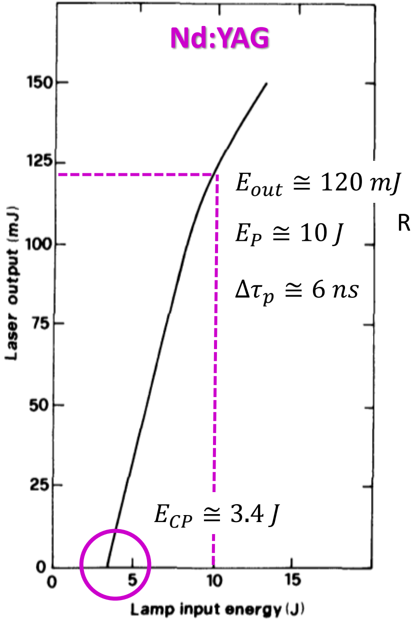
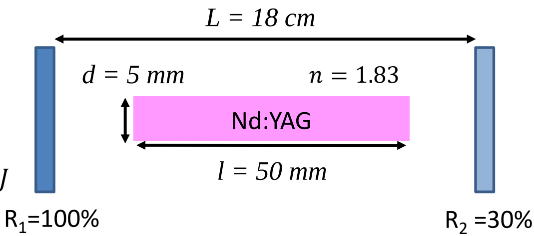
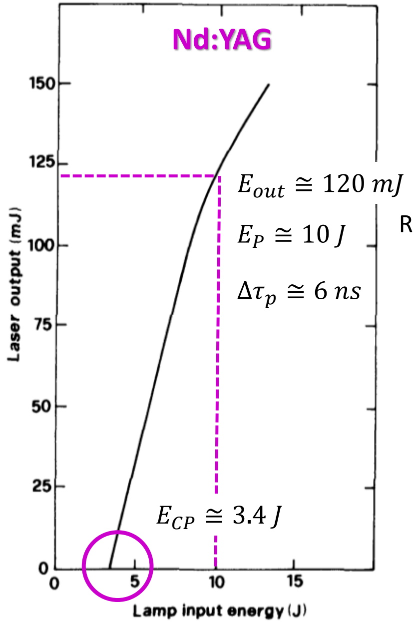
Q-switch

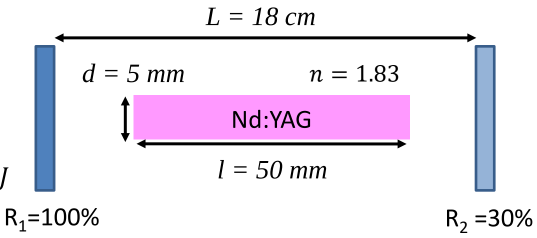




- The laser is pumped with flash lamps
- Nd:YAG rod: 5 x 50 mm
- Fabry-Perot cavity: $L = 18\ cm$
- $R_1 = 100\%$, $R_2 = 30\%$
- $L_i = 15\%$
- Active Q-switch with a Pockels cell (KDP, deuterated potassium dihydrogen phosphate, KD_2PO_2)

Q-switch



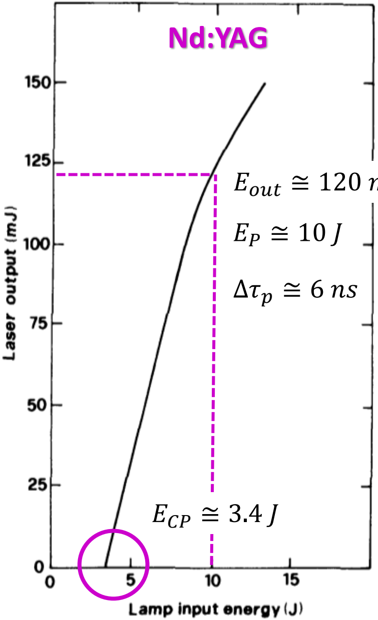


$$x = \frac{N_i}{N_P} = \frac{E_P}{E_{PC}} = \frac{10\ J}{3.4\ J} = 2.9$$

$$E = \eta_E \left(\frac{\gamma_2}{2}\right)\left(\frac{A_b}{\sigma}\right)\left(\frac{N_i}{N_P}\right) h\nu$$

