Wave optics

Difraction and interference of light,
dispersion, optical grating.
Polarization of light, Brewster angle,
double refraction.

Wave optics

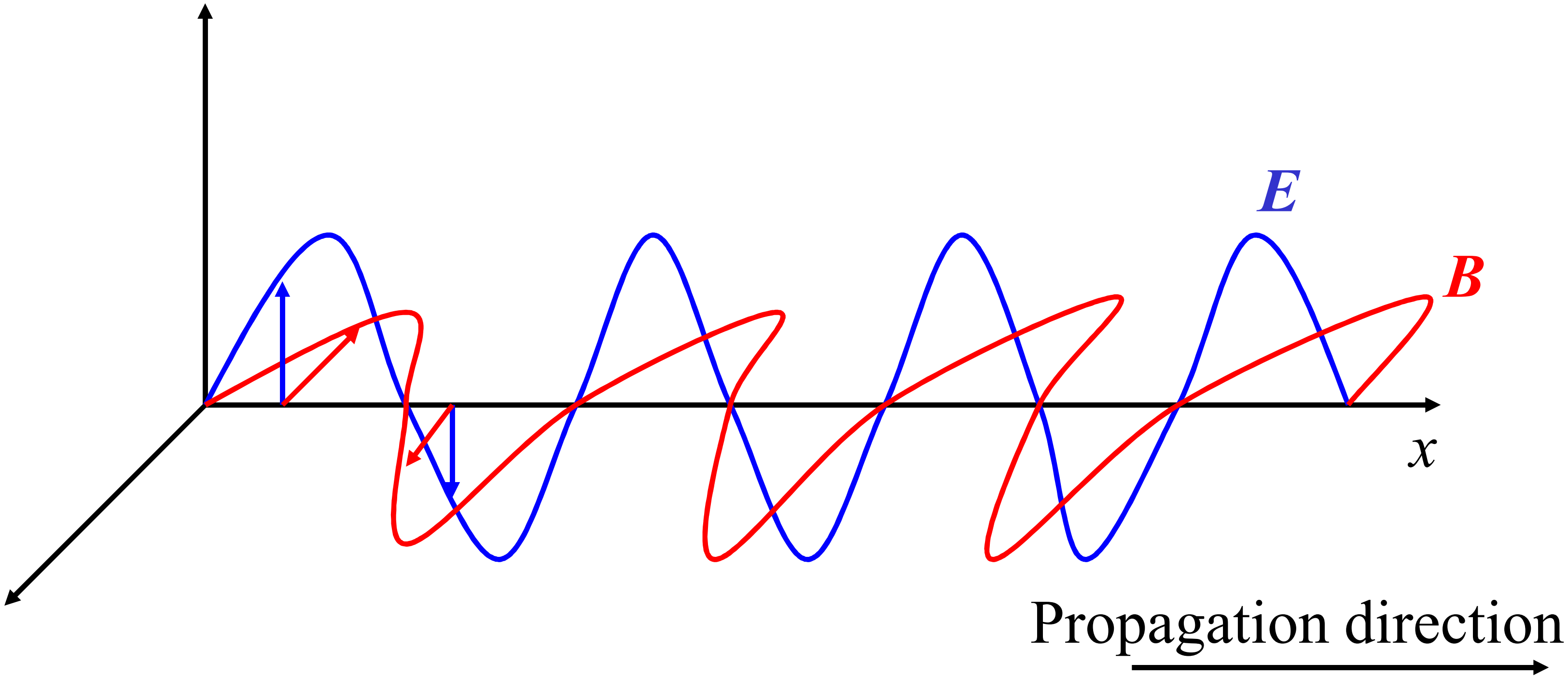
Wave properties of light

Light propagation described by wavefront, phase shift for interference of waves etc.

- Interference
- Diffraction
- Dispersion
- Polarization

Light

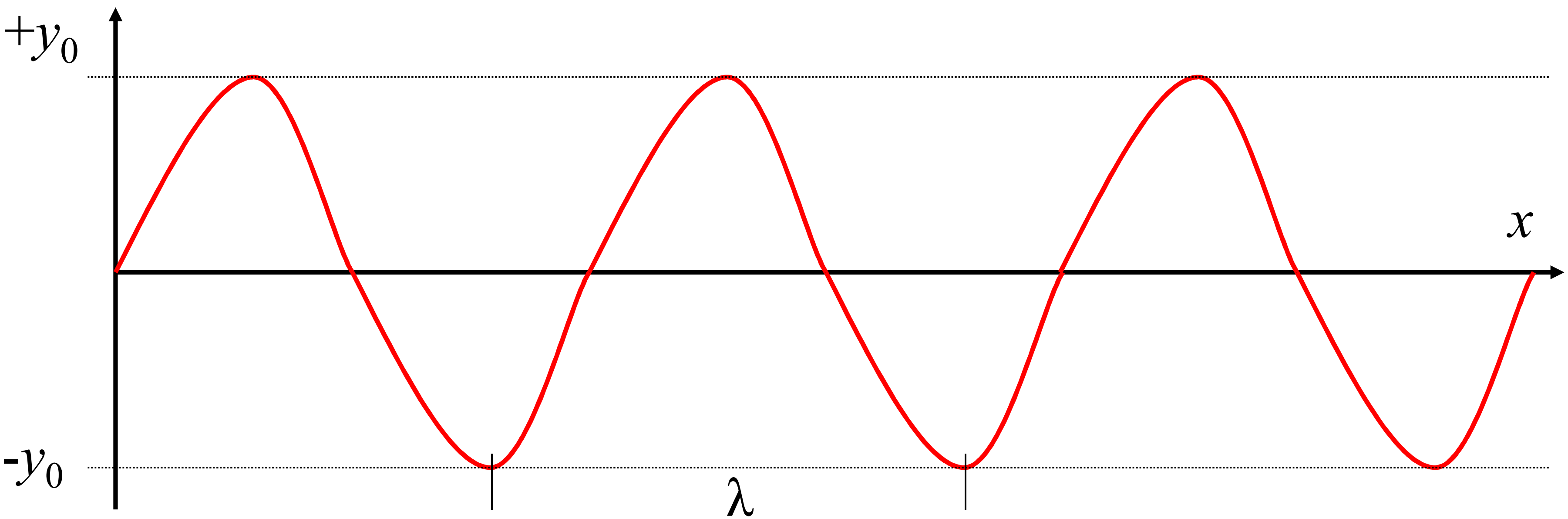
Electromagnetic wave – transversal wave



Waves

- Phase velocity c, wave vector $k=\omega/c$
- Amplitude y_0
- Polarization

$$y = y_0 \sin(\omega t - kx)$$



Wavelength, phase velocity

Phase velocity

$$c = \frac{1}{\sqrt{\varepsilon_r \mu_r \varepsilon_0 \mu_0}} = \frac{c_0}{\sqrt{\varepsilon_r \mu_r}} \leq c_0 = 300.000 kms^{-1}$$

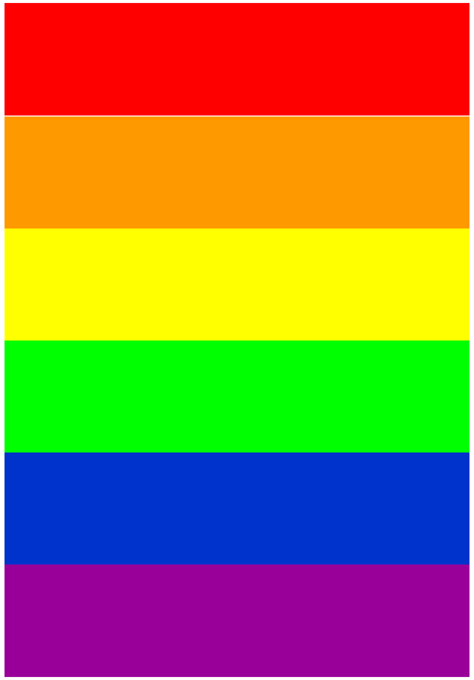
Permittivity of free space $\varepsilon_0 = 8.854 \cdot 10^{-12} Fm^{-1}$

Permeability of free space $\mu_0 = 4\pi \cdot 10^{-7} Hm^{-1}$

Wavelength $\lambda = \frac{c}{f}$ frequency f

Light wavelengths

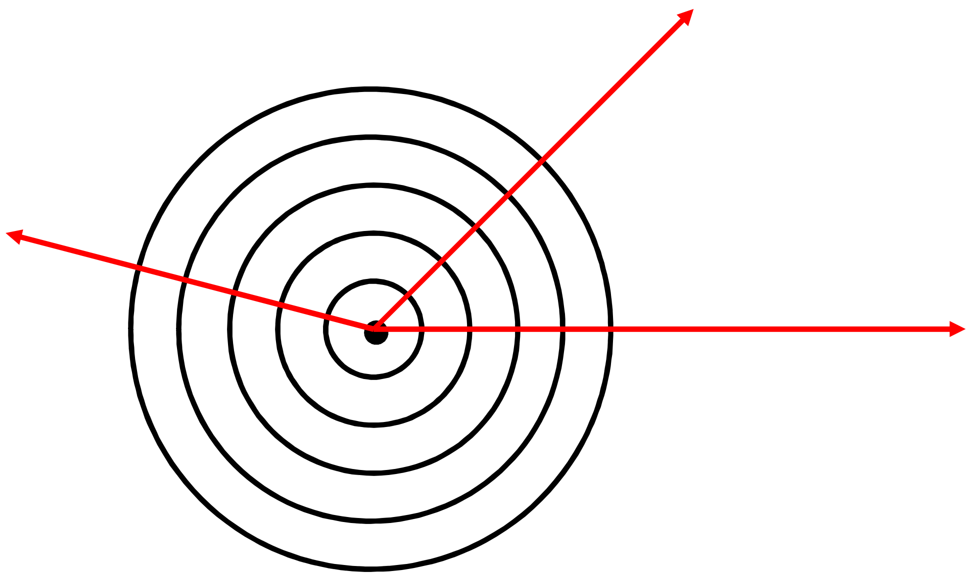
Red	720-627nm
Orange	627-589nm
Yellow	589-566nm
Green	566-495nm
Blue	495-436nm
Violet/purple	436-380nm



Wavefront, ray

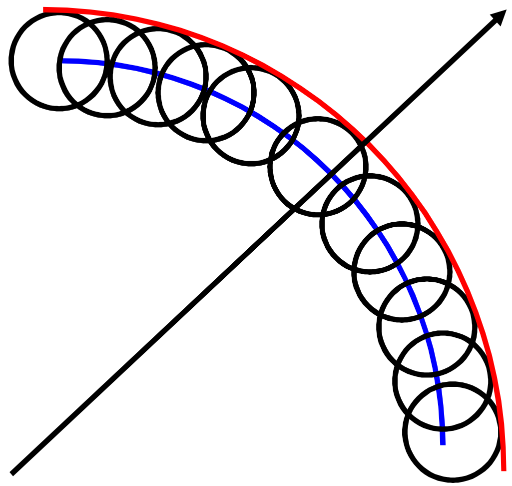
Wavefront propagates by phase velocity *c*

