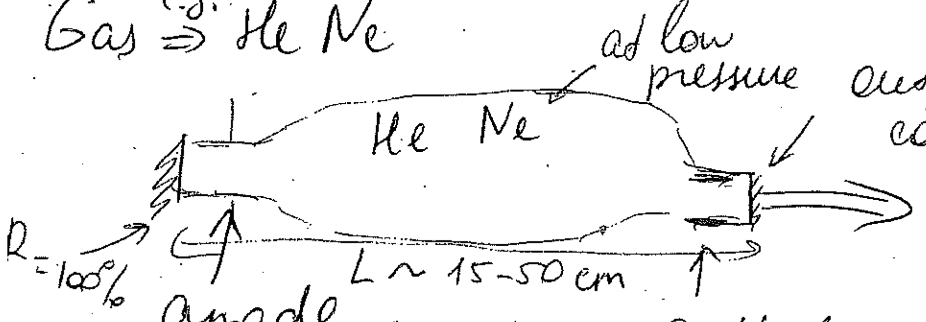
PH 585
AMO

Lecture # 25

Examples of lasers

Gas $\overset{e.g.}{\Rightarrow}$ He Ne

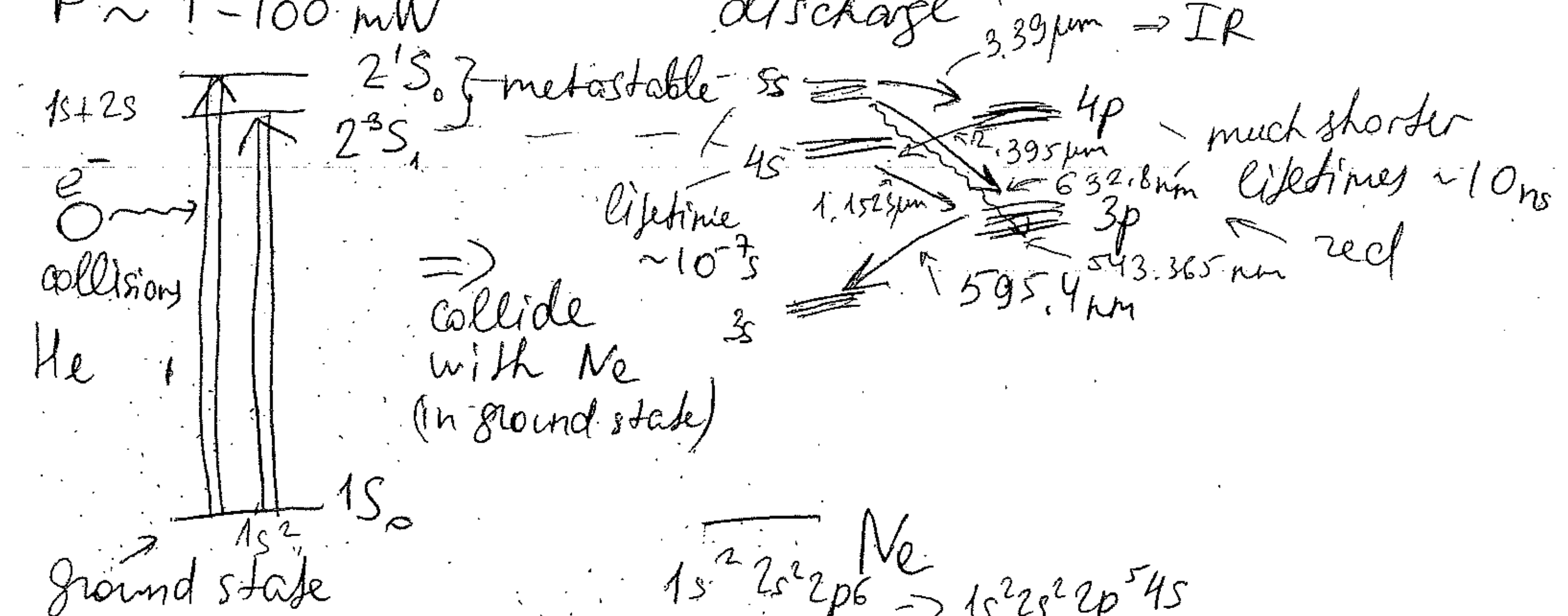


$\frac{He}{Ne} = \frac{5 \div 20}{1}$

anode ⟷ cathode $\Rightarrow$ current ~ 5 ÷ 100 mA (for cw)

~ 1 kV → electric discharge

P ~ 1-100 mW



$1s^2 2s^2 2p^6 \Rightarrow 1s^2 2s^2 2p^5 \, \overset{4s}{\underset{5s}{}}$

Also have: 543,365 nm, 604,613 nm, 611,8 nm, ...
↑ green, ↑ yellow, ↑ orange

Choose λ by choosing cavity mirrors with maximized $\mathcal{R}$ at λ of interest!