$$\eta_E \left(\frac{N_i}{N_P}\right) = -\ln(1-\eta_E)$$

Q-switch

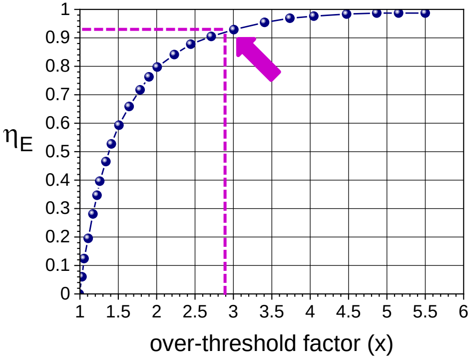


$E_{out} \cong 120\ mJ$

$E_P \cong 10\ J$

$\Delta\tau_p \cong 6\ ns$

$E_{CP} \cong 3.4\ J$

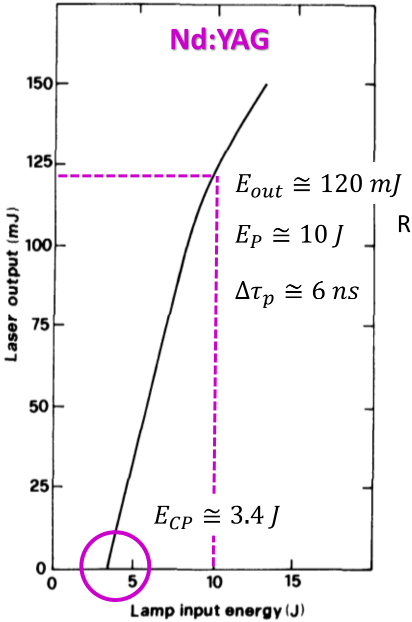


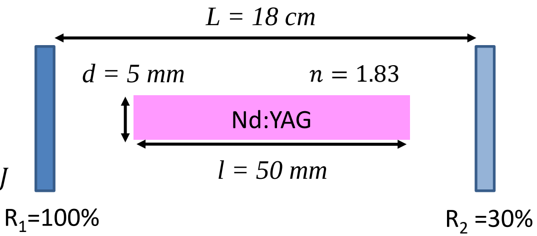
$$x = \frac{N_i}{N_P} = 2.9$$

$$\eta_E \left(\frac{N_i}{N_P}\right) = -\ln(1 - \eta_E) \qquad \eta_E \cong 0.94$$

Solved graphically

Q-switch





$$x = \frac{N_i}{N_P} = \frac{E_P}{E_{PC}} = \frac{10\ J}{3.4\ J} = 2.9$$

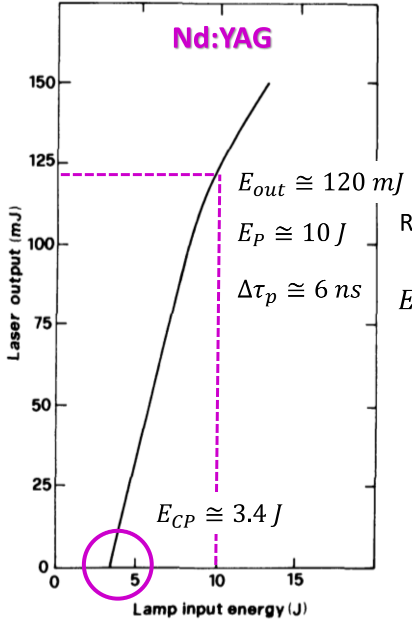
$$E = \eta_E \left(\frac{\gamma_2}{2}\right)\left(\frac{A_b}{\sigma}\right)\left(\frac{N_i}{N_P}\right) h\nu = 200\ mJ$$

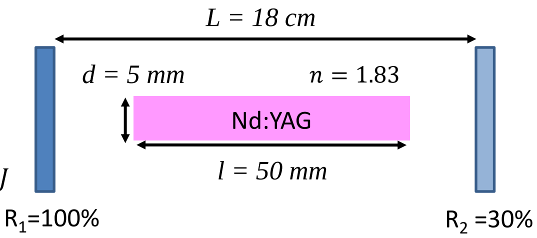
$\eta_E \cong 0.94 \qquad \sigma = 2.8\ 10^{-19} cm^2$

