Optoelectronics

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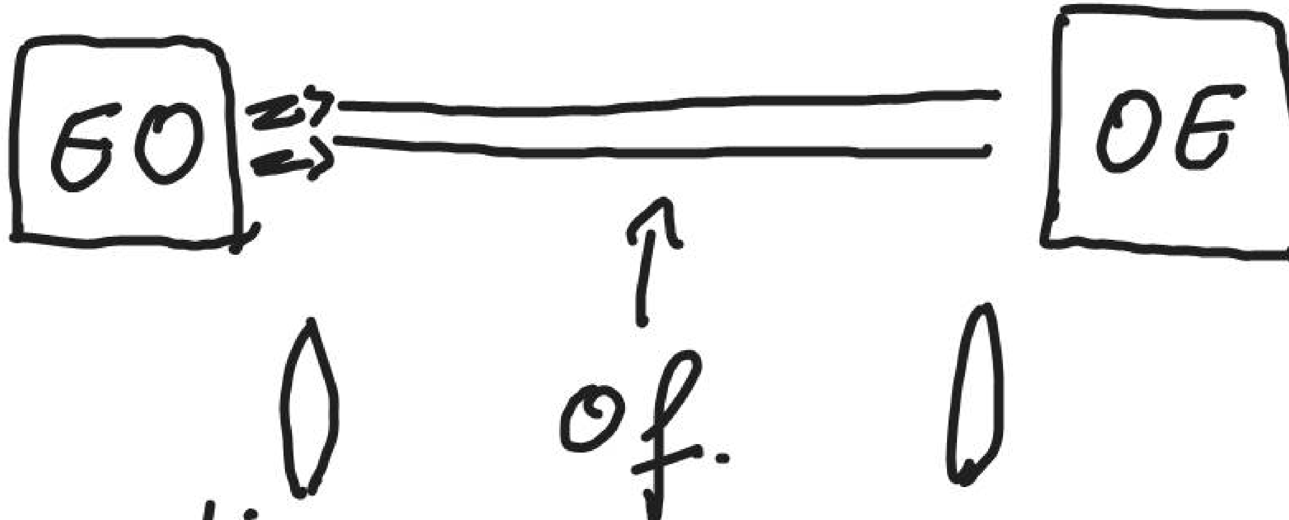
8 Lectures

6 Labs



8

2 optics
2 light sources
2 optical detectors
2 optical fiber

Dual nature of the light

{ wave (EM)
particle (photon)

Newton (1650) – particle — Reflection, Refraction

Huygens – wave

Young (1800) – wave – interferance

Maxwell (1883) – EM wave

Hertz (1887) — sources, detectors EM →

photoelectric effect

Plack (1900)

Einstein (1905): $E = \underline{h} \cdot f$, $h = 6{,}63 \times 10^{-34}$ Js

particle

light sources

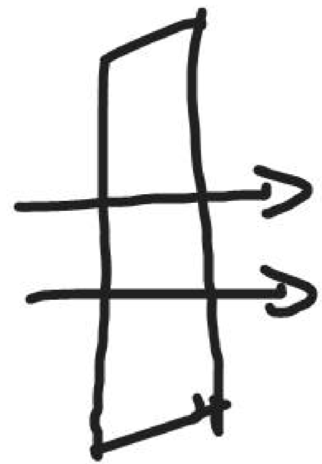
detectors

Reflection ✓
Refraction ✓
Diffraction
Interference
Polarization
Scattering ✓
Dispersion ✓

Geometric optics

Ray concept

λ

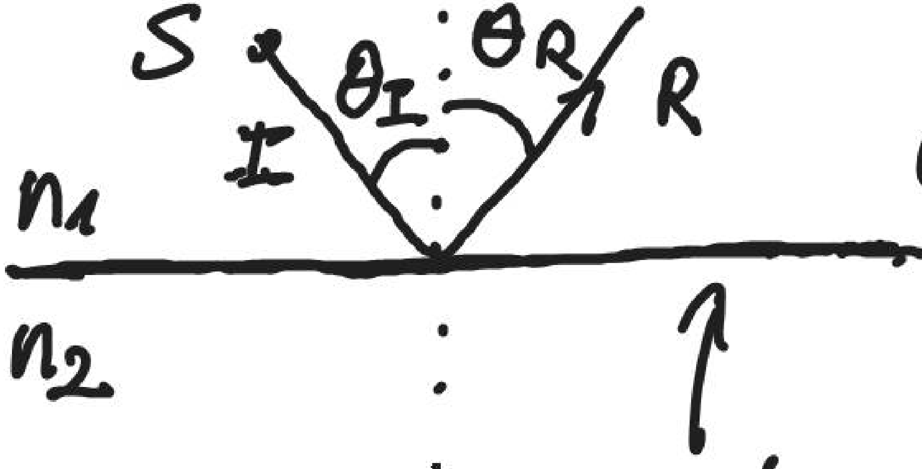


$\underline{\lambda \ll d}$

d

$\lambda \approx d \longrightarrow$ Diffraction

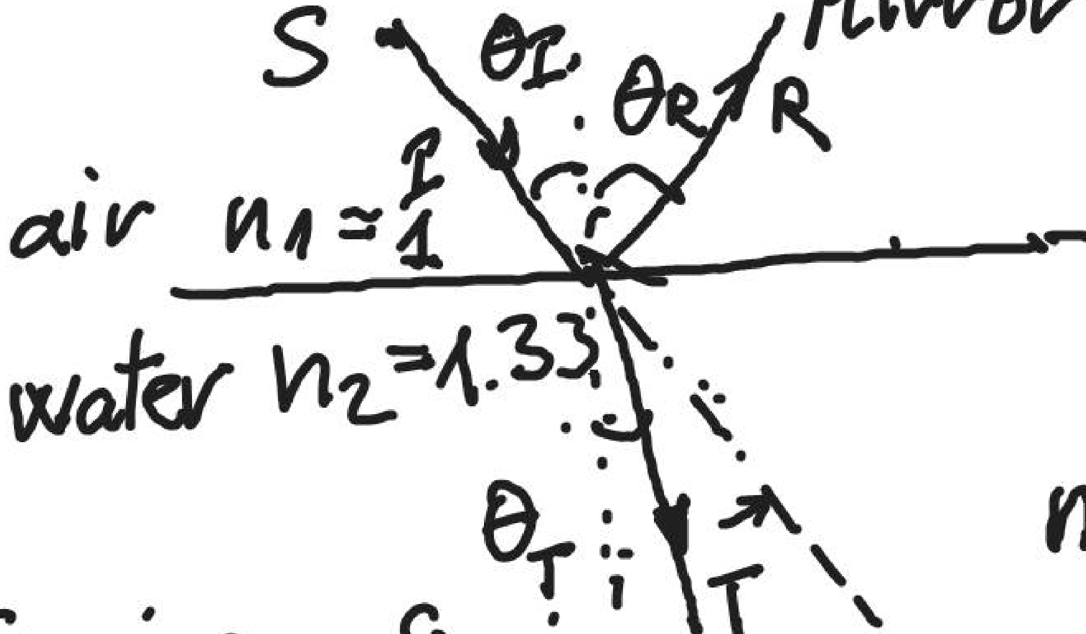
$\lambda \gg d \longrightarrow$ d-source n - index of refraction



$\theta_R = \theta_I$

$\Phi_R = \Phi_I$

Mirror



- direction
- wavelenght
- speed

$n_1 \sin\theta_I = n_2 \sin\theta_T$

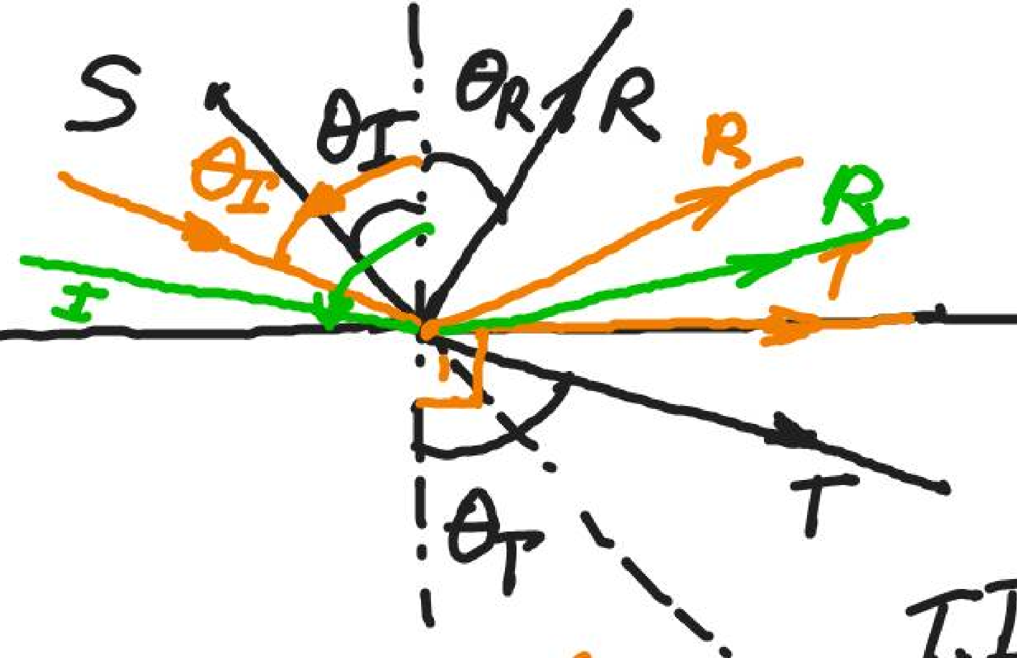
$n = \frac{c}{v}$, $c = 3 \times 10^8 m/s$

$\frac{c}{v_1} \sin\theta_I = \frac{c}{v_2} \sin\theta_T$

$$\Phi_I = \Phi_R + \Phi_T \to 0$$

water $n_1 = 1.33$

air $n_2 = 1$



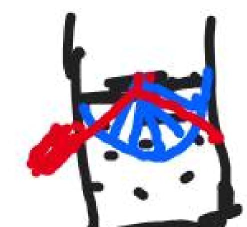
$\boxed{n_1 > n_2}$

T.I.R

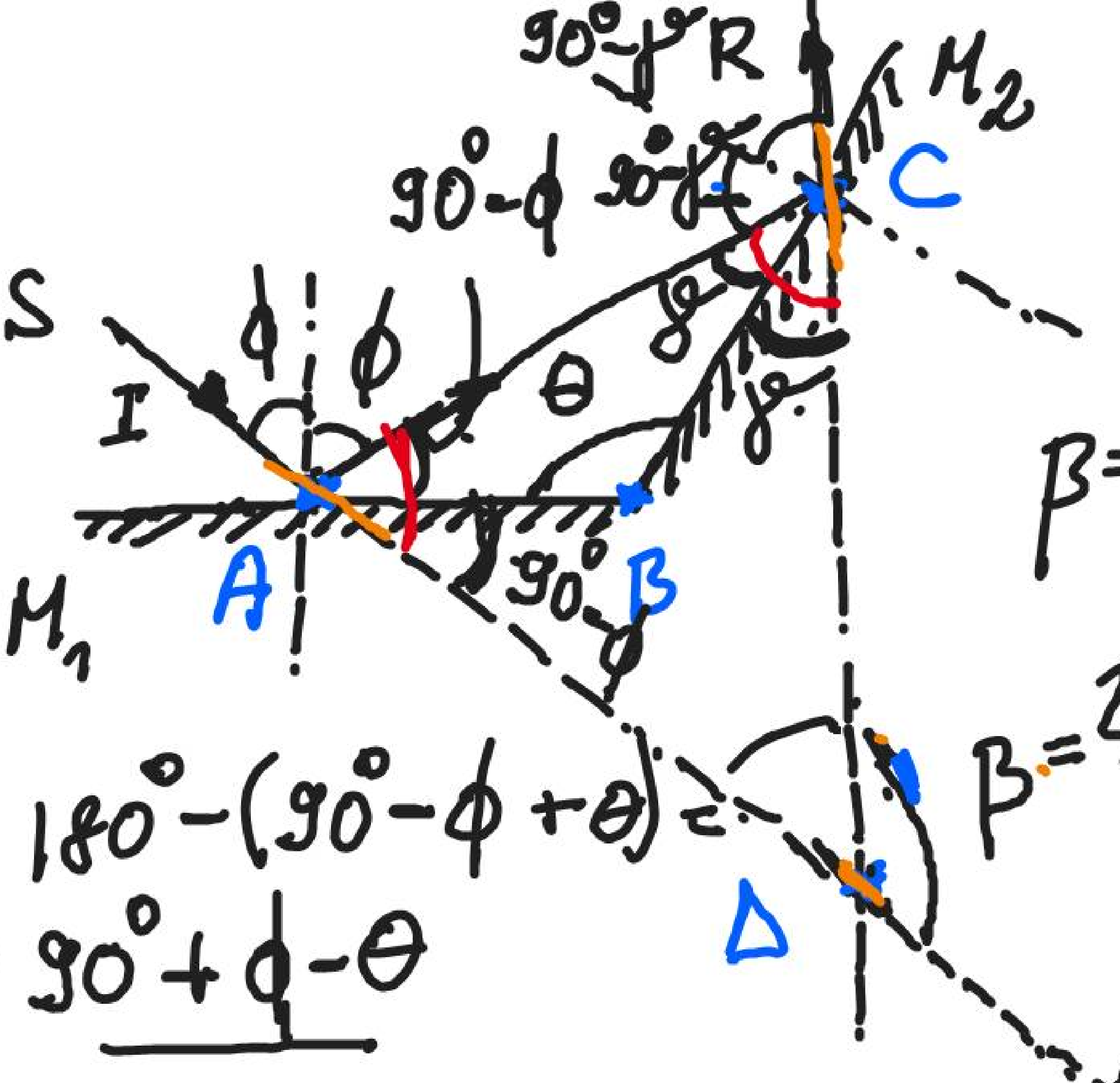
θ_c - critical

$$n_1 \sin\theta_c = n_2 \Rightarrow \boxed{\theta_c = \arcsin\left(\frac{n_2}{n_1}\right)}$$

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



Ex: $\theta_c = \underline{48}^{\circ}$



$\beta = ?$

$\Delta AC\Delta$

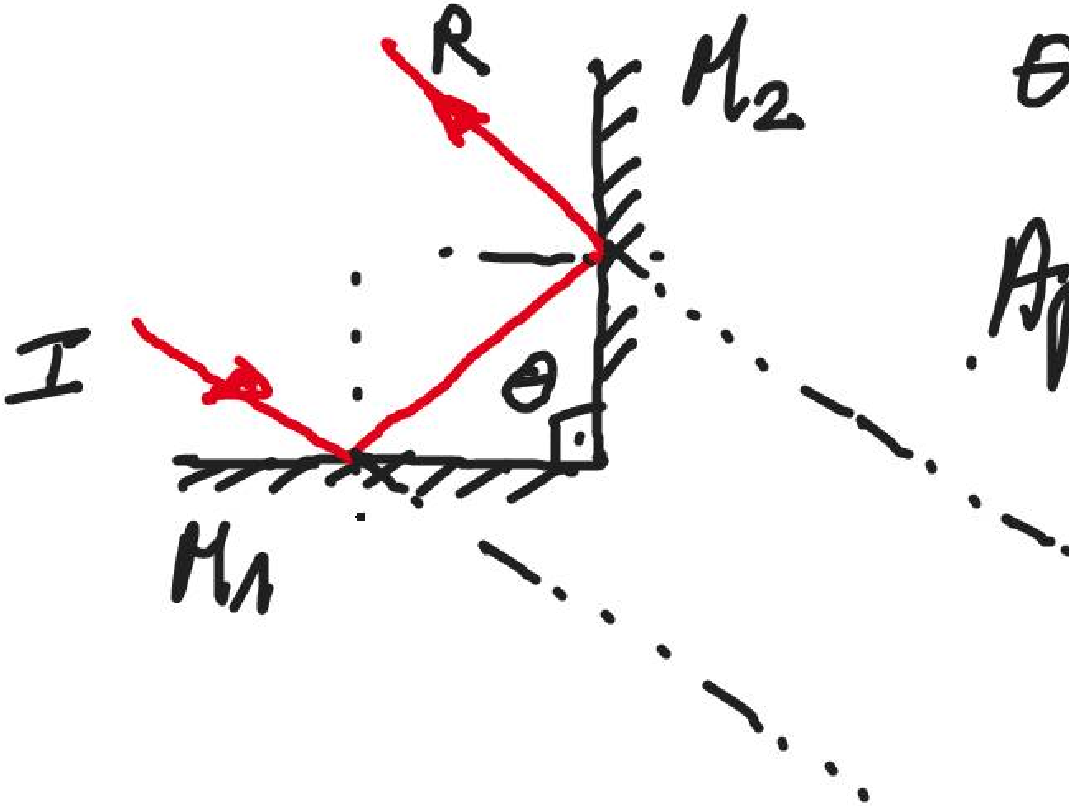
ΔACB

$$\beta = 2(90^\circ - \phi + \gamma) =$$
$$= 2(90^\circ - \cancel{\phi} + 90^\circ + \cancel{\phi} - \theta) = 360^\circ - 2\theta$$

$$\boxed{\beta = 360^\circ - 2\theta}$$

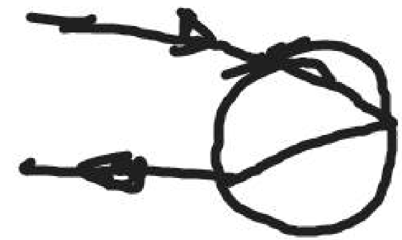
$$\gamma = 180^\circ - (90^\circ - \phi + \theta) =$$
$$= 90^\circ + \phi - \theta$$

ex1
$\theta = 120^\circ \Rightarrow \beta = 120^\circ$
$\theta = 100 \Rightarrow \beta = 160^\circ$
$\theta = 90^\circ \Rightarrow \beta = 180^\circ$



$\theta = 90° \rightarrow$ Retroreflexion

Apollo 11 (1969)



-Fizeau (1850)-

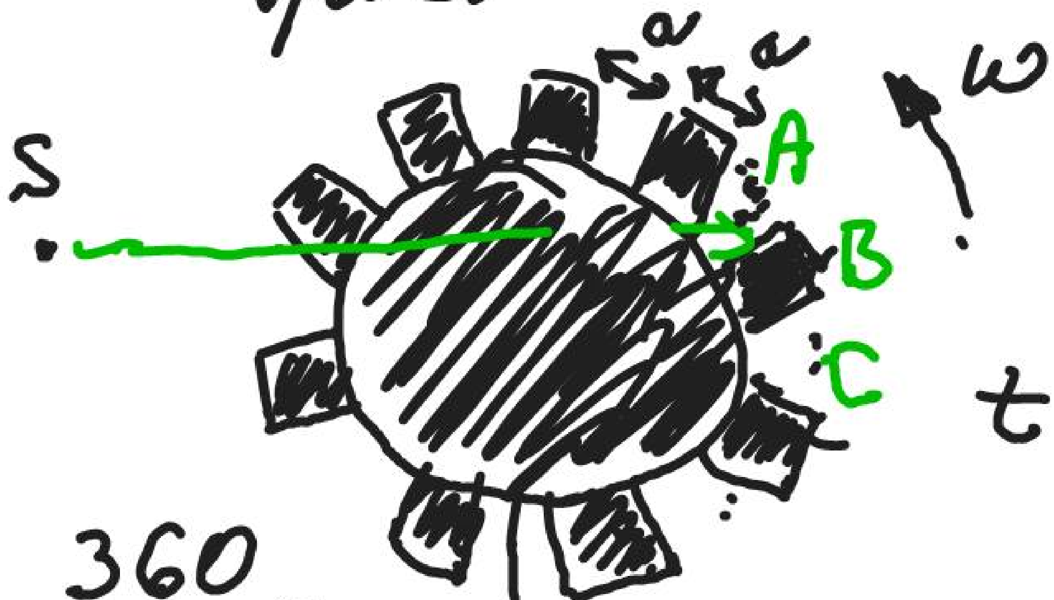
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

$$c = 3.1 \times 10^8 \text{ m/s}$$

$$c = \frac{2d}{t} = 3 \times 10^8 \text{ m/s}$$

$$v = \frac{d}{t}$$

Mirror



c

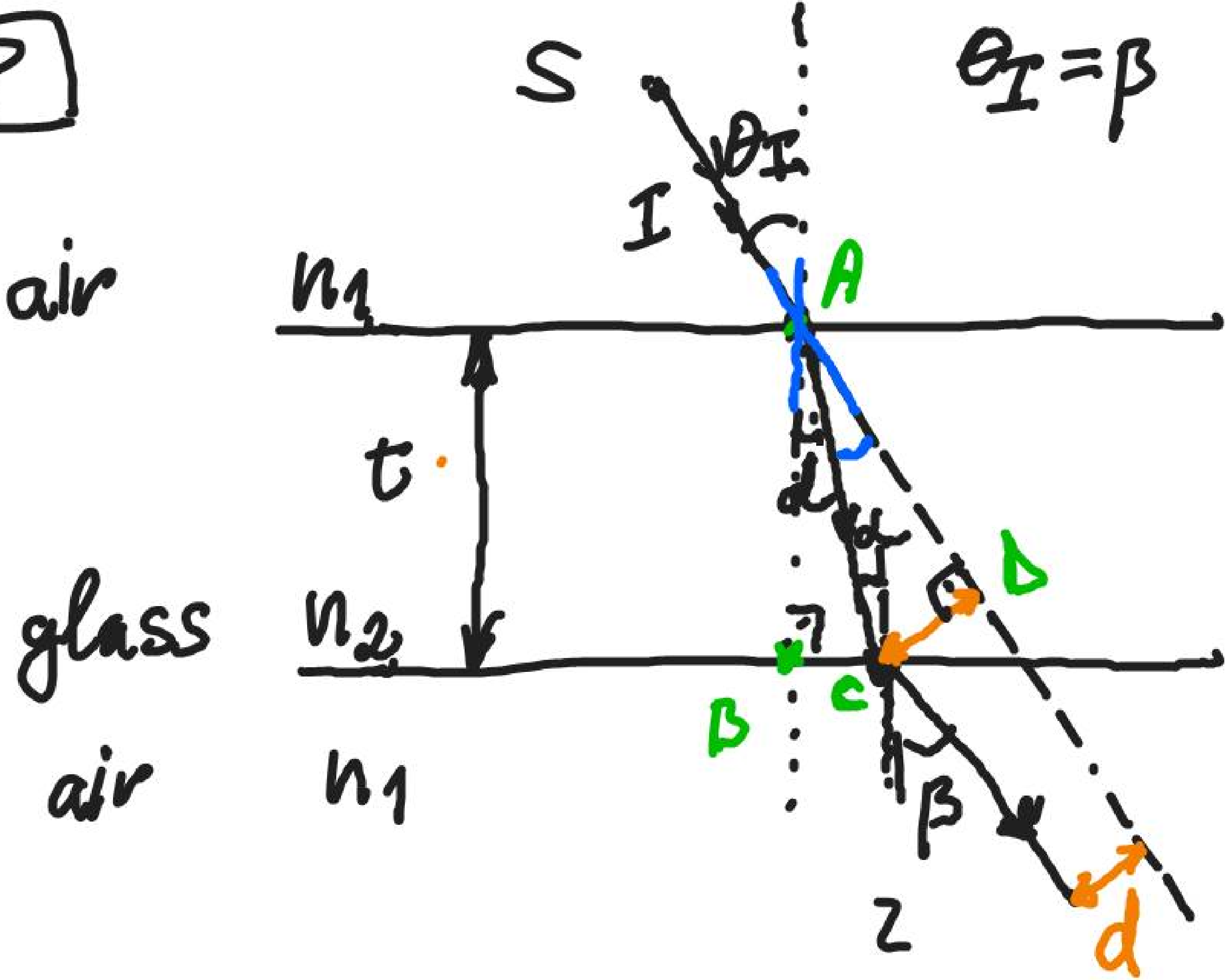
$$t = \frac{\Delta\theta}{\omega} = \frac{\frac{1}{720}\text{ rev}}{27.5 \text{ rev/s}} = 50\,\mu\text{s}$$

$\underline{\omega} = 27.5$ rev/s

$d = 7500$ m

$$\frac{360}{360}$$

$\boxed{P}$



$\theta_I = \beta$

$d = ?$

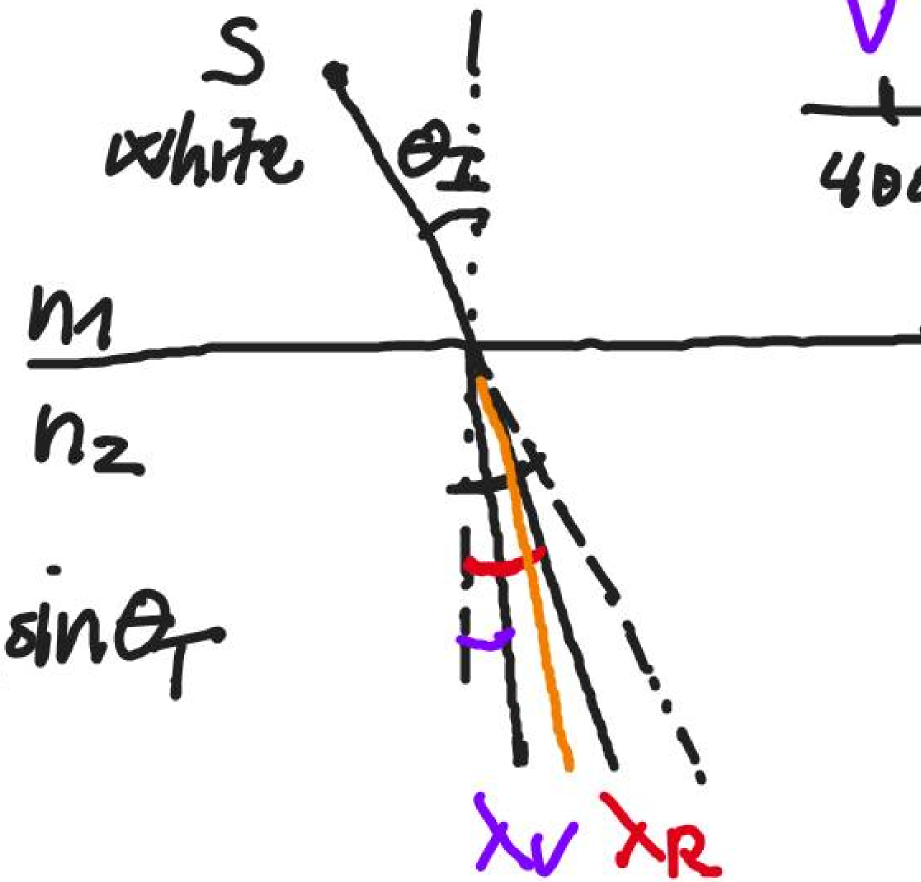
$\Delta ACB: \cos\alpha = \frac{t}{AC}$

$\Delta ACD:$

$\sin(\theta_I - \alpha) = \frac{d}{AC}.$

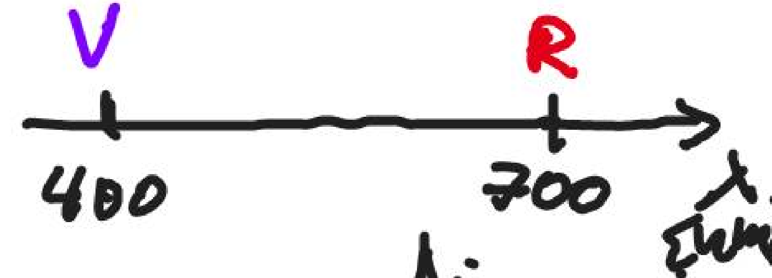
$$\frac{\cos\alpha}{\sin(\theta_I - \alpha)} = \frac{t}{d}$$

$$d = \underline{t}\,\frac{\sin(\theta_I - \alpha)}{\cos\alpha}$$



air

glass



Dispersion

$$\boxed{n_m = \frac{\lambda}{\lambda_m}}$$

$$\underbrace{n_1 \sin\theta_I}_{\text{const}} = n_2 \sin\theta_T$$

$$\left.\begin{array}{l} \text{const} = \underline{n_2(\lambda_R)} \cdot \sin\theta_{T_R} = \underline{n_2(\lambda_V)} \cdot \sin\theta_{T_V} \\ \lambda_R > \lambda_V \Rightarrow n_2(\lambda_R) < n_2(\lambda_V) \end{array}\right\} \Rightarrow \underline{\theta_{T_R} > \theta_{T_V}}$$

s

f

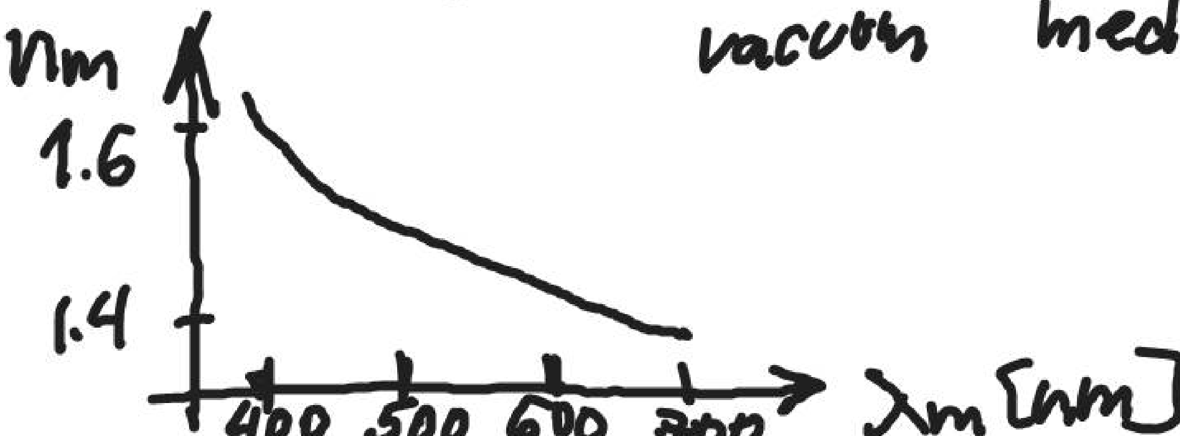
$n = \frac{c}{v}$

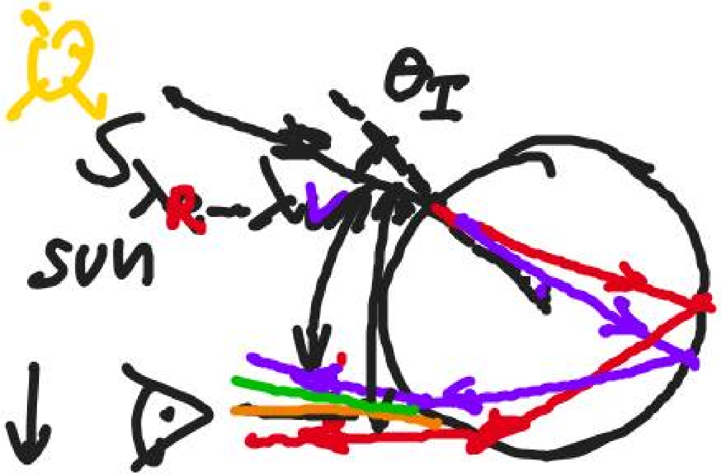
air $n_1 = \frac{c}{\lambda_1 f}$ $= 1$ f const.