Note: gain for 632.8 nm transition is lower than that for 1.15 & 3.39 μm ones

Natural broadening $\Delta\nu_{nat} = \frac{1}{2\pi\tau} \simeq 19$ MHz

↑ for 632.8 nm transition

Doppler broadening

⇓ $\Delta\nu_D \simeq 1{,}5$ GHz ← rather narrow ⇒ $\Delta\nu_q = \frac{c}{2L} = \frac{3\cdot 10^8}{2\cdot 0{,}2} = 750$ MHz

L ↑ ~20 cm

can operate in a single-mode regime ⇐

⇐ tune cavity length by piezo-electric stage

Resonator type: hemispherical ; for polarised output

⇒ stable against misalignment

⇓ insert a plate under Brewster angle

Solid-state lasers ⇒ e.g. Nd: YAG (YLF, YVO$_4$)

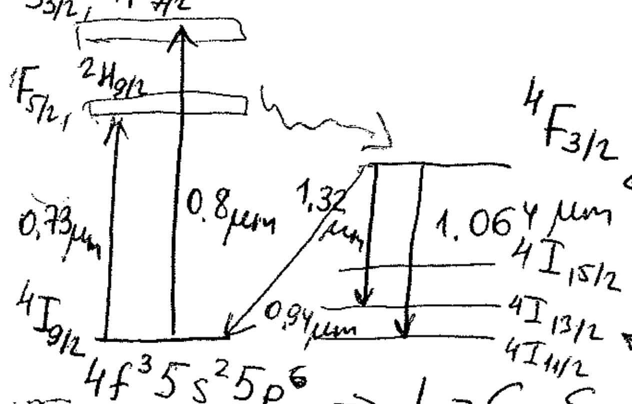
↑ yttrium ↑ aluminium ↑ garnet ; YLF ⇒ YLiF$_4$

host (YAG, YLF, YVO$_4$) with 1% of Y^{3+} ions replaced with Nd^{3+}

$Y_3Al_5O_{12}$

Higher doping: fluo quenching, strained crystals

↑ radius → $r_{Nd^{3+}} > r_{Y^{3+}}$ by ~14%



← τ ~ 230 µs (YAG)
98 µs (YVO$_4$)

↖ most popular transition

$\Delta\nu_{1.064\,\mu m} \sim 126$ GHz homogeneously broadened (interaction with lattice)

↓ can be used for melod operation → 5 ps

$4f^3 5s^2 5p^6 \Rightarrow L = 6,\ S = 3/2$

Note: $\Delta\nu_{\text{Ti-sapprize}} \simeq 100$ THz ⇒ tunability; pulsed operation

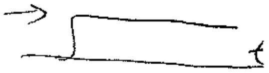
↑ <5 fs pulses achieved!

Ti^{3+} replace Al^{3+} in Al_2O_3

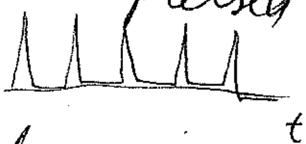
ion ~0.1–0.5% doping

Ti_2O_3

Modes of operation ⇒ CW

I → 

⇒ pulsed

I → 

Pulsed laser operation

⇙ Q-switching

⇓ mode-locking

⇒ pulsed pumping

↙ Q-switching:

- Electro optical
- rotating prisms or mirrors
- Acousto-optic
- Saturable absorber

Charge up capacitors and then discharge them through flashlamps ⇒ pulsed pumping

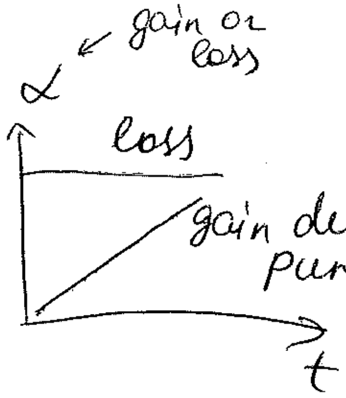
⇓ dye lasers, excimer lasers ← short inverted population time