Ray – normal to wavefront, direction of *k*



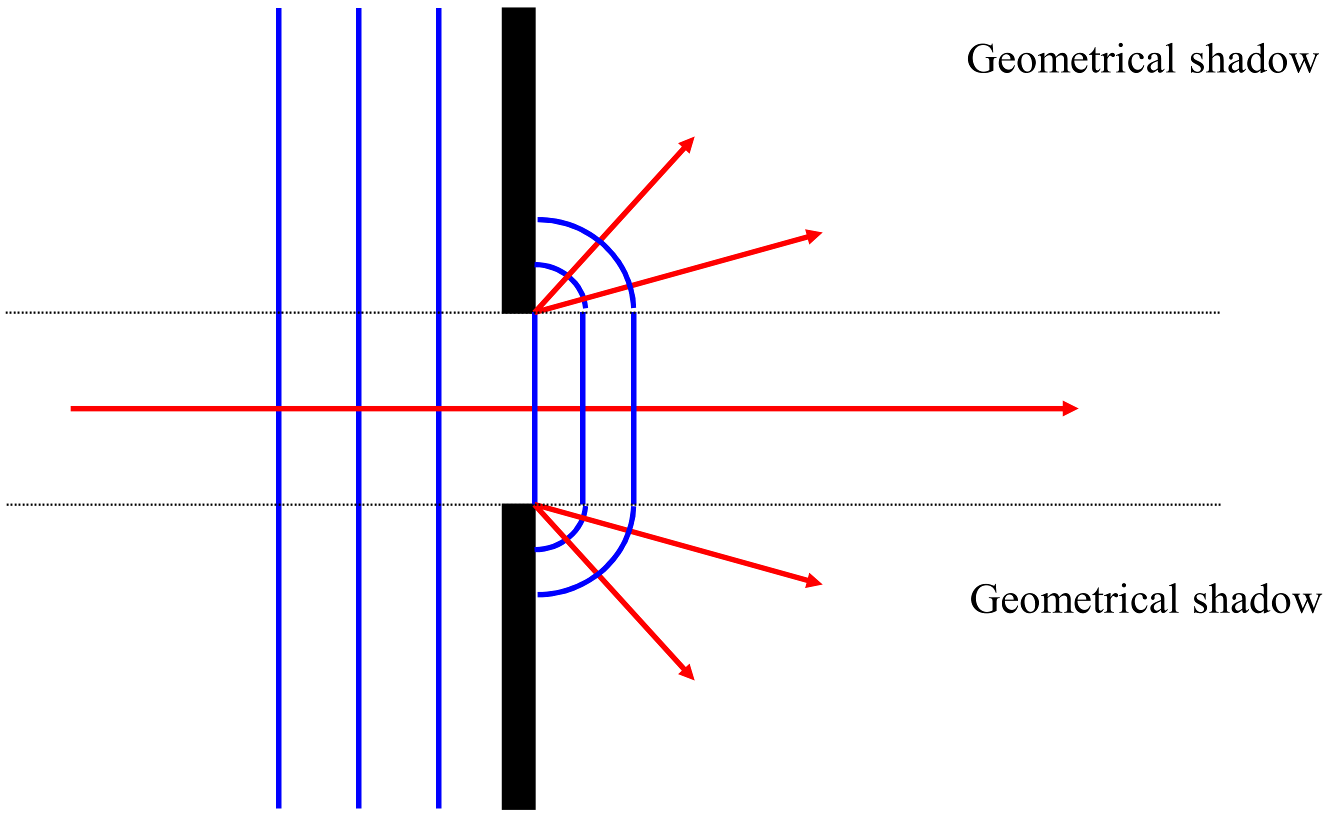
Huygens' principle

Every point on a wavefront can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The new wavefront is the envelope of all the wavelets, that is, the tangent to all of them.