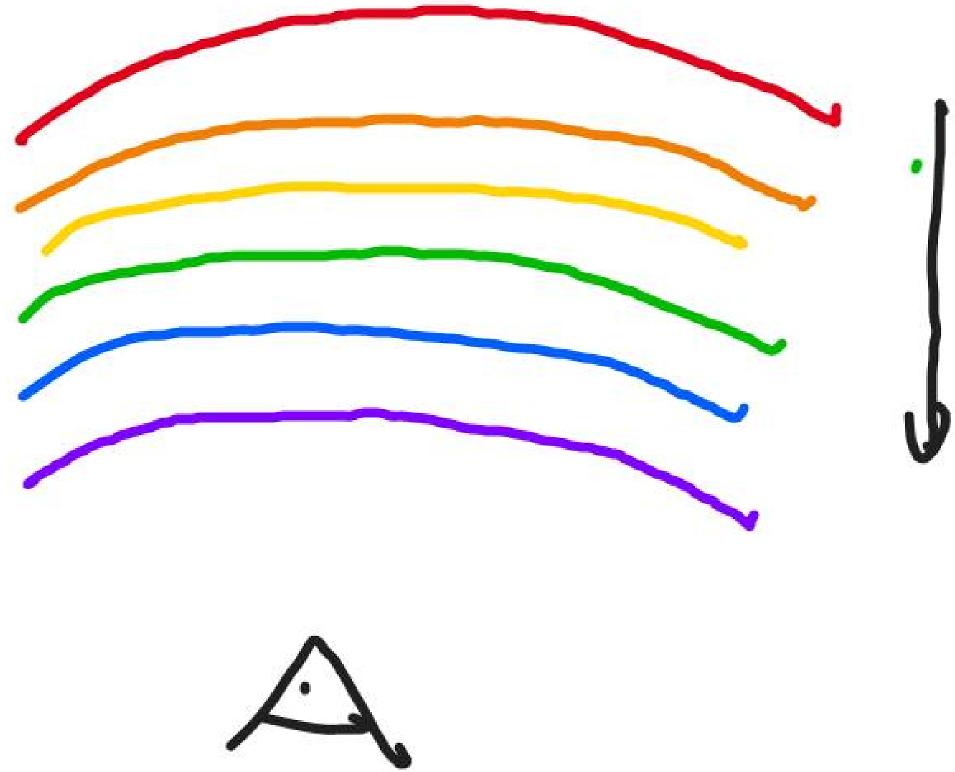
glass $n_2 = \frac{c}{\lambda_2 f}$ $= 1.5$

$$\frac{n_1}{n_2} = \frac{\lambda_2}{\lambda_1} \Rightarrow \underbrace{n_1\lambda_1}_{\text{vaccum}} = \underbrace{n_2\lambda_2}_{\text{medium}} \Rightarrow \lambda = n_m \lambda_m$$

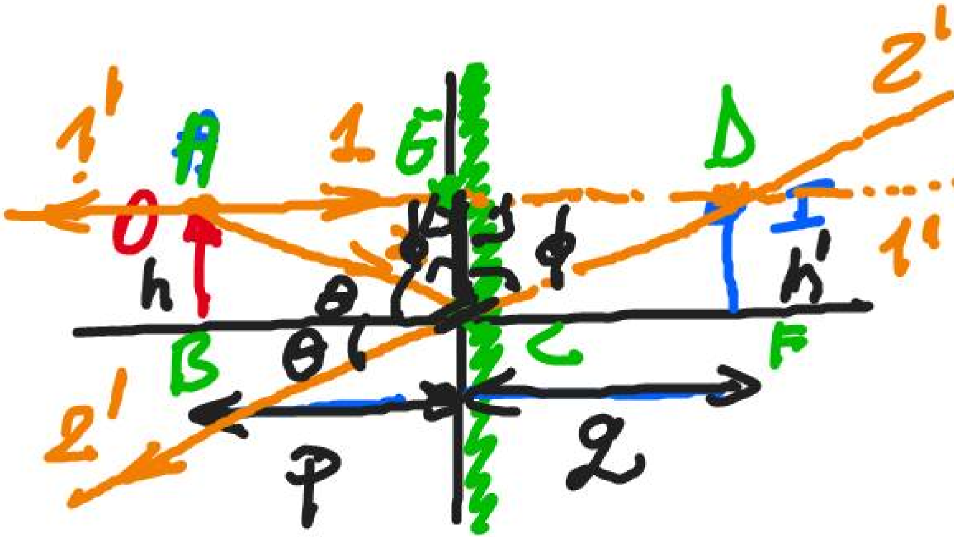
$$\boxed{n_m = \frac{\lambda}{\lambda_m}}$$




θI
R
sun



Images formed by Reflection



flat mirror

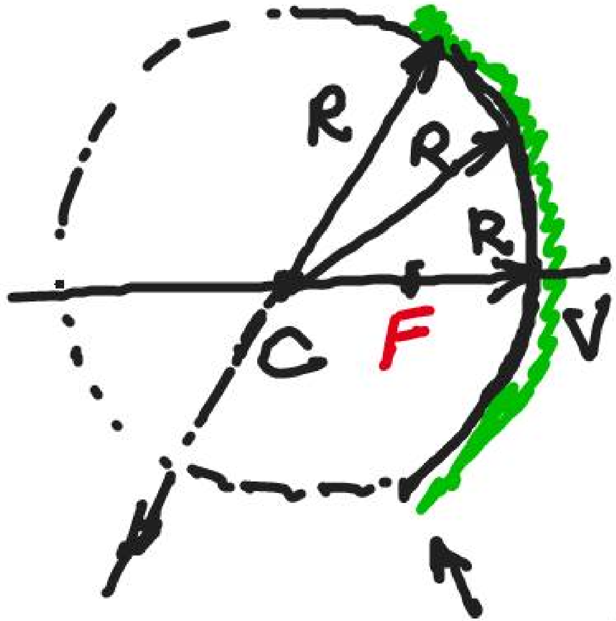
virtual

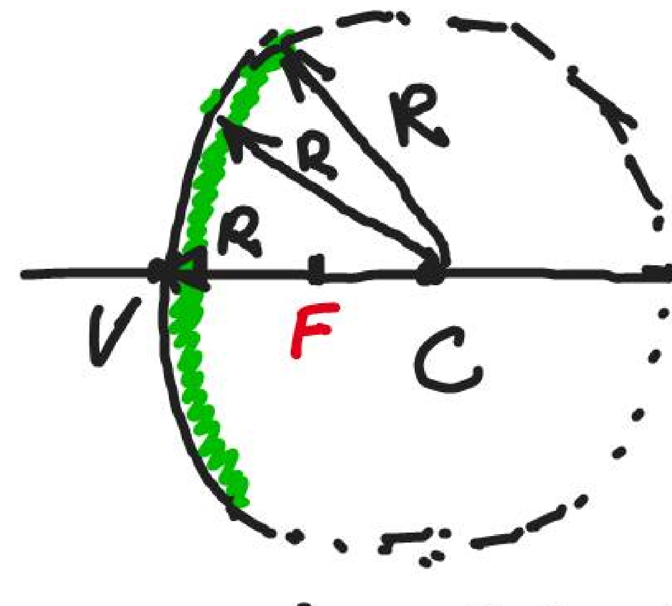
$h' = h$

$M = \frac{h'}{h} = 1$

$\Delta ACG \equiv \Delta DCG$

Spherical Mirrors





concave convex

f - focal length

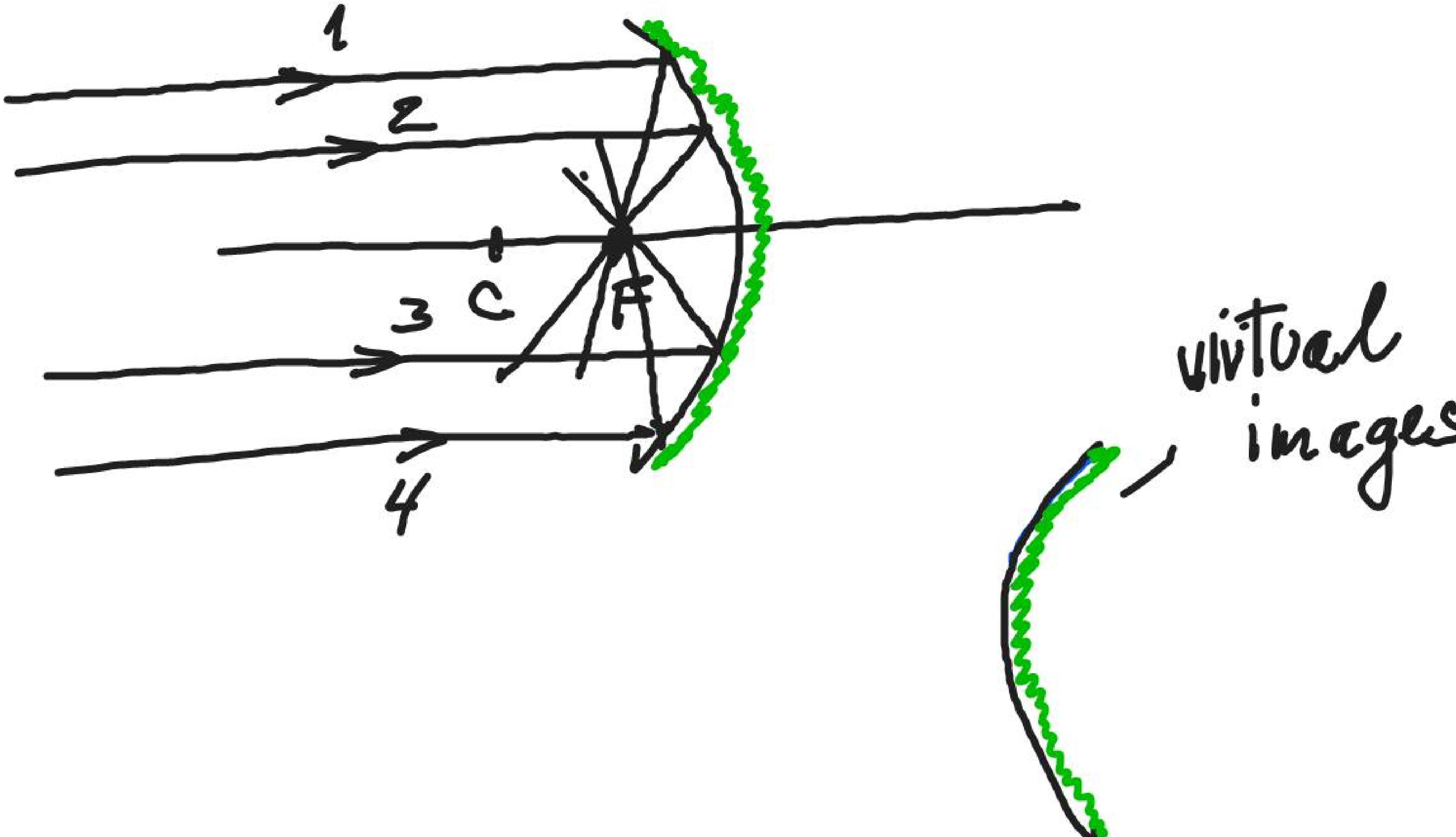
$$f = \frac{R}{2}$$

F - focal point

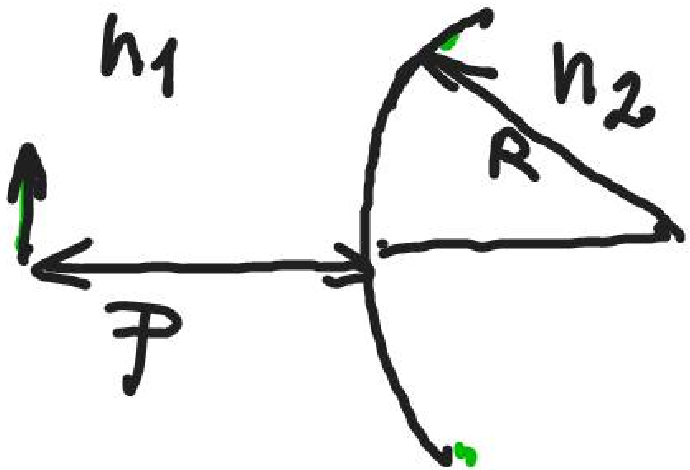
$$\boxed{\frac{1}{p} + \frac{1}{q} = \frac{1}{f} = \frac{2}{R}}$$

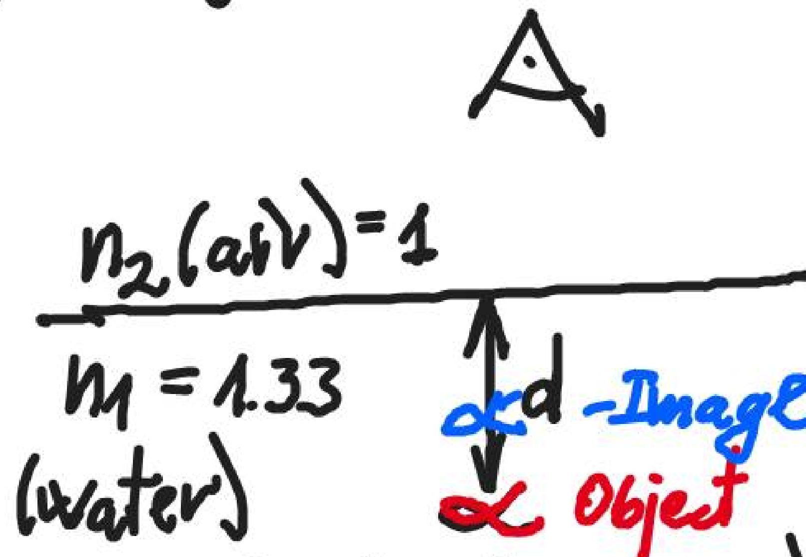
$p \gg R \Rightarrow p \to \infty$

$\frac{1}{p} \to 0 \Rightarrow \frac{1}{q} = \frac{1}{f}$


1
2
C
F
3
4
virtual
images

Images formed by Refractions





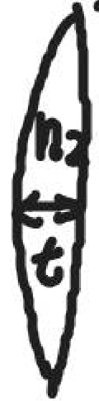
(virtual image)

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

$$R \to \infty \Rightarrow \frac{n_1}{p} = -\frac{n_2}{q} \Rightarrow q = -\frac{n_2}{n_1} p$$

$$q = -0.75\, p$$

Lens

n_1  n_1

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}=(n-1)\underbrace{\left(\frac{1}{R_1}-\frac{1}{R_2}\right)}$$

$t \ll R_1, R_2 \Longrightarrow$ thin lenses

$$\frac{1}{R_1}-\frac{1}{R_2}+\underbrace{\frac{t(n-1)}{R_1 R_2 n}}$$

n_1 - sorounding medium $= n_m$

n_2 - lens material $= n_\ell$

$$\boxed{n=\frac{n_\ell}{n_m}}$$

$\boxed{P_1}$

$f_{air} = +20\,cm$

$n_\ell = 1.52$

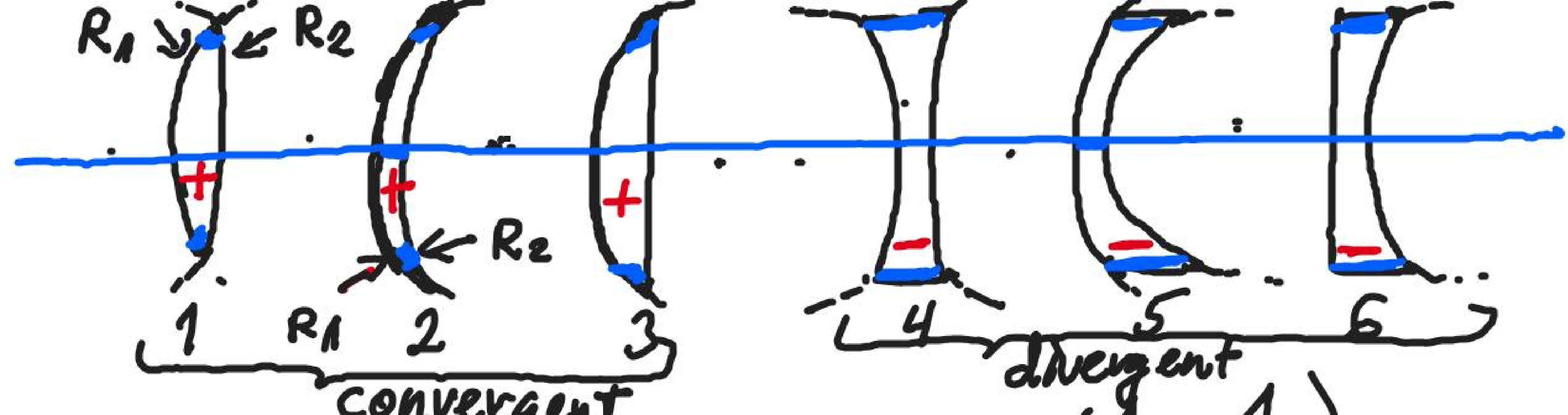
$n_w = 1.33$

$f_w = ?$

$$\left.\begin{aligned} \frac{1}{f_{air}} &= (n_\ell - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \\ \frac{1}{f_w} &= \left(\frac{n_\ell}{n_w} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \end{aligned}\right\} \div \Rightarrow$$

$$\frac{f_w}{f_{air}} = \frac{n_\ell - 1}{\frac{n_\ell}{n_w} - 1} \Rightarrow f_w = \left(\frac{1.52 - 1}{\frac{1.52}{1.33} - 1}\right) 20\,cm =$$

$$\boxed{= +72.8\,cm}$$

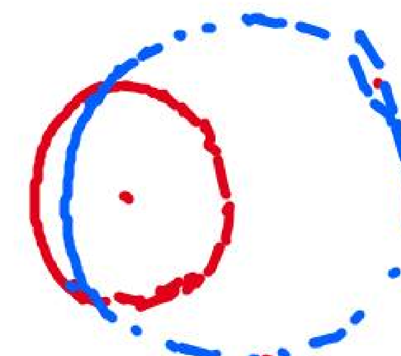


1. biconvex
2. convex-concave −
3. plano-convex
4. biconcave
5. convex-concave −
6. plano-concave

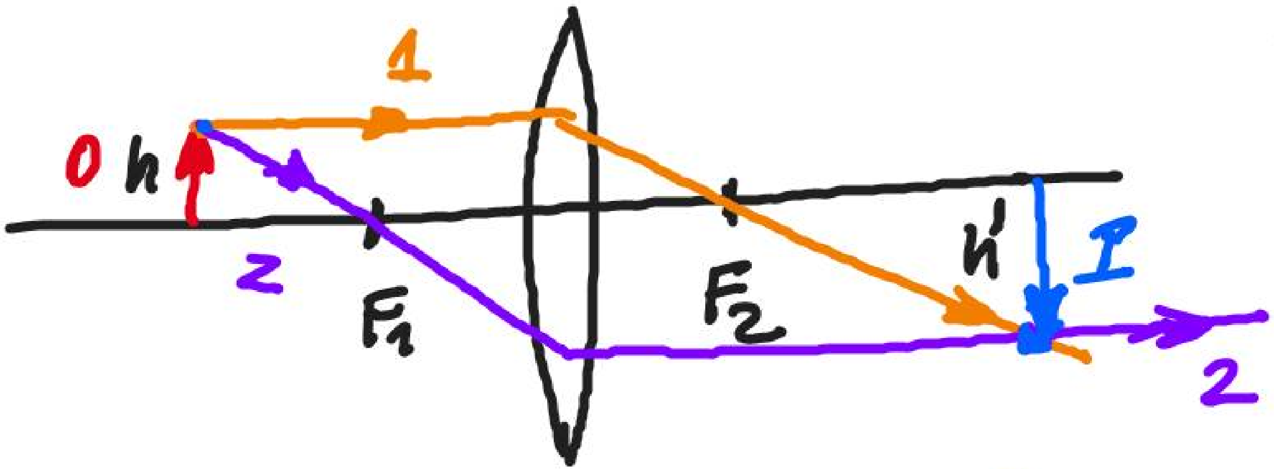
$$\frac{1}{f} = \underbrace{(n-1)}_{+}\underbrace{\left(\frac{1}{R_1} - \frac{1}{R_2}\right)}_{+}$$

$$\left.\begin{array}{l} R_1 > 0 \\ R_2 > 0 \end{array}\right\} \Rightarrow \frac{1}{R_1} > \frac{1}{R_2}.$$

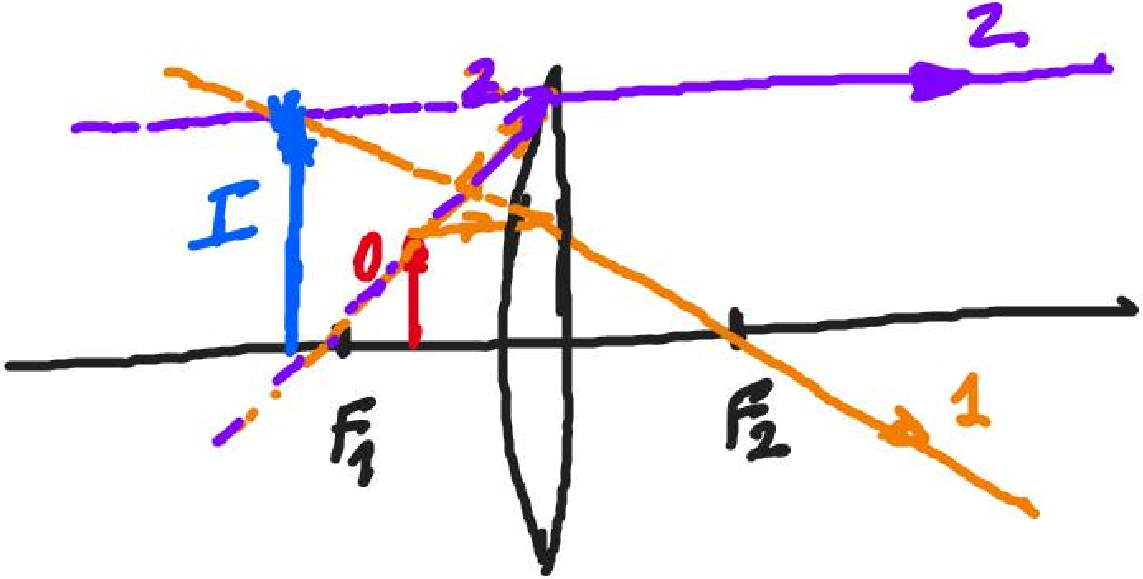
$R_1 < R_2$



$$M = \frac{h'}{h} = -\frac{q}{p}$$

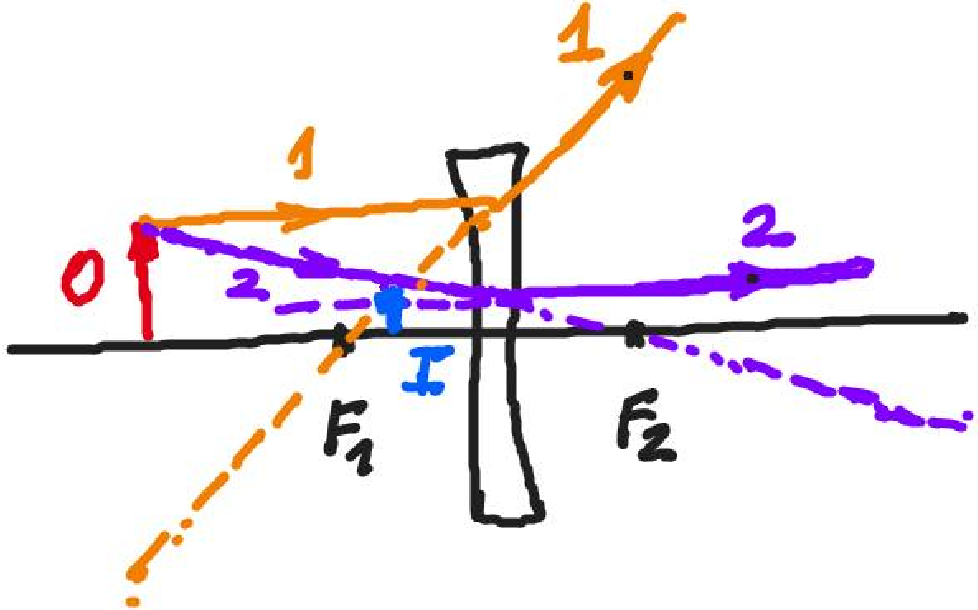


– real image



– virtual image

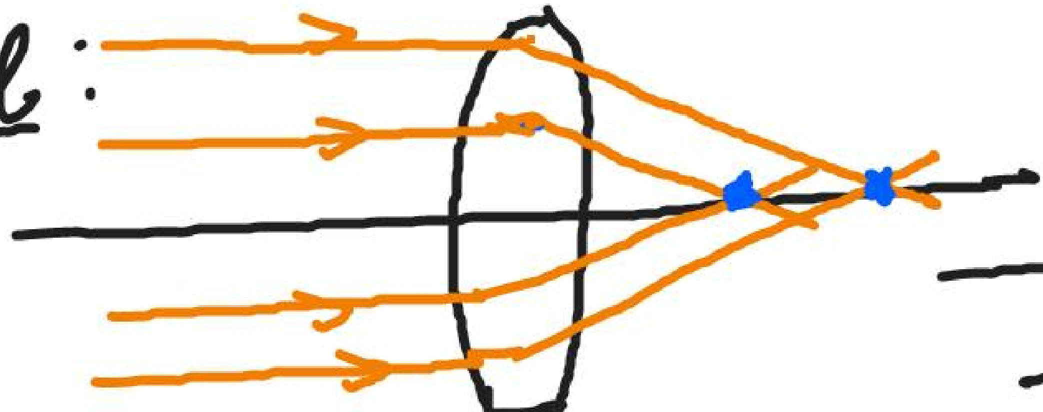
→ Magnifier



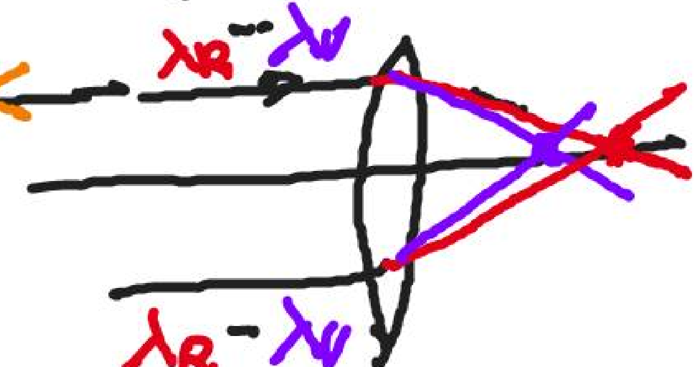
– virtual images

– Aberrations –

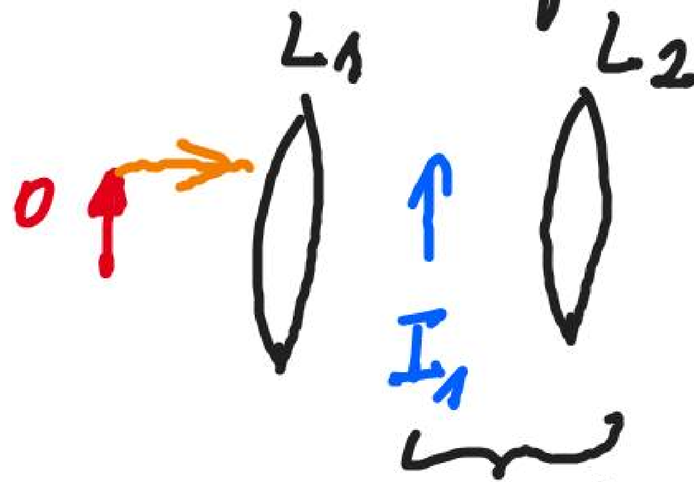
Spherical :



