers*. We will come to that later in more detail.

Most light sources and all hot bodies produce **incoherent light** (travelling in all directions with random phases) and **multi-chromatic** light (having all kinds of frequencies), which is a far cry from the $\boldsymbol{E} = E_0 \cdot \exp(i\underline{kr})$ fully coherent and mono-chromatic plane wave that we like to use as mathematical representation. Sun light or artificial light sources used for illumination thus generate extremely "messy" light from a purists viewpoint. The messy light is nevertheless quite important in a general sense (imagine it missing!) but not of much *technical* interest - besides generating it.
Laser light, by contrast, is a good approximation to the plane wave model but not of much use for illuminating your kitchen.

- What we are interested in here is *working* with light. That means we have to consider manipulating it by running it through or off *materials*. What comes to mind in this context are optical products and components. The table below gives an incomplete list of a few catchwords that you should know in this context

Products and components around light technology		
Components	**Products**	**Field**
Lenses (and apertures)	**Microscope, Glasses, Camera, Film projector**	**Geometric optics**
Mirrors	**Reflector telescope; steppers, optical MEMS**	
Prisms	**Binocular; Reflectors**	
Filters	**Color photography etc.**	
Diffraction gratings	**Spectrometer**	⇓
Anti reflection coatings	**Solar cells, glasses, lenses**	
Linear polarizers	**Cameras, sun glasses, optical measurements,**	
Circular polarizers	**3-D cinema, advaned measurements**	**"Tensor" Optics** **Interference Optics**
Interference filters; Interferometers	**Optical precision measurements**	
Phase shifters, High resolution optics	**Lithography for Microelectronics**	
"Digital" optics	**Beamers, Displays, Cameras, optical MEMS**	
Faraday, Kerr, Pockel, ... effects	**LCD display, ultrafast modulation, advanced analytics**	
Optical fibers	**Optical communication, sensors**	
LED, OLED, Lasers	**High efficiency light sources, Displays, Processing, ..**	⇓
Non-linear materials	**Frequency doubling**	
Photonic crystals	**"Optical" semiconductors**	**Quantum Optics**
Quantum dots	**Optical computing**	

The message is loud and clear. We have to move from simple **geometric optics** to **"tensor" optics** and **interference optics**, arriving finally at **quantum optics**. We keep in mind, however, that there is only one *kind of optics* - those catchwords do not describe different optic realities but just different approaches to one and the same thing.