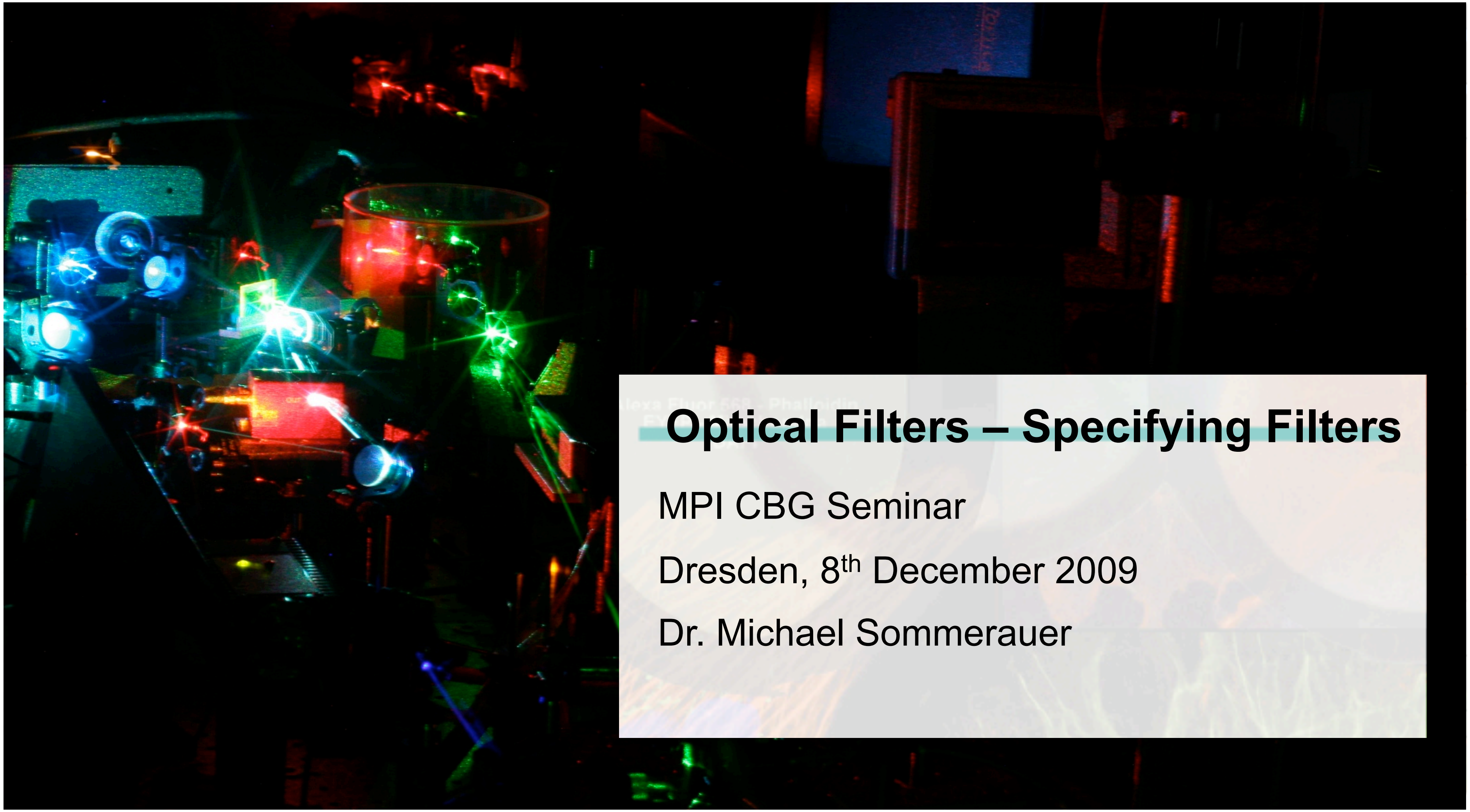

Optical Filters – Specifying Filters

MPI CBG Seminar

Dresden, 8th December 2009

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ANALYSENTECHNIK

Content

1. Filter specifications (bandpass, longpass, shortpass,…)
2. Transmitted and reflected wavefront errors
3. Angle of incidence and cone angles
4. Optical density
5. Dispersion
6. Polarization
7. Combining filters