Chromatic



real object



real object for L_2

virtual object for L_2

$\boxed{P}$

$f_1 = +10\,cm$

$f_2 = +20\,cm$

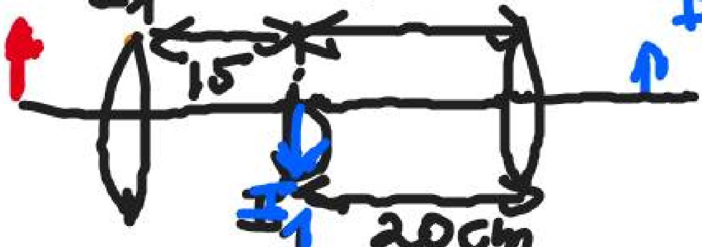
$d_{L_1-L_2} = 20\,cm$

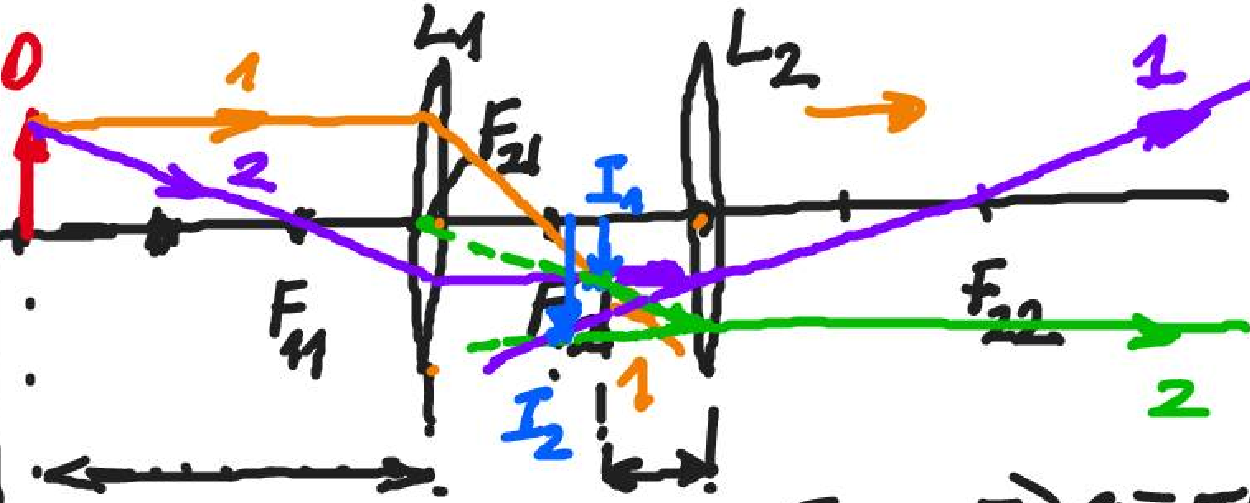
$q_2 = ?$

$M = ?$ $> q_1 + f_2$

$p_1 = 30\,cm$

$> 15\,cm + 20\,cm$





p_1

$p_2 = 5\,cm \Rightarrow q_2 = -6.6\,c$

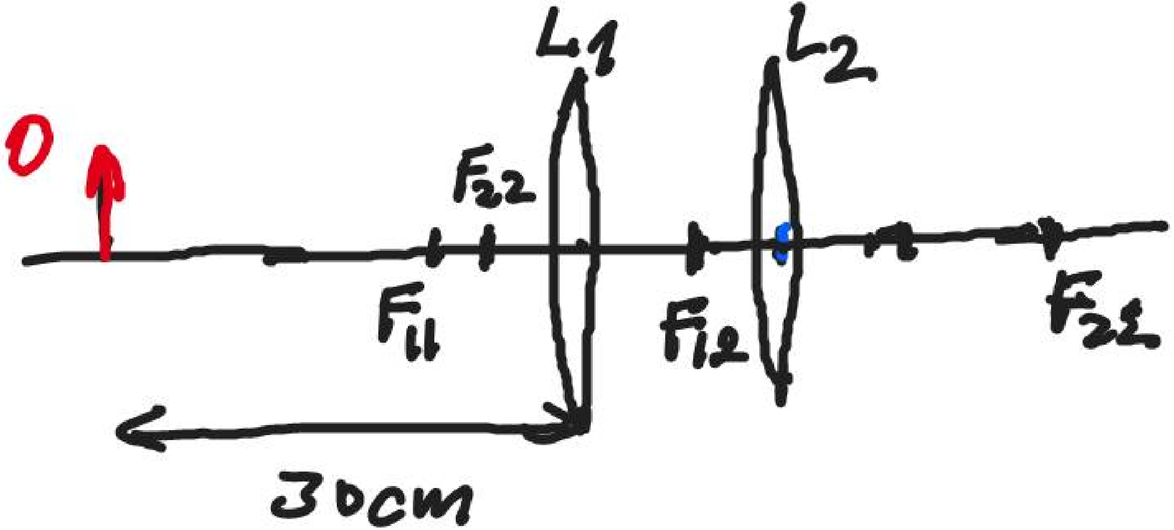
$M_2 = -\frac{q_2}{p_2} = 1.33$

I_1 - real image
- inverted
- object for L_2 - (real one)

$q_1 = ?$ $\quad \frac{1}{p_1} + \frac{1}{q_1} = \frac{1}{f_1} \Rightarrow q_1 = 15\,cm$

$M_1 = -\frac{q_1}{p_1} = -0.5$

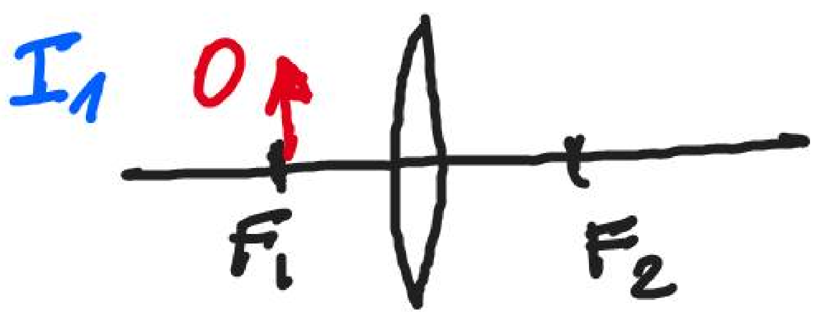
$M = M_1 \times M_2 = -0.66$



$$\rightarrow \frac{1}{p_2} + \frac{1}{q_2} = \frac{1}{f_2}$$

$$p_2 = 0 \Rightarrow$$

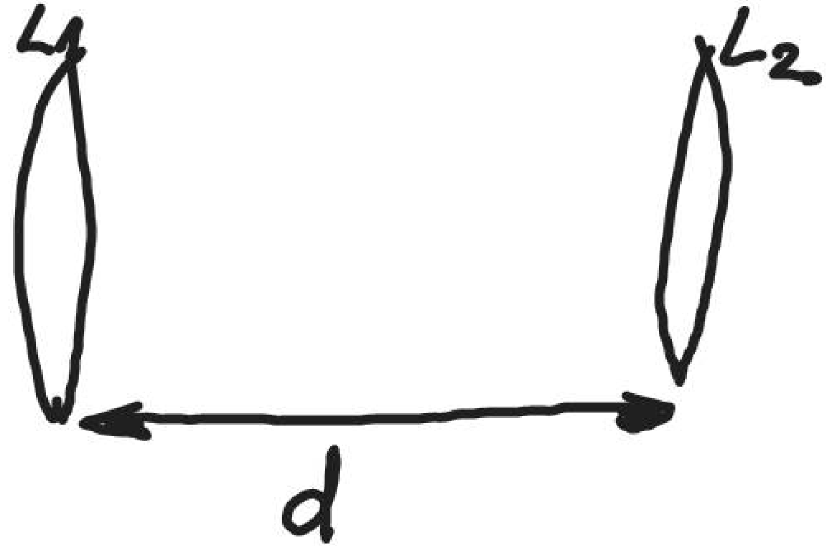
$$\frac{1}{p_2} \rightarrow \infty$$



$$\frac{1}{p_1} + \frac{1}{q} = \frac{1}{f} \Rightarrow \frac{1}{q} = 0 \Rightarrow$$

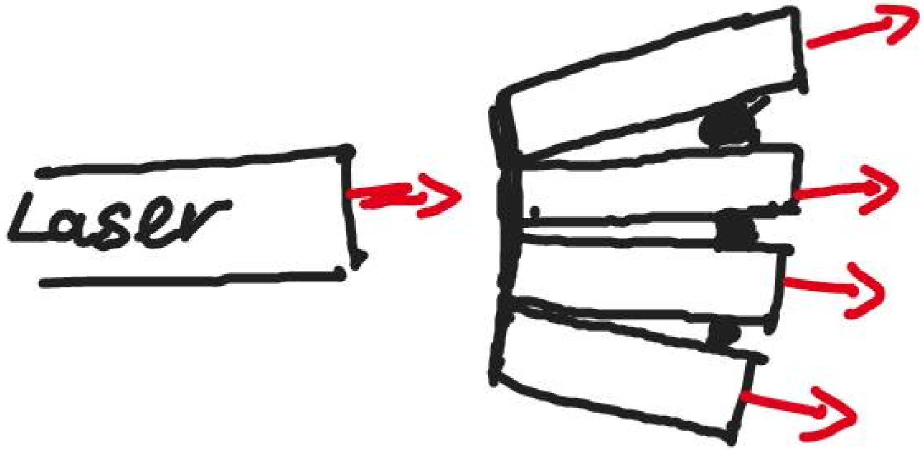
$$p_1 = f$$

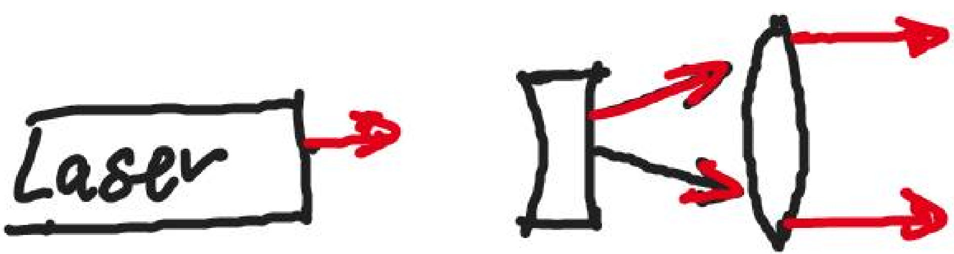
$$q \rightarrow \infty$$



$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \times f_2}$$

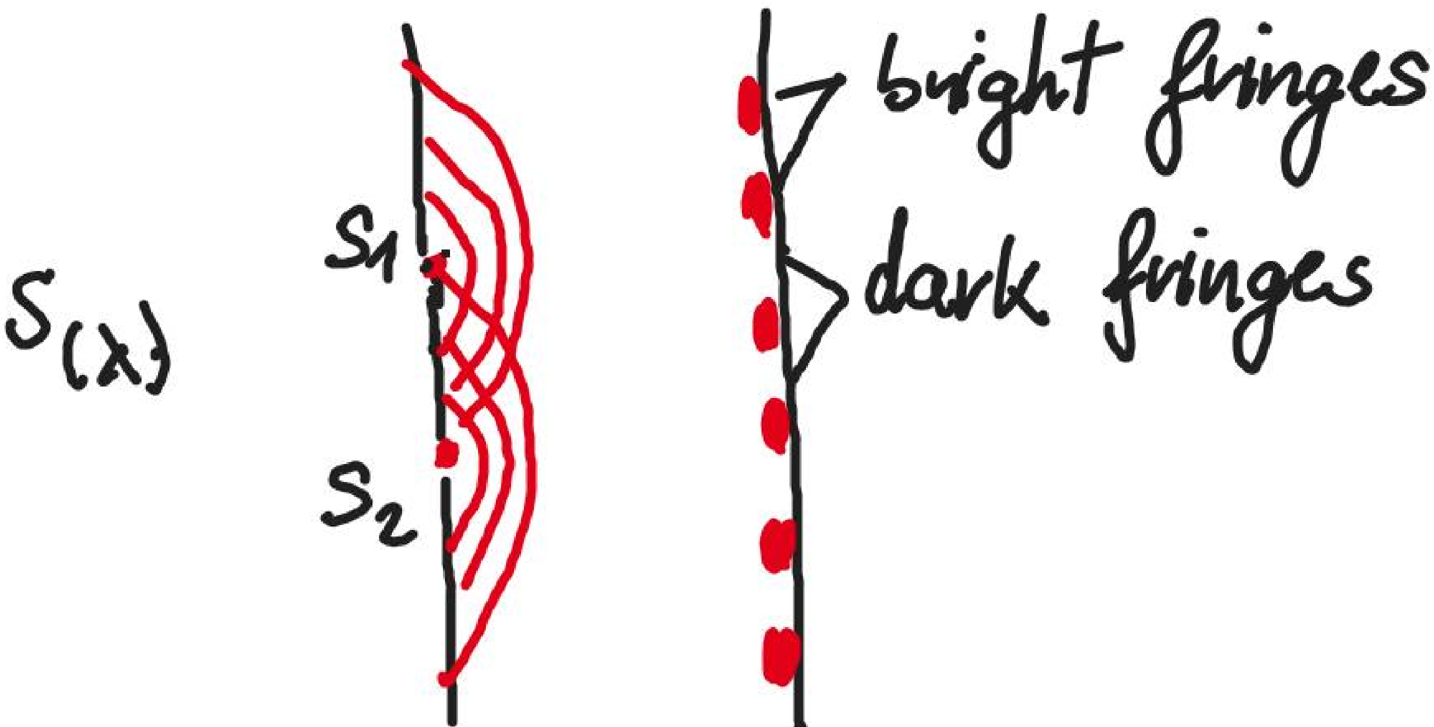
Filters - R (pointer)

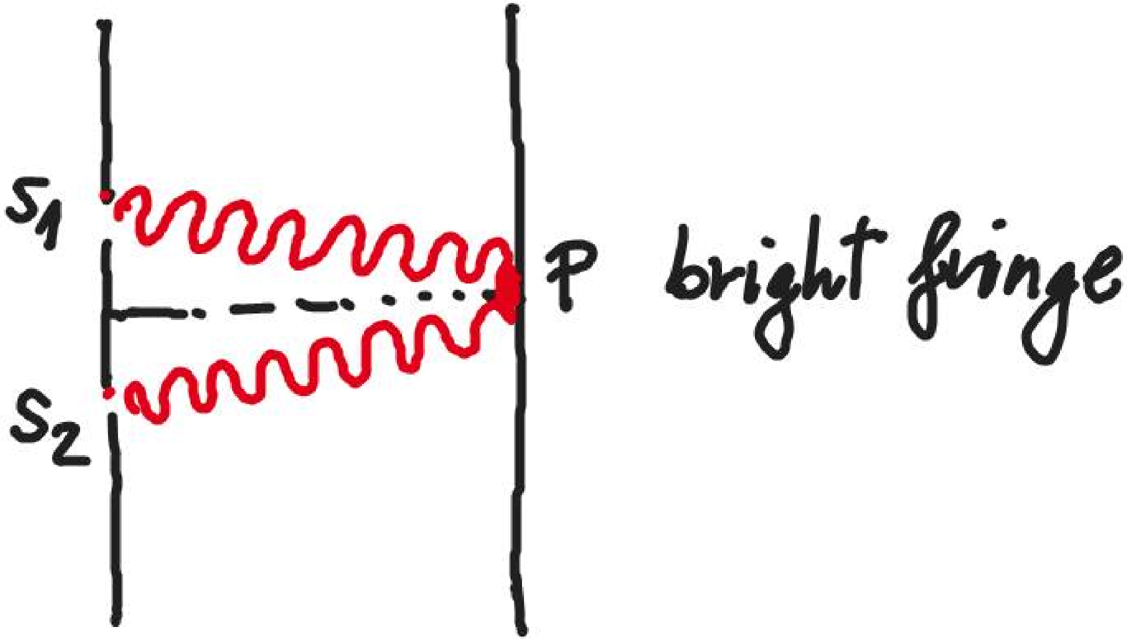


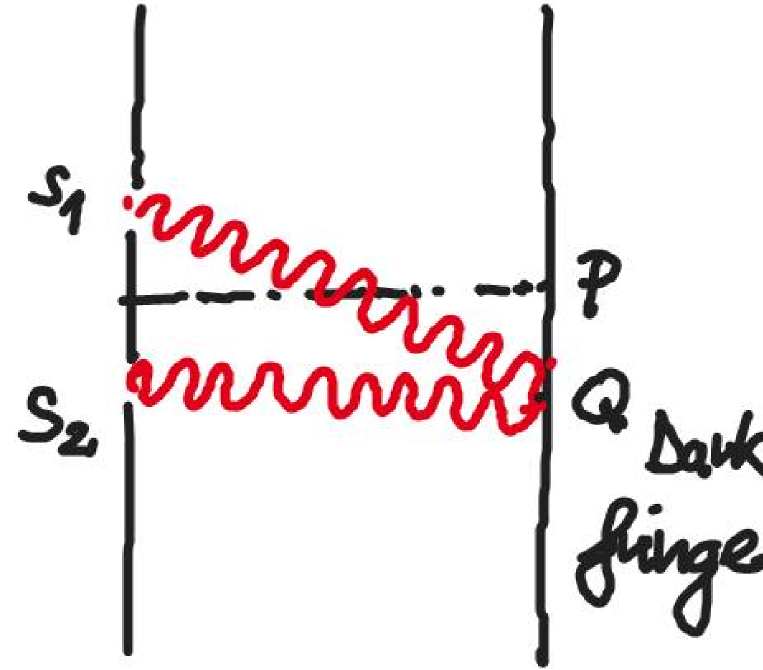


Interferance of Light

S - coherent (phase)
→ monochromatic (λ)

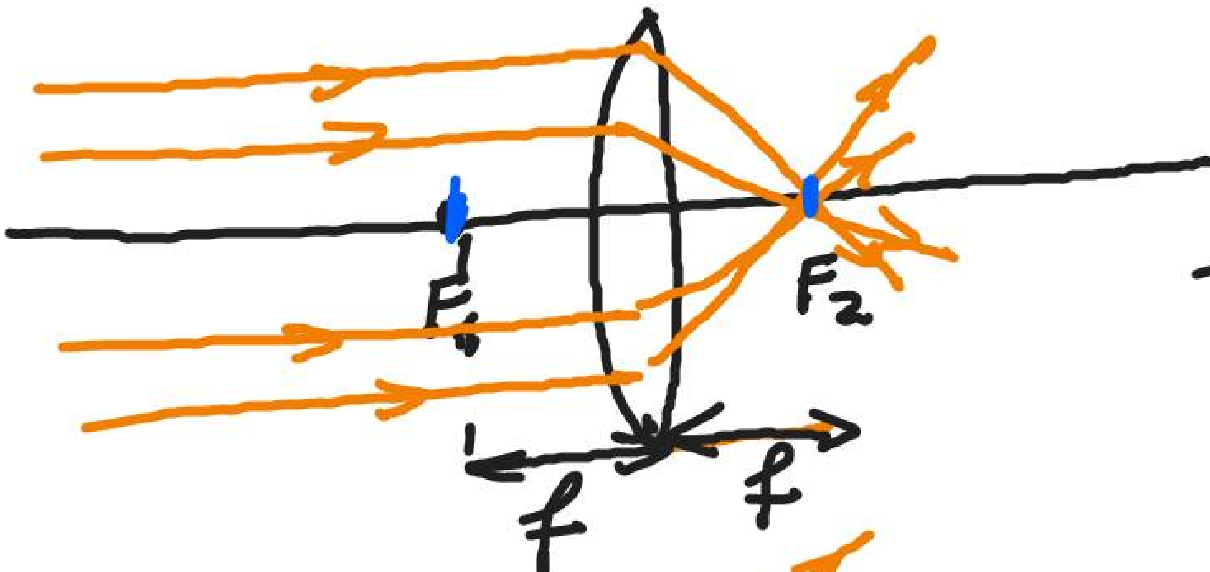



S_1
S_2
P
bright fringe


S_1
S_2
P
Q
Dark fringe

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \qquad p \to \infty \Rightarrow q = f$$

$$\frac{1}{q} = \frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$



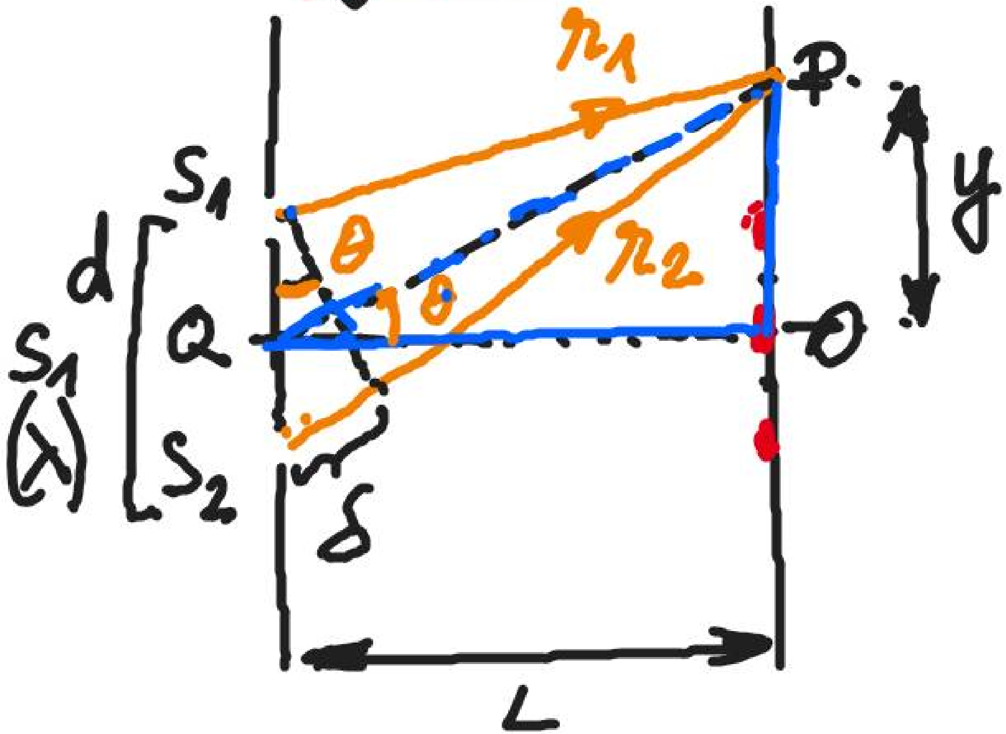
- convergent lenses

- divergent lenses

$f > 0 \Rightarrow$ convergent lens +
$f < 0 \Rightarrow$ divergent lens −

Parameter	" + "	" − "
p - object distance	object in front of the lens (real)	object is in the back of the lens (virtual)
z - image distance	image is the back lens (real)	image in the front of the lens (virtual)
R_1, R_2 - surface radius	center of curvature is in the back of the lens	center of curvature is in the front of the lens

$$\boxed{y = \tan\theta \, L}$$



λ – fraction of μm

d – fraction of mm

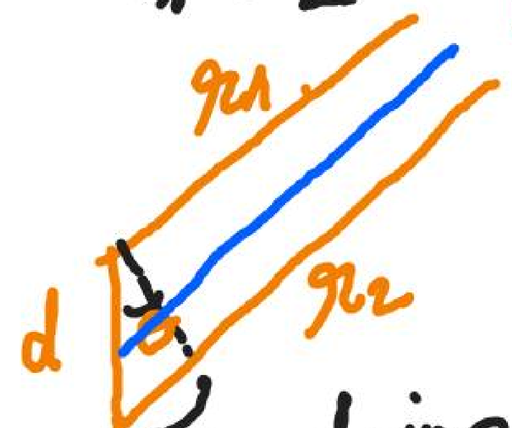
L – a few m

$\theta < 4^\circ$

$r_1 \approx r_2$

$$\boxed{\sin\theta \simeq \tan\theta}$$

$L >> d$



$\delta = d \sin\theta$

$$\delta = d \sin\theta_{bright} = m\lambda$$

$$\delta = d \sin\theta_{dark} = \left(m + \frac{1}{2}\right)\lambda$$

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

$y \approx L \sin\theta$

· $y_{bright} = \frac{\lambda L}{d} m \quad (m = 0, \pm 1, \pm 2 \ldots)$ (1)

· $y_{dark} = \frac{\lambda L}{d}\left(m + \frac{1}{2}\right) \quad (m = 0, \pm 1, \pm 2, \ldots)$ (2)