Assuming $\quad A_b \cong A = 0.19\ cm^2$

$\gamma_2 = -\ln R_2 \cong 1.2$

Q-switch





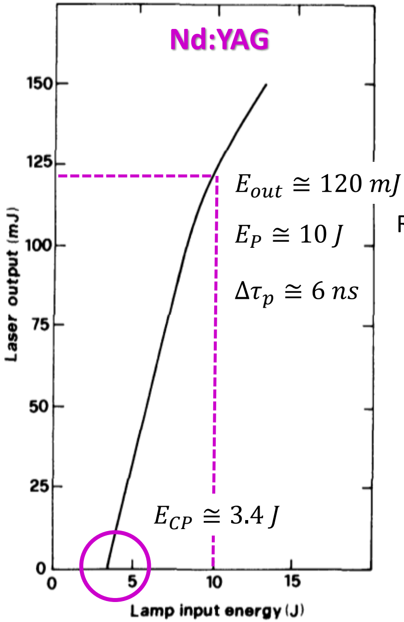
$$E_{out}(th) = 200\ mJ > E_{out}(exp) \cong 120\ mJ$$

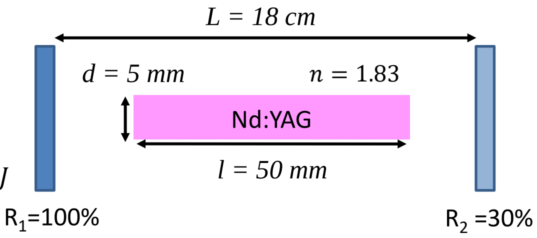
1. $A_b < A$, while we assumed $A_b \cong A$

2. Since the cavity is very short ($L = 18\ cm$), the fast-switching condition (i.e., the switching time is much shorter than the build-up time) could be not-satisfied.

Part of the energy could be lost during the switching process.

Q-switch





Pulse duration

$$\Delta\tau_p = \eta_E \tau_c \frac{x}{x - 1 - \ln(x)} = 3.3\ ns$$

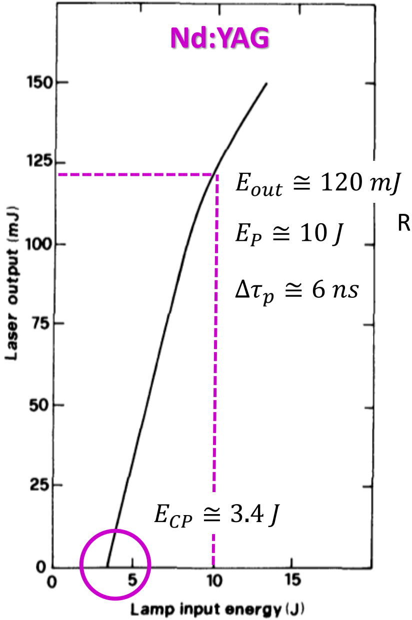
$$x = 2.9 \qquad \eta_E \cong 0.94 \qquad \tau_c = \frac{L_e}{c\gamma} \cong 1\ ns$$

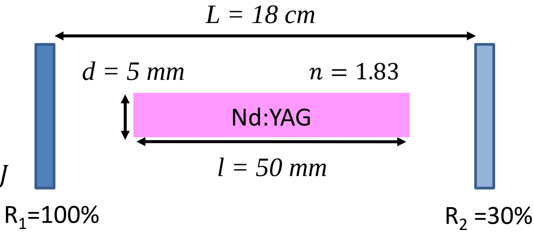
$$L_e = L + (n-1)l \cong 22\ cm$$

$$\gamma = \gamma_i + \frac{\gamma_1 + \gamma_2}{2} \cong 0.762 \qquad \gamma_2 = -\ln R_2 \cong 1.2$$

$$\gamma_i = -ln(1 - L_i) \cong 0.162 \qquad \gamma_1 = -\ln R_1 \cong 0$$

Q-switch





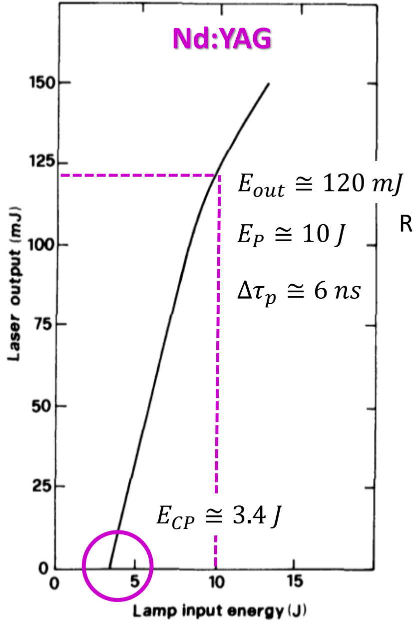
$$\Delta\tau_p(th) = 3.3\ ns < \Delta\tau_p(exp) \cong 6\ ns$$