:: Filter specifications

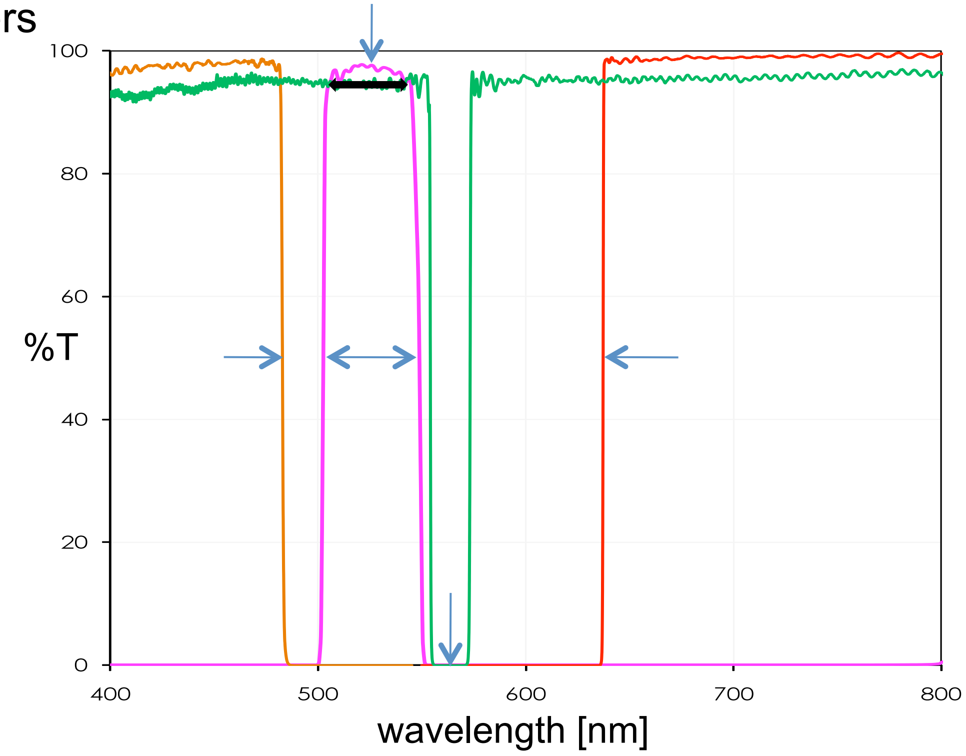
Filters and beamsplitters

:: Bandpass 525/50

:: Longpass 640 LP

:: Shortpass 490 SP

:: Notch 561 nm



Define:

:: CWL or notch wavelength

:: FWHM

:: GMBW*

:: Cut-on

:: Cut-off

:: Blocking range

:: AOI (angle of incidence)

*FWHM=GMBW+ 0,01xCWL

:: Transmitted and reflected wavefront errors

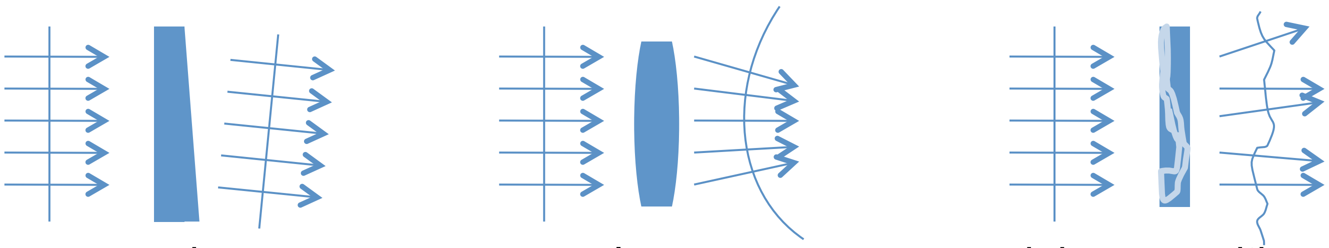
Wavefront distortion

:: WD = TWD + RWD (transmitted and reflected wavefront distortion)

TWD caused by:

:: non plane-parallelity and / or lense effects due to thickness deviations

:: inhomogenities of the substrate (refraction index change)



wedge lense inhomogenities

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:: Transmitted and reflected wavefront errors

Wavefront distortion

:: inhomogenities effect the image quality

:: lense effects cause focal shift and spot broadening

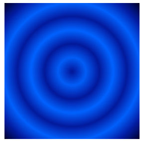
:: wedge effects cause pixel-shift
every optical component in the image pathway is responsible for the pixelhift

$$pixelshift = 0{,}005 \frac{tubelength * \Sigma beamdeviation}{pixelspacing}$$

e.g. tubelength in a microscope ~ 200 mm, pixel spacing of the camera ~6,7 µm
=> less than 1 pixel shift for beam deviation < 7 arcsec

:: Transmitted and reflected wavefront errors

Transmitted wavefront distortion



:: TWD is specified as absolute peak-to-peak error or RMS error, measured with a interferometer at 546 nm (ISO standard)

:: RMS (root-mean-square) is used when irregularities dominate the flatness
RMS = ¼ absolute peak-to-peak error

:: for filters ¼ λ …. 1 λ RMS mostly fits

:: for most filters the transmitted wavefront distortion matters, there is no need to specify any reflected wavefront distortion

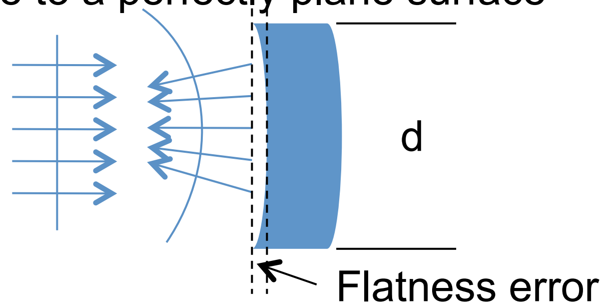
:: Transmitted and reflected wavefront errors

Reflected wavefront distortion

:: Deviation of the perfect wavefront reflected off a surface relative to a perfectly plane surface
RWD = 2 x Flatness error

