A DIVE INTO PULSED LASER GENERATION TECHNIQUES

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Why pulsed laser

Cavity Dumping

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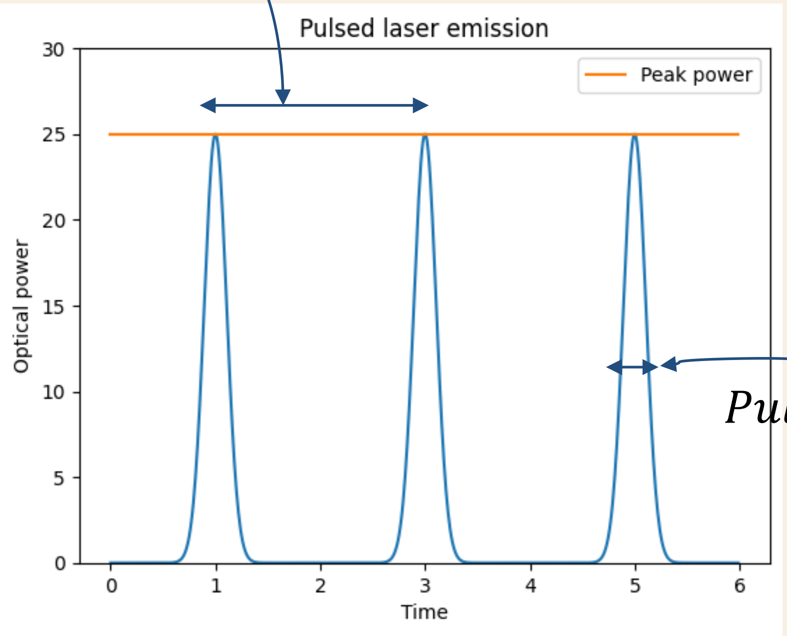
Method of Mode locking

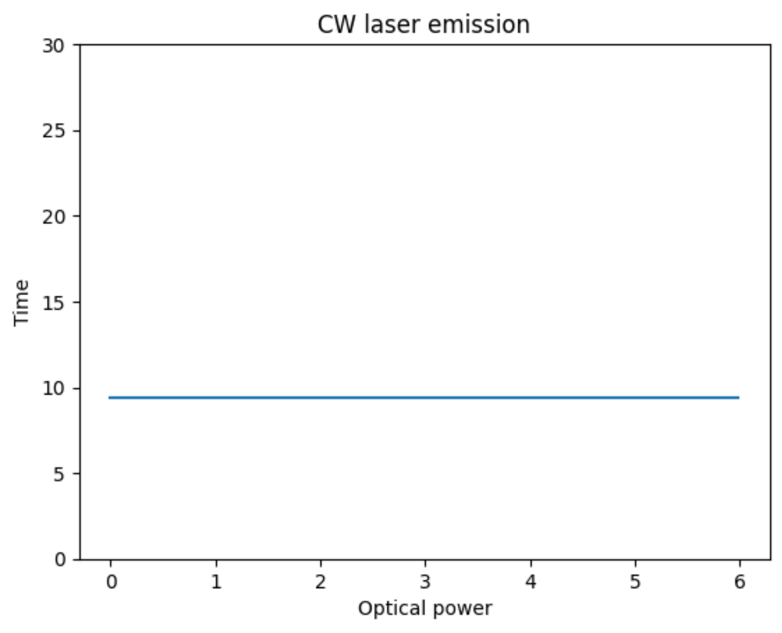
INTRODUCTION

- A type of laser system that emits lights in short pulse rather than a continuous wave

Pulse duration



Pulse width



The average power of pulsed and CW laser is almost equal.