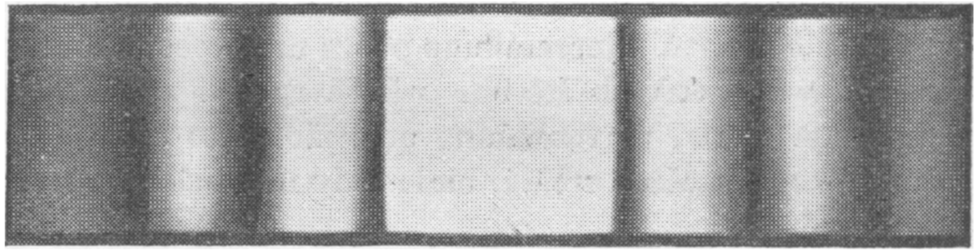
Diffraction at hole

Wave also propagates into geometrical shadow area

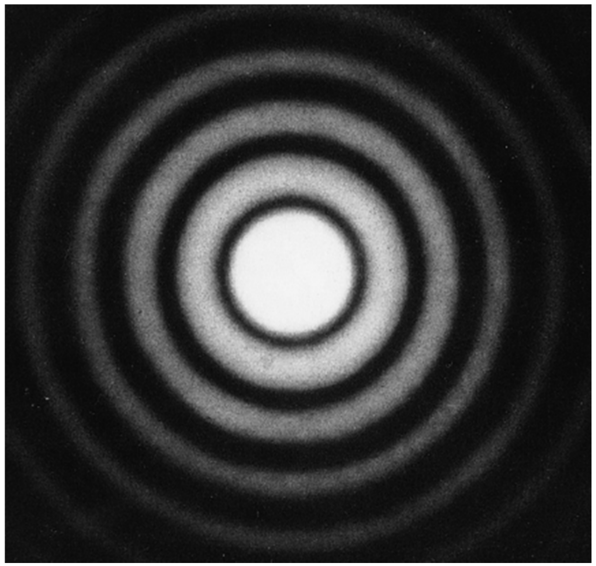


Diffraction pattern at hole

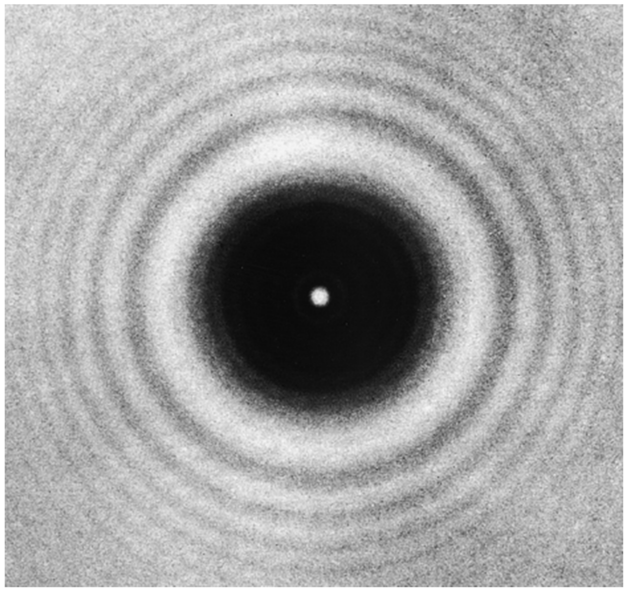
Hole/Slit



Circular hole

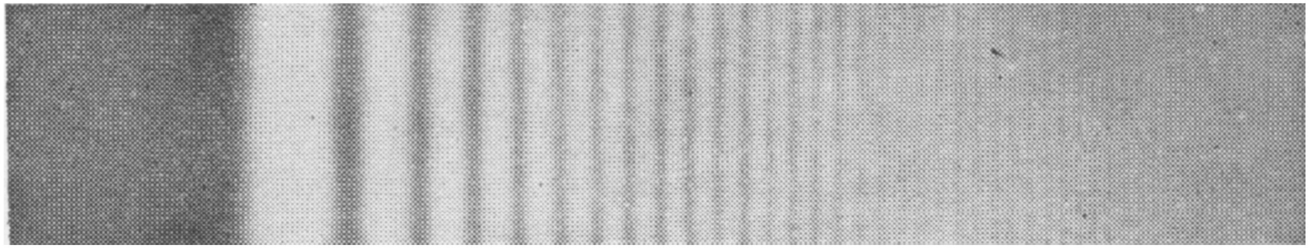


circular obstacle

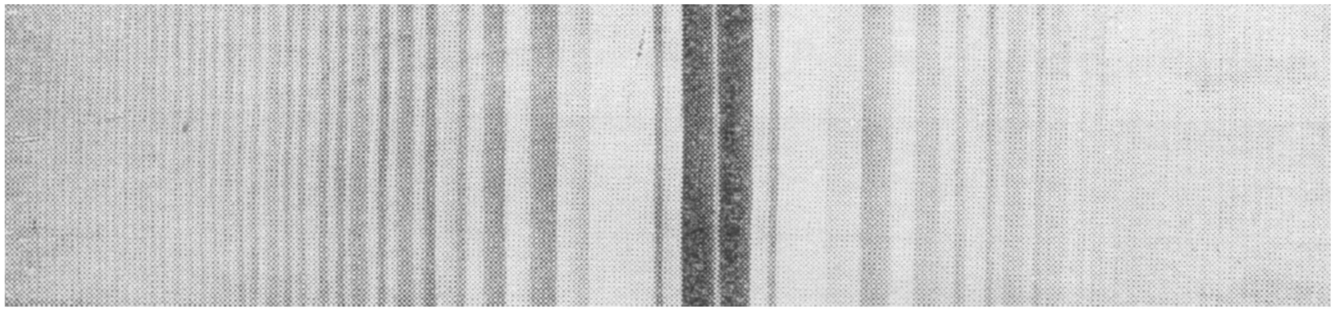


Diffraction pattern at the edge

Edge

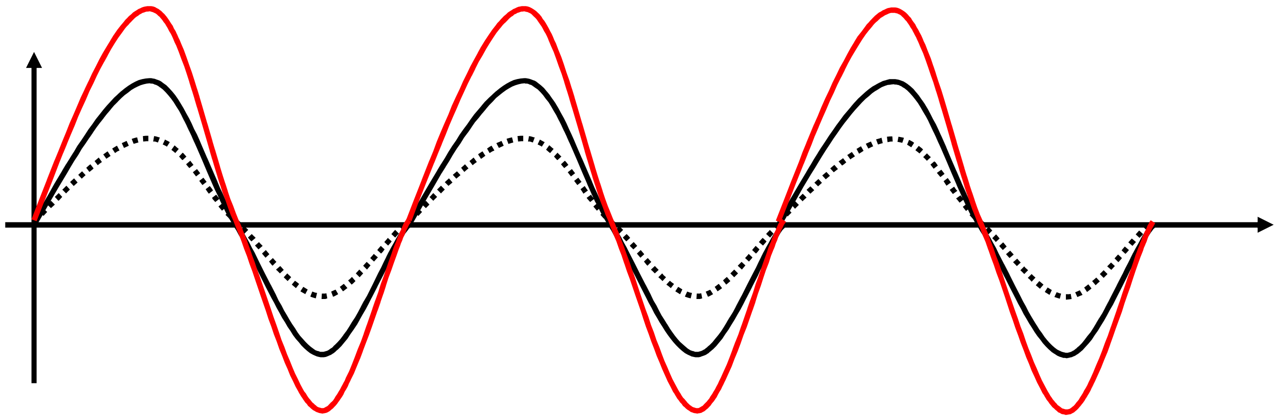


Fiber

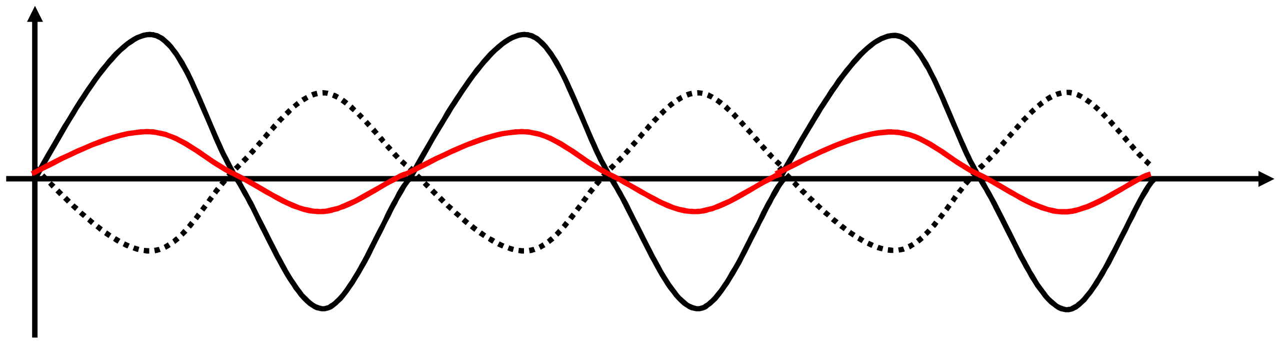


Interference

Maximum – constructive interference



Minimum – destructive interference



Coherence of light

Interference is only possible for two waves with stable (constant) phase shift

Coherent waves = stable phase shift

Most of light sources do not generate coherent light, coherence is only possible for wavefronts generated from near points of light source = coherence length

Laser light is coherent and moreover almost monochromatic, i.e. laser light has the high coherence length!

Geometrical and optical path

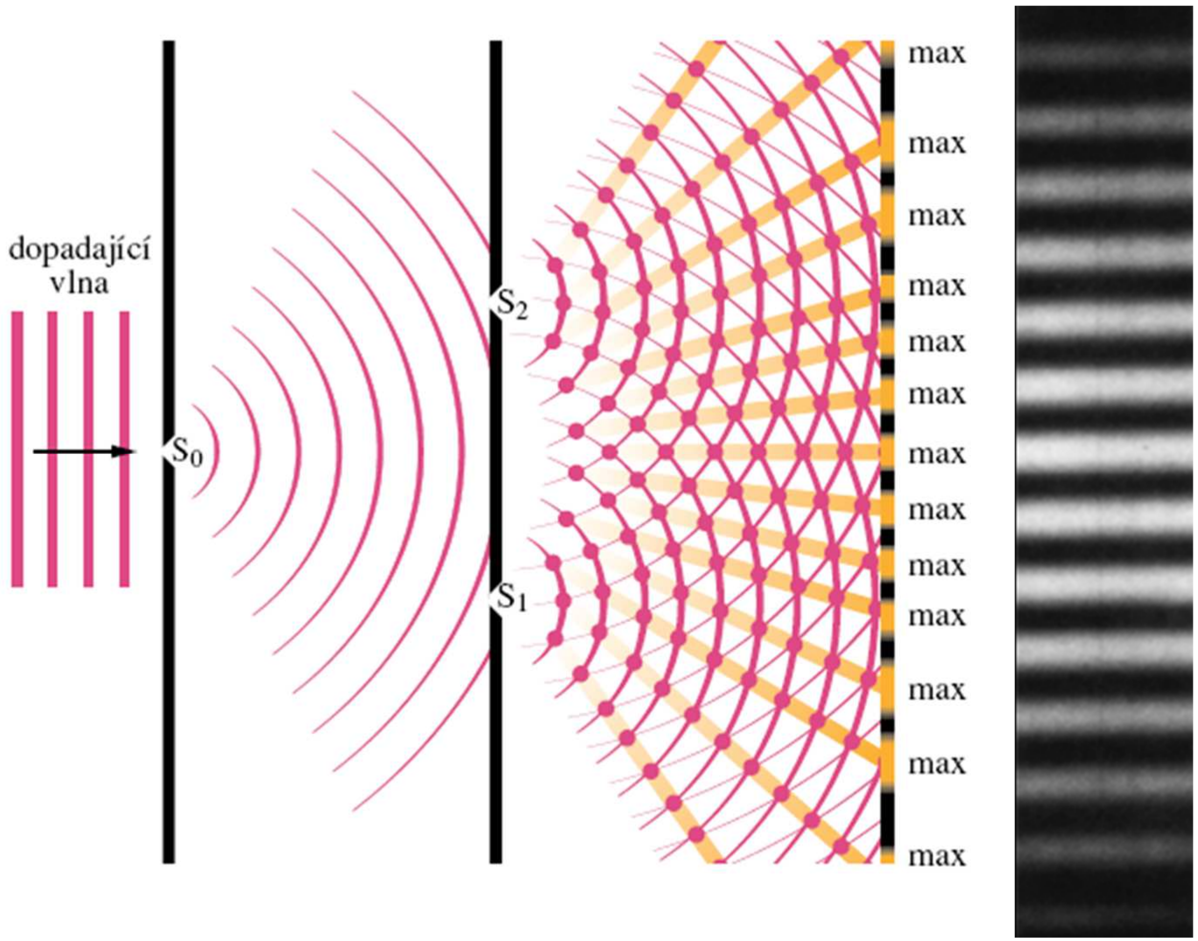
Wave phase changes by:

- Different length (wave travels in one material only) of geometrical path = L
- Different phase velocity on the path (wave travels in different materials), optical path = $N \cdot L$