:: mostly caused by bent substrates

:: only matters when a filter or beamsplitter is used in a
reflection geometry (microscope beamsplitter, image splitting)



:: bent filters act like lenses with a focal length of Radius/2
$f = r/2$ => $f = d^2/RWD$ (d = diameter of the region where the flatness is specified)

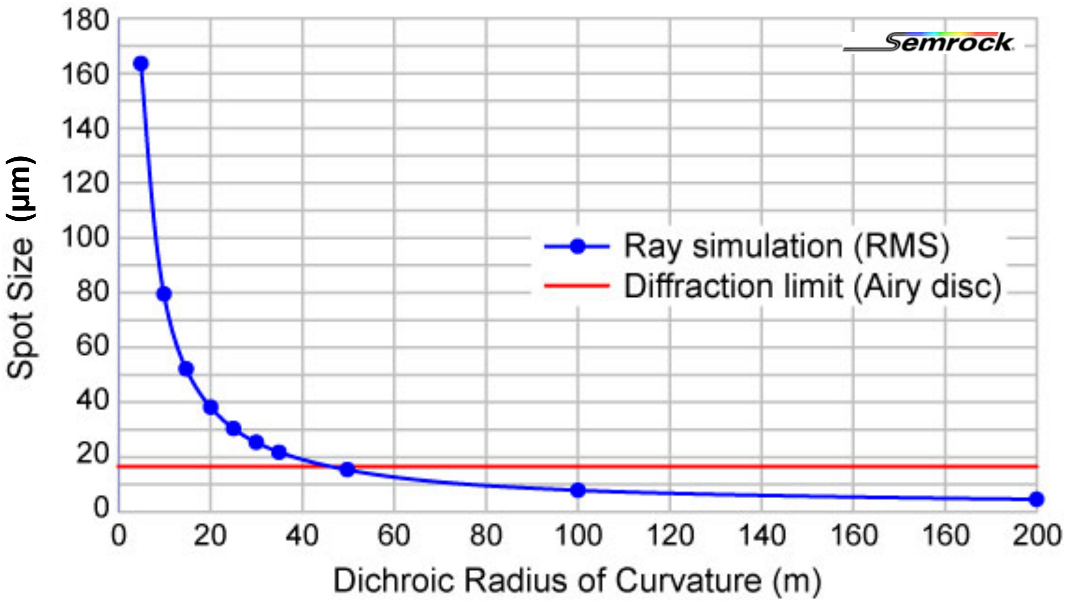
:: e.g. beamsplitter d= 20mm = 0,02m; flatness error = 5µm = 0,000005m => f = 40m

:: Transmitted and reflected wavefront errors

Reflected wavefront distortion

:: focal shift due to bent optics causes
an increase of the spot size
e.g. 40x objective, NA 0,75
focal length of tube lense = 200 mm
wavelength 510 nm

:: for most beamsplitters ¼ λ RMS
is sufficient (TIRF, image splitting,…)



:: Angle of incidence and cone angles

Influence of AOI and CHA

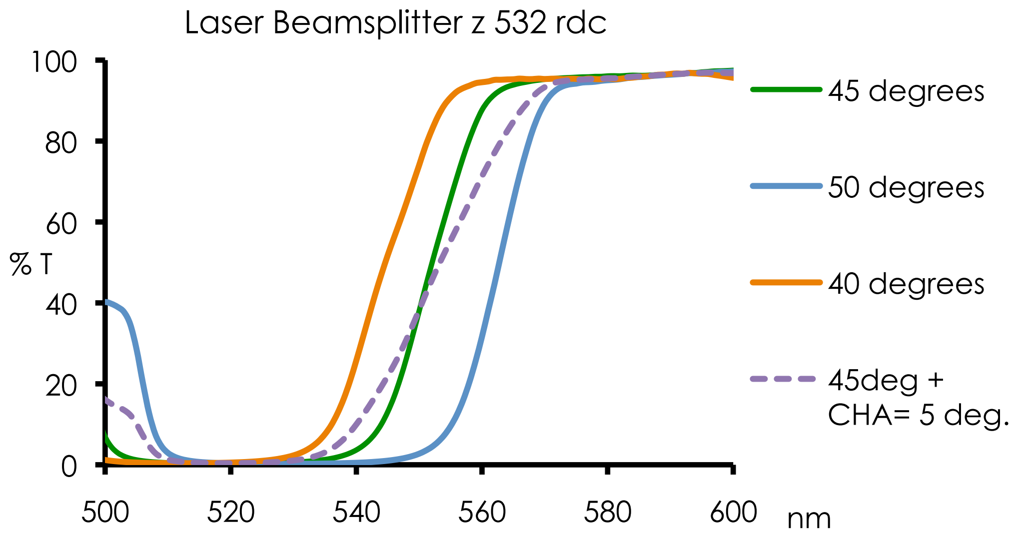
:: interference filters are mostly used under an angle of incidence AOI = 0 degree
AOI >0° causes shift according to:

$$\lambda(AOI) = \lambda_0 \sqrt{(1-(\sin(AOI)/n_{eff}))^2}$$

:: cone angles or cone half angles (CHA)

$$\lambda_{(CHA)} = \sum_{0}^{AOI} \lambda(AOI)$$

n_{eff} = effective refraction index
(polarization matters)