↑ a lot of disruption in the gain medium during lasing

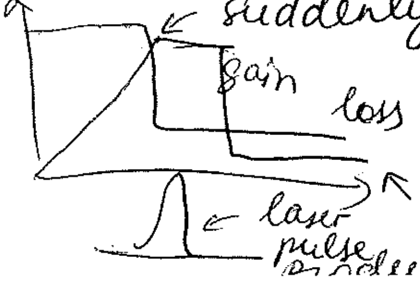
can't ⇒ operate in CW mode

⇓

Main idea: increase loss in order to accumulate more of the inverted population; then rapidly decrease loss and dump all inversion in a single pulse

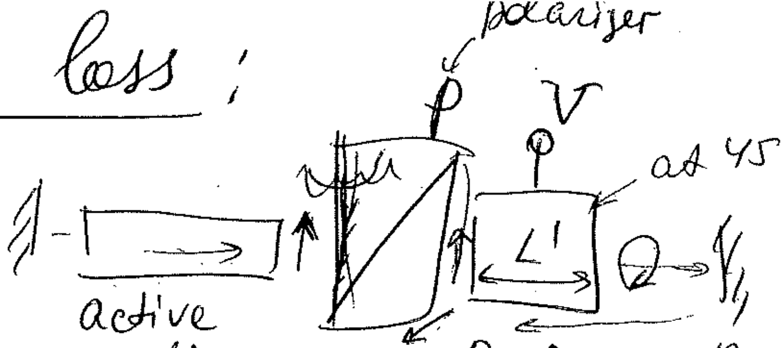


⇒



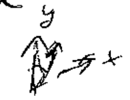
How to manipulate loss;

Electro-optically;



active medium

Pockels cell (KDP) or other NLO crystal ⇒ $\Delta n \sim V$, with $\overbrace{\Delta n}^{n_x - n_y}$; $\uparrow$ linear EO effect



$\frac{\lambda}{4}$ - voltage ↖ ~1-5kV

↓

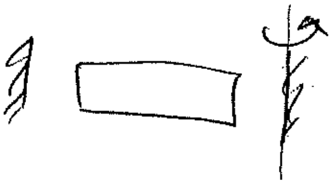
choose V at which $\Delta\varphi = \frac{\pi}{2}$ ⇐ $\Delta\varphi = \frac{2\pi}{\lambda}\underbrace{\Delta n}_{\sim V} L'$ introduces ↗ Pockels cell

⇒ circular polarization

Back through Pockels cell ⇒ $\Delta\varphi_{total} = \pi$ ⇒ not transm. by polarizer

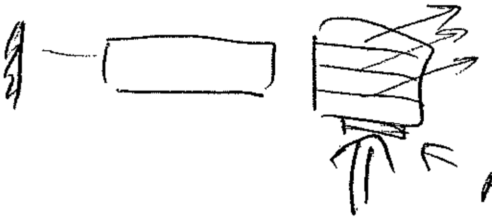
For lasing ⇒ remove V (within < 20ns)

Rotating mirror ⇒



spinning

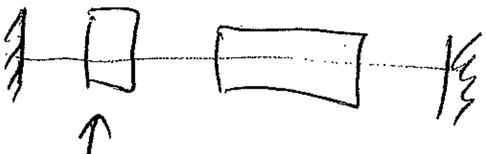
AOM;



during lasing ⇒ switch off rf

rf ⇒ acoustic wave

Saturable absorber: dye cell



↑ acts like a two-level system with low I_{sat}

abs coeff. → $\alpha_{dye} = \frac{\alpha_0}{1 + I/I_{sat}}$ ⇒ At $I > I_{sat}$ ⇒ transparent

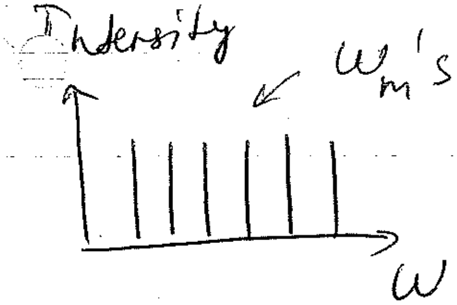
Mode-locking ⇒ to produce sub-ps pulses

⇓

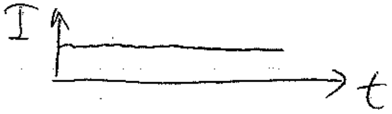
fixed phase relationship between the modes of the laser's cavity