N is refraction index of material

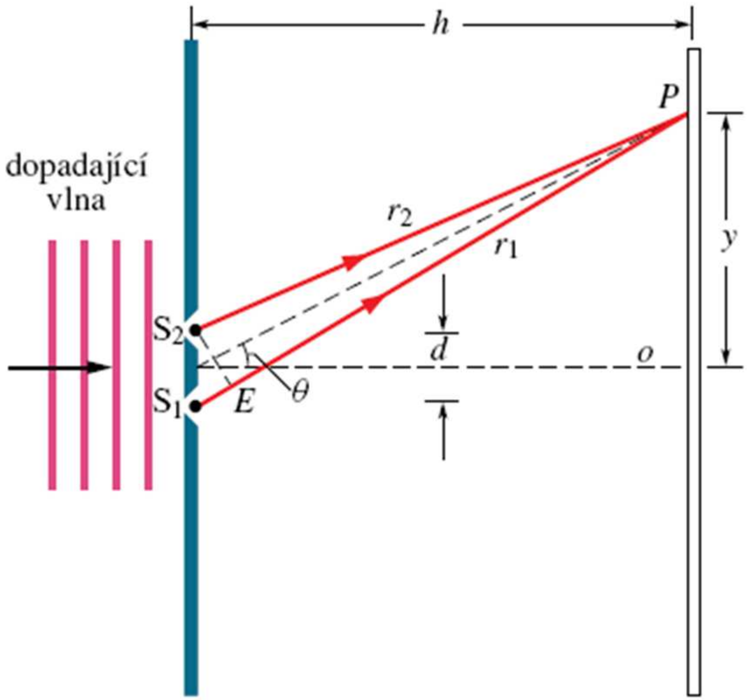
Young's double-slit experiment

Young (1801)
Proof of light
as a wave

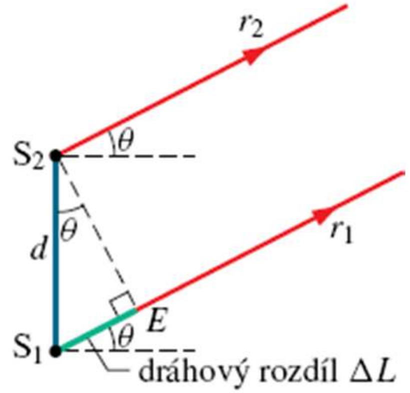


Young's double-slit experiment

Path difference for interfering rays



approximation $r_1 \approx r_2$, $h >> d$



$$\Delta L = d \sin\theta$$

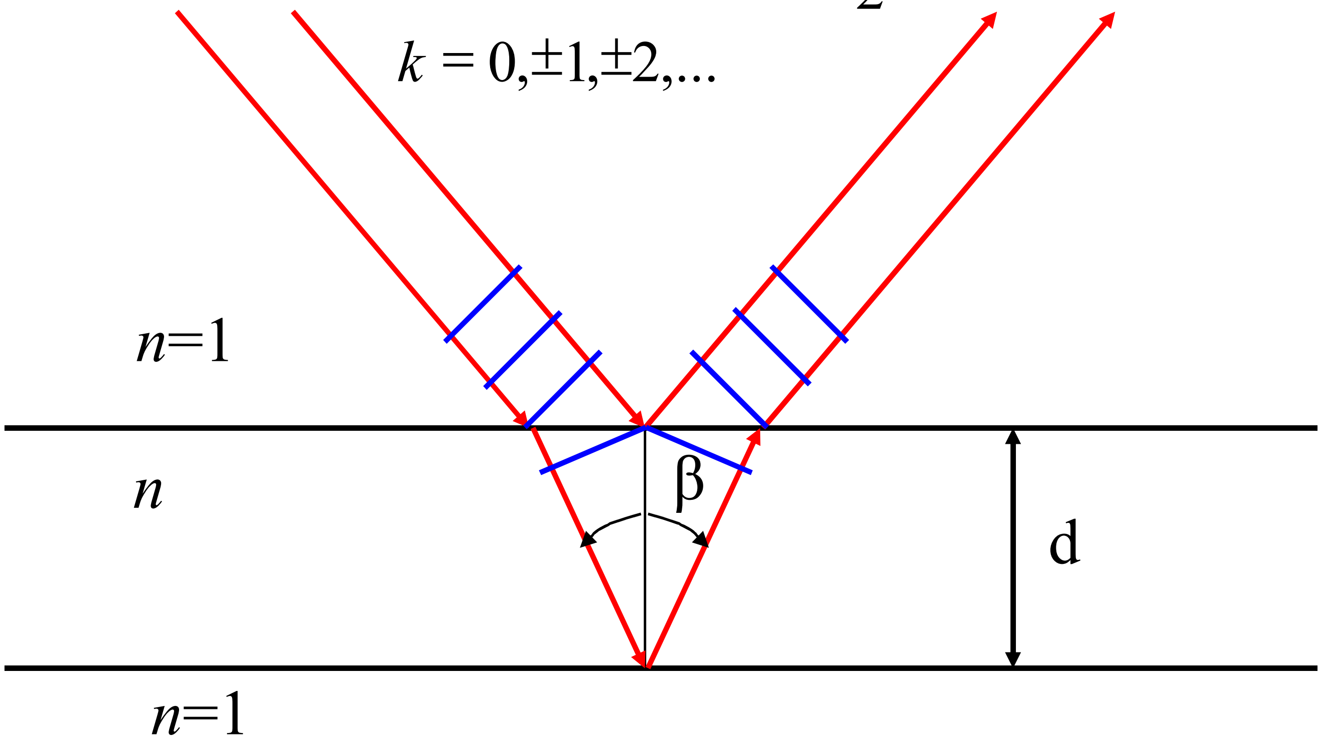
interference maximum

$$\Delta L = m\lambda$$

Interference in thin film

Maximum $2nd\cos\beta = (2k+1)\dfrac{\lambda}{2}$

$k = 0, \pm 1, \pm 2, \ldots$



Phase shift for reflection at interface

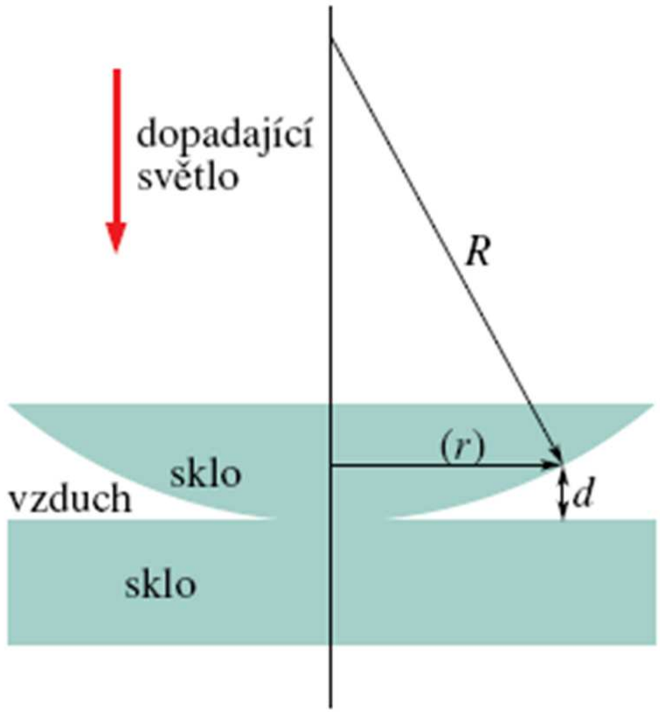
Analogy to reflection of mechanical wave at free or clamped end

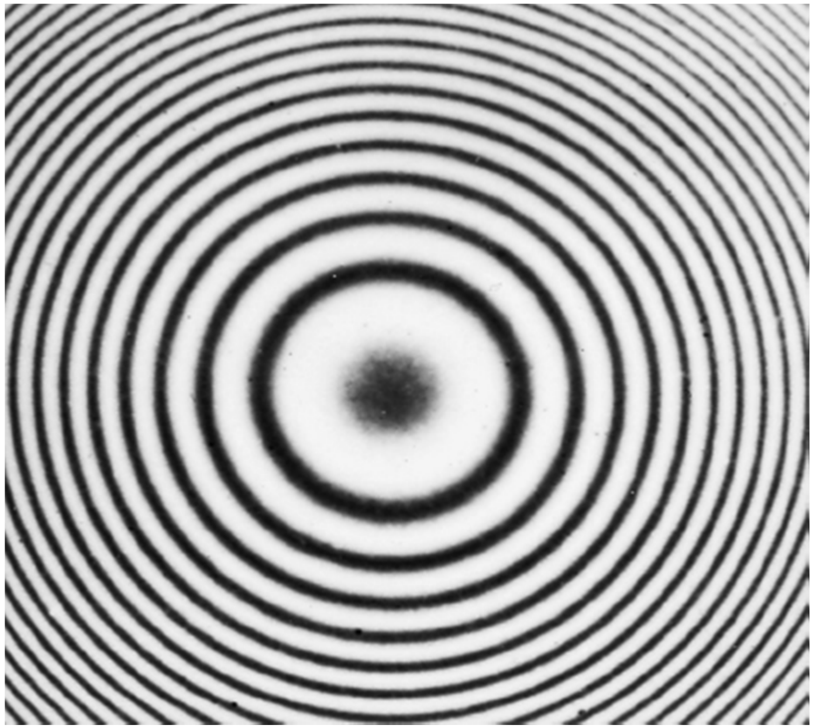
Beam of light, reflected by a material with index of refraction greater than that of the material in which it is traveling, changes phase by π rad (180^{o}) or half cycle ($\lambda/2$)

No phase shift at opposite refraction index values!

Newton’s rings

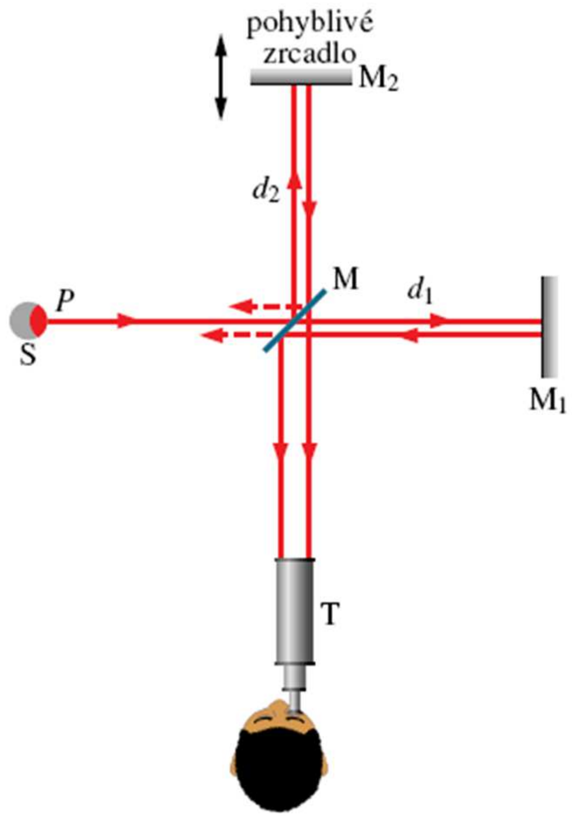
Interference of transmitted and reflected waves