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:: Optical density

Optical density OD

:: OD = -log (Transmission)

Blocking range of a fluorescence filter depending on

:: the light source => exciter
blocking must cover the emission range of the lightsource out of transmission band

:: detector => emitter
must suppress the transmitted light of the exciter

:: exciter and emitter must block each other with min. OD 6

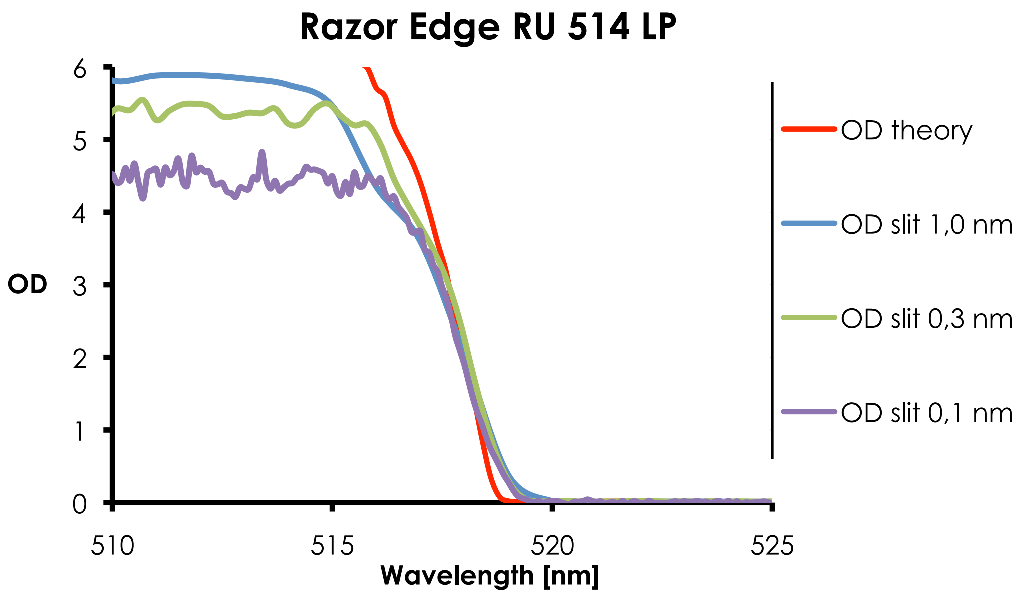
:: Optical density

Measuring optical density

:: spectrometer with double monochromator and PMT

:: limitations:

- noise limit ~ OD 6
- rounding of steep edges by slit width
- side lobes of the measuring beam
  (depends on spectrometer design)
- reduced slit width causes noise



:: Dispersion

Consider dispersion when filters

:: are used in an interferometer

:: transmit or reflect a short pulse (<< 1 ps)

=> are used in optical systems which are sensitive to the phase of the light

$I = |E|^2$

$I_T = T(\lambda) I = |E_t|^2$

$I_R = R(\lambda) I = |E_r|^2$

$E_r = r(\lambda) e^{i\phi_r(\lambda)} E$ $\quad$ $E_t = t(\lambda) e^{i\phi_t(\lambda)} E$

amplitude $\quad$ phase (response)

I intensity

E electrical field

$T(\lambda)$ and $R(\lambda)$ intensity transmission and reflection coefficients

$r(\lambda) e^{i\phi_r(\lambda)}$ amplitude reflection

$t(\lambda) e^{i\phi_t(\lambda)}$ amplitude transmission

:: Dispersion

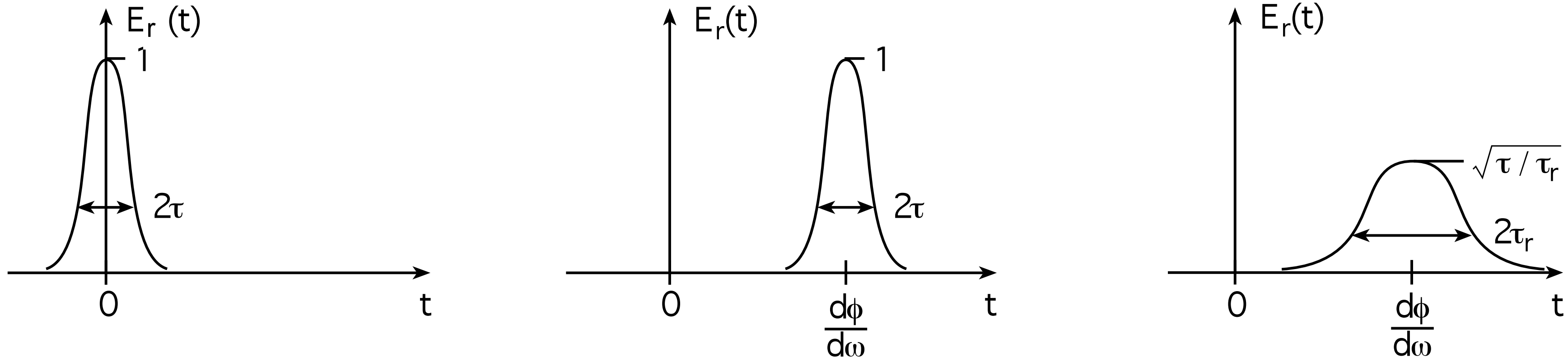
phase response $e^{i\phi_r(\lambda)}$ can be written as:

$$\phi_r(\omega) = \phi_r(\omega_0) + (\omega-\omega_0)\frac{\partial \phi_r}{\partial \omega}\Big|_{\omega_0} + \frac{1}{2}(\omega-\omega_0)^2\frac{\partial^2 \phi_r}{\partial \omega^2}\Big|_{\omega_0} \qquad \omega = \frac{2\pi c}{\lambda}$$

constant phase

time delay

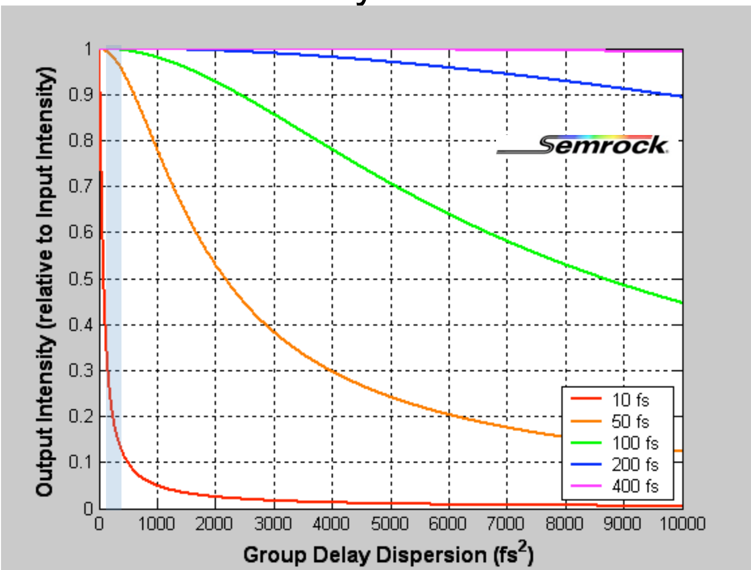
group delay dispersion (pulse broadening)



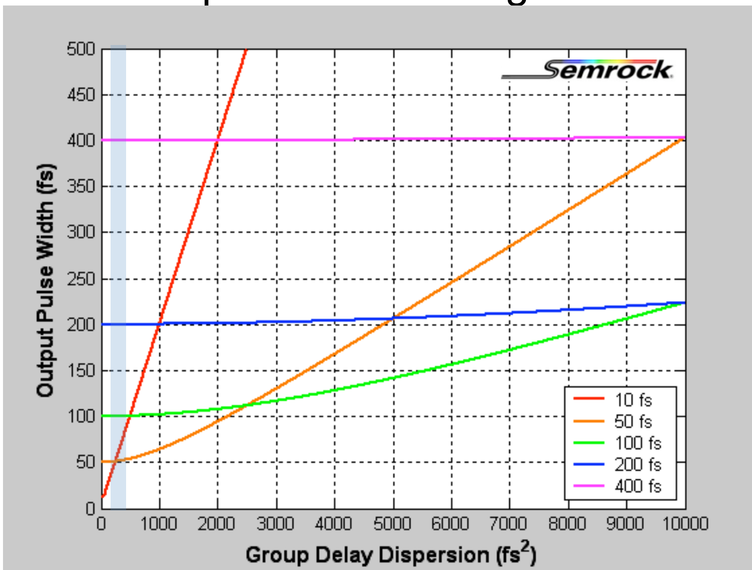
:: Dispersion

:: what happens in real life with e.g. multiphoton filters and beamsplitters?

intensity loss



pulse broadening



:: Polarization

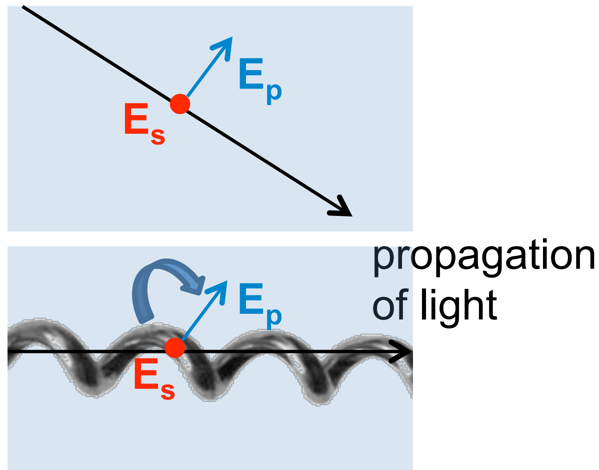
Polarization states:

:: linear polarization

s-polarization (E perpendicular to the plane of incidence)

p-polarization (E parallel to the plane of incidence)