The average power, $P_{avg} = P_{peak} * \tau/T$

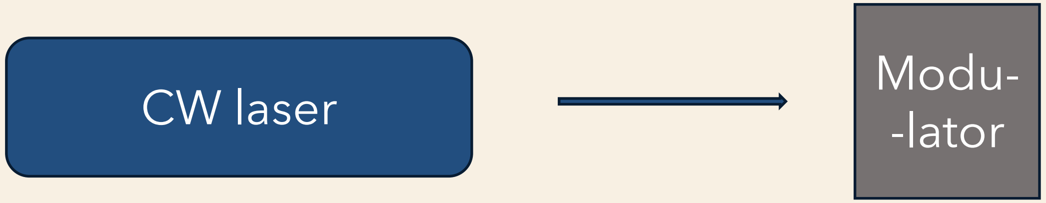
Energy per pulse, $E = P_{avg}T = P_{peak}\tau$

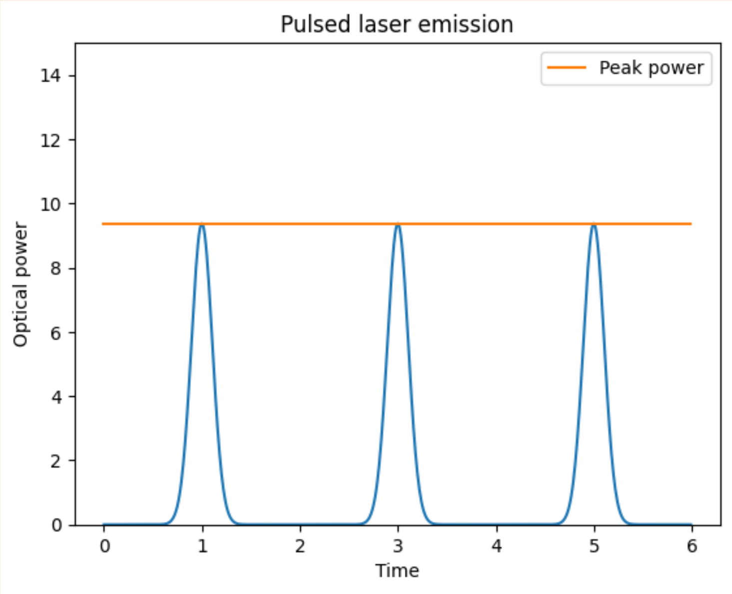
WHY PULSED LASERS

- **Medical Application:** Pulsed lasers are commonly used for procedures like eye surgery(LASIK), tattoo removal, and dental treatments.
- **Optical Communication:** Pulsed lasers are employed in free-space optical communication systems for transmitting data in the form of modulated light pulses.
- **Material Processing:** Applications such as laser cutting, welding, drilling, and pulsed lasers are advantageous.pplications such as laser cutting, welding, and drilling, pulsed lasntageous
- **Scientific Research**
- **Atomic Clock**
- **Frequency Comb**

EXTERNAL MODULATION

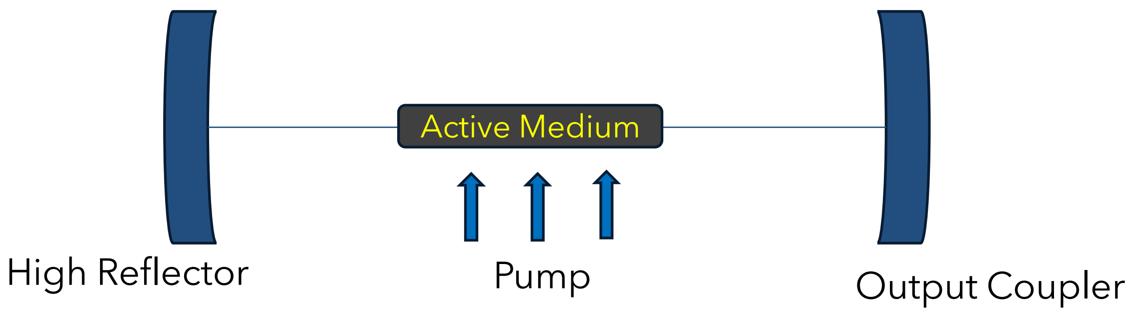
An optical signal generated by a continuous-wave (CW) laser is modulated by an external modulator(e.g. , Optical chopper, electro-optic modulator (EOM), acoustic-optic modulator(AOM)).