$\boxed{P}$

$L = 1.2\,m$

$d = 0.03\,mm$

$m = 2$

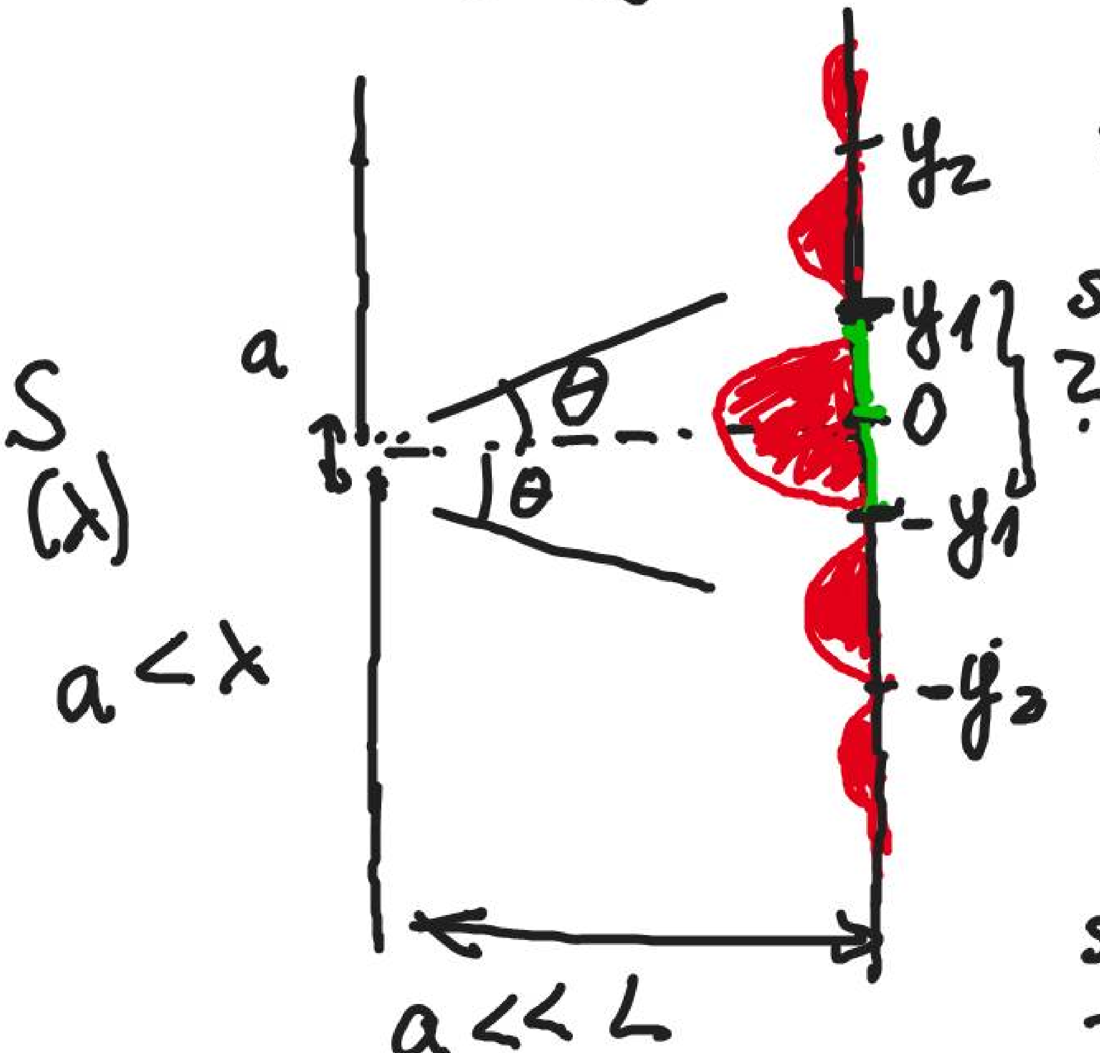
$y_2 = 4.5\,cm$

$\lambda = ?$

$\lambda = 562.5\,nm$

$\rightarrow$ 2.25 cm

Diffraction of Light



$$\sin\theta_{dark} = \frac{2\lambda}{a}$$

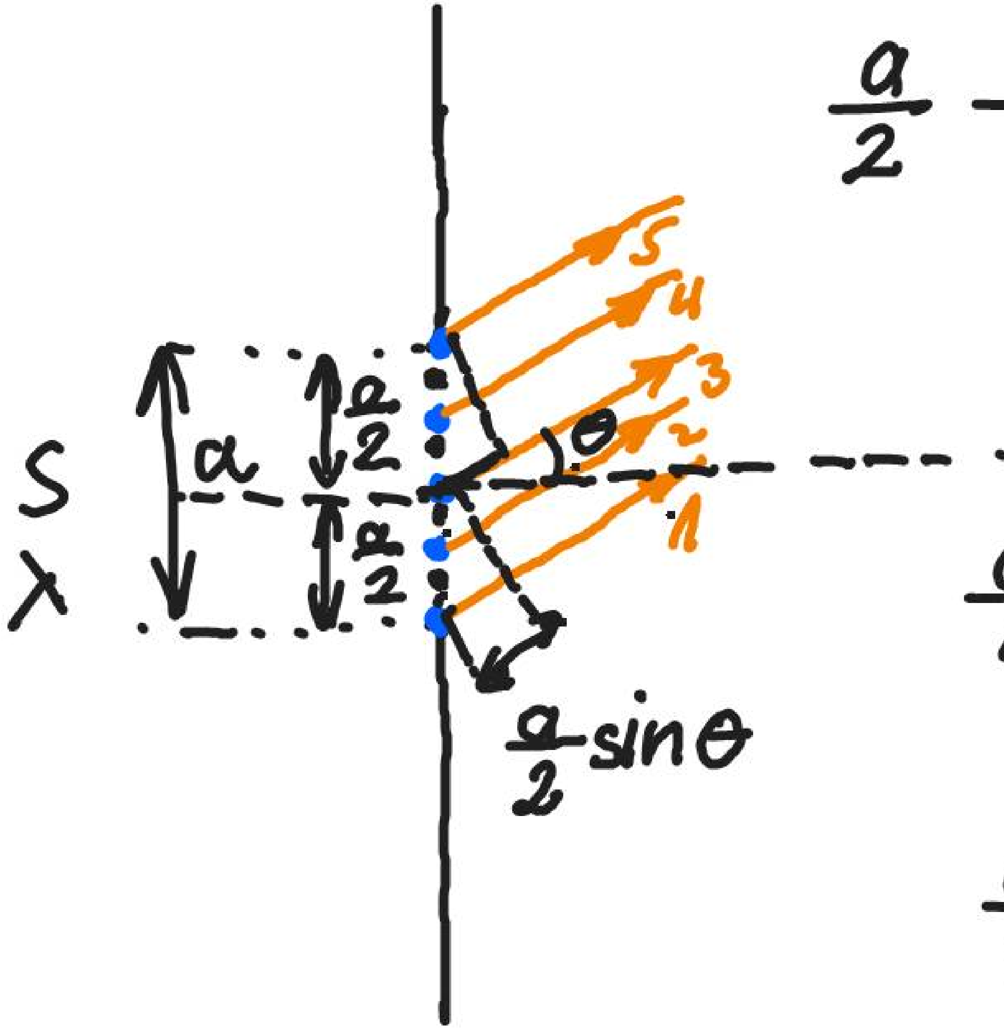
$$\sin\theta_{dark} = \frac{\lambda}{a}$$

$$\sin\theta_{dark} = -\frac{\lambda}{a}$$

$$\sin\theta_{dark} = -\frac{2\lambda}{a}$$

$$\sin\theta \simeq \tan\theta \simeq \theta\ (\text{rad})$$

$$\tan\theta_{dark} = \frac{y_1}{L}$$



$$\frac{a}{2} \rightarrow \frac{a}{2}\sin\theta = \pm\frac{\lambda}{2}$$

$$\sin\theta = \pm\frac{\lambda}{a}$$

$$\frac{a}{4} \rightarrow \frac{a}{4}\sin\theta = \pm\frac{\lambda}{2}$$

$$\sin\theta = \pm\frac{2\lambda}{a}$$

$$\frac{a}{6} \rightarrow \frac{a}{6}\sin\theta = \pm\frac{\lambda}{2}$$

$$\sin\theta = \pm\frac{3\lambda}{a}$$

$$\vdots$$

$$\sin\theta_{dark} = m\frac{\lambda}{a},\ m = \pm 1, \pm 2 \ldots$$

$\boxed{P}$ $\lambda = 580nm$

$0.3\,mm$

$L = 2m$

$y_1 = ?$

$m = \pm 1$

$$\sin\theta_{dark} = \pm \frac{\lambda}{a} = \pm \frac{5.8 \times 10^{-7} m}{0.3 \times 10^{-3} m} =$$

$$= \pm 1.933 \times 10^{-3}$$

$$\sin\theta_{dark} = \tan\theta_{dark} \approx \frac{y_1}{L} \Rightarrow$$

$$\Rightarrow y_1 \approx L \cdot \sin\theta_{dark} = 3.87 \times 10^{-3} m$$

width of the central bright fringe:

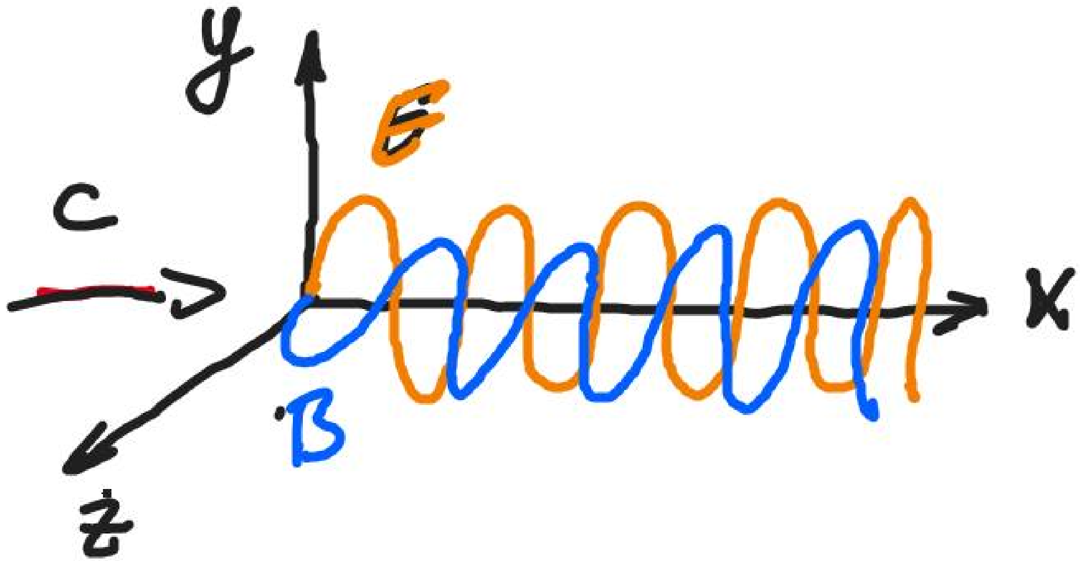
$$= 2 \times y_1 = 7.74\,mm$$

if $a = 3mm$: $\sin\theta_{dark} = \pm\frac{\lambda}{a} = \pm 1.933 \times 10^{-4}$

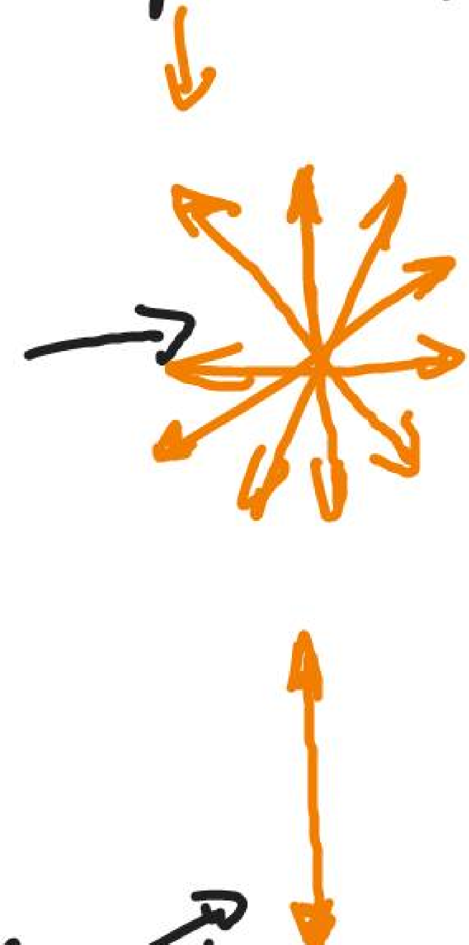
$y_1 \approx L\sin\theta_{dark} = \pm 3.87 \times 10^{-4} m$

$2y_1 = 0.774 mm$

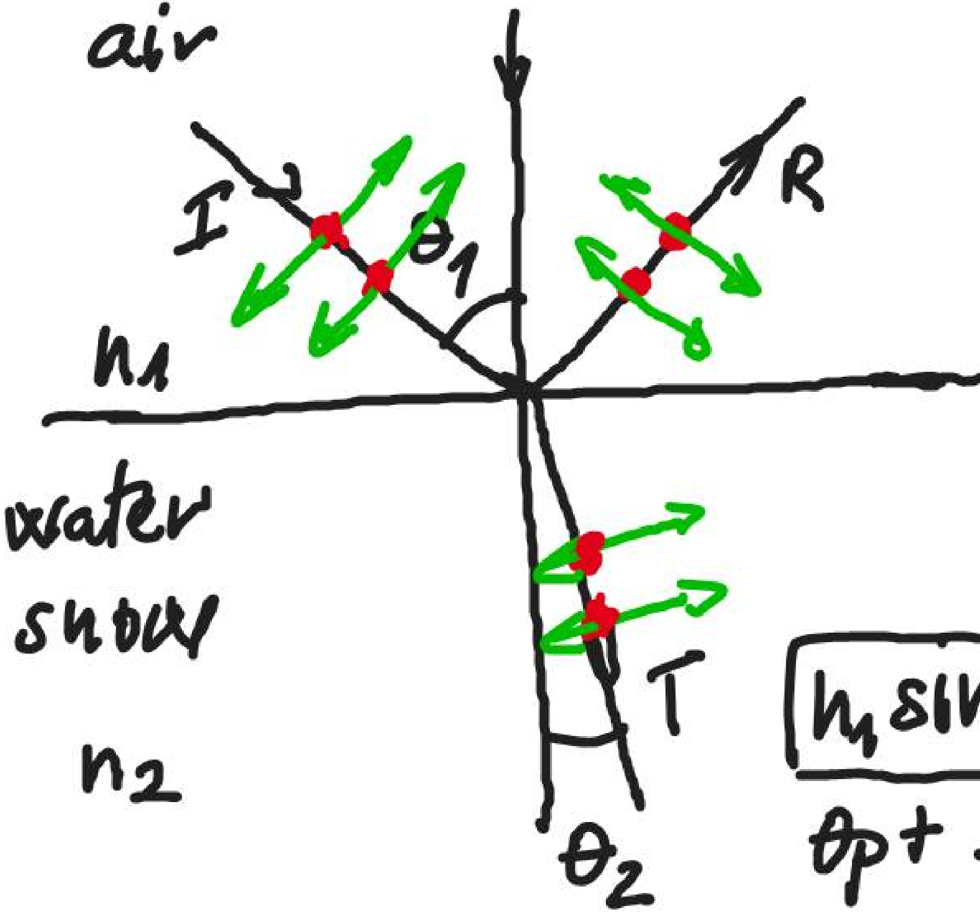
Polarization of Light



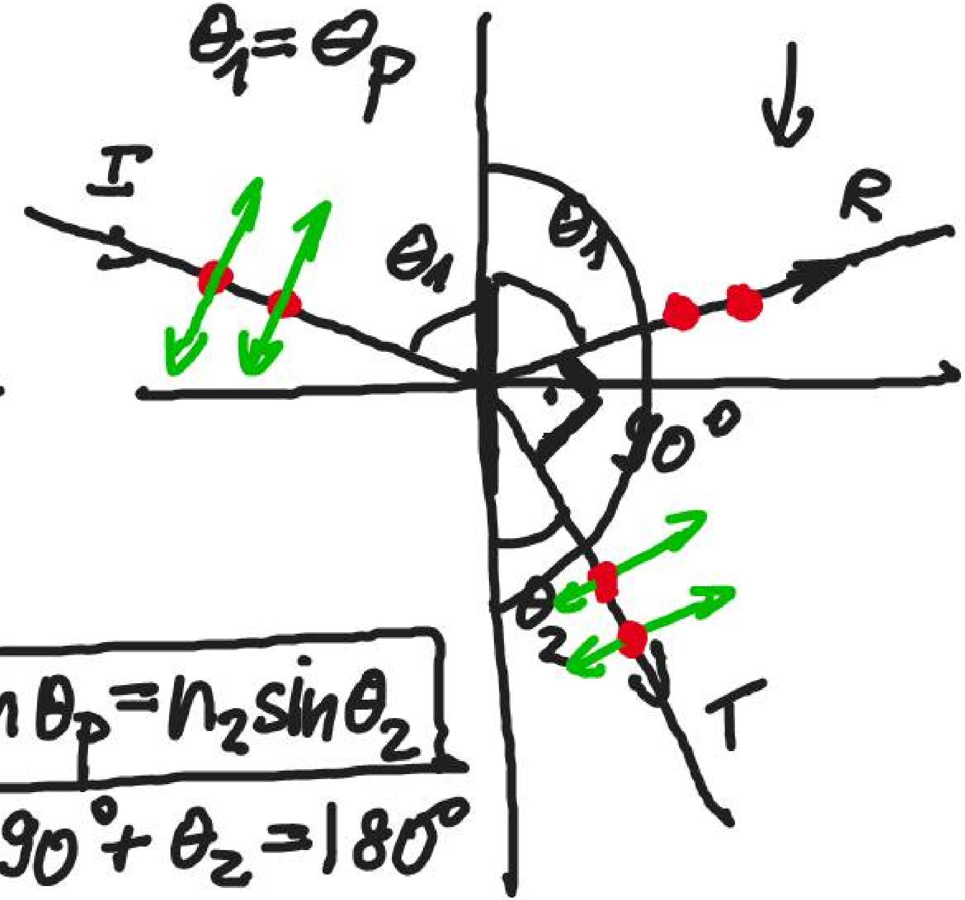
unpolarised



polarized



$\theta_1 = \theta_p$



$$\boxed{n_1 \sin\theta_p = n_2 \sin\theta_2}$$

$$\theta_p + 90^\circ + \theta_2 = 180^\circ$$

$$\theta_2 = 90^\circ - \theta_p$$

$$n_1 \sin\theta_p = n_2 \cos\theta_p$$

Polarized light by reflection

$$\left.\begin{aligned} & n_1 \sin\theta_p = n_2 \cos\theta_p \\ & n_1 - \text{air} \end{aligned}\right\} \Rightarrow n_2 = \frac{\sin\theta_p}{\cos\theta_p} = \tan\theta_p$$

Brewster's Law

$$n_2 - \text{water} = 1.33 \Rightarrow \underline{\theta_p = 53^\circ}$$

Optical Fibers

1880

1930 – TV signal – optical fiber without cladding

1951 – 1000 dB/Km

1960 → LASER → 1970 2 dB/Km

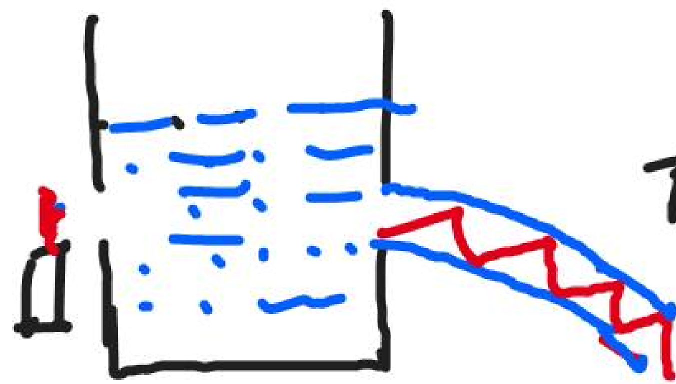
3 dB → $\frac{P_{in}}{2}$

Today 0.1 dB/Km

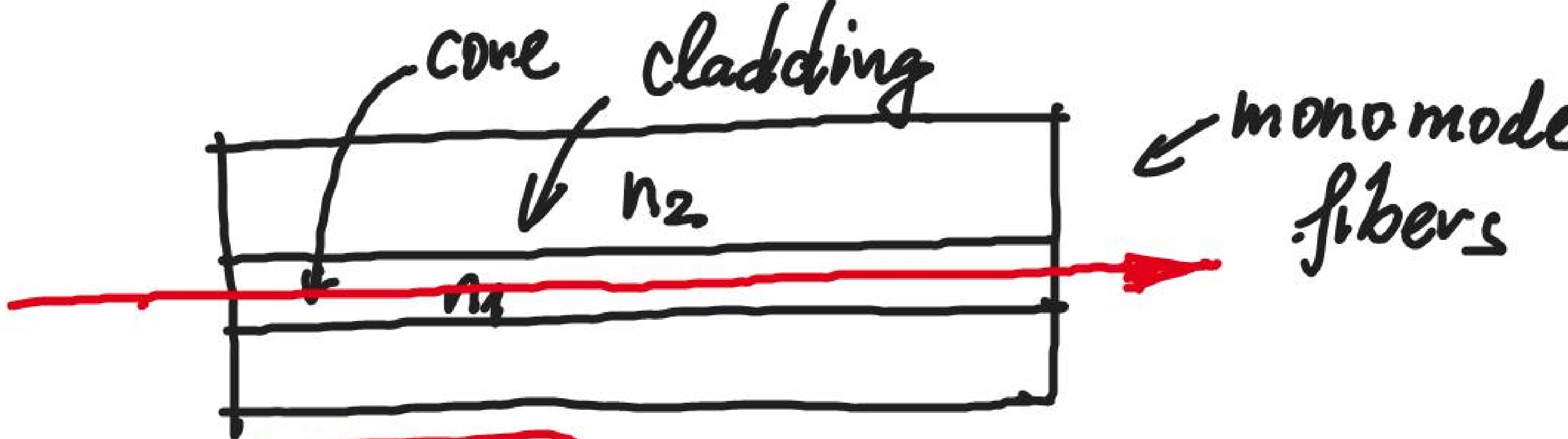
· **Advantages:**

1. High bandwith
2. Imune to EM interference.
3. Lighter than the copper.
4. Security

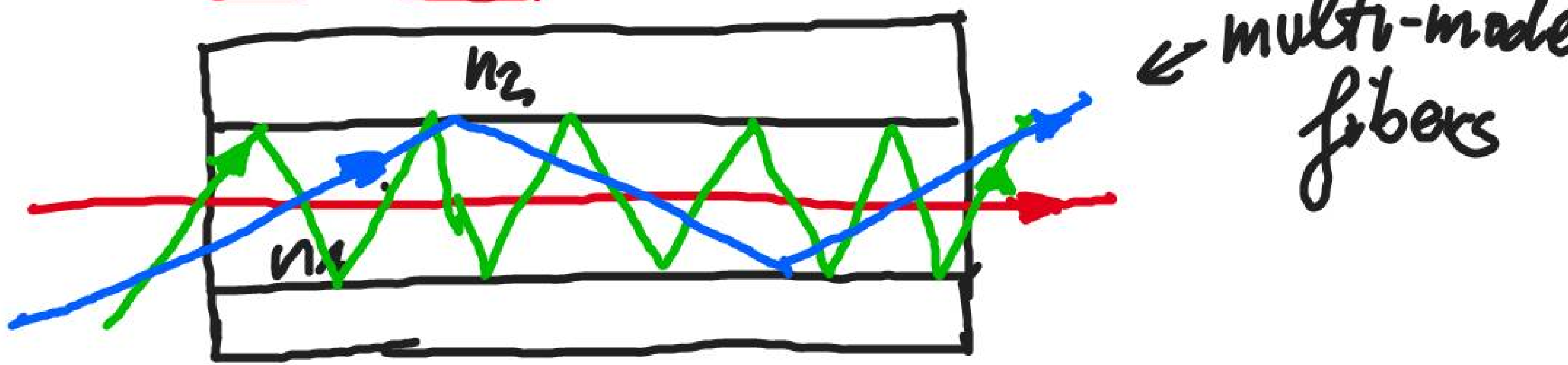
Propagation of light



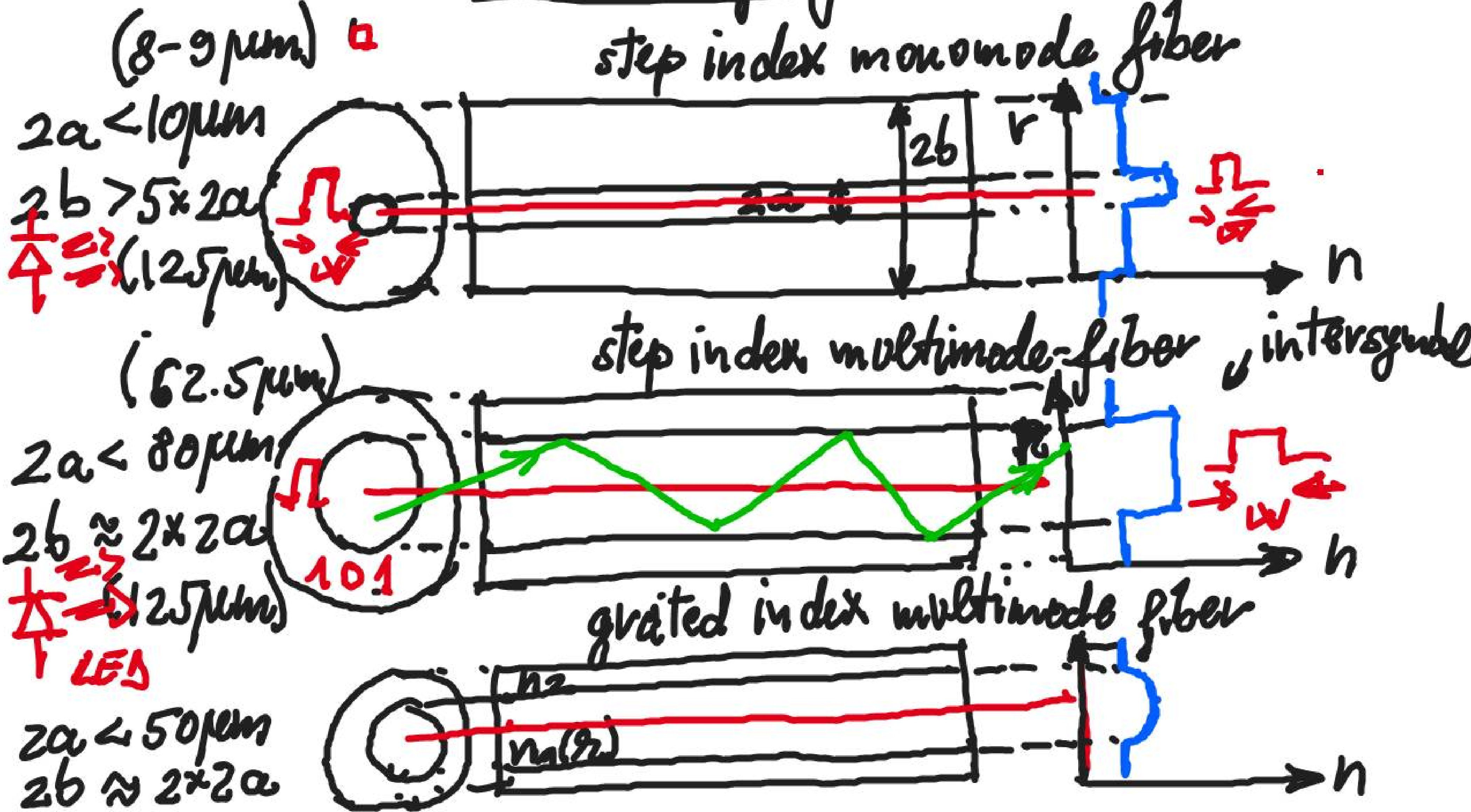
T.I.R.

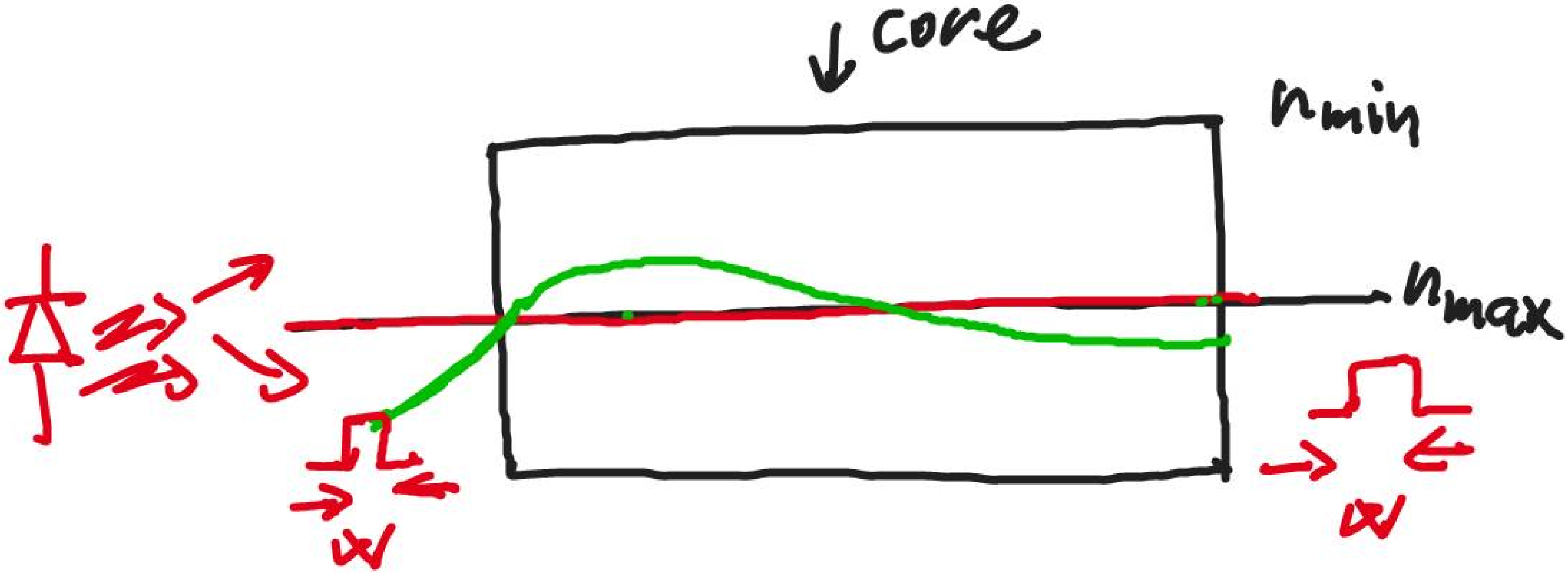


$$\boxed{n_1 > n_2}$$



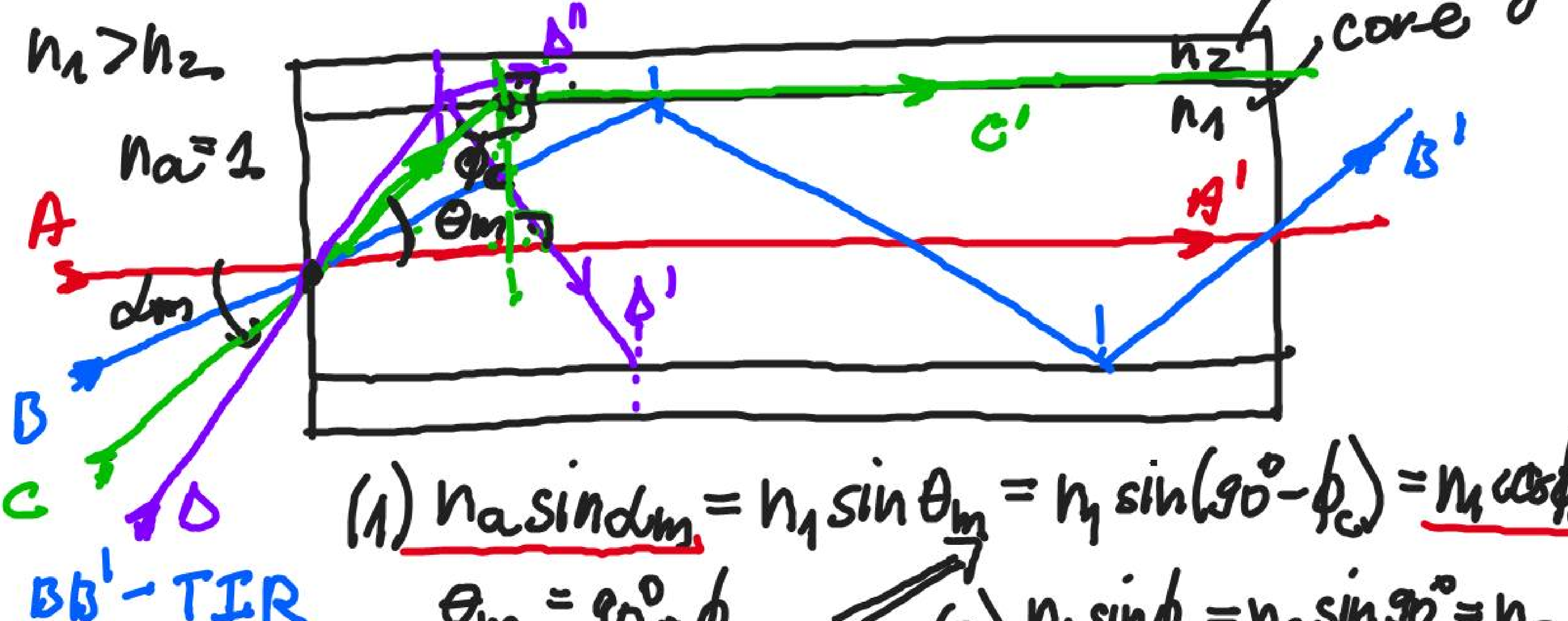
Index profile




core
n min
n max

Angle of acceptance

α_m - critical case



(1) $n_a \sin\alpha_m = n_1 \sin\theta_m = n_1 \sin(90^\circ - \phi_c) = n_1 \cos\phi_c$