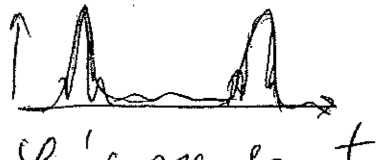
$$\underset{\substack{\uparrow\\ \text{electric field}\\ \text{in a laser cavity}}}{E(t)} = \sum_m E_m e^{i(\omega_m t + \underset{\substack{\uparrow\\ \text{initial phase of}\\ \text{the } m\text{th mode}}}{\varphi_m})}, \quad I \sim \langle |E(t)|^2 \rangle$$

Mode-locking: $\varphi_m = \varphi \leftarrow$ constant for all m's



if φ_m's are random

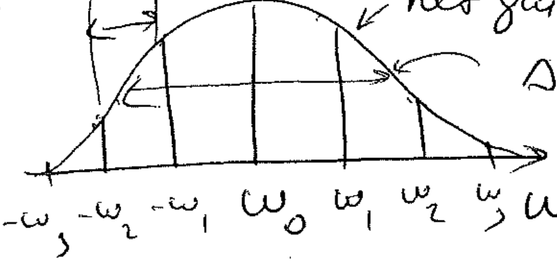




⇐ achieve peak high-energy short pulses

if φ_m's are same

$$\delta\omega = \frac{2\pi}{T} = \frac{\pi c}{L}$$

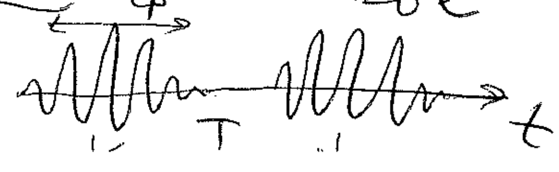


$$\Delta\omega = \frac{2\sqrt{2}\,\ln 2}{\pi}\,\frac{1}{\tau_p} \leftarrow \text{inhomogeneous broadening}$$

$$\text{Mode-locking: } E(t) = \sum_m \underbrace{E_m}_{E_0 e^{-4\ln 2\cdot\left(\frac{m\delta\omega}{\Delta\omega}\right)^2}} e^{i\underbrace{\omega_m}_{\omega_0 + m\delta\omega} t} = \underset{\sim\sim\sim}{E_0 e^{i\omega_0 t}} \cdot$$

$$\underset{\sim\sim\sim\sim\sim\sim\sim\sim\sim}{\sum_m e^{-2\ln 2\left(\frac{t-mT}{\tau_p}\right)^2}}$$

⇒



Bandwidth $\Delta\lambda \Rightarrow \Delta\omega = \Delta\left(\frac{2\pi c}{\lambda}\right) \simeq \left|\frac{2\pi c\Delta\lambda}{\lambda^2}\right| \Rightarrow$ ⑥

$$\Delta\lambda \simeq \frac{\lambda^2}{2\pi c}\Delta\omega$$

Examples $\Rightarrow$

$Ar^+ \leftarrow$ ion laser $\Rightarrow \Delta\lambda \sim 0.007$ nm $\quad \overset{\#\text{ modes}}{m} = \frac{\Delta\omega}{\delta\omega} \sim 80$

$\tau_{p_{min}} \sim 150$ ps

$\uparrow$ pulse duration $\leftarrow \frac{0{,}44}{M\delta\nu}$ $\leftarrow$ Gauss $\quad 0{,}315 \leftarrow \mathrm{sech}^2$

modes $\rightarrow M$

Nd: YAG $\Rightarrow \Delta\lambda \sim 10$ nm, $m \sim 25000$, $\tau_{p_{min}} \sim 120$ fs

Dye $\Rightarrow \Delta\lambda \sim 100$ nm, $m \sim 8 \cdot 10^5$, $\tau_{p_{min}} \sim 12$ fs

Ti: Sapphire $\Rightarrow \Delta\lambda \sim 400$ nm, $m \sim 2 \cdot 10^6$, $\tau_{p_{min}} \sim 3$ fs

How to achieve mode-locking

active $\Downarrow$
- amplitude modulation $\rightarrow$ AOM
- frequency modulation $\rightarrow$ EO effect

passive $\rightarrow$ Saturable absorber
- Kerr-lens, or self-modelocking $\Rightarrow n = n_0 + n_2 I$

$\uparrow$ refractive index $\quad \uparrow$ optical Kerr effect $\Rightarrow$ $n \uparrow$ as $I \uparrow$ $\rightarrow$ focusing

also need a compensator (prism pair or chirped mirrors) to compensate dispersion due to ω-depend. optical properties of components $\Rightarrow$