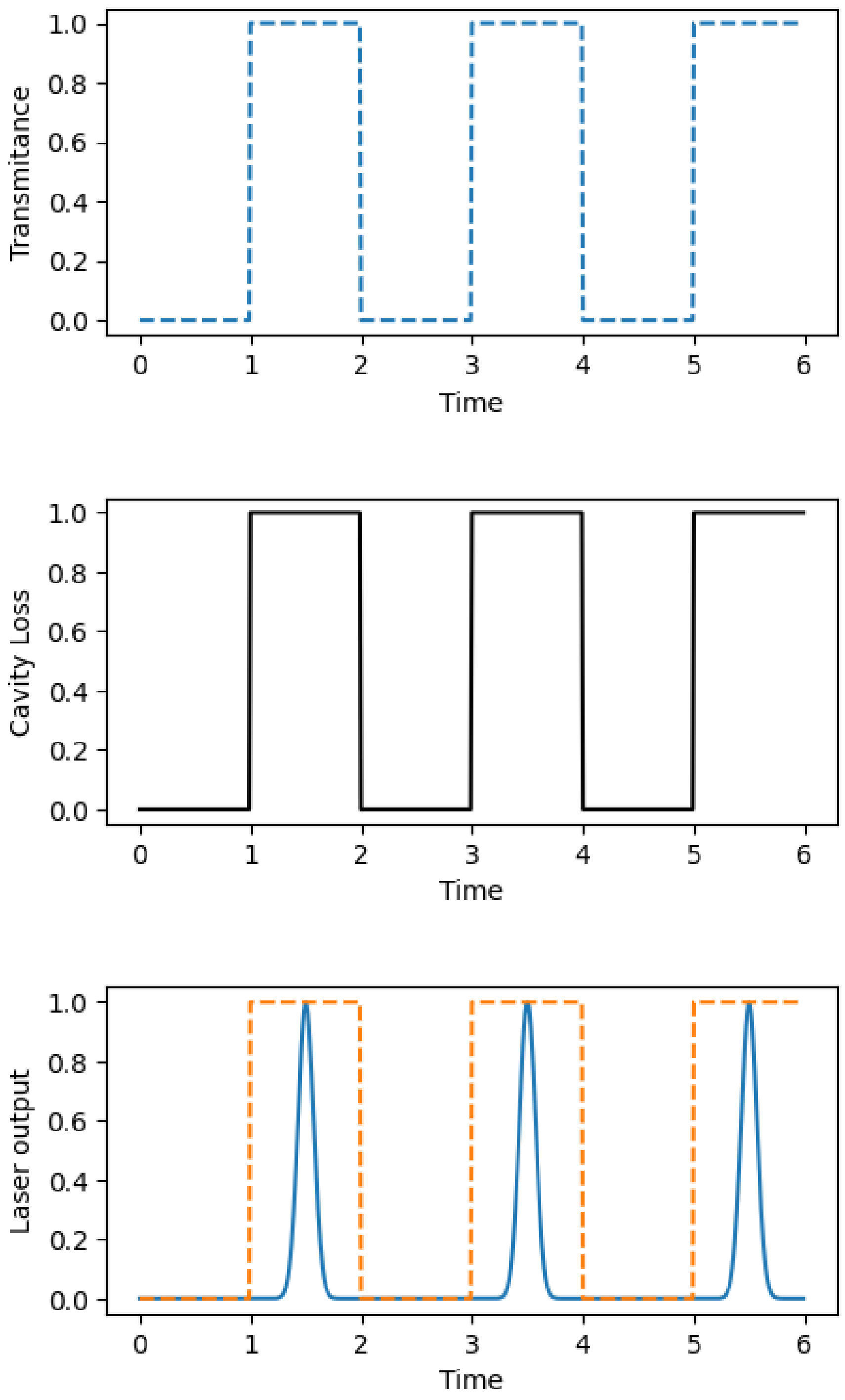
- Useful if CW laser is available but pulsed laser is needed.
- Energy inefficient, since the energy is wasted during off time

CAVITY DUMPING



In this technique, we create a large no of stimulated photons inside the cavity and both the mirror is high reflectors.