$\theta_m = 90^\circ - \phi_c$

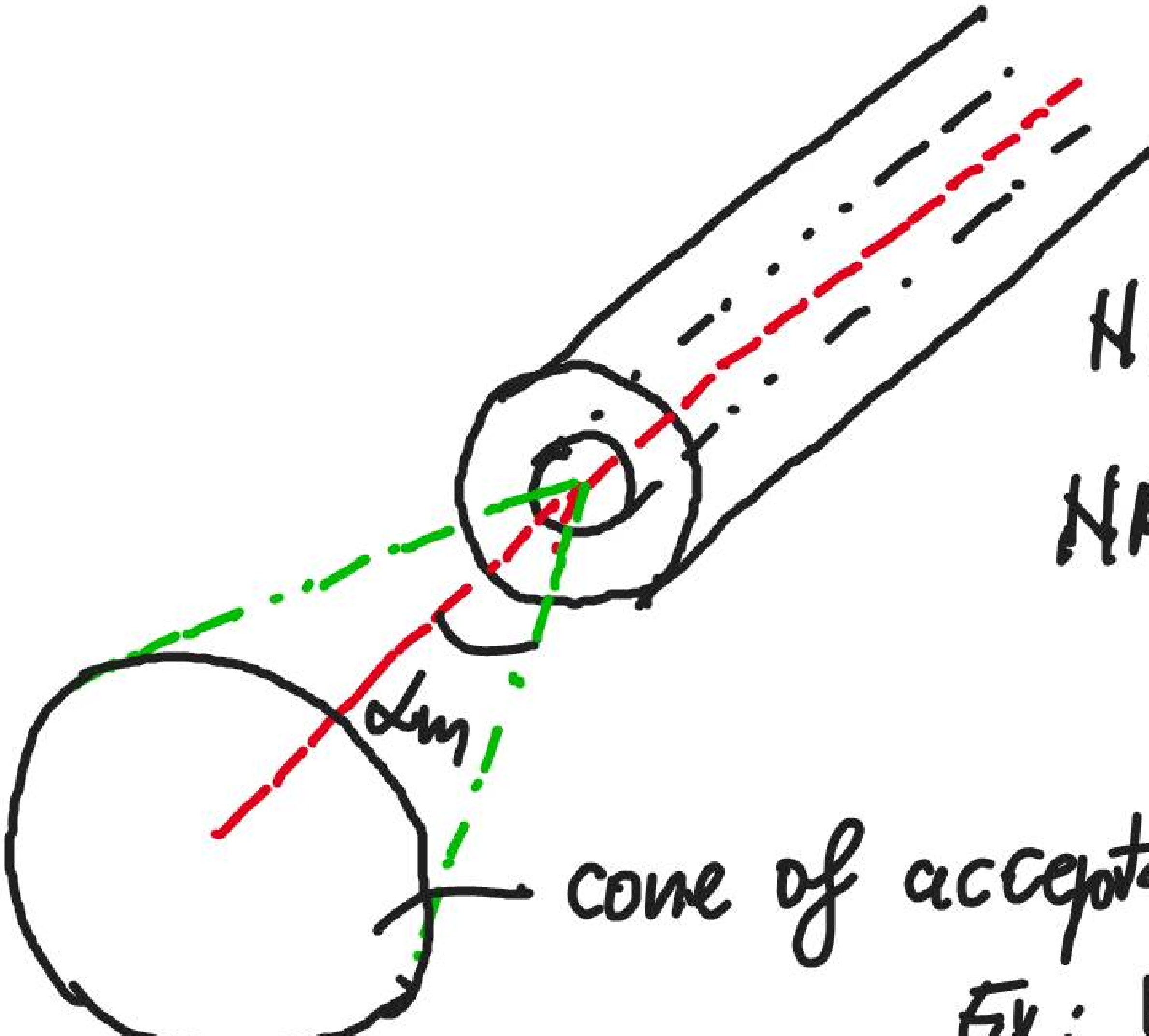
(2) $n_1 \sin\phi_c = n_2 \sin 90^\circ = n_2$

$$\left.\begin{aligned} &\sin\phi_c = \frac{n_2}{n_1} \qquad \Rightarrow \cos\phi_c = \sqrt{1-\sin^2\phi_c} \\ &n_a \sin\alpha_m = n_1 \cos\phi_c \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow n_a \sin\alpha_m = n_1 \sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \sqrt{n_1^2 - n_2^2}$$

$$\sin\alpha_m = \frac{\sqrt{n_1^2-n_2^2}}{n_a}$$

$$\alpha_m = \arcsin\left(\frac{\sqrt{n_1^2-n_2^2}}{n_a}\right)$$



cone of acceptance

Numerical Aperture

$$NA = n_a \cdot \sin\alpha_m = \sqrt{n_1^2 - n_2^2}$$

$$n_a = 1$$

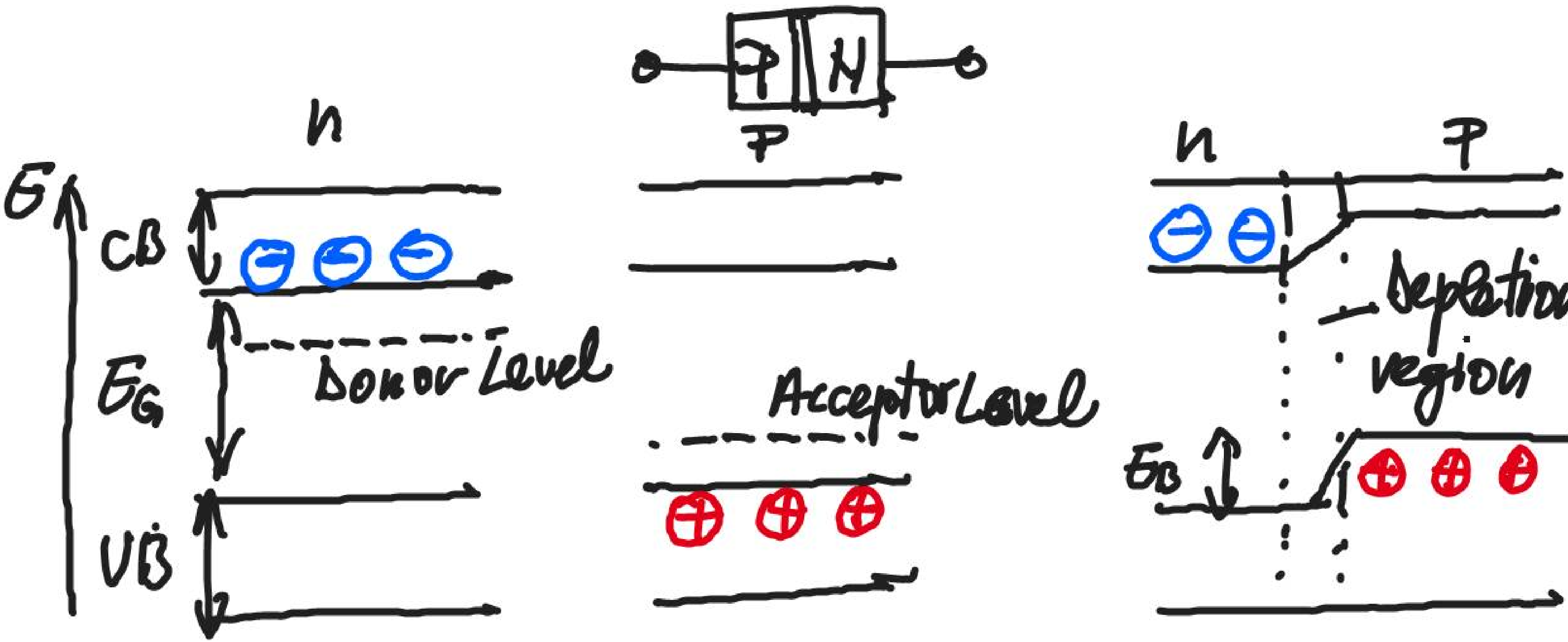
<u>Ex</u>: $\left.\begin{array}{l} n_{core} = 1.5 \\ n_{cladding} = 1.46 \end{array}\right\} \begin{array}{l} \alpha_m ? \\ NA ? \end{array}$

Light Sources

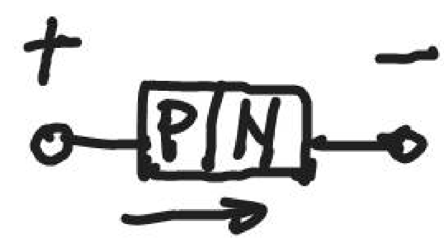
LED LASER

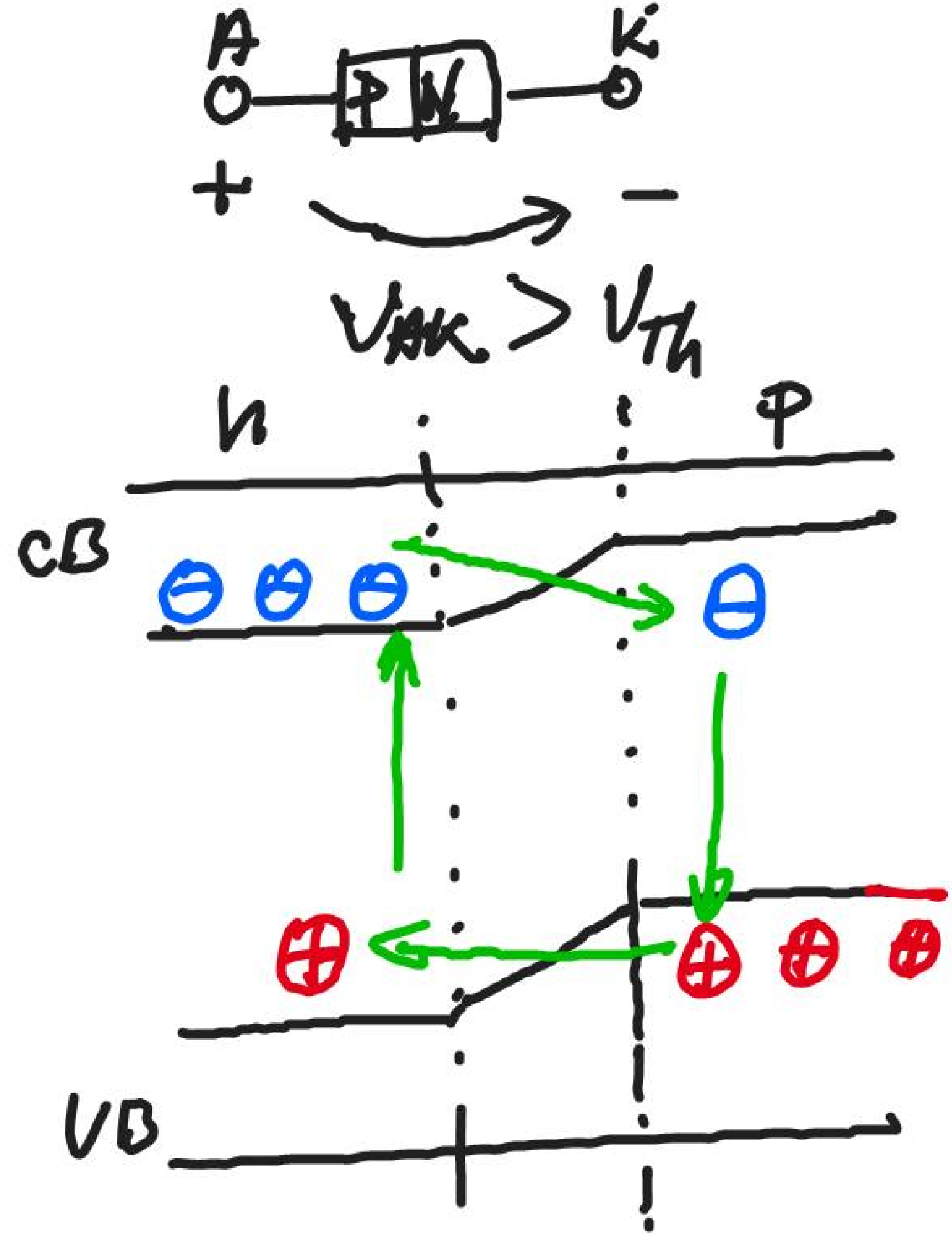
Lossew (1923)

Injection Electroluminiscence

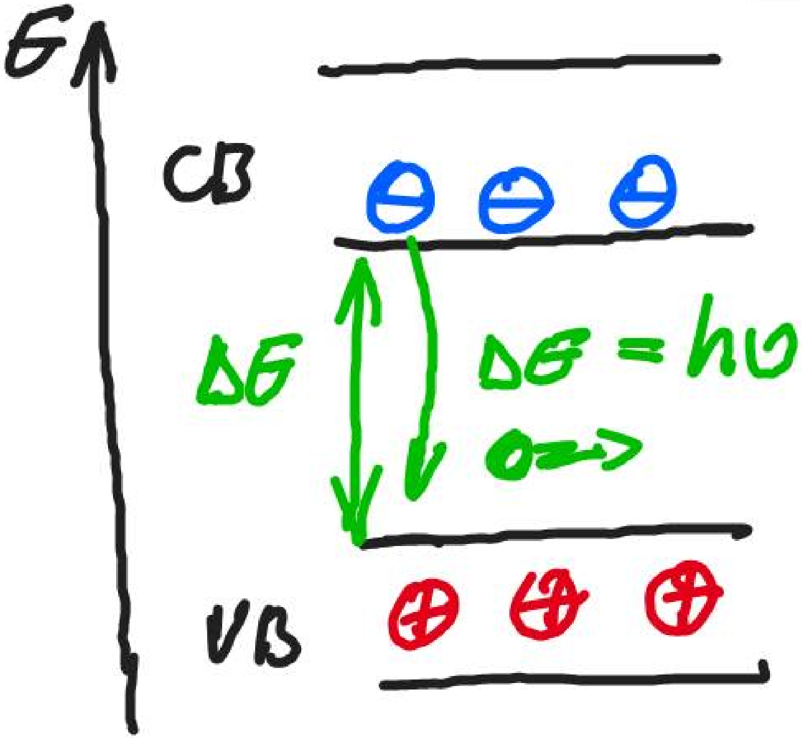


Si, Ge




A
K
P
N
+
−
$V_{AK} > V_{Th}$
n
p
CB
VB

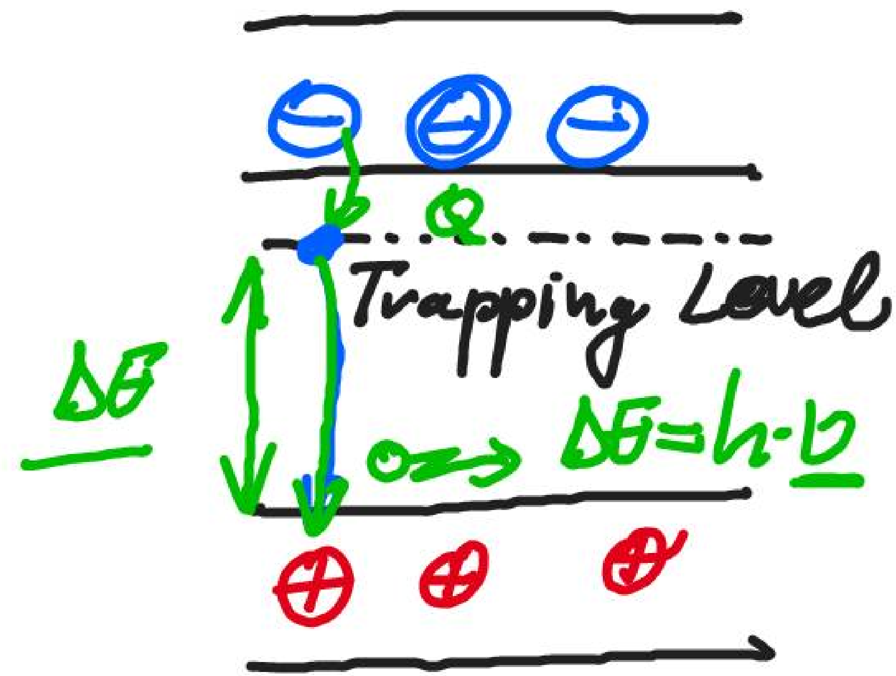
Direct Emission



GaAs

GaAsP

Indirect Emission



GaP

non-radiative emission
+
radiative emission

$$\lambda_{[nm]} = \frac{1240}{\Delta E\,[eV]} \quad , \quad \lambda_{[\mu m]} = \frac{1.24}{\Delta E\,[eV]}$$

$$\Delta E = h\nu = h \times \frac{c}{\lambda} \Rightarrow \lambda = \frac{hc}{\Delta E}$$

Si: $V_{Th} \simeq 0.6 \div 0.7\,V$, $\Delta E = 1.09\ eV \Rightarrow \lambda = 1140\,nm$

Ge: $V_{Th} \simeq 0.2 \div 0.3\,V$, $\Delta E = 0.66\ eV \Rightarrow \lambda = 1880\,nm$

GaAs: $\Delta E = 1.4\,eV \Rightarrow \lambda = 900\,nm$

GaAsP : $\Delta E \approx 1.9\,eV$

GaP : $\Delta E \approx 2.2\,eV$

$n_1 - n_3 \Rightarrow T = 0.69 = 69\%$

$$\eta_i = \frac{\text{radiative recombinations}}{\text{total recombination}} = \frac{r_r}{r_r + r_{nr}}$$

epoxy

$3.5 = n_1$(semiconductor) Φ_{int}

$1.6 = n_2$(epoxy)

$1. \quad n_3$(air)

$T_{12} = 0.86 = 86\%$

$T_{23} = 0.95 = 95\%$

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

$T = 1 - R$

$\Phi_{out} = 0.82 \times \Phi_{int}$

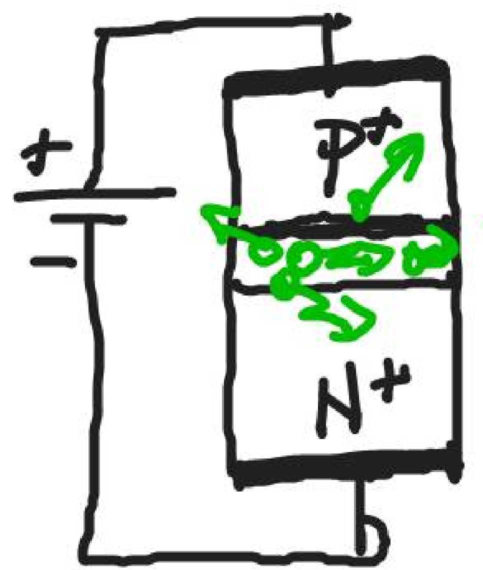
LED Structures

SLED surface emitting

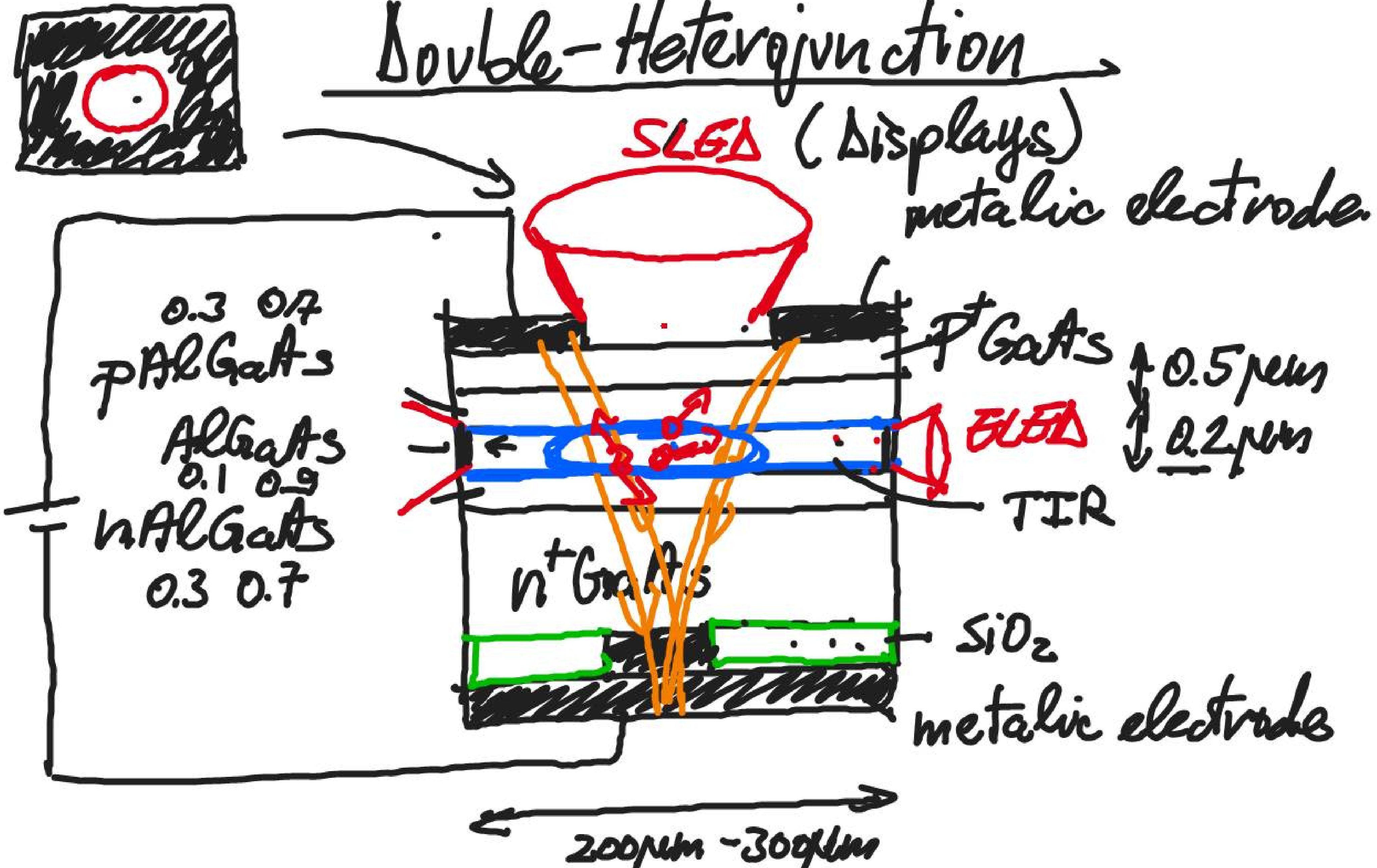
ELED edge emitting

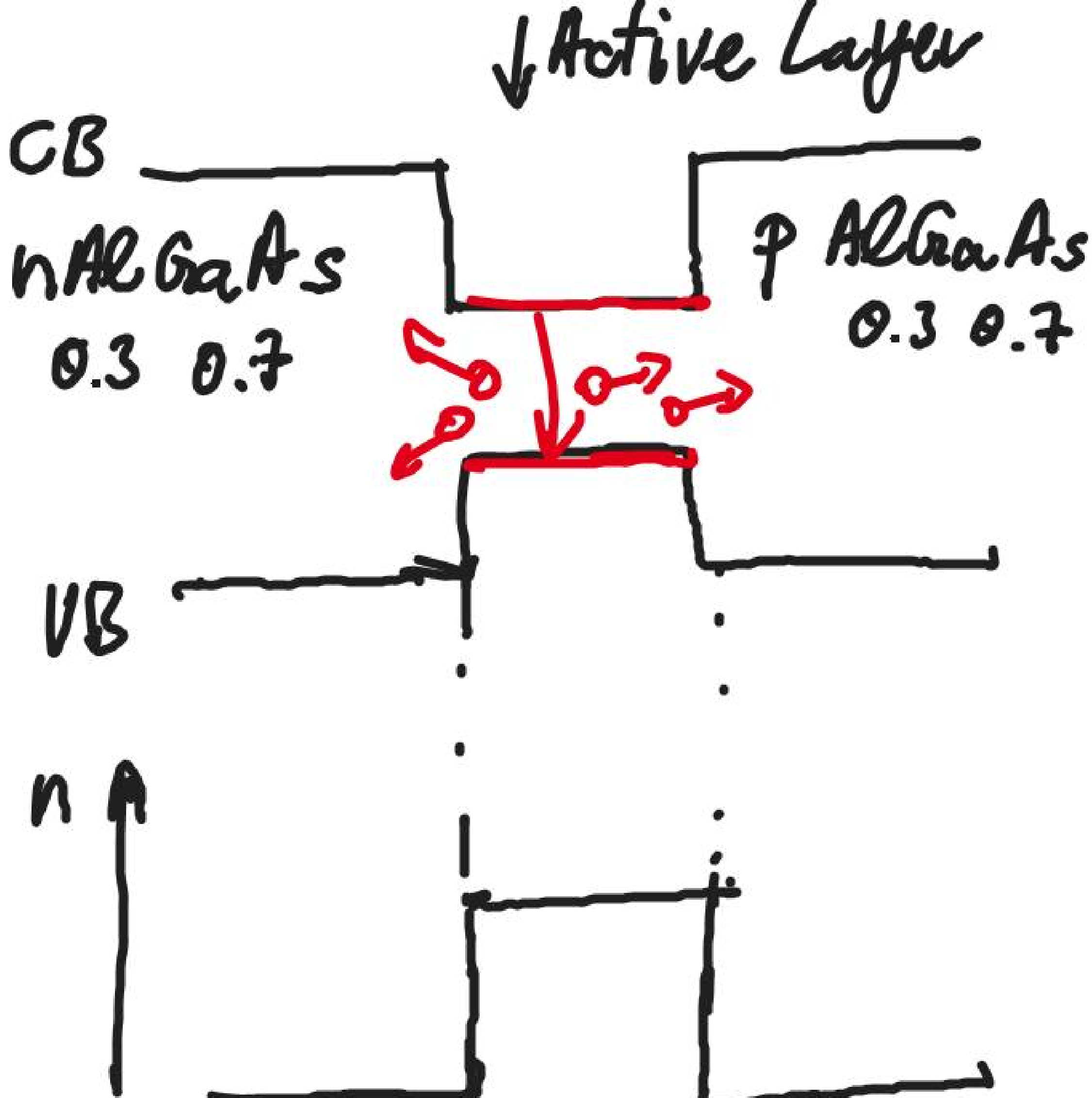
SLD superluminescent

Homojunction:



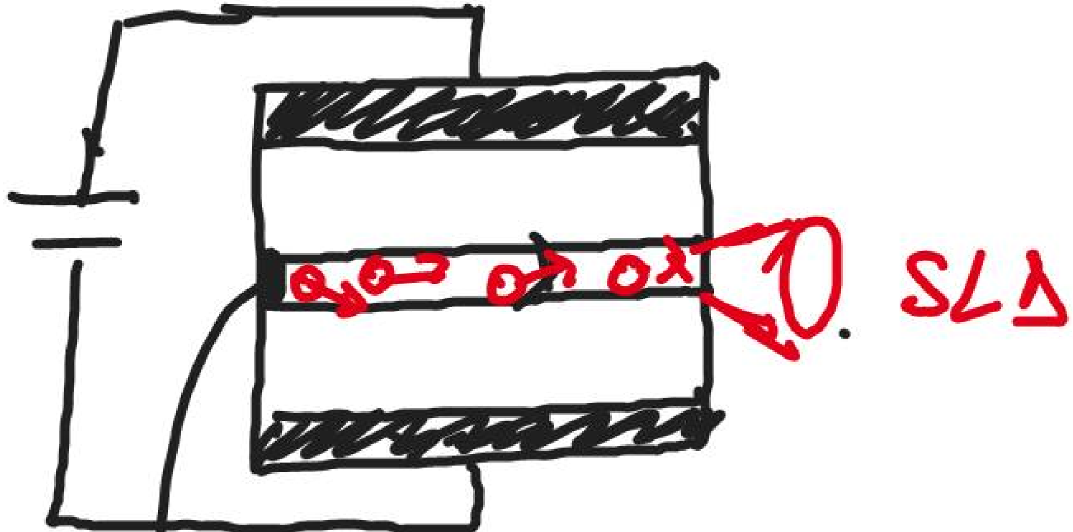
Double-Heterojunction



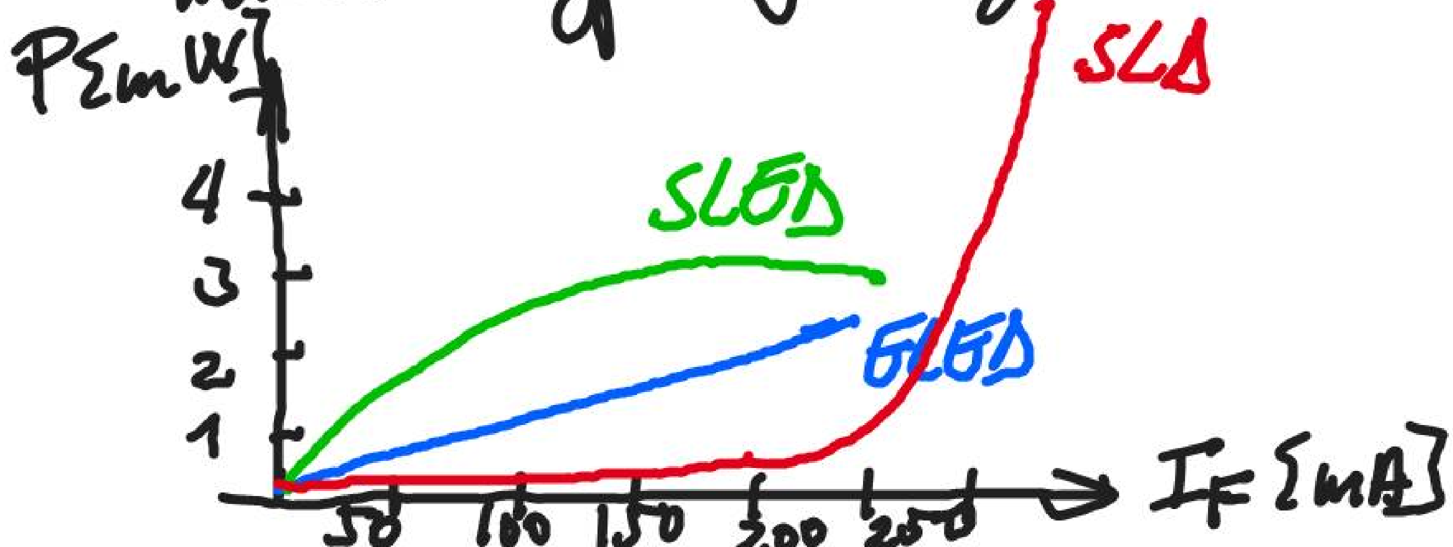


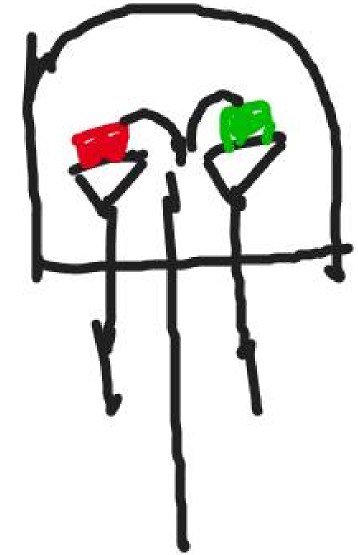
reduce the Absorbtion losses

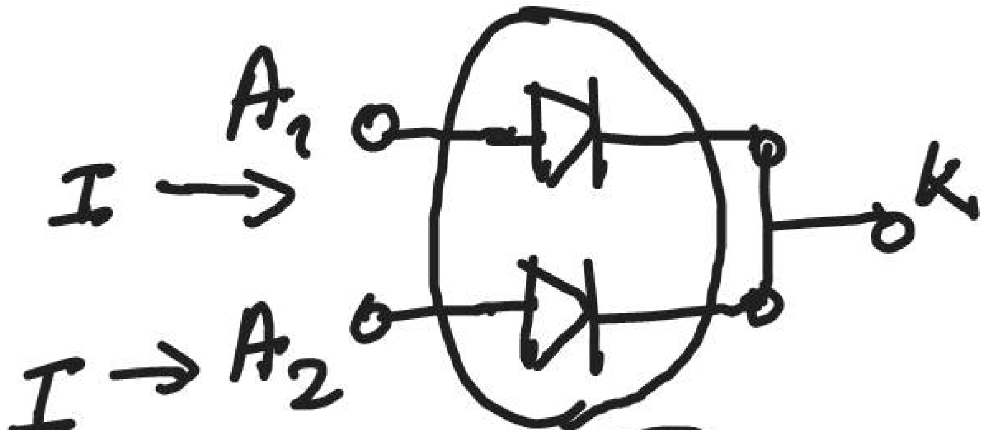
ELED, SLD

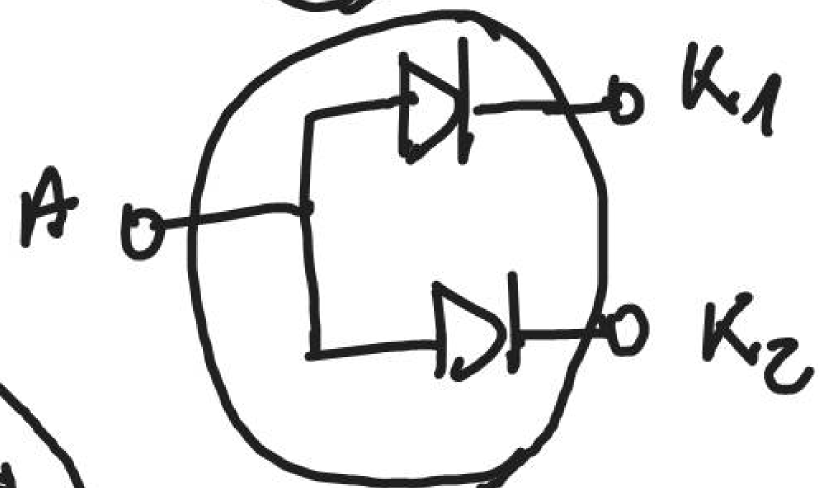


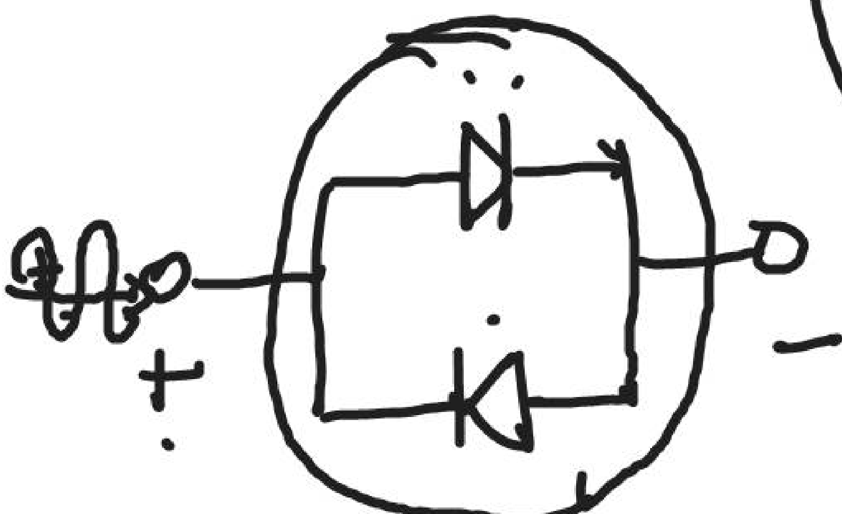
mirror type of surface.



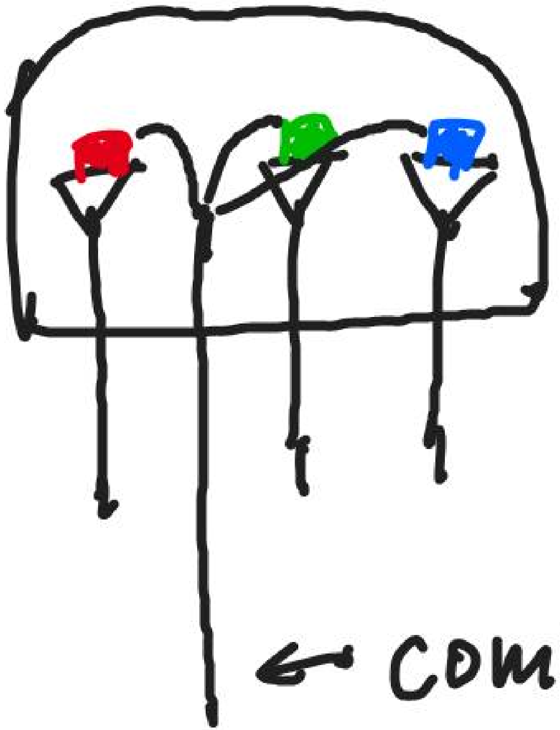




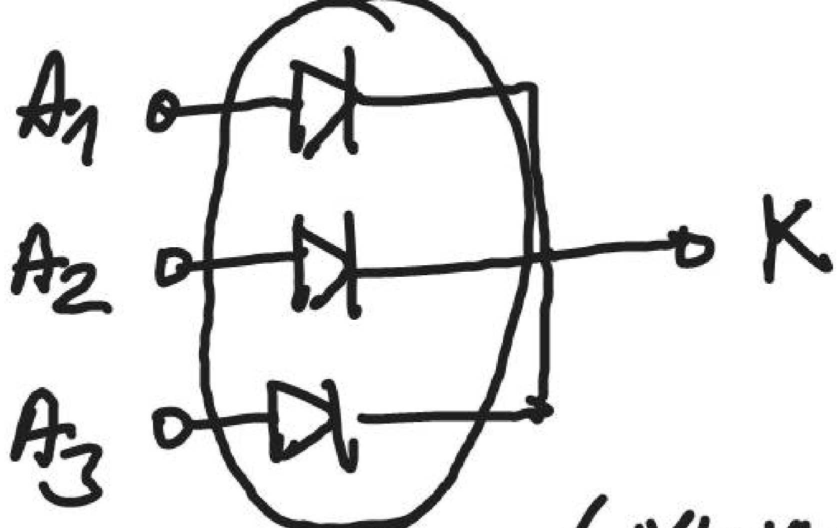




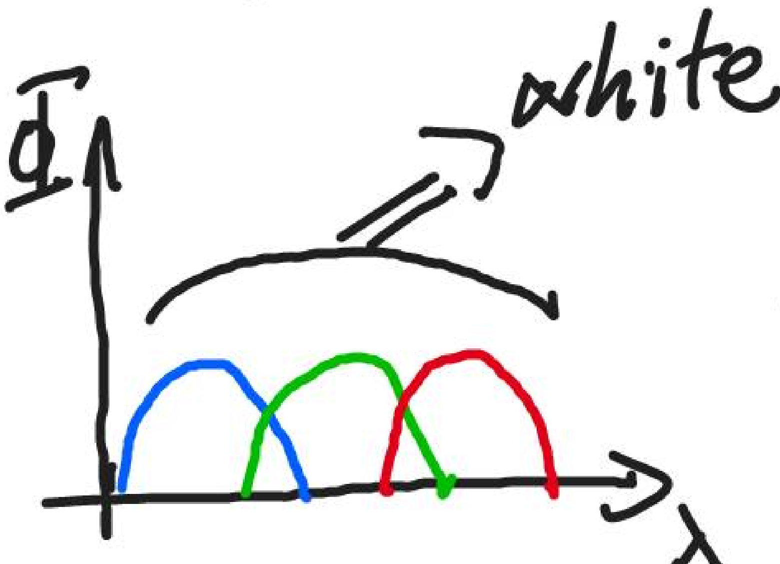
$f > 60\,\text{Hz}$

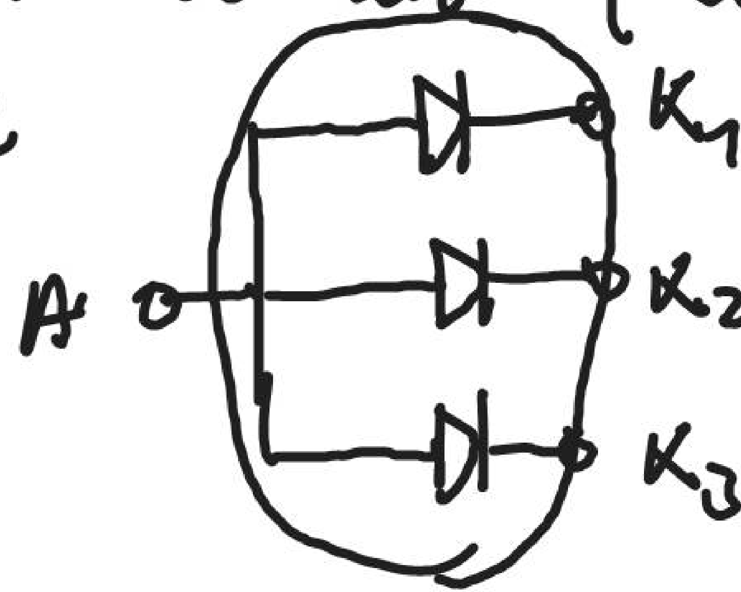


← common electrode



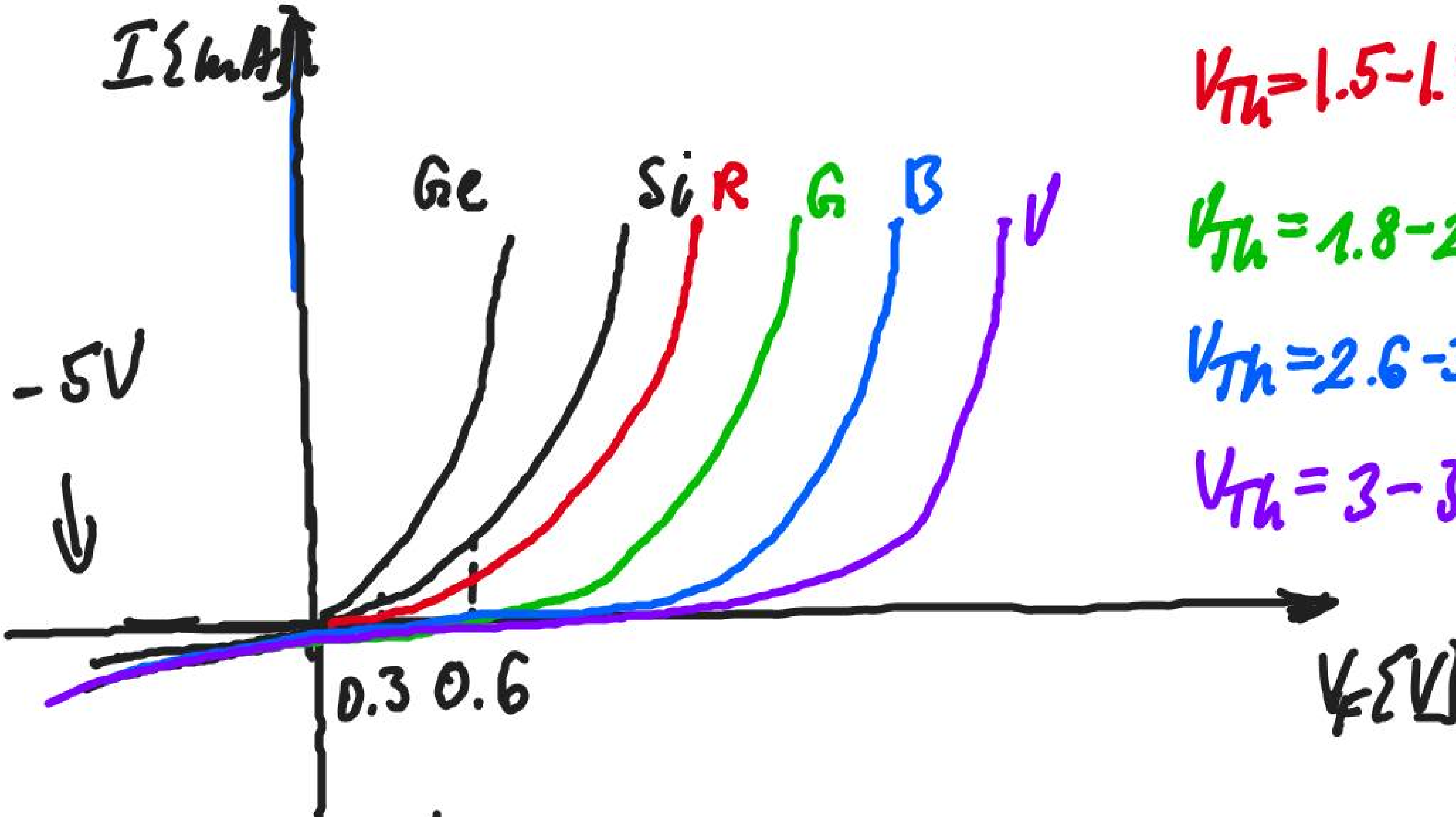
warm white
cold white





White Light

- RGB
- Phosphors
  - Blue
    - red
    - green
  - Violet
    - red
    - green
    - blue



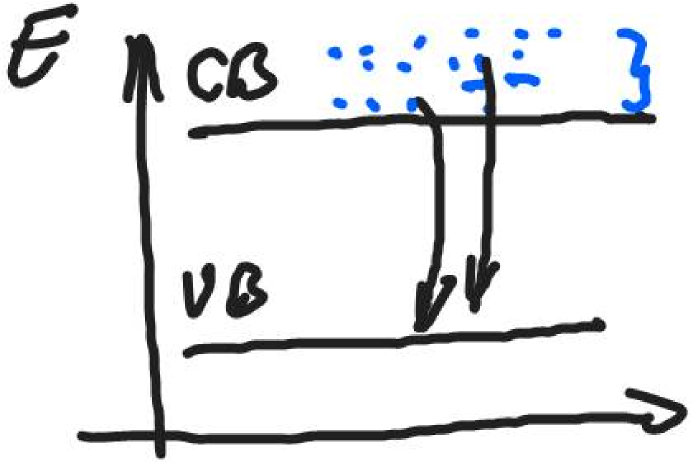
$V_{Th} = 1.5-1.8V$

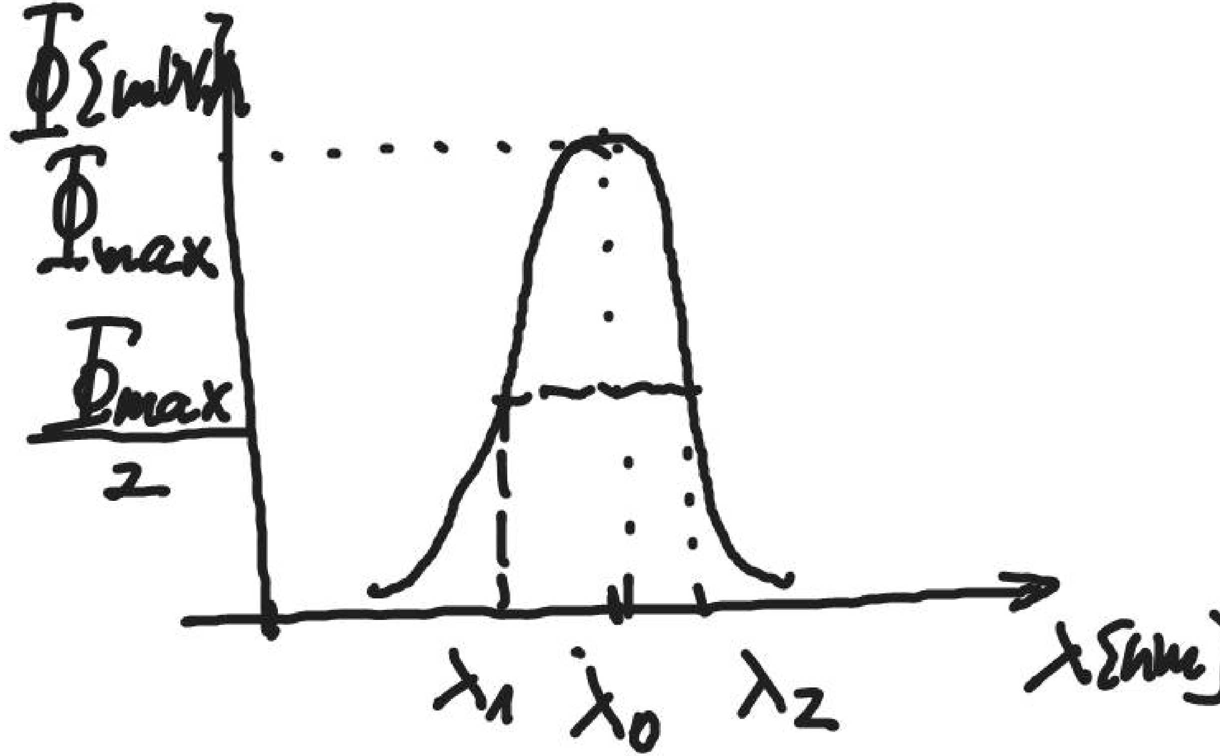
$V_{Th} = 1.8-2.2V$

$V_{Th} = 2.6-3V$

$V_{Th} = 3-3.4V$

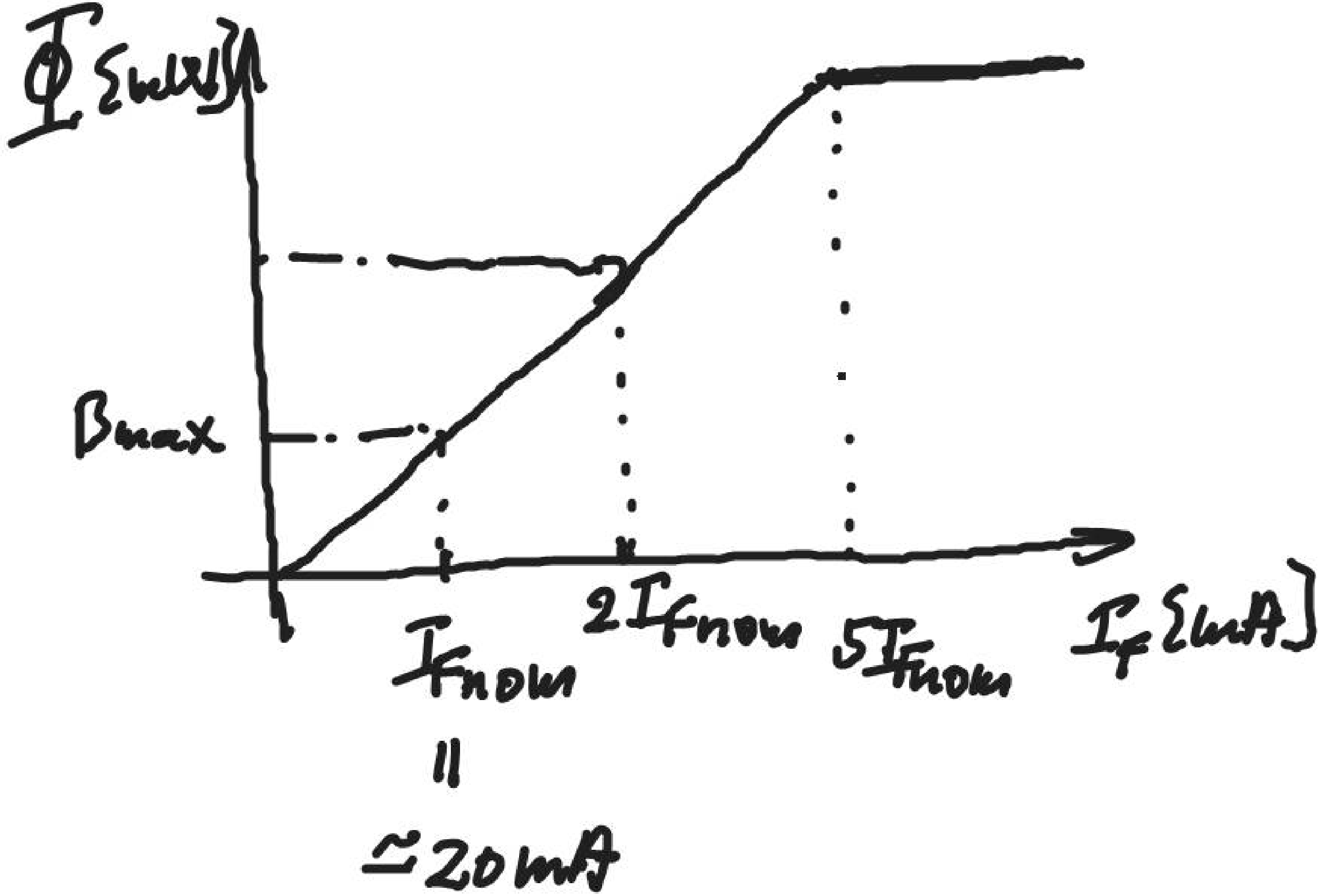
Spectral emission

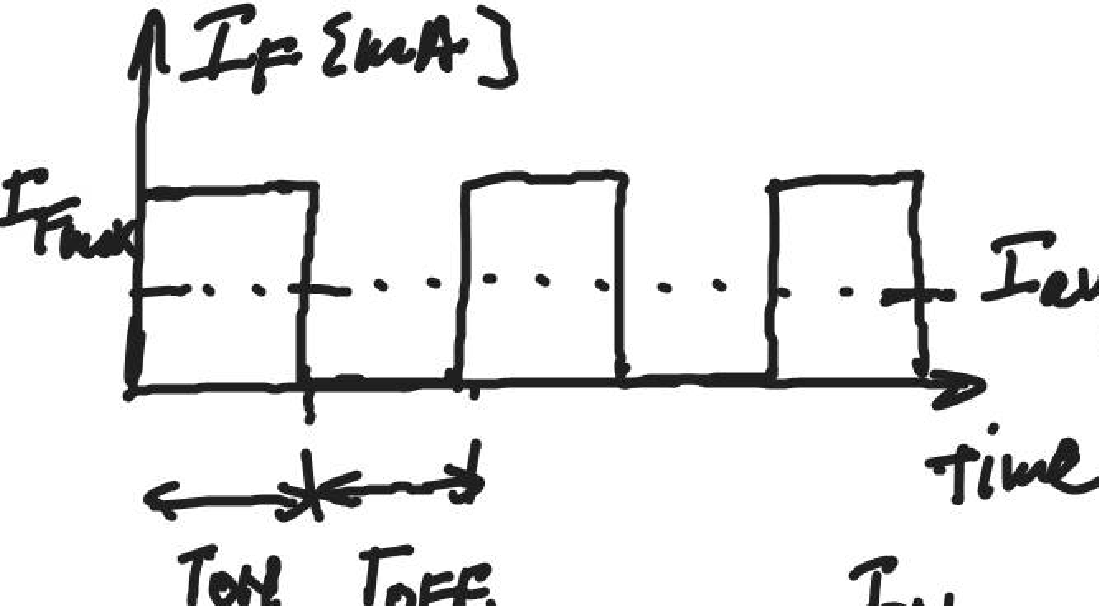




$\lambda_2 - \lambda_1 \simeq$ tens of nm

Brightness dependency by the current





$I_{avg} \leq I_{Fnom}$ ($\simeq$ 20mA)