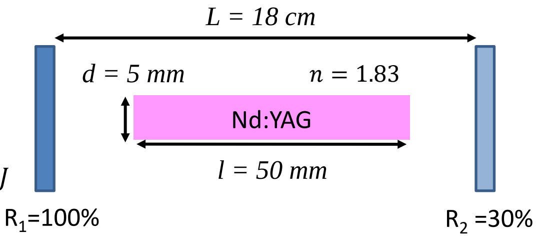
1. Multi-mode oscillation:

   the build-up time is different for the different modes oscillating in the cavity (for the different gain)

2. fast-switching condition not-satisfied: pulse broadening

Q-switch





Build-up time

$$\tau_d = \frac{\tau_c}{x-1}\ln\left(\frac{\phi_P}{10}\right) \cong 20\ ns$$

$$x = 2.9 \qquad \eta_E \cong 0.94 \qquad \tau_c = \frac{L_e}{c\gamma} \cong 1\ ns$$

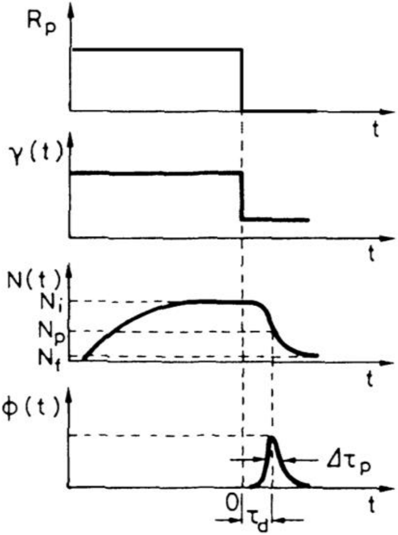
$$\phi_P = V_a N_P[x-1-\ln(x)] \cong 4.54\ 10^{17}$$

$$N_P = N_C = \frac{\gamma}{\sigma l} \cong 5.44\ 10^{17}\,cm^{-3}$$

Assuming $V_a = A_b l \cong A l \cong 1\ cm^3$

Q-switch

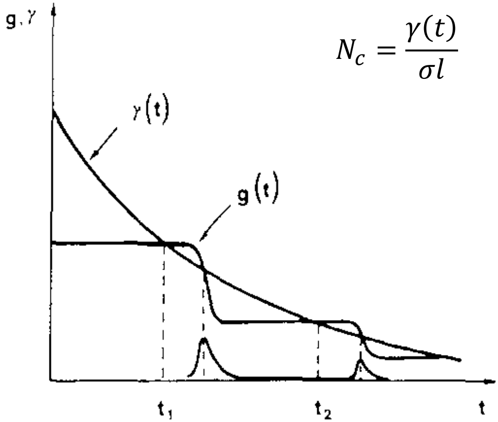
Fast Q-switch



Slow Q-switch

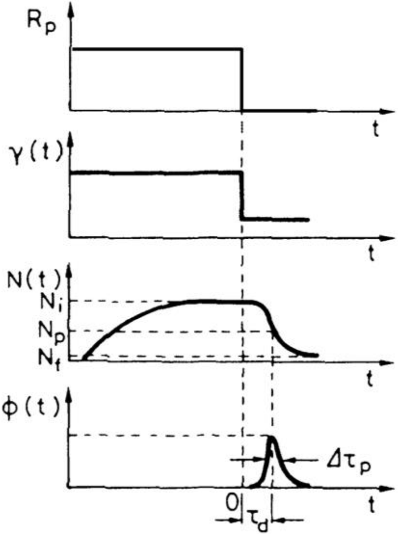
$$g(t) = \sigma(N_2 - N_1) = \sigma N(t)$$