Energy increases in the cavity, after storing in a pulse we take the output with switchable mirror.



Q-SWITCHING

$$Q = 2\pi \frac{Energy\ stored\ in\ cavity}{Energy\ loss\ per\ optical\ cycle}$$

Increase the loss in the cavity.

⬇

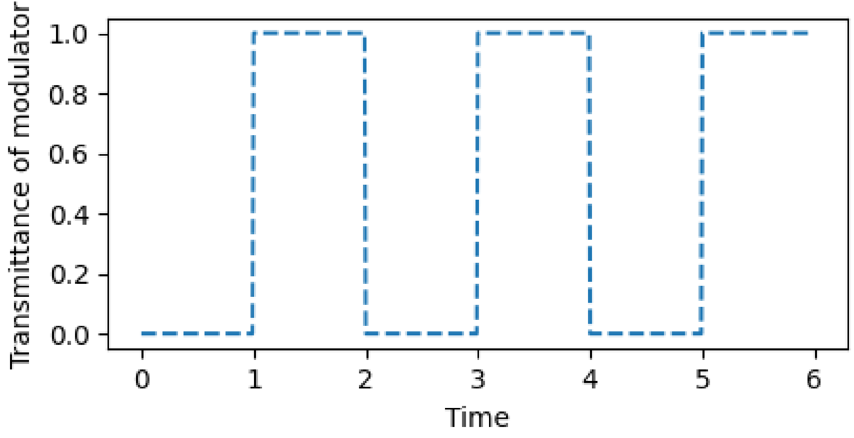
Create population inversion.