125°C

$\simeq$ -50°C

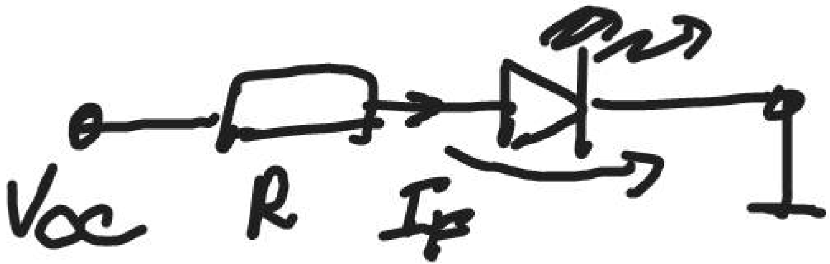
$$D = \frac{T_{ON}}{T}$$

$$I_{avg} = D \times I_{Fmax}$$

$$20mA = D \; 100mA$$

<u>ex</u>: $I_{Fmax} = 100\,mA$

$f = 1KHz$, $D = 10\%$



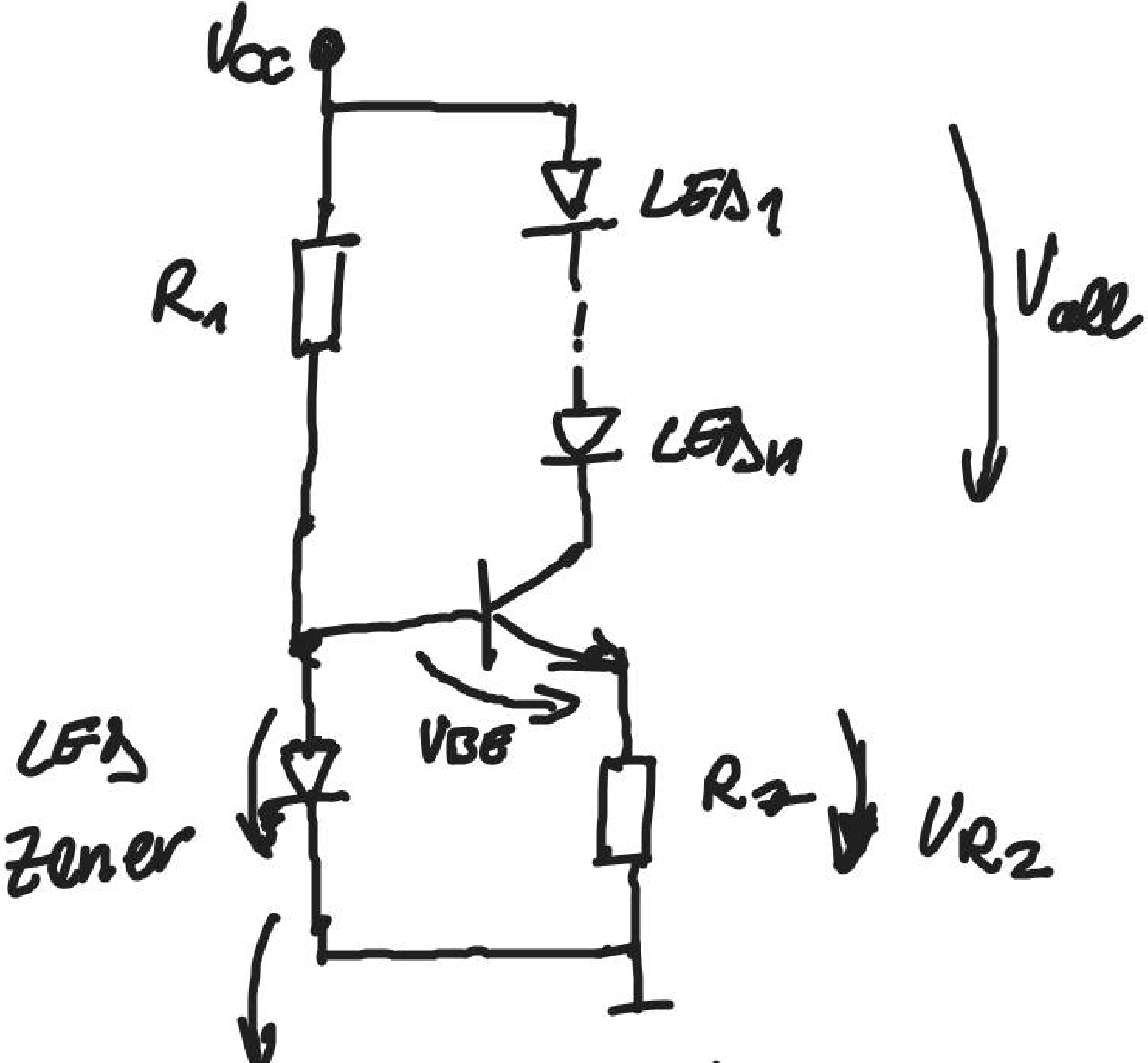
5V

$V_{th} = 1.5V$

$I_F \leq 20mA$

$V_R = 3.5V \Rightarrow R \simeq 175\Omega$

$R \simeq 180\Omega$

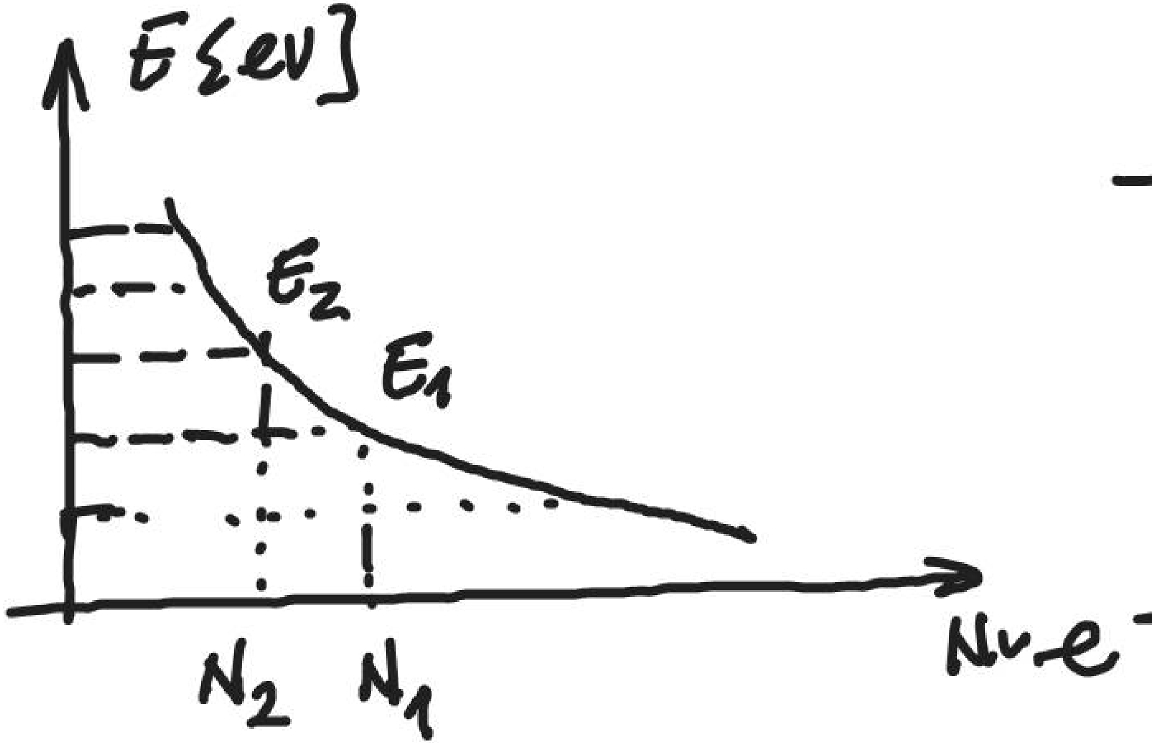


$$V_{CC\,min} = V_{all} + V_{CE} + V_{R_2}$$

$$V_{CE} \simeq 0.1 \div 0.2\,V$$

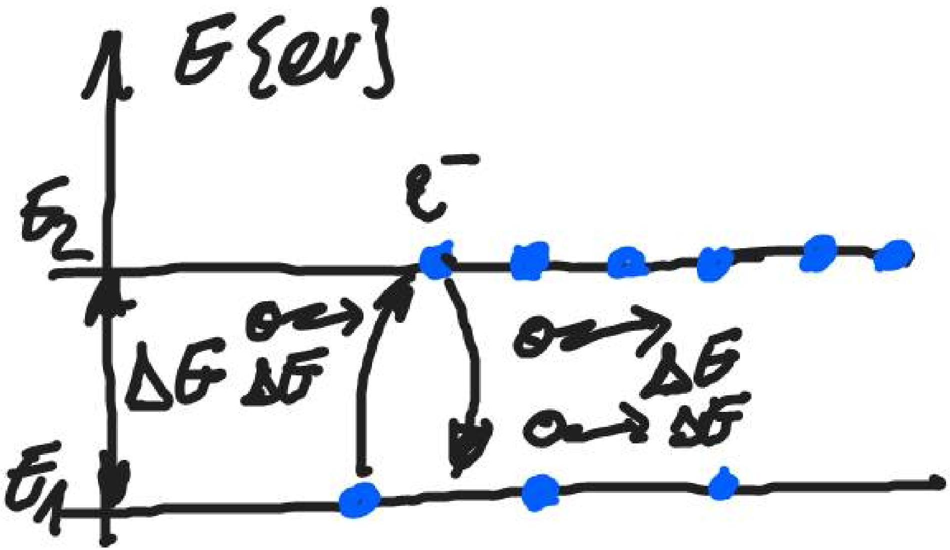
$$1.2 = 0.6 + \underset{\approx 0.5}{V_{R_2}}$$

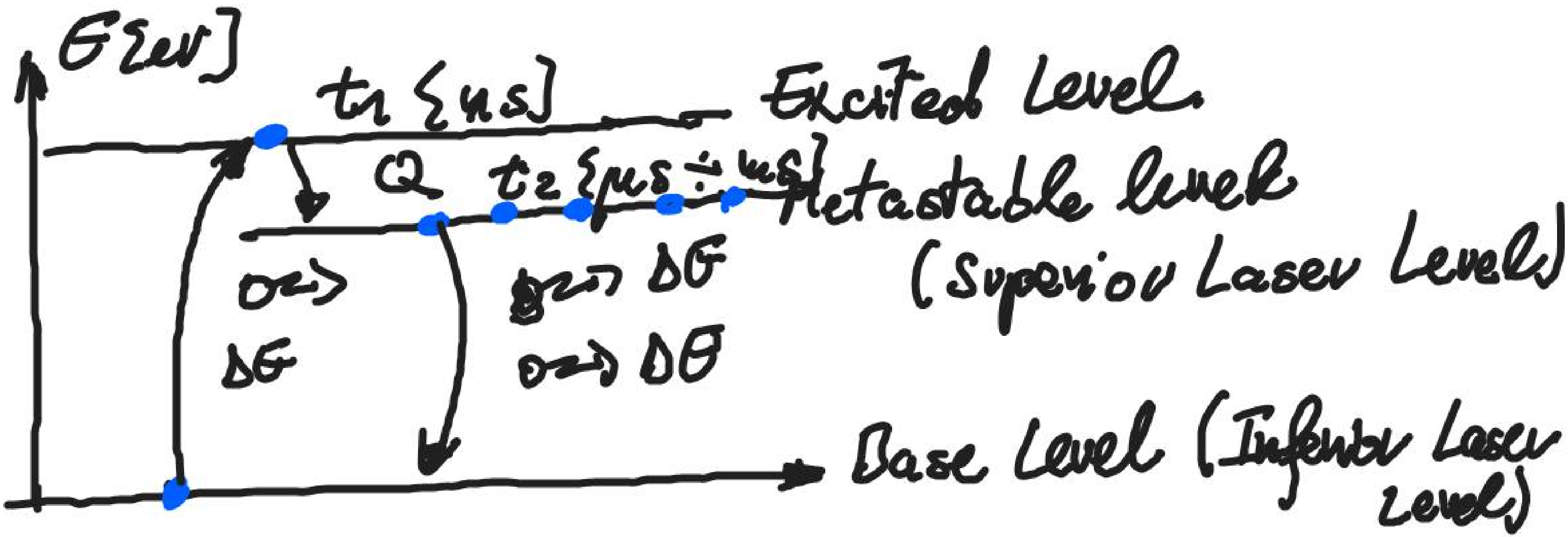
LASER



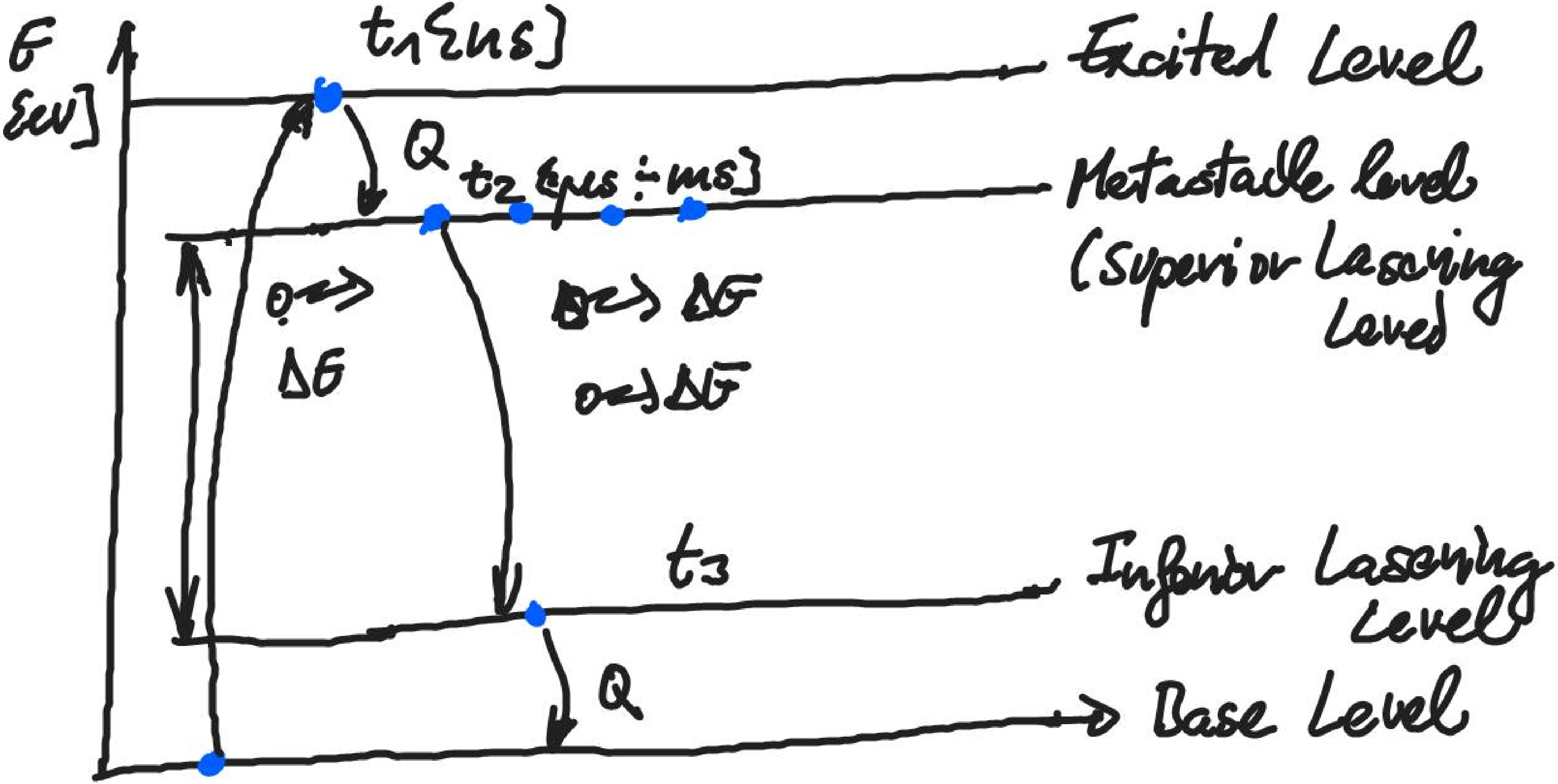
$$\frac{N_2}{N_1} = e^{-\left(\frac{E_2 - E_1}{KT}\right)} < 1$$

population inversion


E [eV]
E2
E1
e⁻
ΔE
ΔE
ΔE
ΔE


E [eV]
t1 [ns]
Excited Level
Q
t2 [μs ÷ ms]
Metastable level
(Superior Laser Level)
ΔE
ΔE
ΔE
Base Level (Inferior Laser Level)

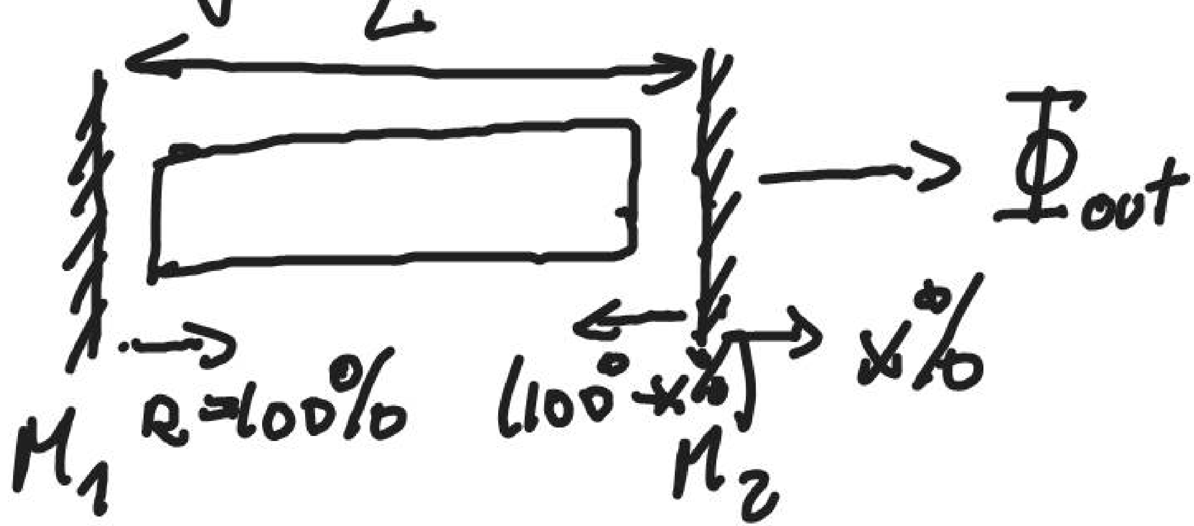
4 Level Laser



1. Active material

2. Energy pump

3. Resonant cavity



$A = (1+G)^L$, G - gain of the material

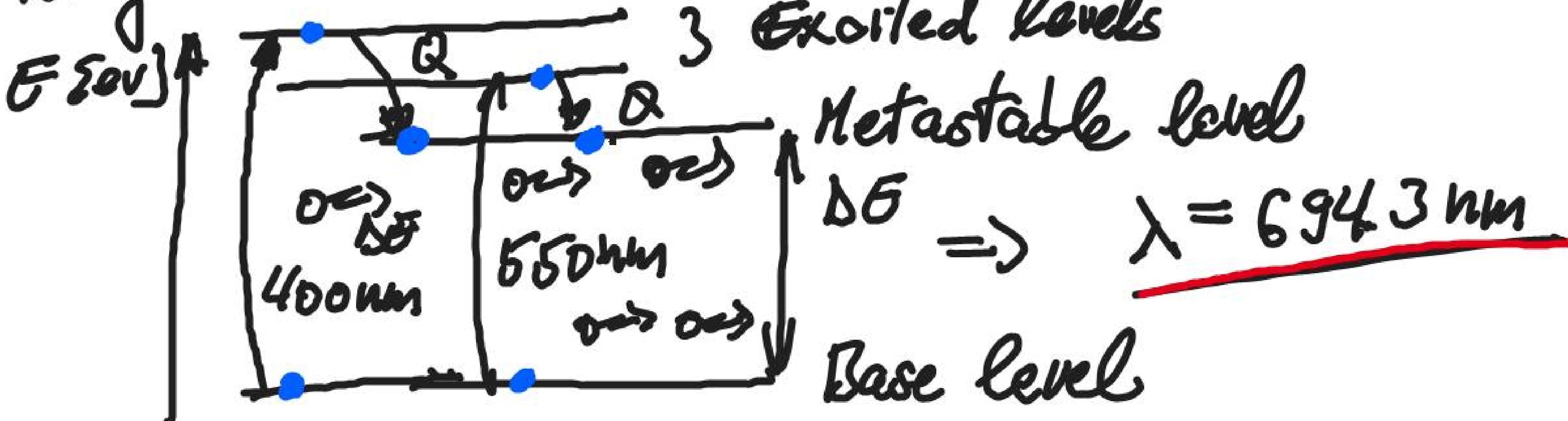
Solid state Lasers

Active material : host material + ions

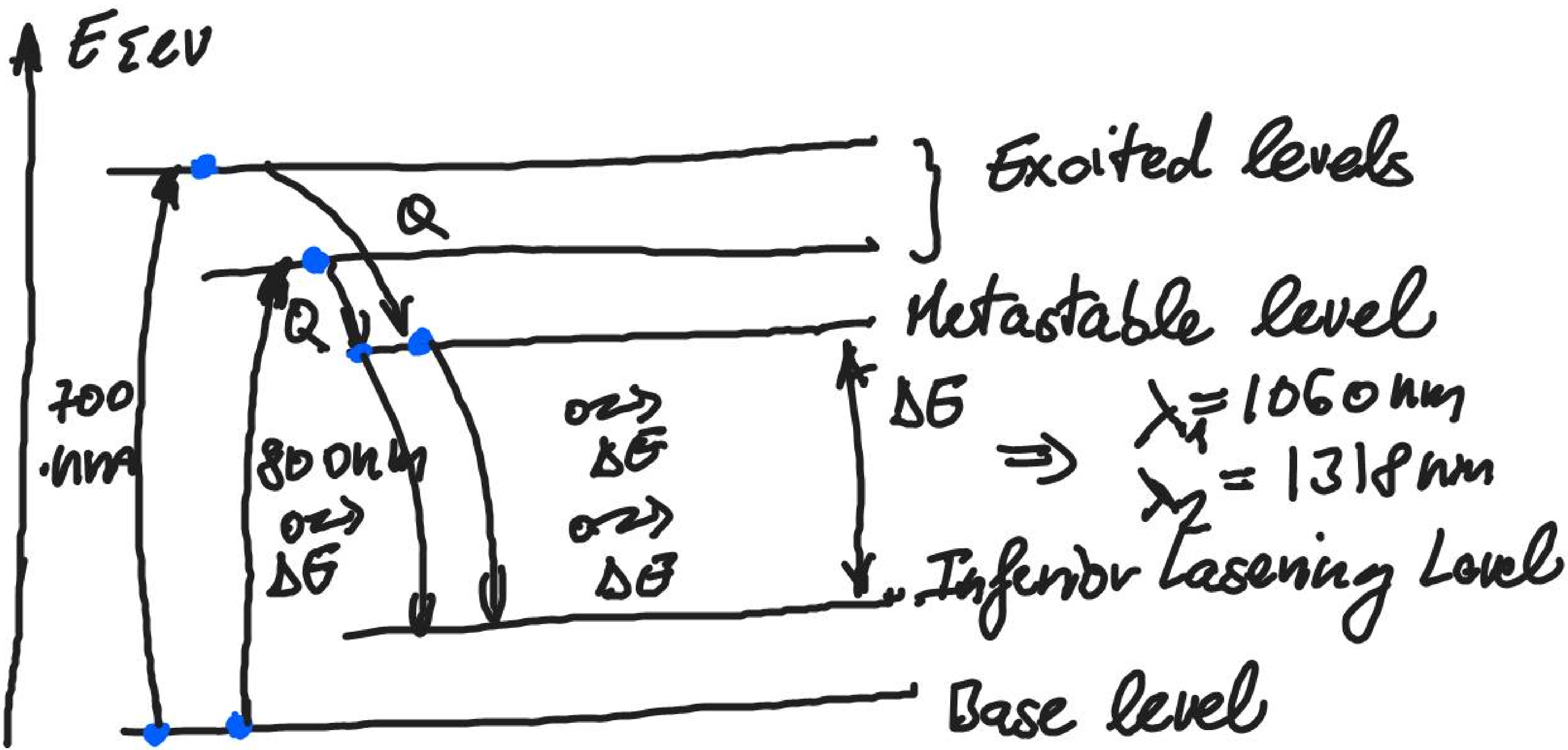
1%

Cr^{+3}, Nd^{+3}, Er^{+}, Ho^{+3}

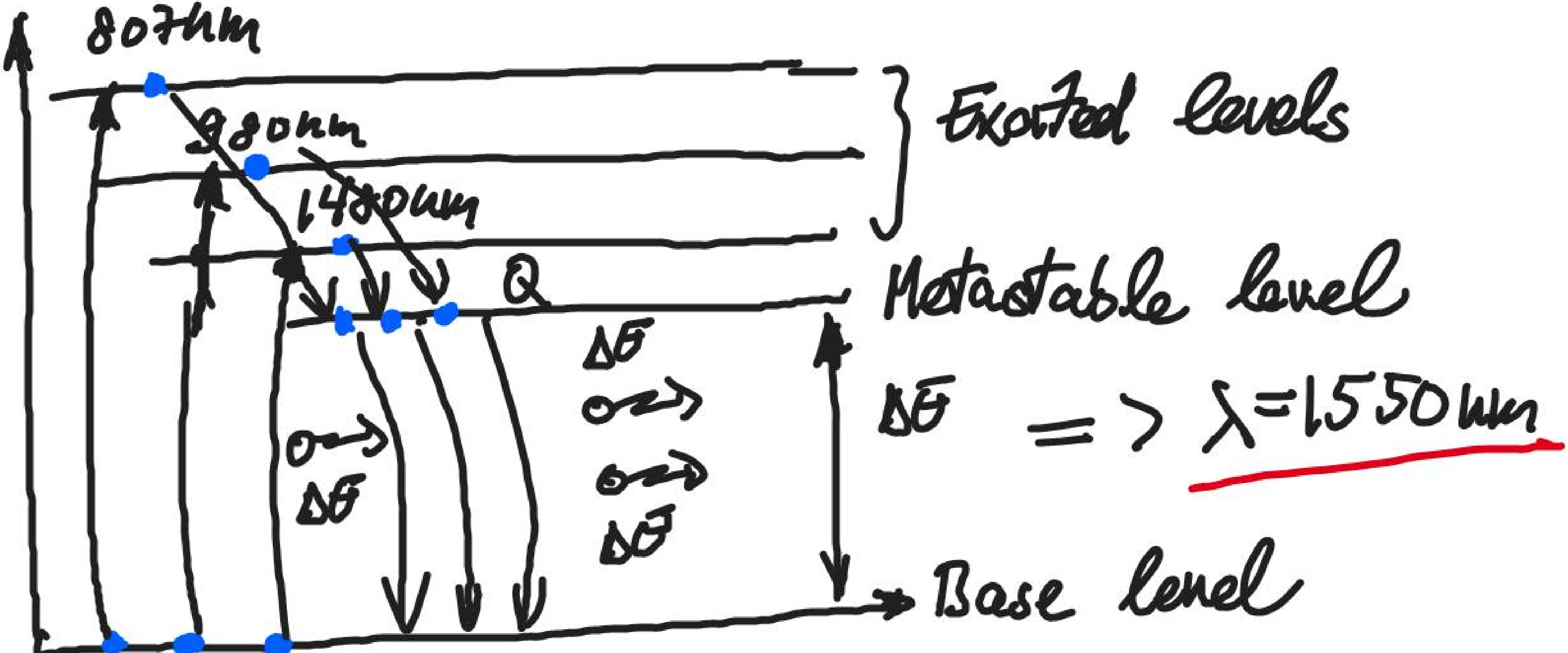
Ruby LASER : $Al_2O_3 + Cr^{+3}$

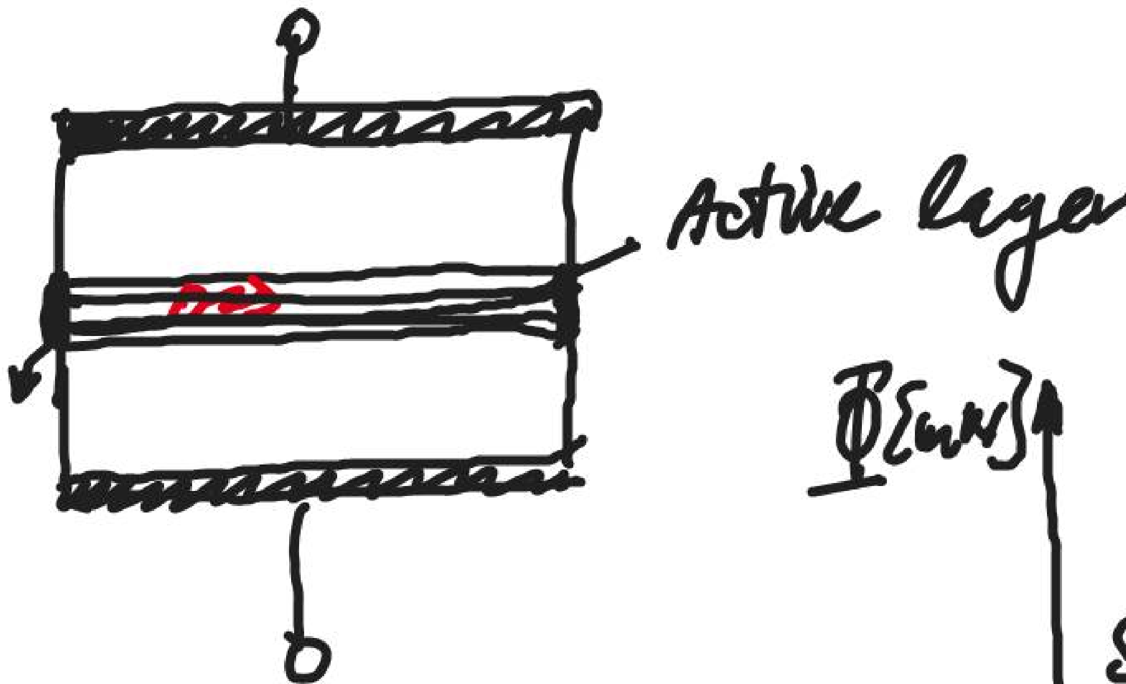


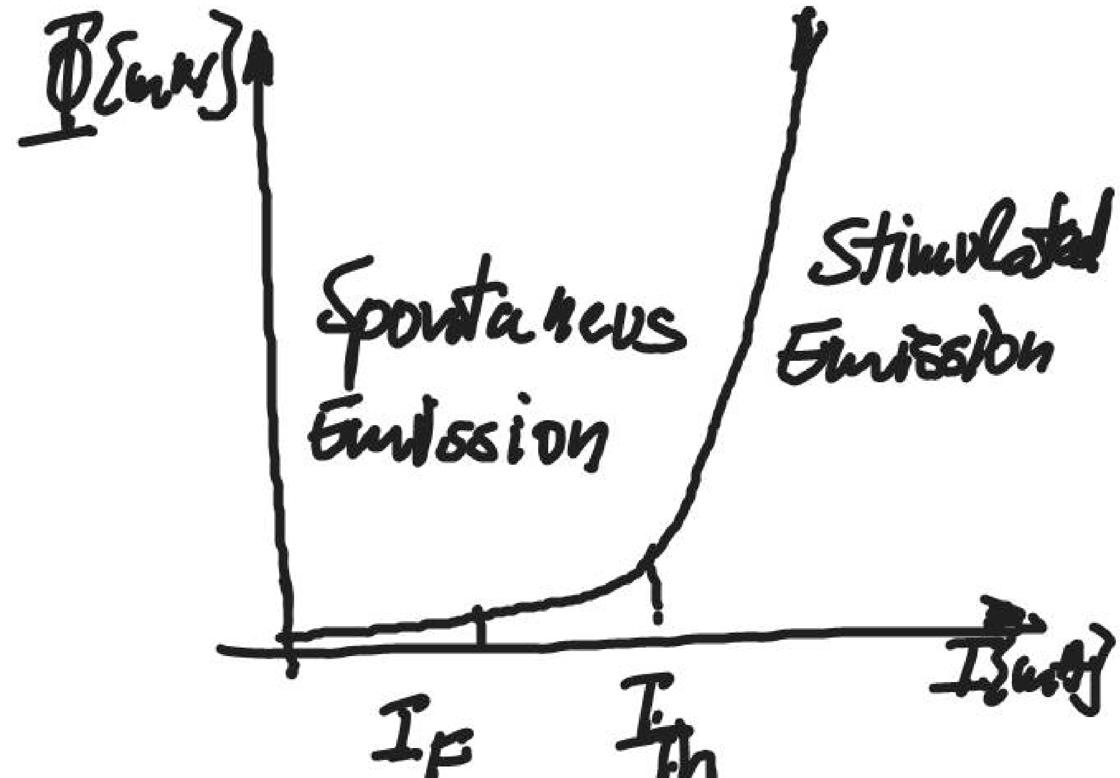
Neodinium LASER : $Y_3Al_5O_{12}$ (YAG) + Nd^{+3}