$$N_c = \frac{\gamma(t)}{\sigma l}$$

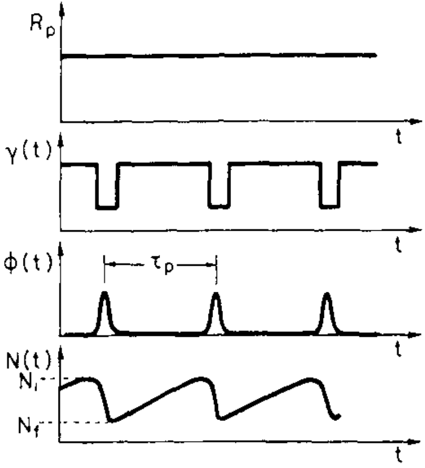


Q-switch

Pulsed operation



Continuously pumped, repetitively Q-switched operation

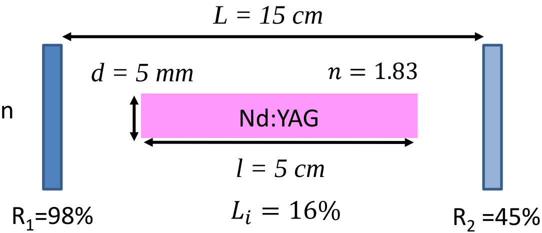


Q-switched Nd:YAG

A Nd:YAG laser ($n = 1.83$) oscillating at the fundamental line ($\lambda = 1064\ nm$) is operated in Q-switch mode. The active medium is a cylindric rod of length $l = 5\ cm$ and diameter $d = 5\ mm$. The resonant cavity is a Fabry-Perot cavity of length $L = 15\ cm$, made of a first mirror with reflectivity $R_1 = 98\%$ and a second mirror (outcoupling mirror) with $R_2 = 45\%$. The laser has a threshold energy of $E_{th} = 4\ J$ and is pumped with an energy $E_p = 8\ J$.
Assuming that the internal losses for single pass are $L_i = 16\%$, and that the beam spot coincides with the transverse section of the rod and the volume of the mode coincides with the active medium volume, determine:

1. the pulse energy
2. the pulse duration
3. the photon lifetime
4. the peak population inversion
5. the critical population inversion
6. the peak photon number
7. the build-up time

$h = 6.63\ 10^{-34}\ Js$ $\qquad c = 3\ 10^8\ m/s$



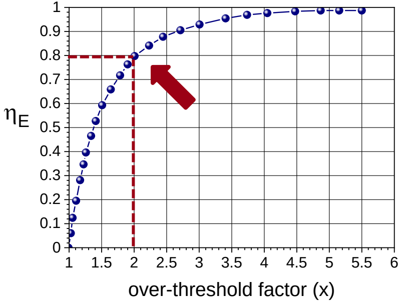
Q-switched Nd:YAG

1. the pulse energy

$$E = \eta_E\left(\frac{\gamma_2}{2}\right)\left(\frac{A_b}{\sigma}\right)\left(\frac{N_i}{N_P}\right)h\nu = 83.7\ mJ$$

$$x = \frac{N_i}{N_P} = \frac{E_p}{E_{th}} = \frac{8\ J}{4\ J} = 2 \qquad \eta_E = 0.8$$

$$\gamma_2 = -\ln R_2 \cong 0.7985$$

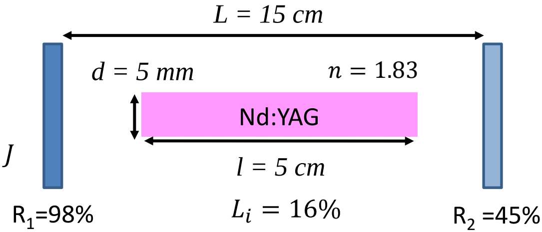


$$h = 6.63\ 10^{-34}\ Js \qquad c = 3\ 10^{8}\ m/s$$

$$A_b \cong A = \pi\left(\frac{d}{2}\right)^2 \cong 0.19635\ cm^2$$

$$\lambda = 1.064\ \mu m \qquad h\nu = 1.87\ 10^{-19}\ J$$

$$\sigma = 2.8\ 10^{-19}\ cm^2$$



Q-switched Nd:YAG

2. the pulse duration

$$\Delta\tau_p = \eta_E \tau_c \frac{x}{x - 1 - \ln(x)} = 5.7\, ns$$

$$x = \frac{N_i}{N_P} = \frac{E_p}{E_{th}} = \frac{8\,J}{4\,J} = 2 \qquad \eta_E = 0.8$$