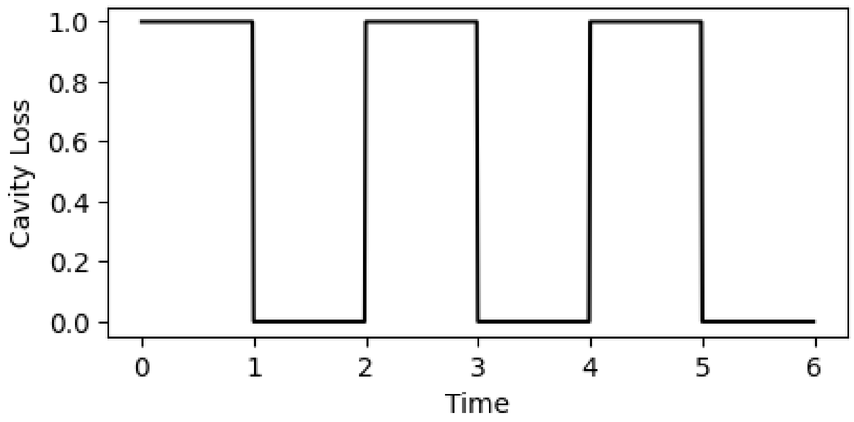
⬇

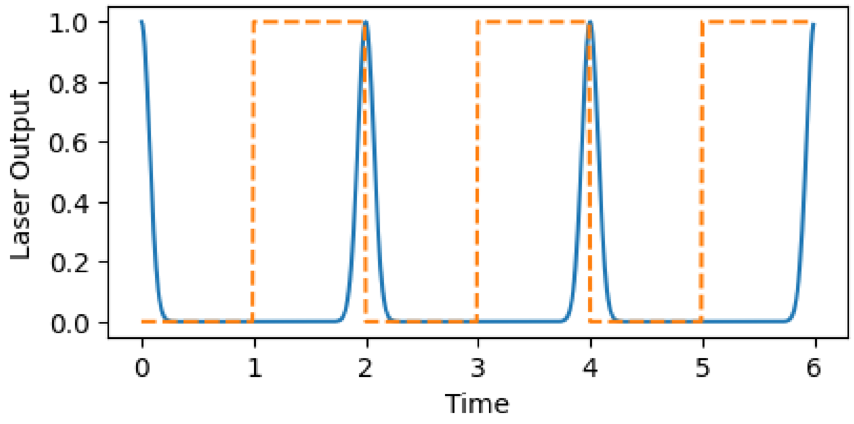
Enough PI achieved, reduce the loss

⬇

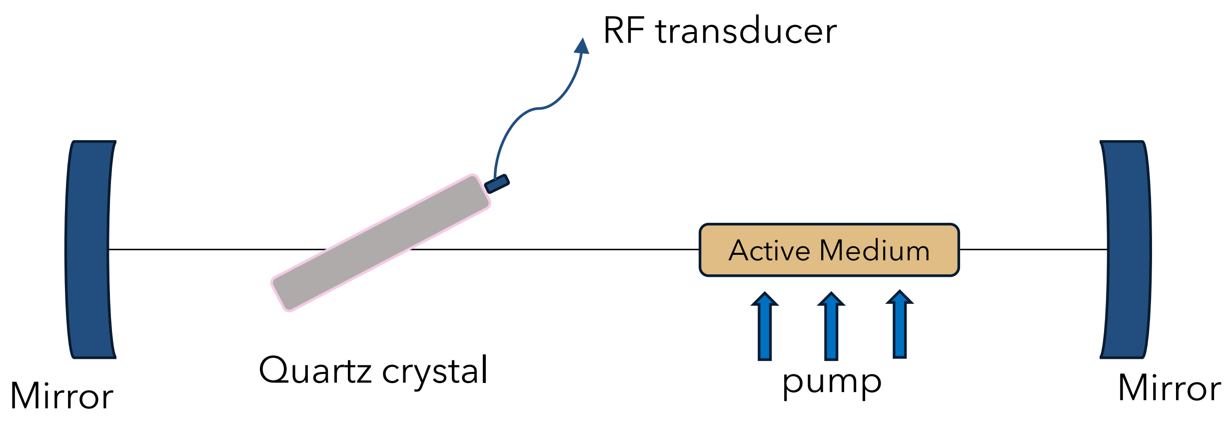
Release Large number of photon in short time