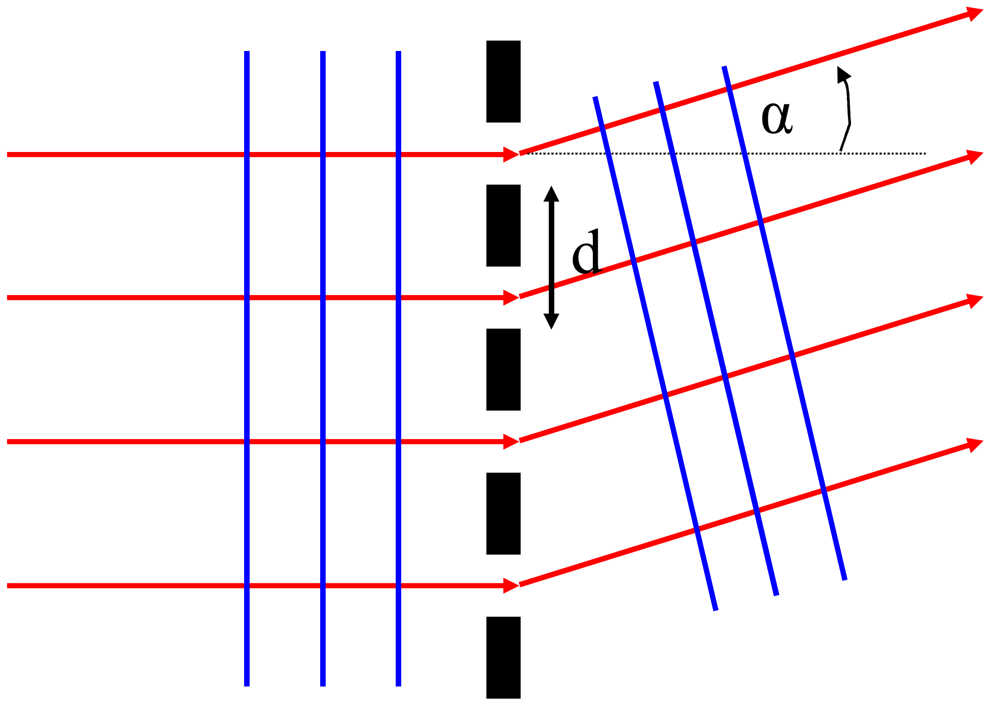


Michelson interferometer

Measurement of displacements comparable to the wavelength of light



Difraction grating



Maximum

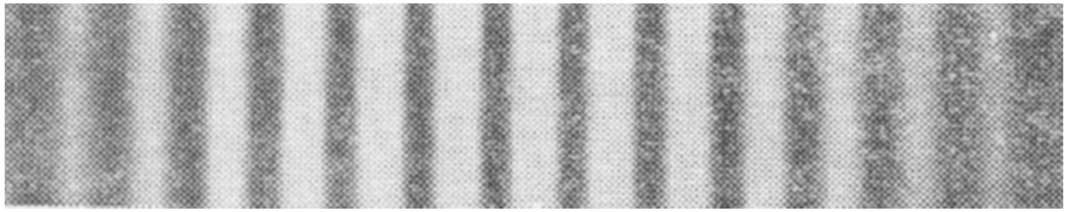
$$d \sin \alpha = k\lambda$$

$$k = 0, \pm 1, \pm 2, \ldots$$

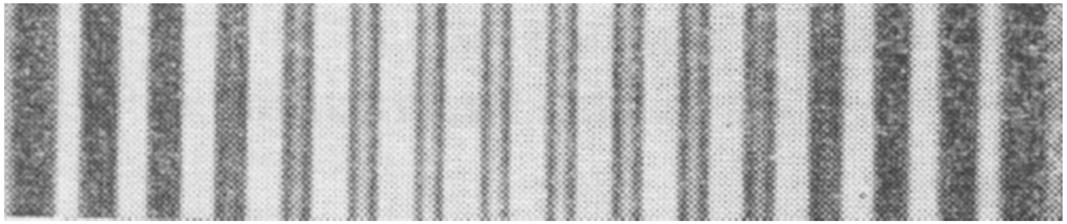
Interference on diffraction grating

Diffraction grating = regular set of slits

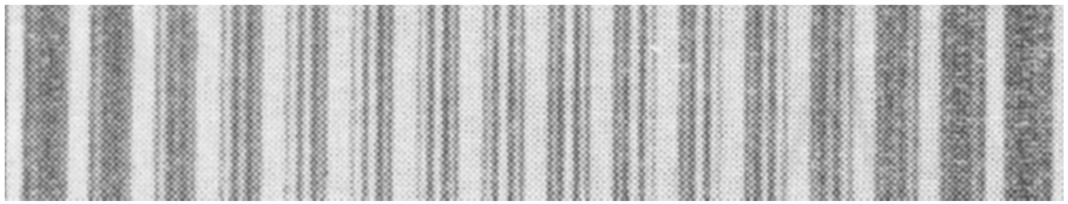
N=2



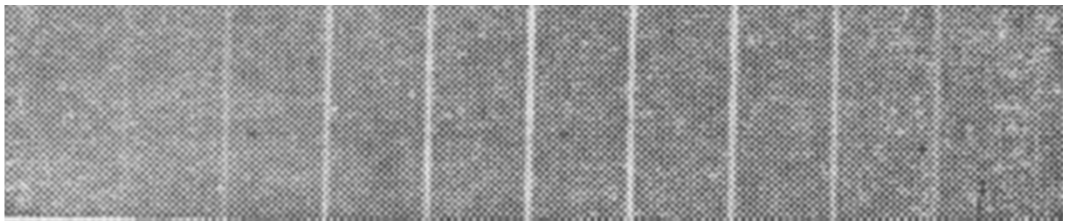
N=3



N=5



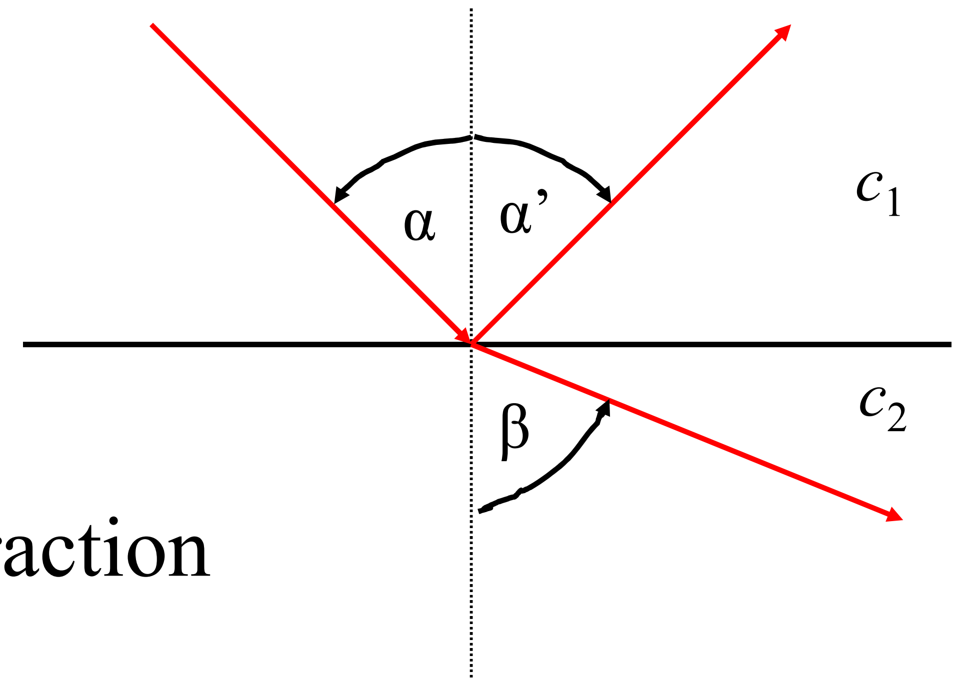
N=40



Laws of reflection and refraction

Law of reflection

$$\alpha' = \alpha$$



Snell’s Law of refraction

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$$

Refraction index

- Absolute

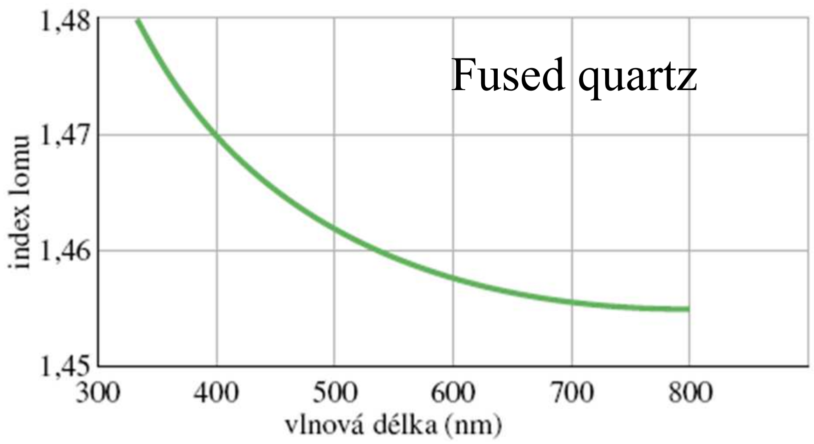
$$N = \frac{c_0}{c}$$

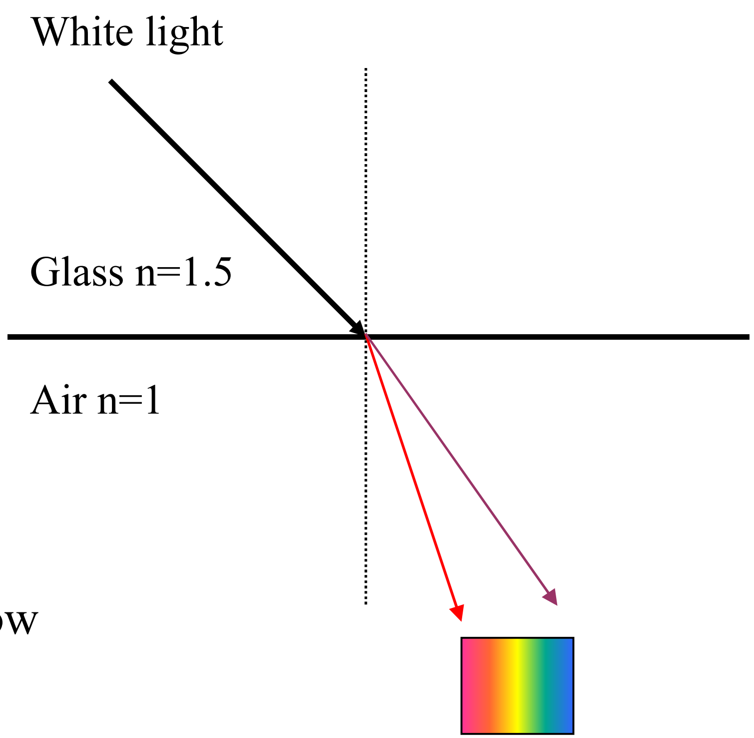
- Relative

$$n = \frac{c_1}{c_2}$$

Dispersion

Refraction of different wavelengths takes place at different angles, refraction index is dependent on wavelength

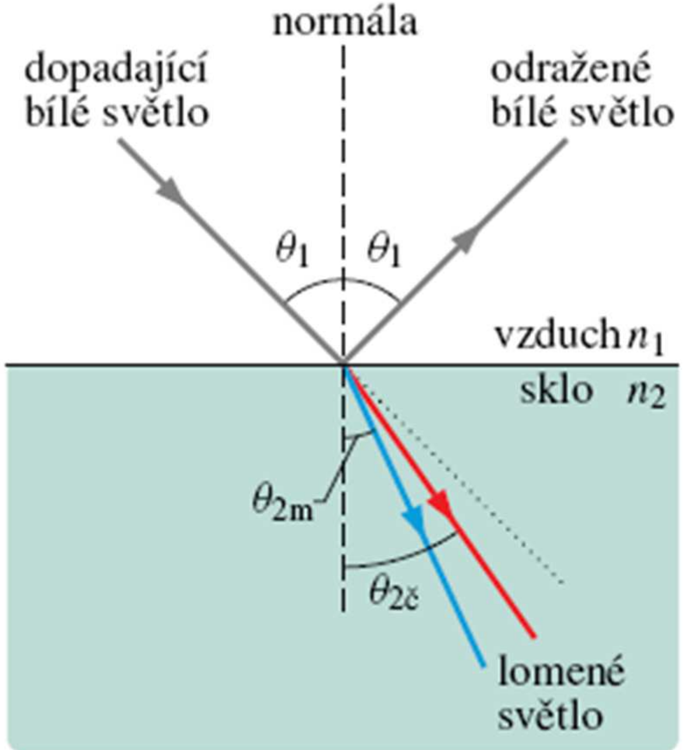




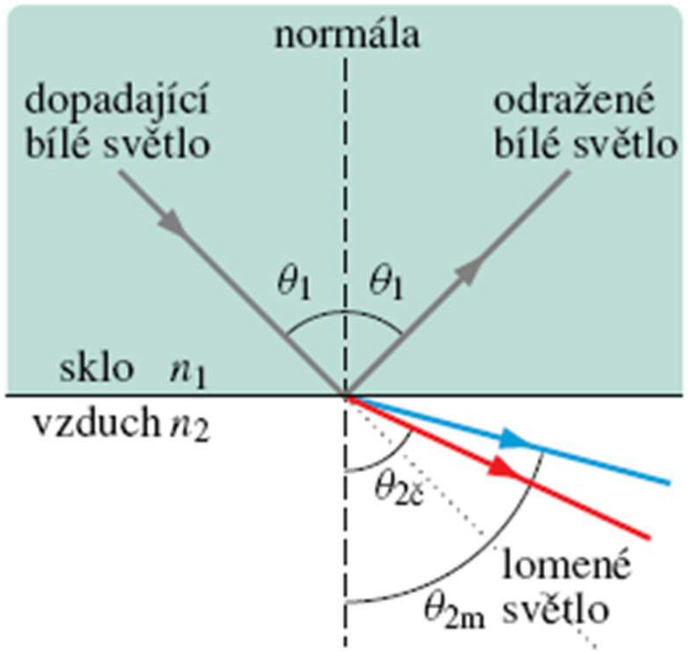
Example – water

λ=405nm	n=1.342742 blue
λ=546nm	n=1.334466 yellow
λ=768nm	n=1.32889 red

Dispersion



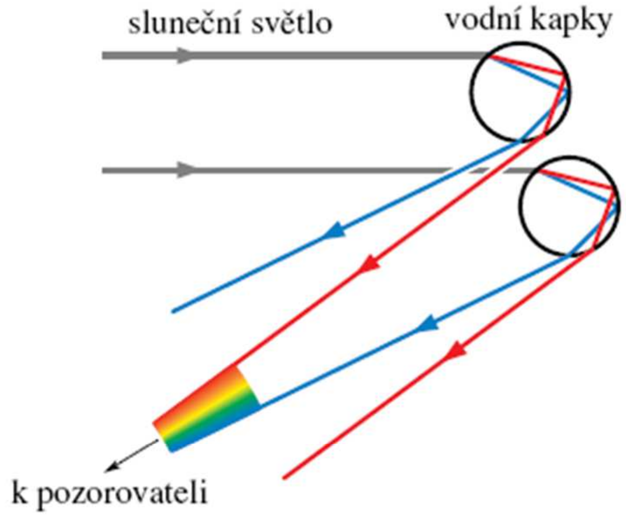
normála
dopadající bílé světlo
odražené bílé světlo
θ1
θ1
vzduch n1
sklo n2
θ2m
θ2č
lomené světlo