:: circular polarization or more general elliptical polarization



:: Polarization

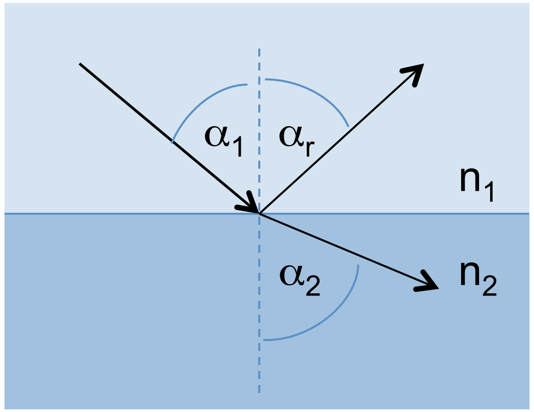
Some general optical laws

:: law of reflection $\alpha_1 = \alpha_r$

:: law of refraction $n_1 \sin\alpha_1 = n_2 \sin\alpha_2$ (Snell's law)

:: law of total reflection $\alpha_{critical} = \arcsin\left(\frac{n_2}{n_1}\right)$

:: Transmission = 1 - Reflection



$n_1 > n_2$

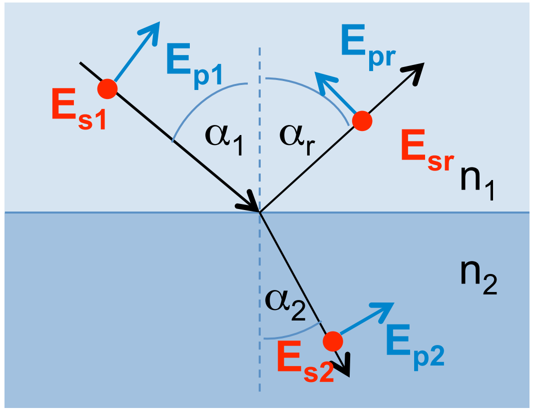
:: Polarization

Reflection for different polarization states

:: different polarizations are reflected by different amounts => Fresnel reflection

:: each polarization state has to be processed separately

:: amplitude reflection coefficient r and reflection R (reflectivity) is described by:

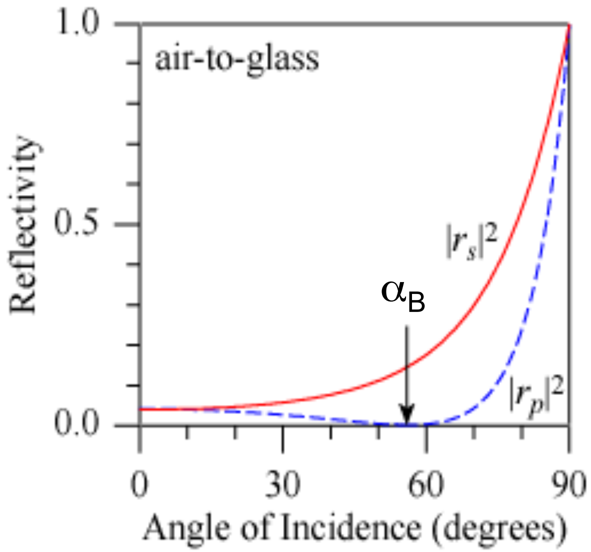


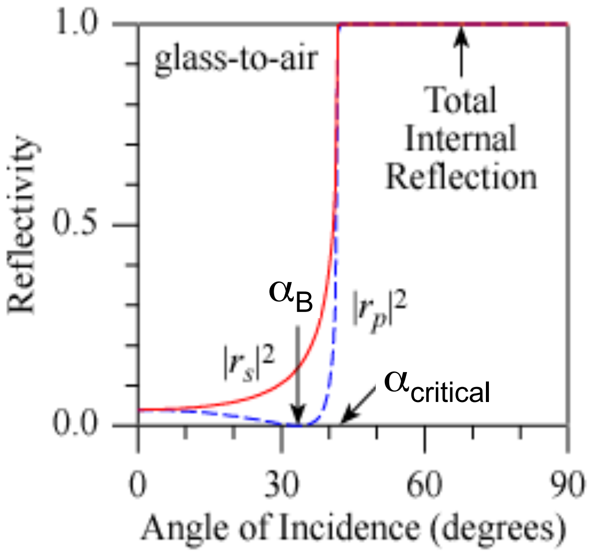
$$r_s = \left|\frac{E_{sr}}{E_{s1}}\right| = \frac{n_1 \cos\alpha_1 - n_2 \cos\alpha_2}{n_1 \cos\alpha_1 + n_2 \cos\alpha_2} \quad \Rightarrow \quad R_s = |r_s|^2$$

$$r_p = \left|\frac{E_{pr}}{E_{p1}}\right| = \frac{n_2 \cos\alpha_1 - n_1 \cos\alpha_2}{n_2 \cos\alpha_1 + n_1 \cos\alpha_2} \quad \Rightarrow \quad R_p = |r_p|^2$$