$$\gamma_2 = -\ln R_2 \cong 0.7985$$

$$\gamma_1 = -\ln R_1 \cong 0.0202$$

$$\gamma_i = -ln(1 - L_i) \cong 0.17435$$

$$\gamma = \gamma_i + \frac{\gamma_1 + \gamma_2}{2} \cong 0.5837$$

$$A_b \cong A = \pi\left(\frac{d}{2}\right)^2 \cong 0.19635\, cm^2$$

$$\lambda = 1.064\,\mu m \qquad h\nu = 1.87\;10^{-19}\,J$$

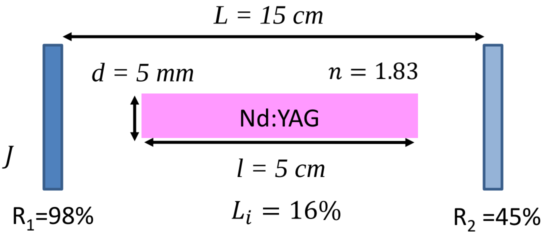
$$\sigma = 2.8\;10^{-19}\,cm^2$$

3. the photon lifetime

$$\tau_c = \frac{L_e}{c\gamma} = 1.09\, ns$$

$$L_e = L + (n-1)l = 19.15\, cm$$

$$h = 6.63\;10^{-34}\,Js \qquad c = 3\;10^8\,m/s$$



Q-switched Nd:YAG

4. the peak population inversion

$$N_P = \frac{\gamma}{\sigma l} = N_C = 4.17\ 10^{17}\ cm^{-3}$$

$$x = \frac{N_i}{N_P} = \frac{E_p}{E_{th}} = \frac{8\ J}{4\ J} = 2 \qquad \eta_E = 0.8$$

$$\gamma_2 = -\ln R_2 \cong 0.7985$$

$$\gamma_1 = -\ln R_1 \cong 0.0202$$

$$\gamma_i = -ln(1 - L_i) \cong 0.17435$$

$$A_b \cong A = \pi\left(\frac{d}{2}\right)^2 \cong 0.19635\ cm^2$$

$$\lambda = 1.064\ \mu m \qquad h\nu = 1.87\ 10^{-19}\ J$$

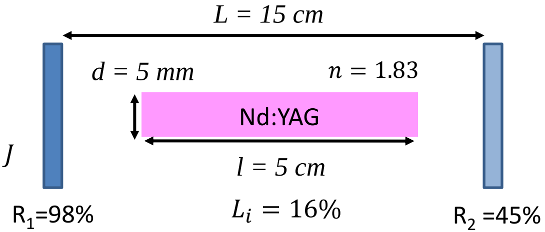
$$\sigma = 2.8\ 10^{-19}\ cm^2$$

5. the critical population inversion

$$L_e = L + (n-1)l = 19.15\ cm$$

$$\gamma = \gamma_i + \frac{\gamma_1 + \gamma_2}{2} \cong 0.5837 \qquad \tau_c = \frac{L_e}{c\gamma} = 1.09\ ns$$

$$h = 6.63\ 10^{-34}\ Js \qquad c = 3\ 10^8\ m/s$$



Q-switched Nd:YAG

6. the peak photon number

$$\phi(N) = V_a\left[N_i - N - N_P \ln\left(\frac{N_i}{N}\right)\right]$$

$$\phi_P = V_a N_P[x - 1 - \ln(x)] = 1.26\ 10^{17}$$

$$N_P = \frac{\gamma}{\sigma l} = N_C = 4.17\ 10^{17}\ cm^{-3}$$

$$x = \frac{N_i}{N_P} = \frac{E_p}{E_{th}} = \frac{8\ J}{4\ J} = 2 \qquad \eta_E = 0.8$$

$$L_e = L + (n-1)l = 19.15\ cm$$

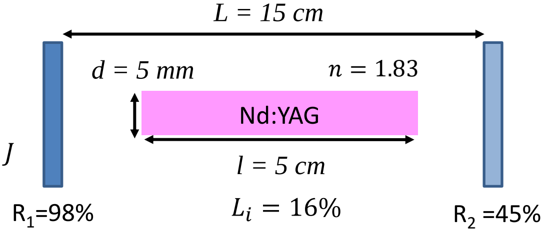
$$\gamma_2 = -\ln R_2 \cong 0.7985 \qquad \gamma = \gamma_i + \frac{\gamma_1 + \gamma_2}{2} \cong 0.5837 \qquad \tau_c = \frac{L_e}{c\gamma} = 1.09\ ns$$

$$\gamma_1 = -\ln R_1 \cong 0.0202$$

$$\gamma_i = -ln(1 - L_i) \cong 0.17435$$

$$h = 6.63\ 10^{-34}\ Js \qquad c = 3\ 10^8\ m/s$$

$$A_b \cong A = \pi\left(\frac{d}{2}\right)^2 \cong 0.19635\ cm^2$$



$$\lambda = 1.064\ \mu m \qquad h\nu = 1.87\ 10^{-19}\ J$$

$$\sigma = 2.8\ 10^{-19}\ cm^2$$

Q-switched Nd:YAG

7. the build-up time

$$\phi_P = V_a N_P[x - 1 - \ln(x)] = 1.26\ 10^{17}$$

$$\tau_d = \frac{\tau_c}{x-1} \ln\left(\frac{\phi_P}{10}\right) = 37\tau_c \cong 40.3\ ns$$