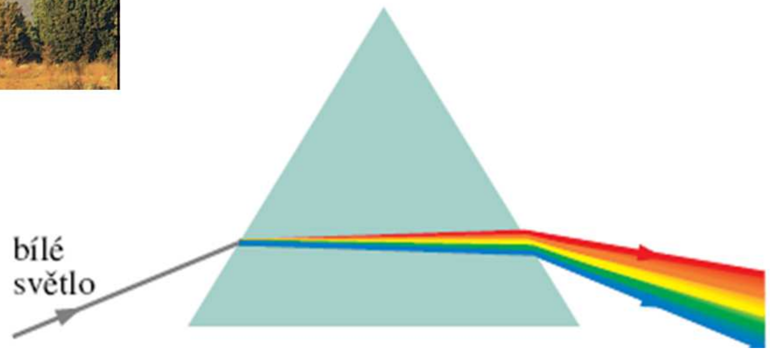
normála
dopadající bílé světlo
odražené bílé světlo
θ1
θ1
sklo n1
vzduch n2
θ2č
lomené světlo
θ2m

Dispersion

- Rainbow

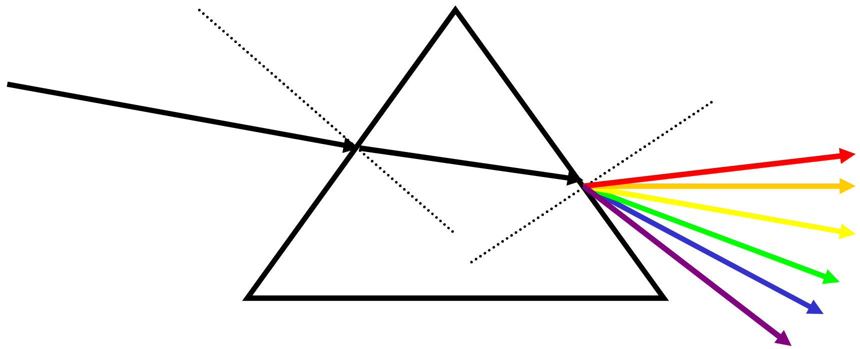


- Spectroscopy



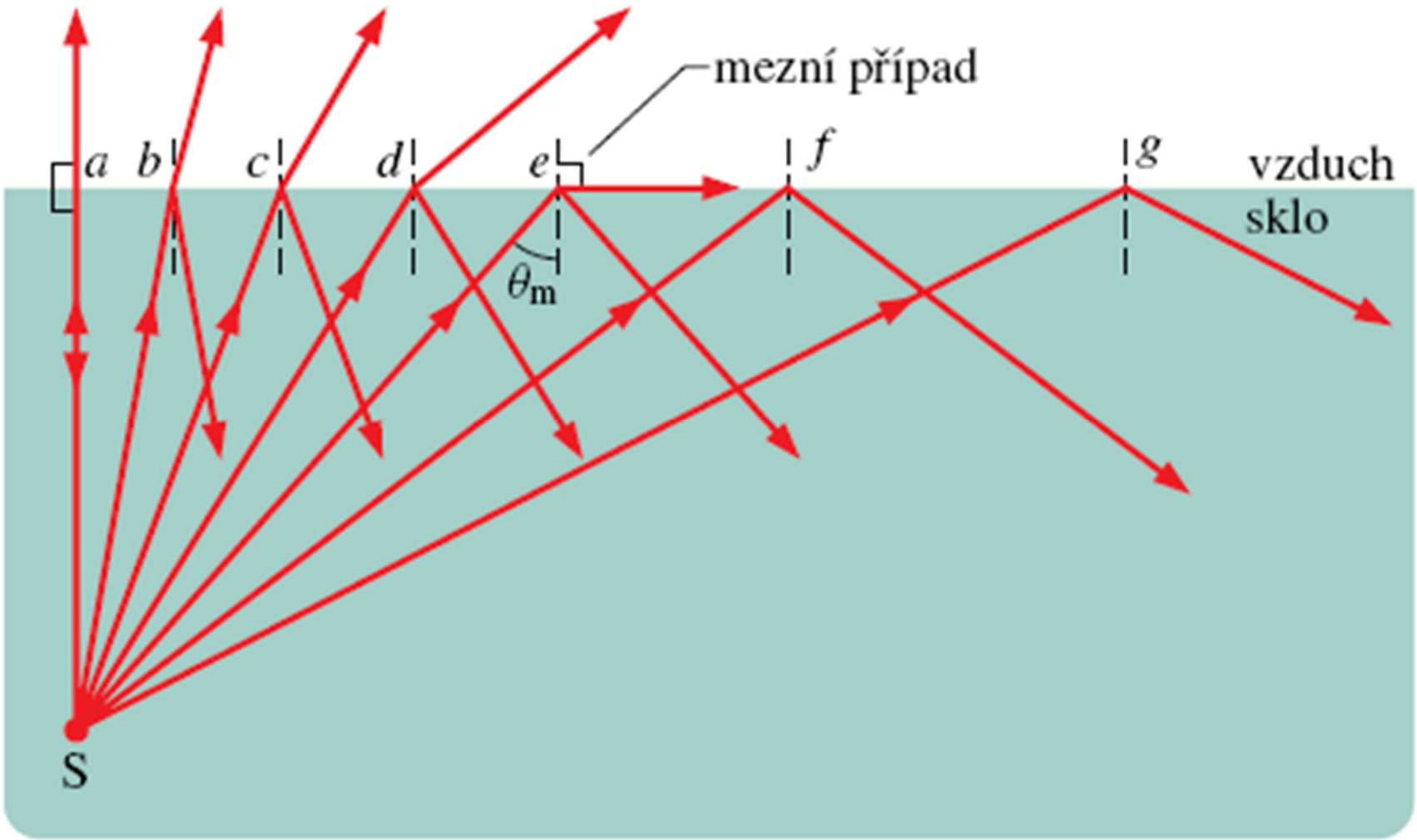
Spectroscopy

Spreading of white light by refraction on optical prism



Application of dispersion for (angular) separation of various wavelengths

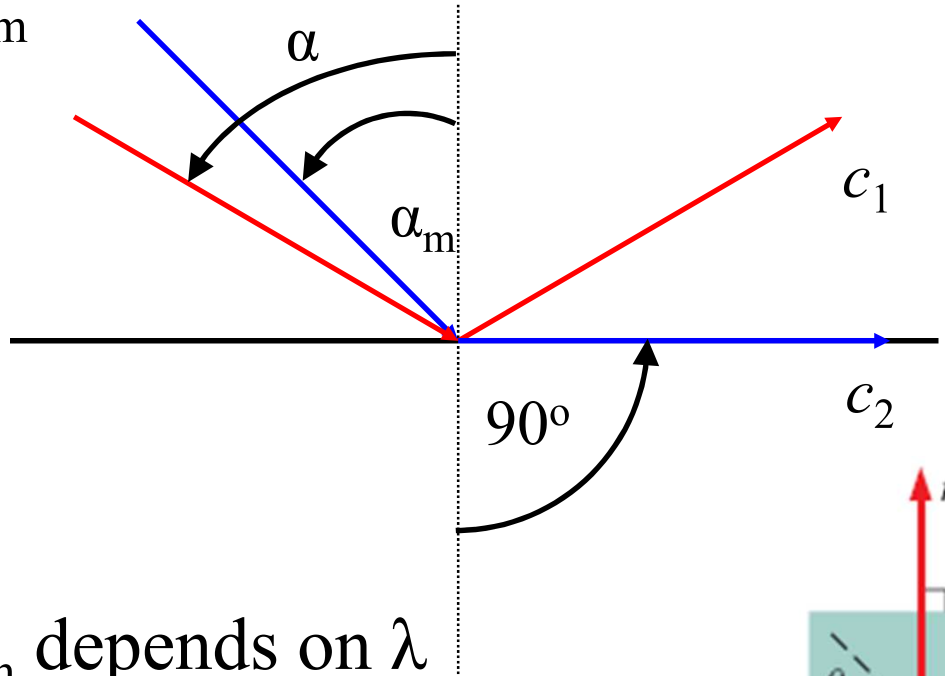
Total reflection



Total reflection

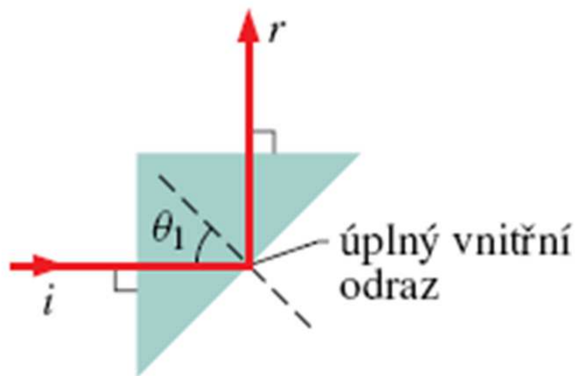
Only reflection is possible for refraction index $n_1>n_2$ at angles $\alpha>\alpha_m$