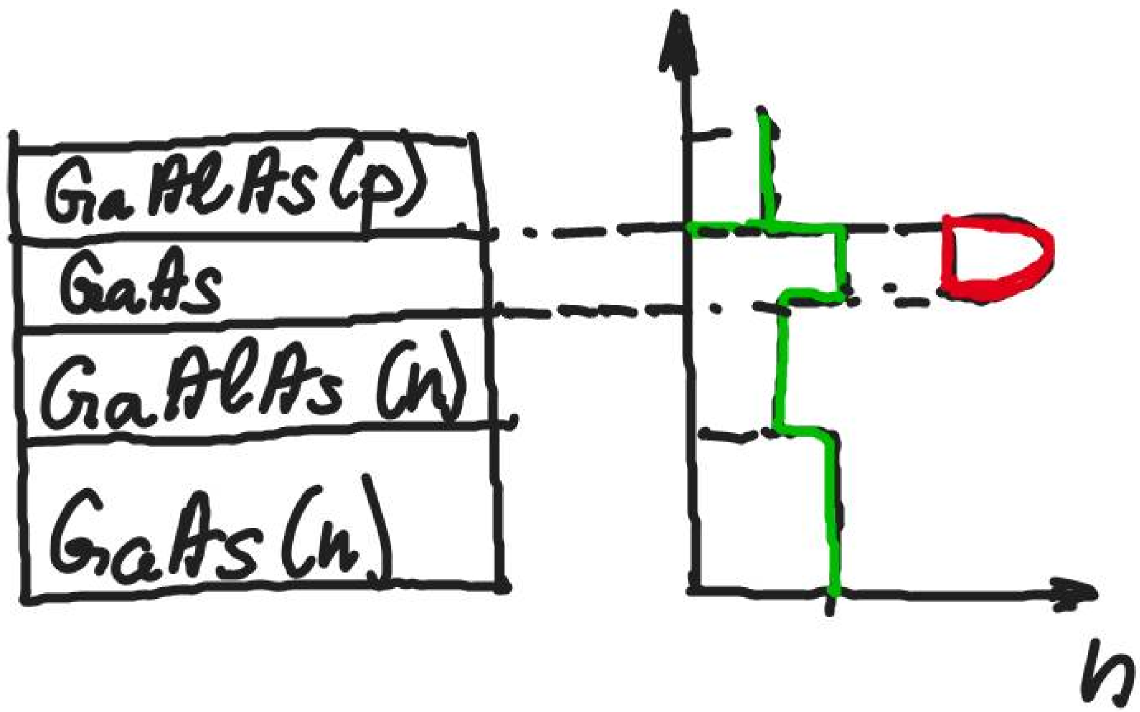


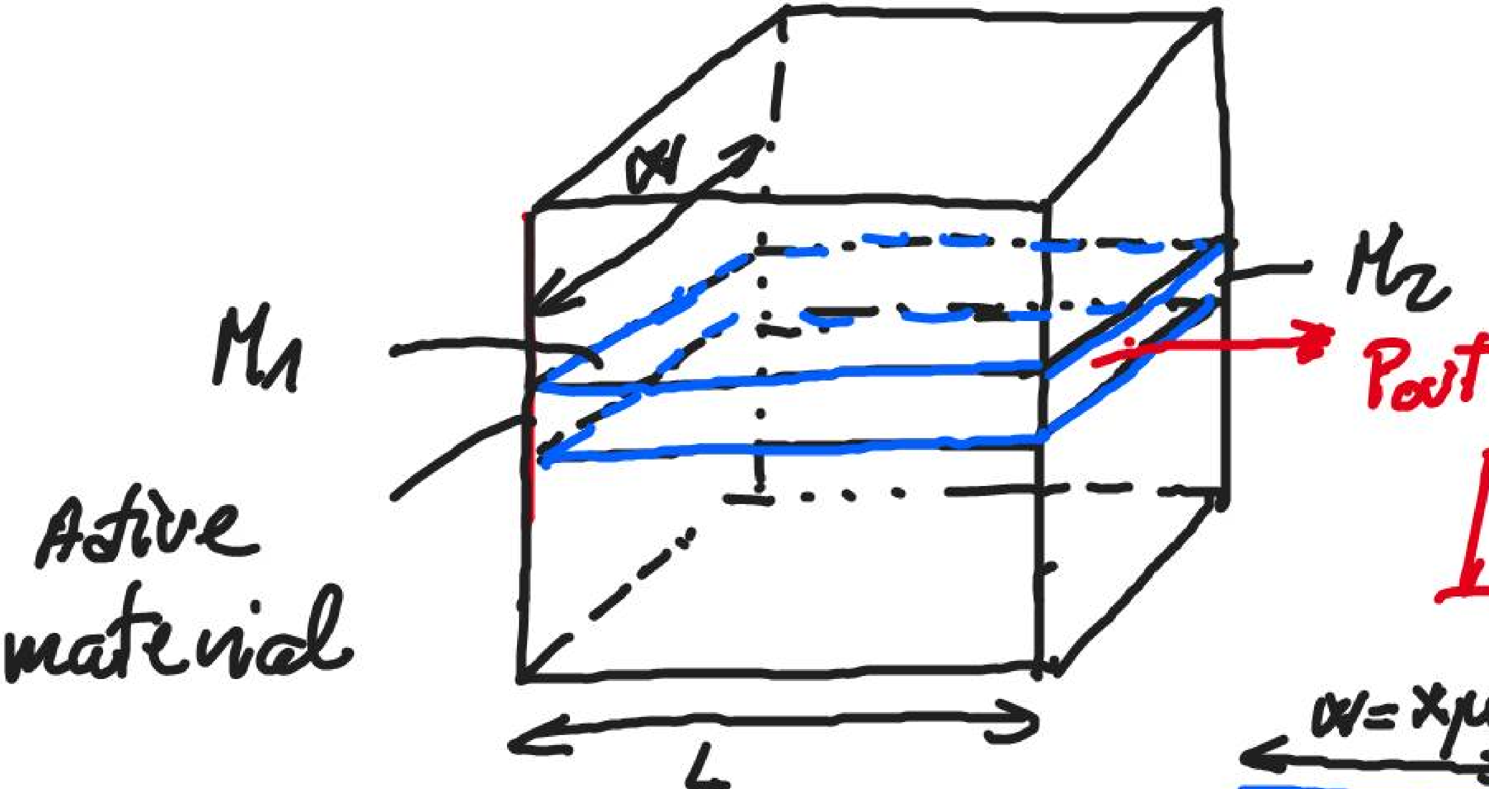
Erbium LASER: glass + Er^{+3}
(monomode optical fiber)




Active layer

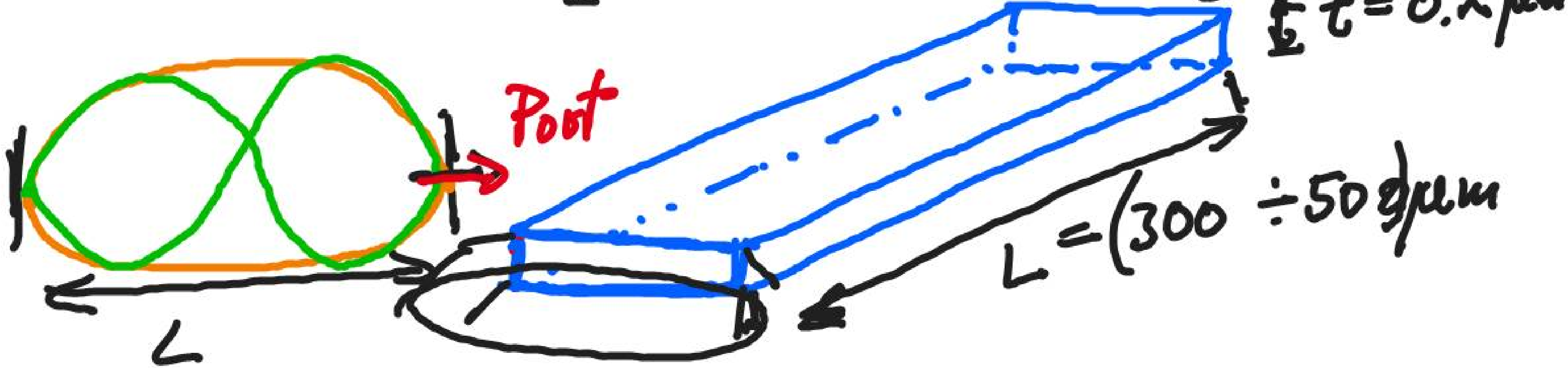

Φ [mW]
Spontaneous Emission
Stimulated Emission
I_F
I_{th}
I [mA]


GaAlAs (p)
GaAs
GaAlAs (n)
GaAs (n)
n

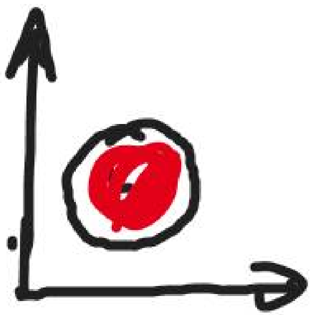


$$\boxed{2Ln = N\lambda}$$

long. mode no.

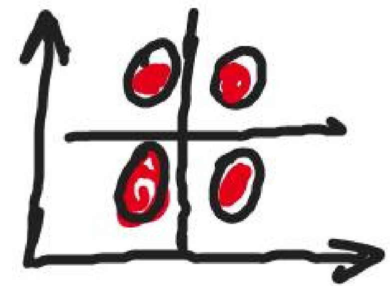


Transverse mode of the ILD:



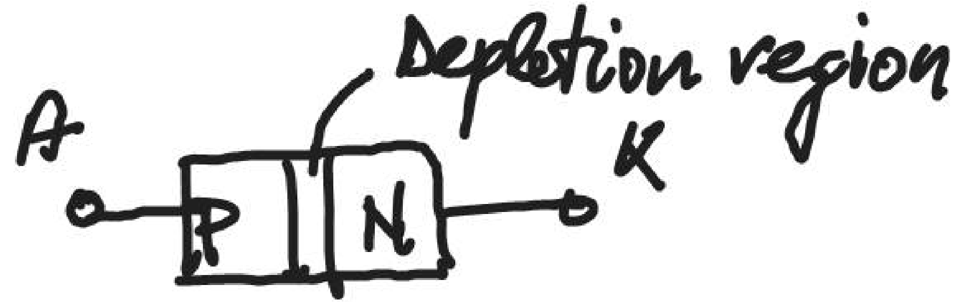
TEM 00

TEM 10

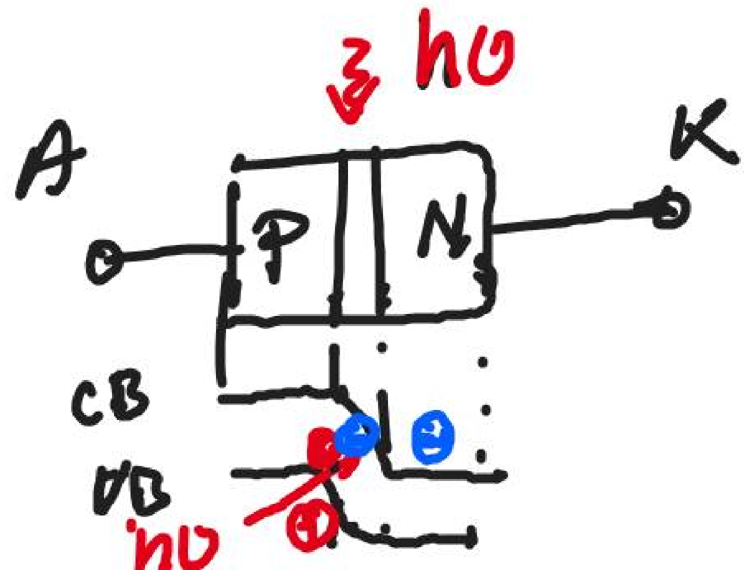


TEM 11

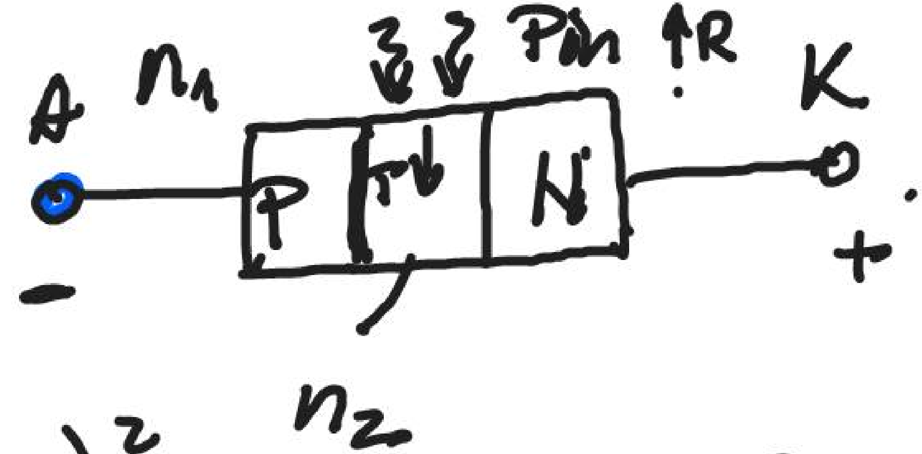
Photodetectors



$V_{AK} \geq V_{th}$



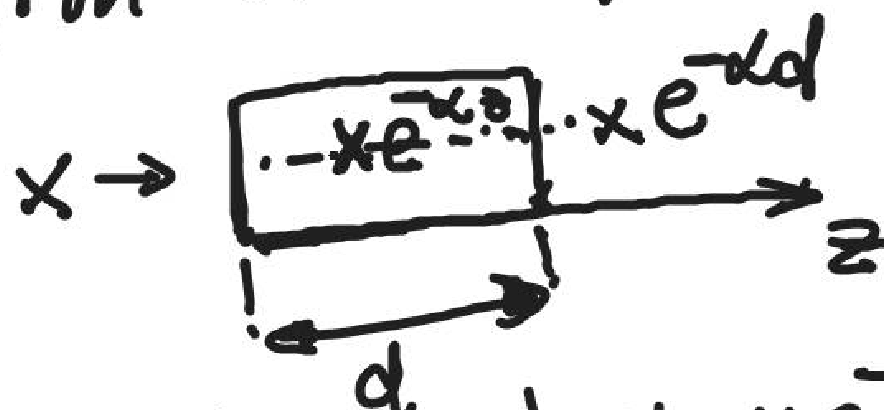
$E_{ph} \geq E_G$



$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \Rightarrow T = 1 - R$$

α - absobtion coeff. of the material

$$P_{abs} = (1-R)\,P_{in} \cdot \left(1 - e^{-\alpha d}\right)$$



$$\Downarrow \quad x - x e^{-\alpha d} = \underbrace{\left(1 - e^{-\alpha d}\right)} x$$

$$P_{abs} = (1-R)\left(1 - e^{-\alpha d}\right) P_{in}$$

$$r_{abs} = \frac{P_{abs}}{E_{ph}} = \frac{P_{abs}}{h\nu} = P_{in}\,\frac{(1-R)(1-e^{-\alpha d})}{h\nu}$$

$$I_p = r_{abs} \times e = \frac{(1-R)\quad(1-e^{-\alpha d})\,e}{h\nu}\quad P_{in}$$

$$\eta = \frac{r_e}{r_p} \quad \left(\frac{\text{rate of } e^- \text{ collected at the terminals}}{\text{rate of incident photons}}\right)$$

$$\mathcal{R} = \frac{I_p}{P_{in}} \quad \left[\frac{A}{W}\right]$$

responsivity

$$\left.\begin{aligned} I_p &= r_e \times e \\ \eta &= \frac{r_e}{r_p} \end{aligned}\right\} \Rightarrow I_p = e\,\eta\, r_p$$

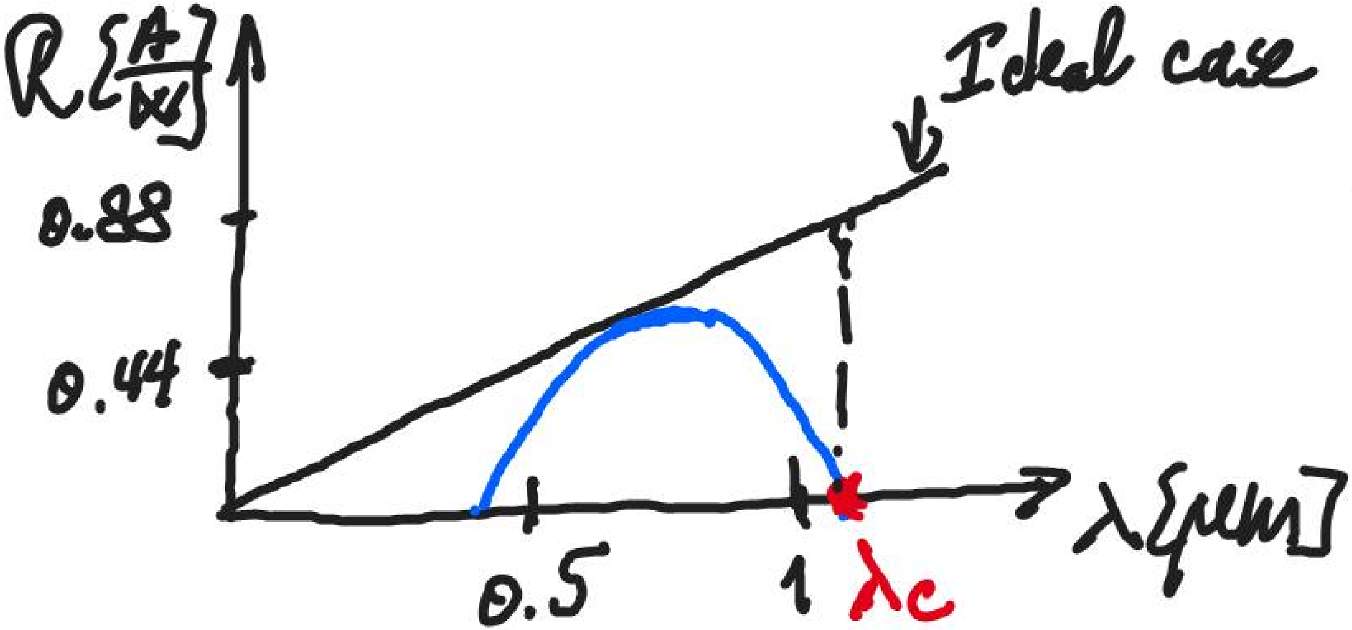
$$\underbrace{r_p = \frac{P_{in}}{h\nu}}\quad \left(\frac{\text{Incident optical power}}{\text{Energy of a photon}}\right)$$

$$\Downarrow$$

$$I_p = \frac{\eta e P_{in}}{h\nu}$$

$$R = \frac{\eta e}{h\nu} = \frac{\eta e \lambda}{hc}$$

$$E_{ph} \geqslant E_G$$



Si

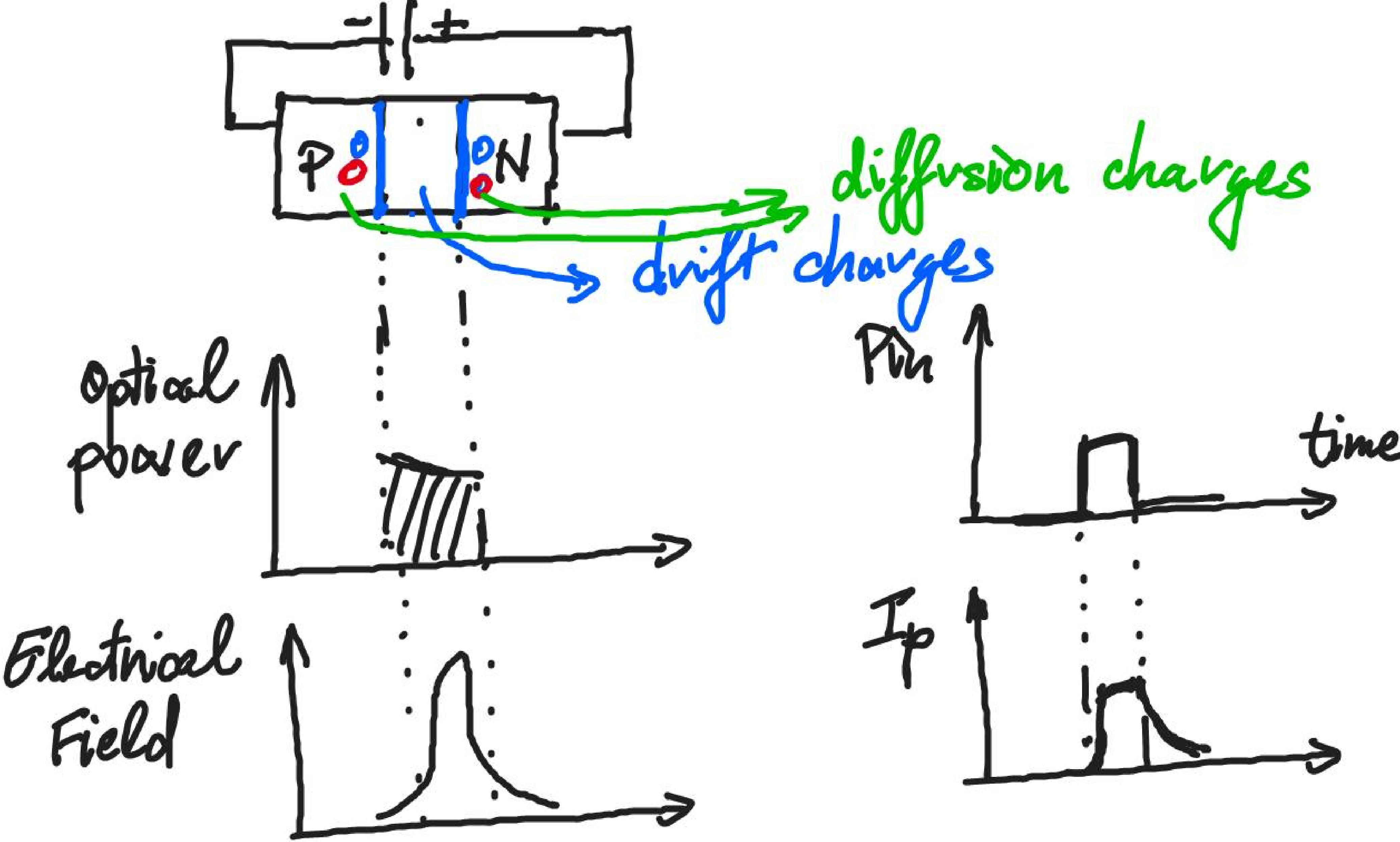
$$\frac{hc}{\lambda} \geq E_G$$

$$h = 6.626 \times 10^{-34} \text{ Js}$$

$$c = 3 \cdot 10^{8} \text{ m/s}$$

$$1\text{eV} = 1.6 \times 10^{-19} \text{ J}$$

$$\underset{[\mu m]}{\lambda_c} = \frac{1.24}{E_G\,[\text{eV}]}$$



P
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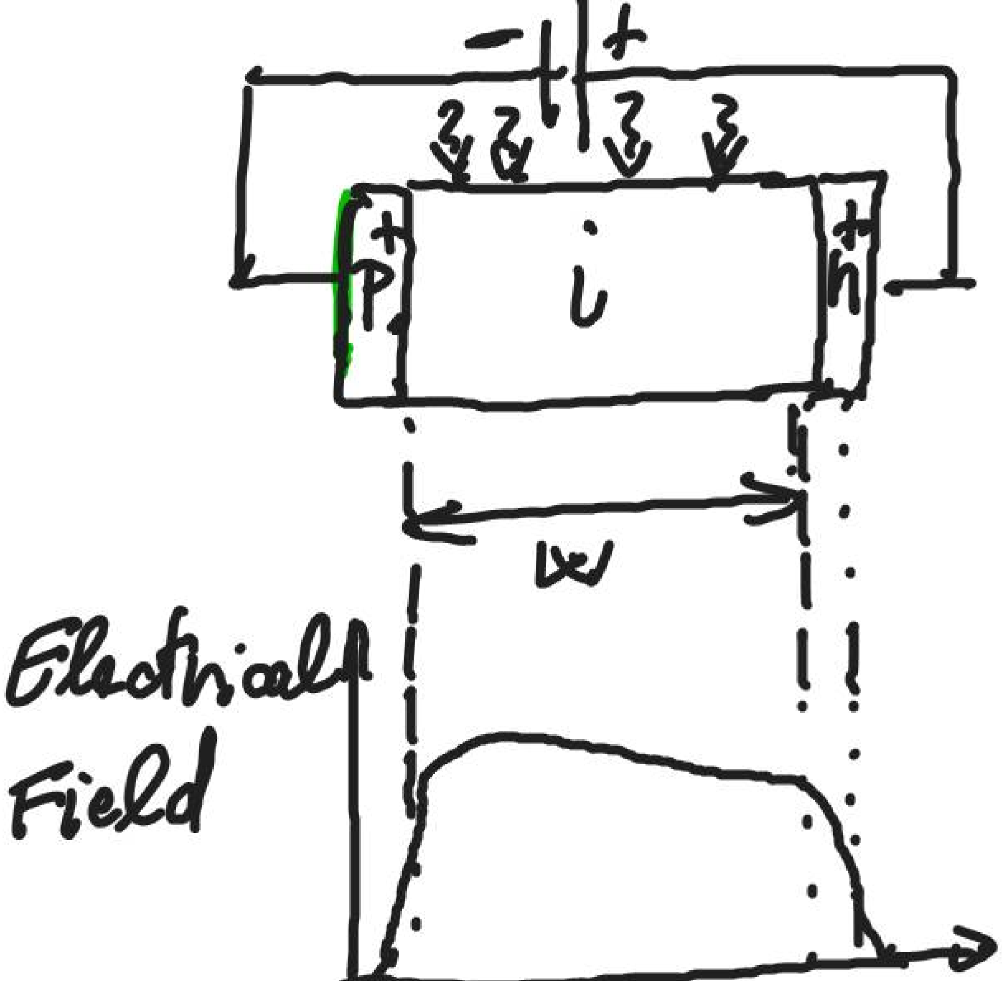
diffusion charges
drift charges
Optical power
Electrical Field
Pin
time
Ip



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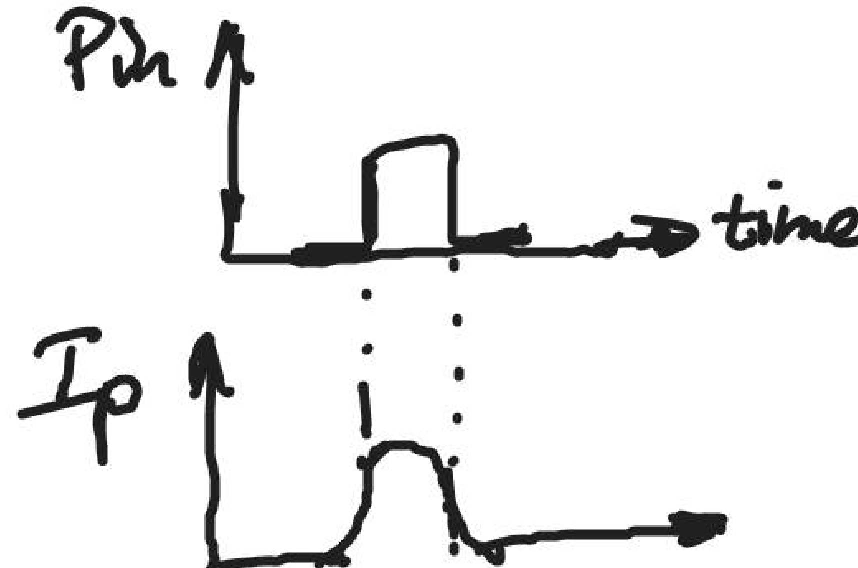
Electrical Field



Pin
time
Ip