$$N_P = \frac{\gamma}{\sigma l} = N_C = 4.17\ 10^{17}\ cm^{-3}$$

$$x = \frac{N_i}{N_P} = \frac{E_p}{E_{th}} = \frac{8\ J}{4\ J} = 2 \qquad \eta_E = 0.8$$

$$L_e = L + (n-1)l = 19.15\ cm$$

$$\gamma_2 = -\ln R_2 \cong 0.7985$$

$$\gamma = \gamma_i + \frac{\gamma_1 + \gamma_2}{2} \cong 0.5837 \qquad \tau_c = \frac{L_e}{c\gamma} = 1.09\ ns$$

$$\gamma_1 = -\ln R_1 \cong 0.0202$$

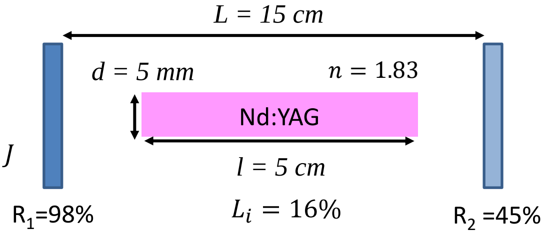
$$h = 6.63\ 10^{-34}\ Js \qquad c = 3\ 10^8\ m/s$$

$$\gamma_i = -ln(1 - L_i) \cong 0.17435$$

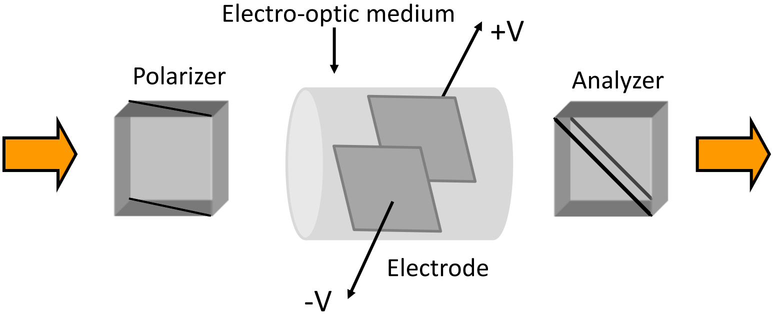
$$A_b \cong A = \pi\left(\frac{d}{2}\right)^2 \cong 0.19635\ cm^2$$

$$\lambda = 1.064\ \mu m \qquad h\nu = 1.87\ 10^{-19}\ J$$

$$\sigma = 2.8\ 10^{-19}\ cm^2$$



Electro-optic Kerr effect



$$\Delta n = (n_{//} - n_{\perp}) = K\lambda E^2$$

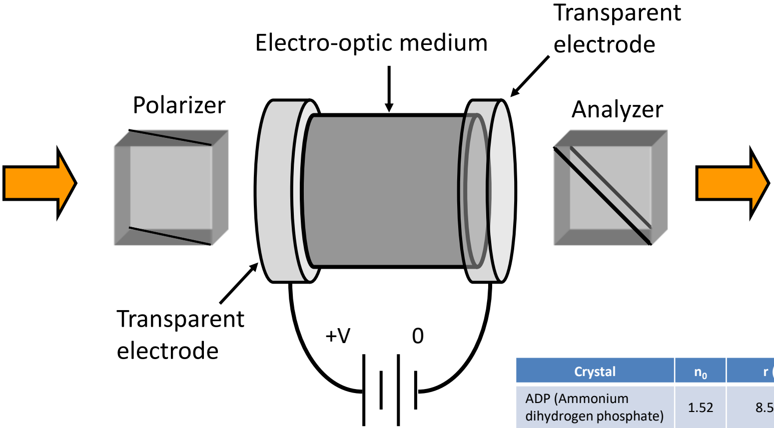
$$\Delta\phi = kl\Delta n = 2\pi l K \left(\frac{\Delta V}{d}\right)^2$$

1 statvolt = 300V

TABLE 8.3 Kerr constants for some selected liquids (20°C, λ_0 = 589.3 nm).