$$\sin\alpha_m = \frac{n_2}{n_1}$$



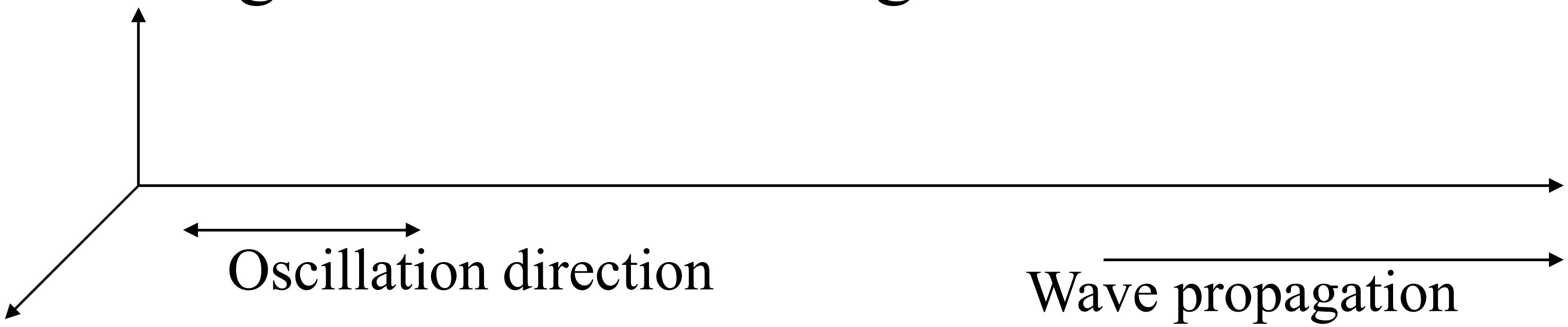
Critical angle α_m depends on λ

Application to optical fibers

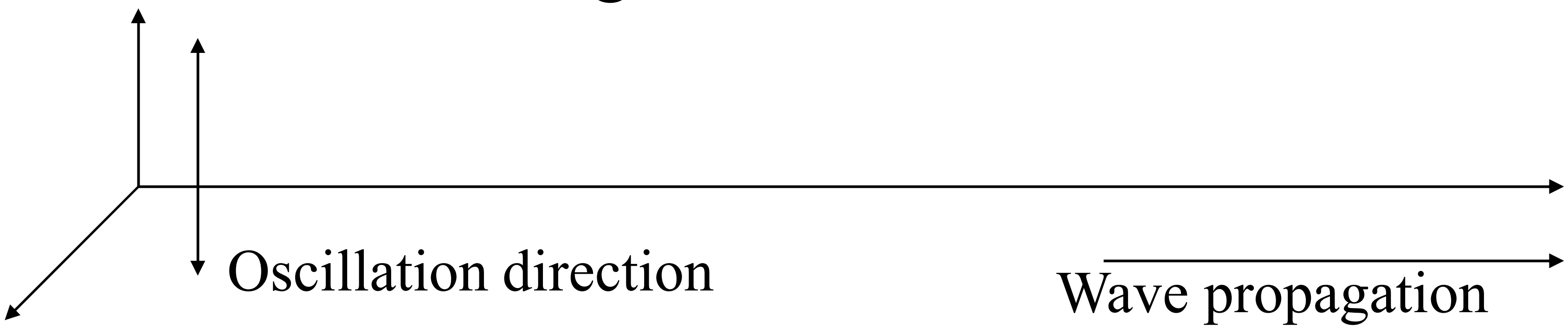


Polarization of waves

- Longitudinal – not for light!

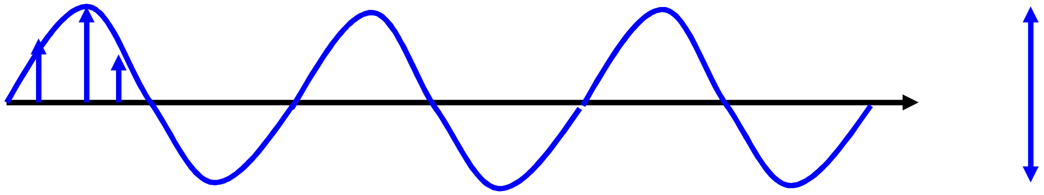


- Transversal - light

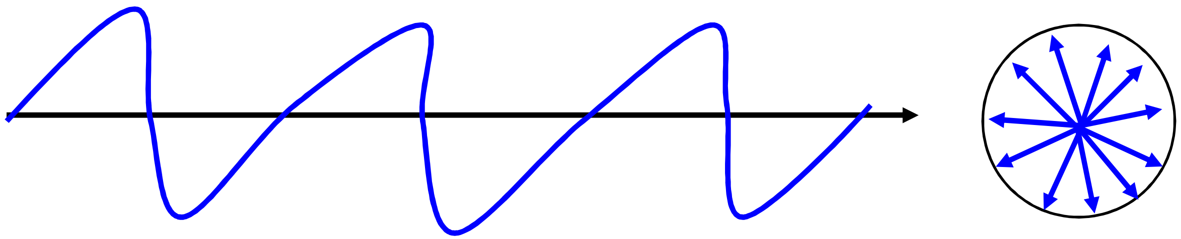


Polarization of light

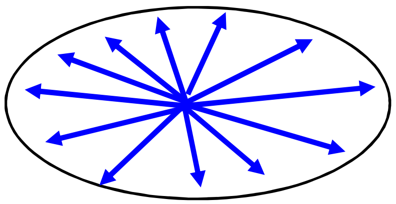
- Linearly polarized



- Circularly polarized

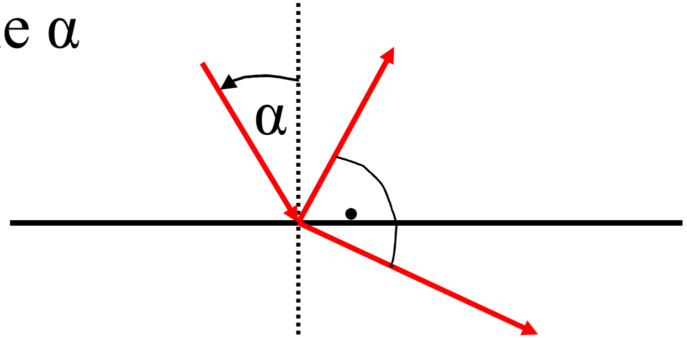


- Eliptically polarized



Polarization

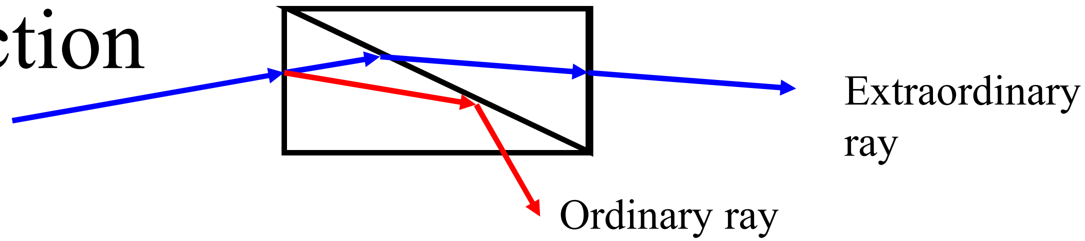
- Polarizing filter
- Polarization by reflection – linear polarization normal to the incidence plane, full polarization – Brewster's angle α



$$\tan(\alpha) = n$$

- Polarization by refraction

- double refraction

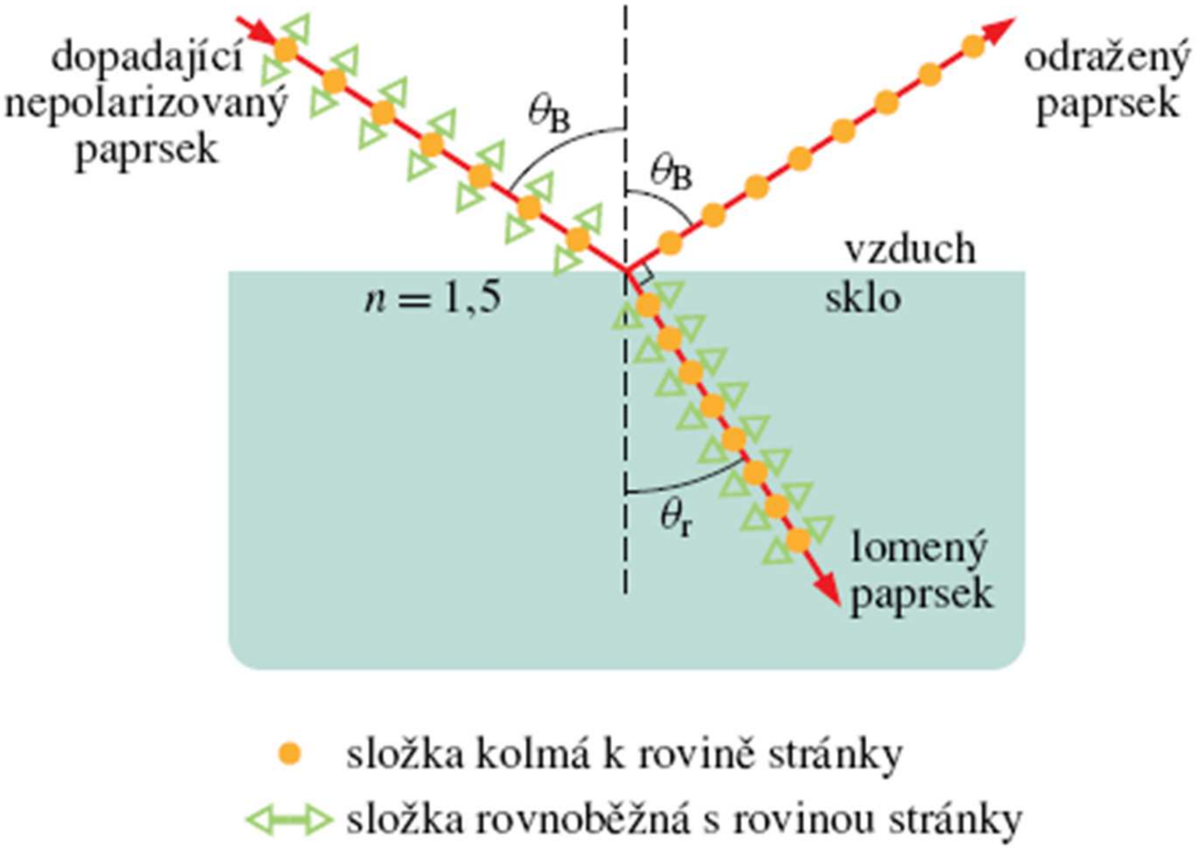


Polarization by reflection

Brewster's angle

$$\tan(\theta_B) = n$$

David Brewster (1812)