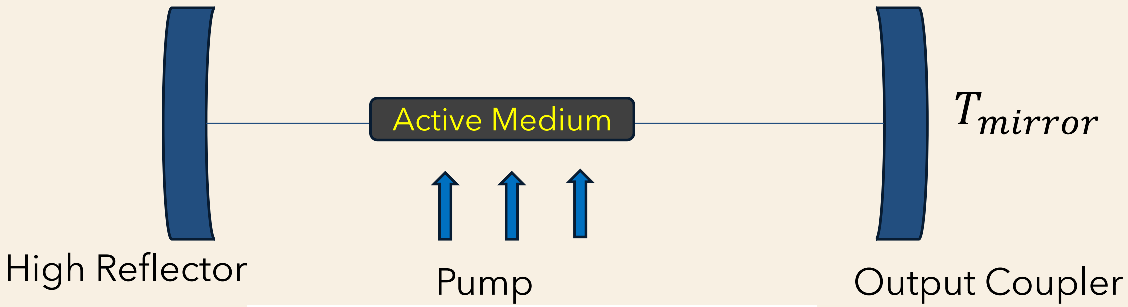
ACOUSTO-OPTIC SHUTTER

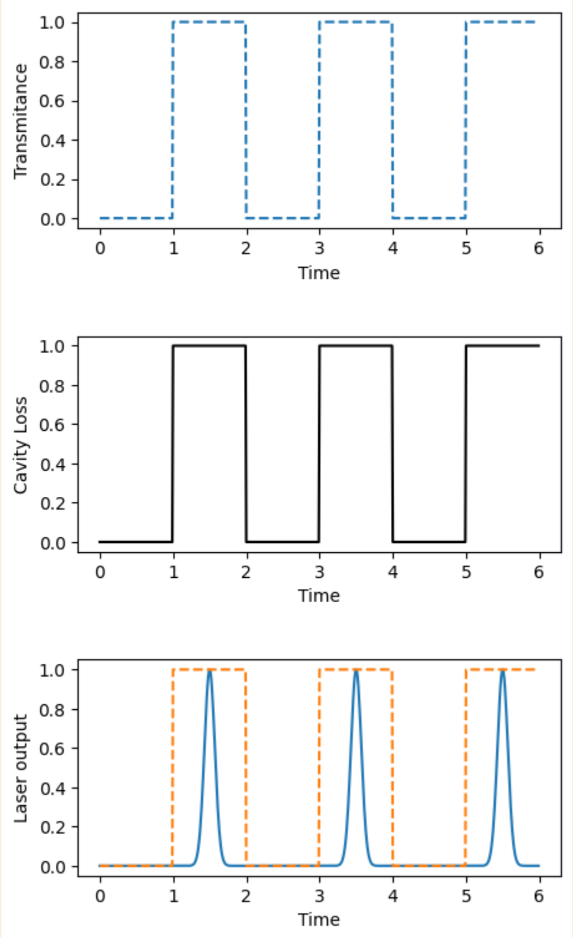


RF on – Beam deflected out of the cavity, yielding high loss.

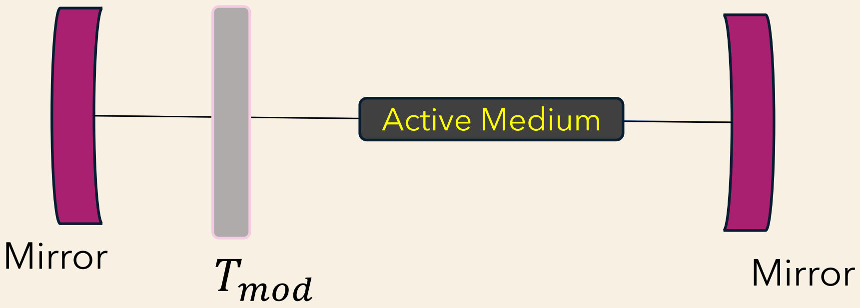
RF off – Beam transits the cavity with low loss.