	Substance	K (in units of 10^{-7} cm statvolt^{-2})
Benzene	C_6H_6	0.6
Carbon disulfide	CS_2	3.2
Chloroform	$CHCl_3$	−3.5
Water	H_2O	4.7
Nitrotoluene	$C_5H_7NO_2$	123
Nitrobenzene	$C_6H_5NO_2$	220

Pockels effect



Crystal	n_0	r (m/V)
ADP (Ammonium dihydrogen phosphate)	1.52	8.5×10^{-12}
KDP (Potassium dihydrogen phosphate)	1.51	10.6×10^{-12}

$$n_x = n_0 - \frac{1}{2} n_0^3 r E_z$$
$$n_y = n_0 + \frac{1}{2} n_0^3 r E_z$$

$$\Delta\phi = kl\Delta n = \frac{2\pi}{\lambda_0} n_0^3 r \Delta V$$

Active shutter

l is the length of the nonlinear crystal in the PC

the Pockels cell works as a QWP

$$\Delta\phi = kl\Delta n = \frac{2\pi}{\lambda_0} n_0^3 r \Delta V = \frac{\pi}{2}$$

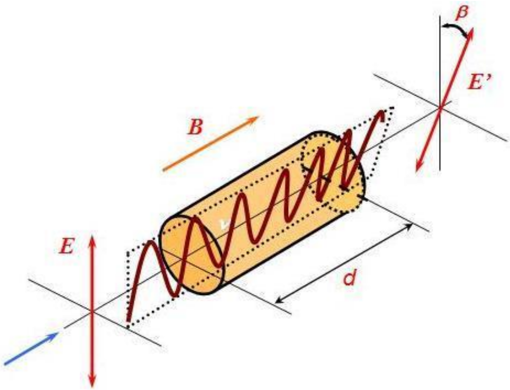
at each pass

Each time the beam passes through the Pockels cell, it acquires a phase-shift of $\frac{\pi}{2}$, so the reflected beam will arrive at the linear polarizer with a total phase-shift of π: its linear polarization will be rotated of 90°.

The shutter will be closed!

This configuration can be used to block reflected beams (e.g., preventing them from entering a laser cavity)

Faraday rotation



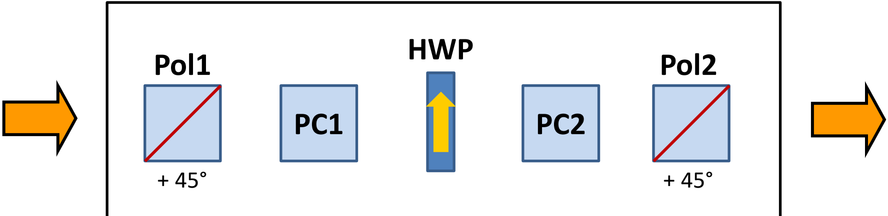
$$\boxed{\beta = V\ B\ d}$$

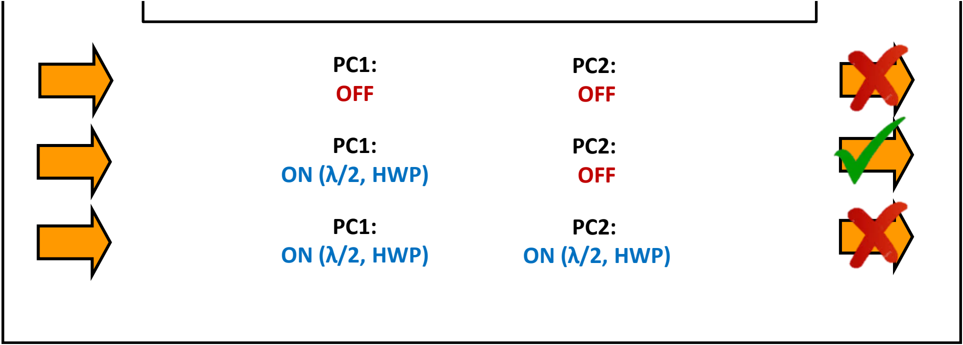
$\beta = 45°$ ➡ Faraday Isolator

V = Verdet's constant (rad/T m)

Pulse slicer

PC $\Delta\phi = kl\Delta n = \frac{2\pi}{\lambda_0} n_0^3 r \Delta V = \pi$ **HWP**




PC1:
OFF
PC2:
OFF
PC1:
ON (λ/2, HWP)
PC2:
OFF
PC1:
ON (λ/2, HWP)
PC2:
ON (λ/2, HWP)