Double refraction

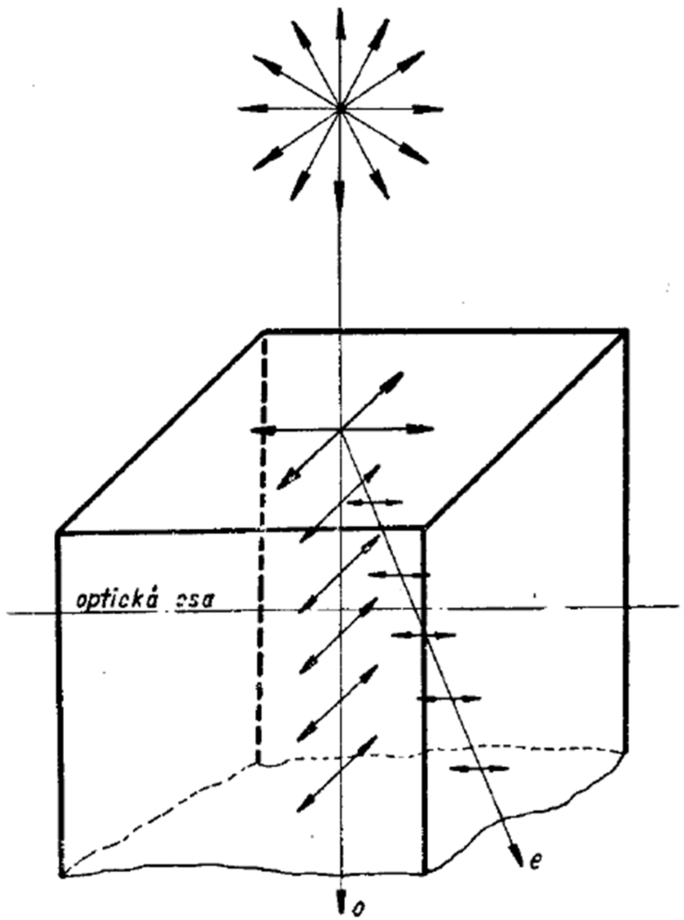
Crystals of lower symmetry

Light propagation other than along optical axis

Optical calcite $CaCO_3$

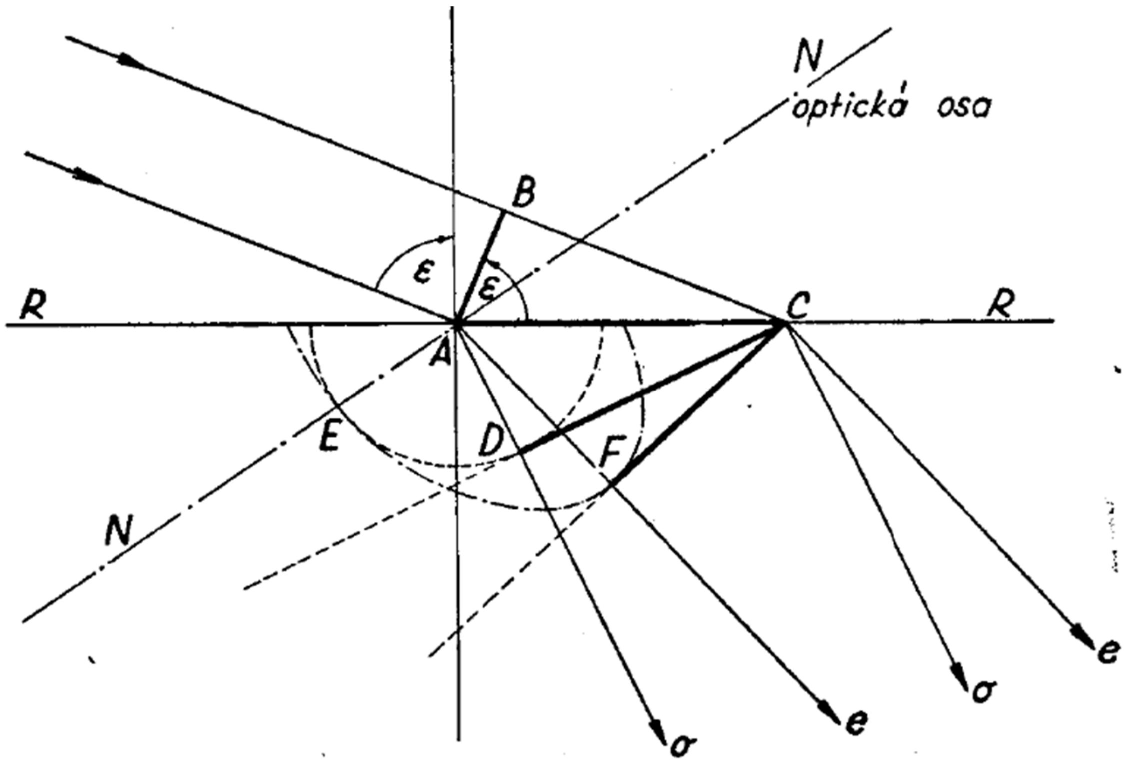
(Iceland spar)

Sodium nitrate $NaNO_3$



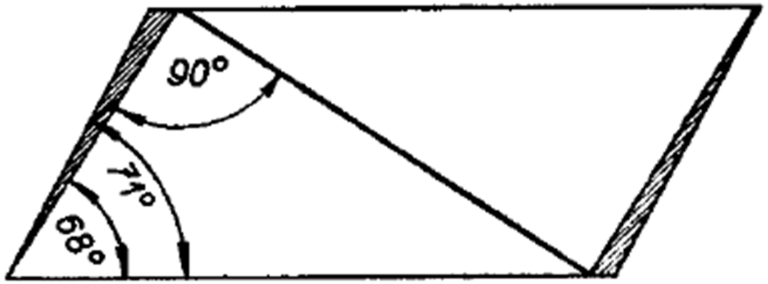
Double refraction

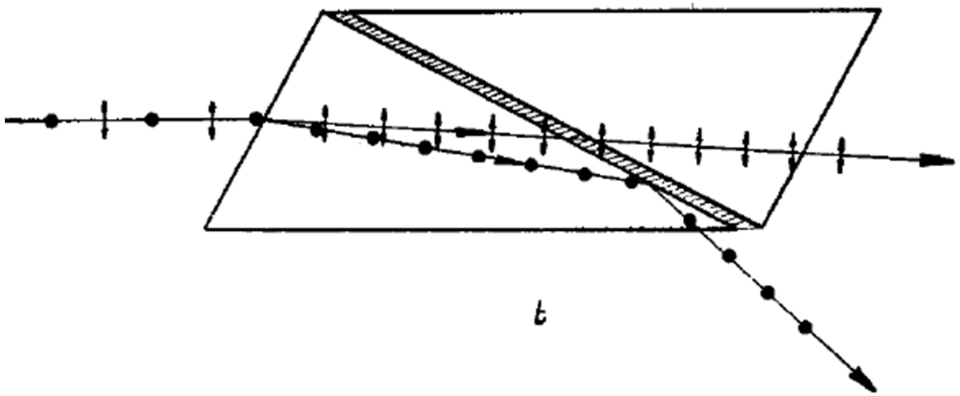
Anisotropy of light velocity

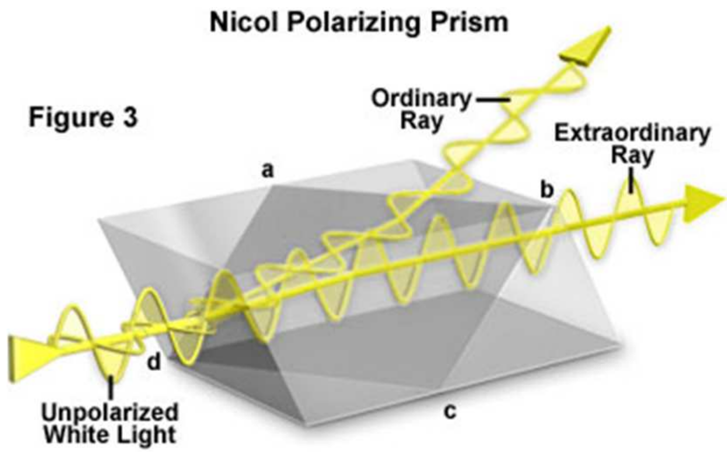


Polarization by refraction – Nicol prism

Optical prism from icelandic spar



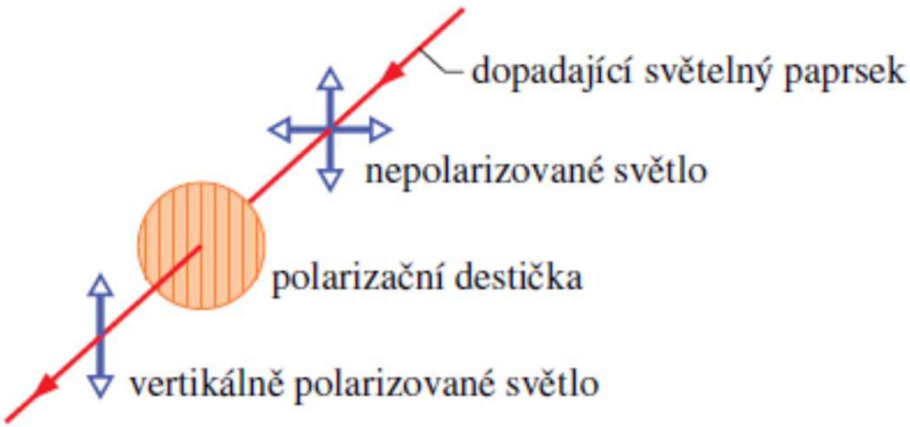




Polarization filter

Polaroid – polarization by absorption

Electric field component parallel to transmission axis can pass through, perpendicular component is absorbed

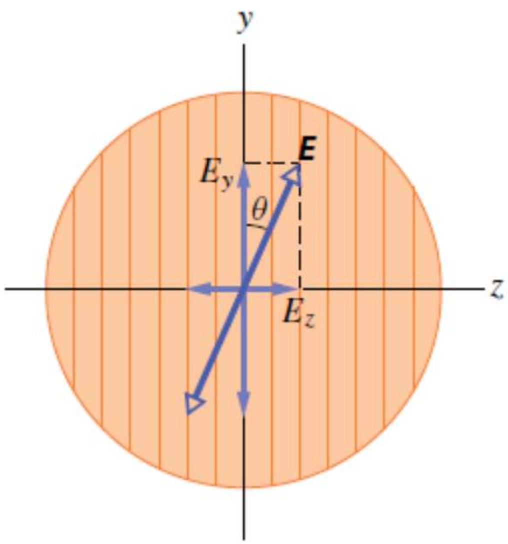


Intensity of unpolarized light passing through filter

$$I = \frac{1}{2} I_0$$

Polarized light at Polaroid

Intensity of passing light depends on angle between incident light polarization plane and transmission axis of Polaroid



Intensity of electric field

$$E_y = E\cos\theta$$

Intensity of transmitted light (Malus' law)

$$I = I_0 \cos^2\theta$$

Literature

Pictures used from the books:

HALLIDAY, D., RESNICK, R., WALKER, J.: Fyzika (část 4 – Elektromagnetické vlny – Optika – Relativita), Vutium, Brno 2000

J.Fuka, J.Havelka: Optika a atomová fyzika: I. optika, SNTL Praha 1961