:: Polarization

e.g. reflection of polarized light at air/glass and glass/air





:: at the Brewster angle α_B p-polarized light is completely transmitted

:: **Polarization**

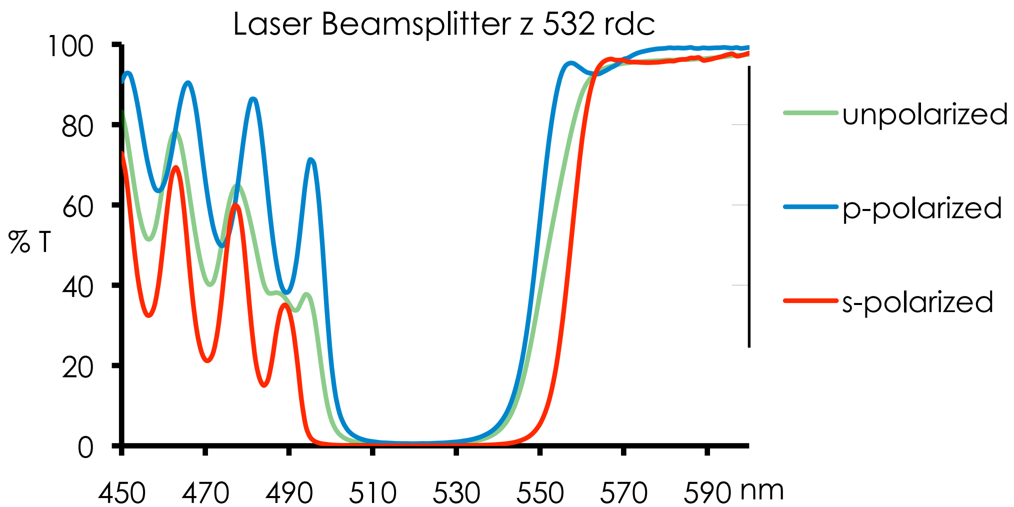
Influence on optical filters and beamsplitters

:: s-polarized light can be better reflected than p-polarized light, if AOI <>0 degrees

:: p-polarized light can be better transmitted (transmitted laser p-pol., reflected laser s-pol.)

:: 45 degrees optical components are not applicable, if high blocking is required

:: optical components working under AOI close to 0 degrees have steeper edges, because the s- and p-splitting is very small



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:: Polarization

Influence on optical filters and beamsplitters

:: amplitude $r_s \neq r_p$ => the amount of s- an p-polarized light is changed, but there is no change of the polarization state

:: phase $\Phi_s \neq \Phi_p$ => the polarization state is changed (birefringent, e.g. λ/4-plates)

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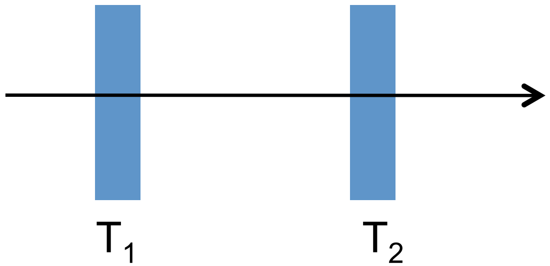
:: Combining filters

Does it make sense?

:: combining filters with no loss of light



$$\frac{1}{T} = \frac{1}{T_1} + \frac{1}{T_2} - 1$$

only for T>80%: $T = T_1 \bullet T_2$

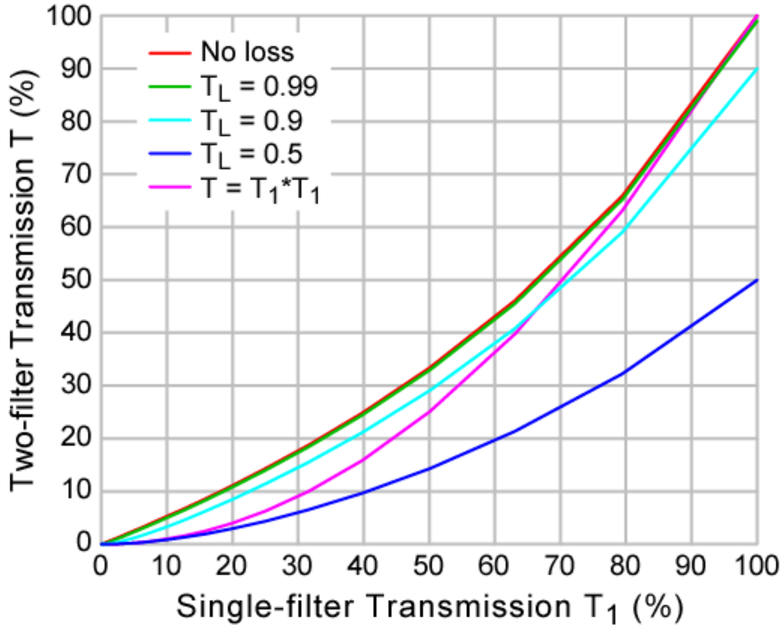
$$OD = \log_{10}\left(10^{OD_1} + 10^{OD_2} - 1\right)$$

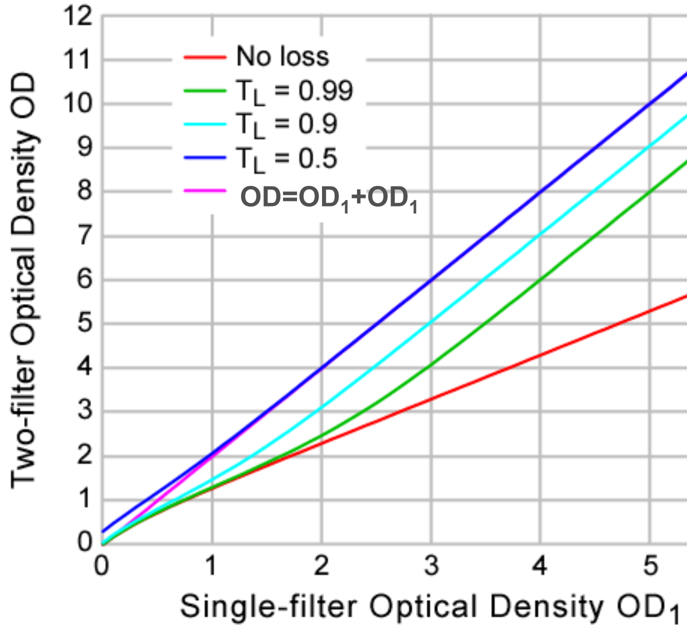
not $OD = OD_1 + OD_2$

:: e.g. both filters have 80% transmission and block with OD 4: T= 66,6% and OD = 4,3

:: Combining filters

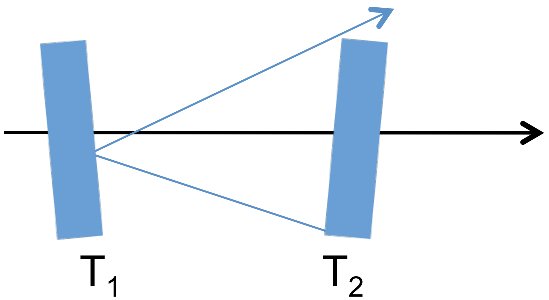
:: adding loss (tilting filters or adding absorption glass) increases blocking, but reduces transmission





:: Combining filters

possible setup for stacked filters

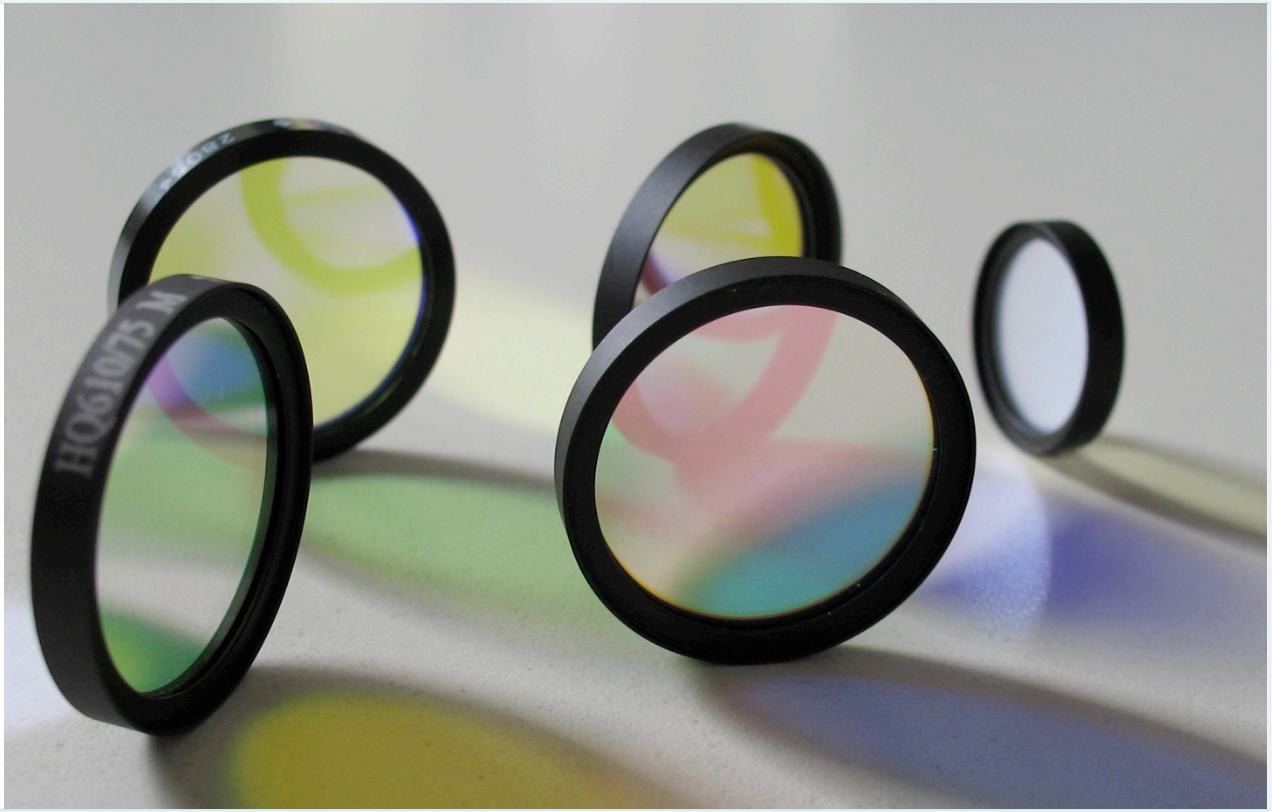


:: 100% loss of reflected light

:: in this case $OD = OD_1 + OD_2$

:: Our experience – your profit

:: Thank you very much



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