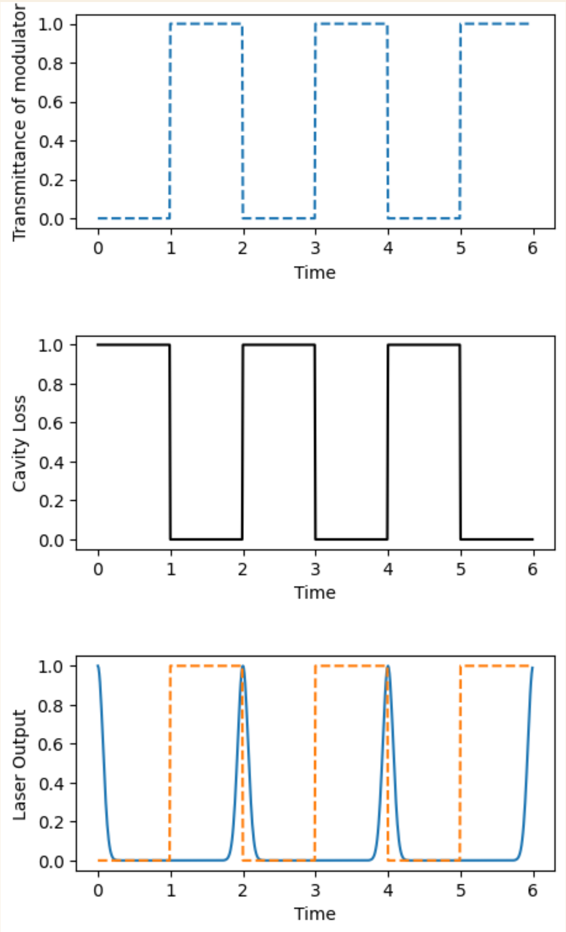
CAVITY DUMPING

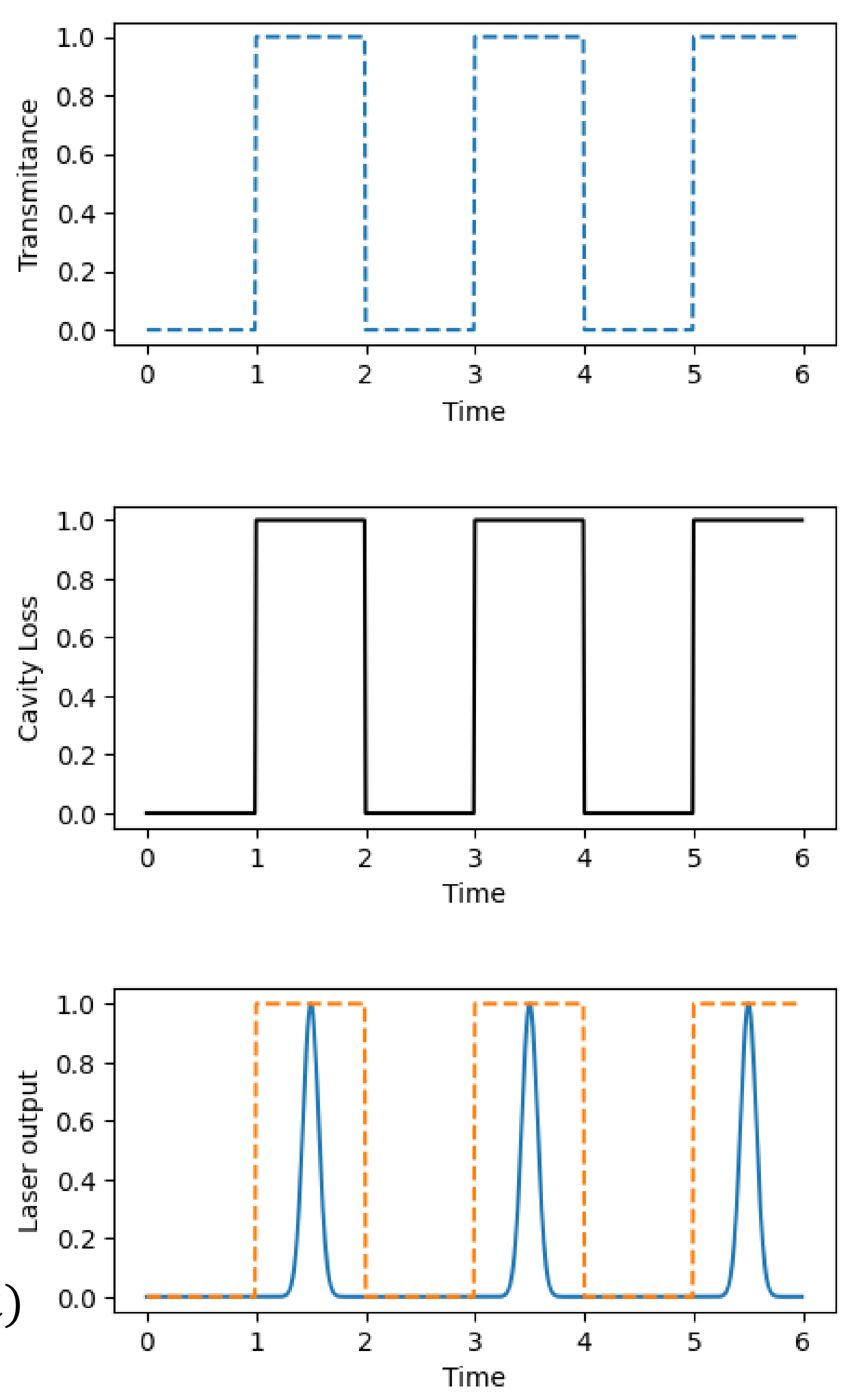




Q-SWITCHING

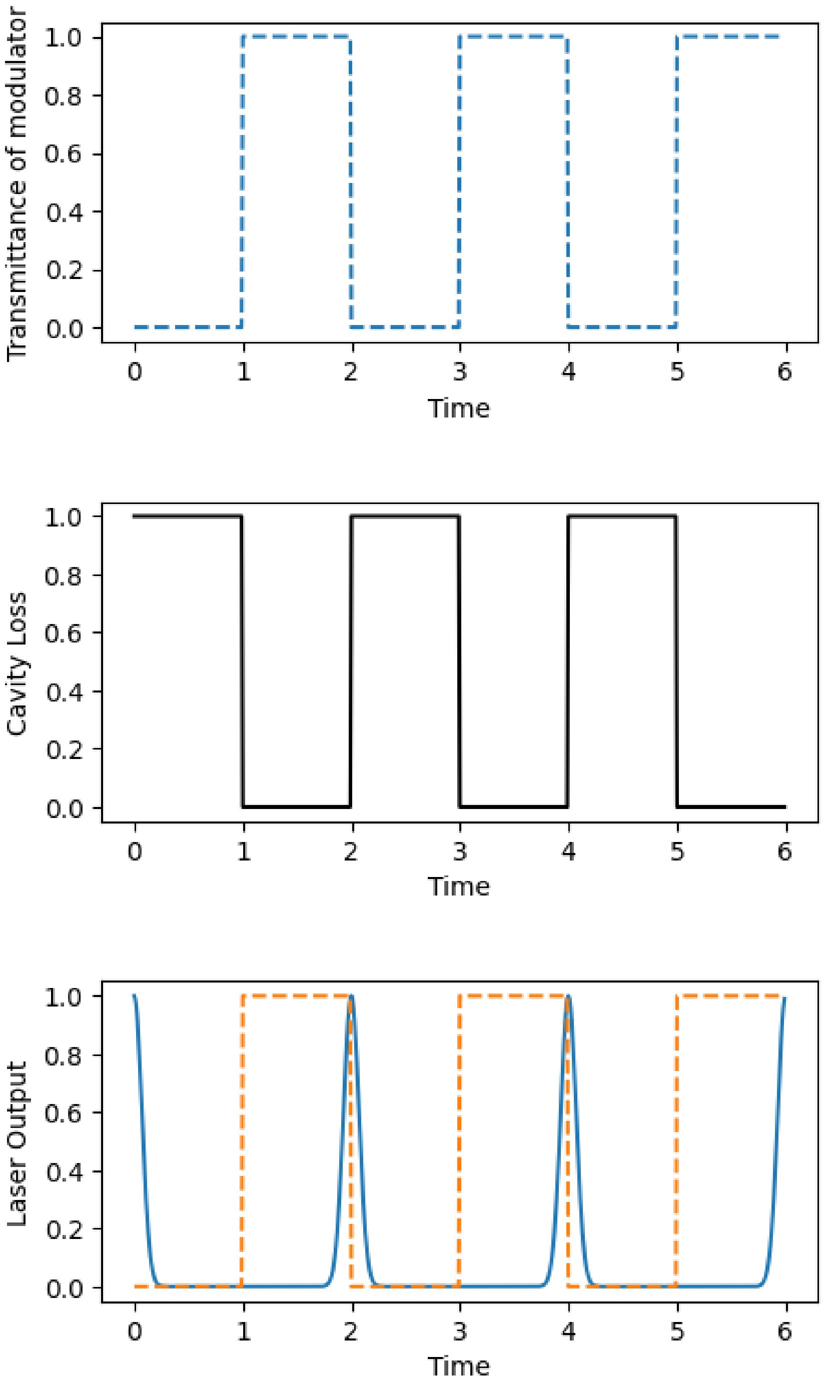






Transmittance
Cavity Loss
Laser output
Time

a)



Transmittance of modulator
Cavity Loss
Laser Output
Time

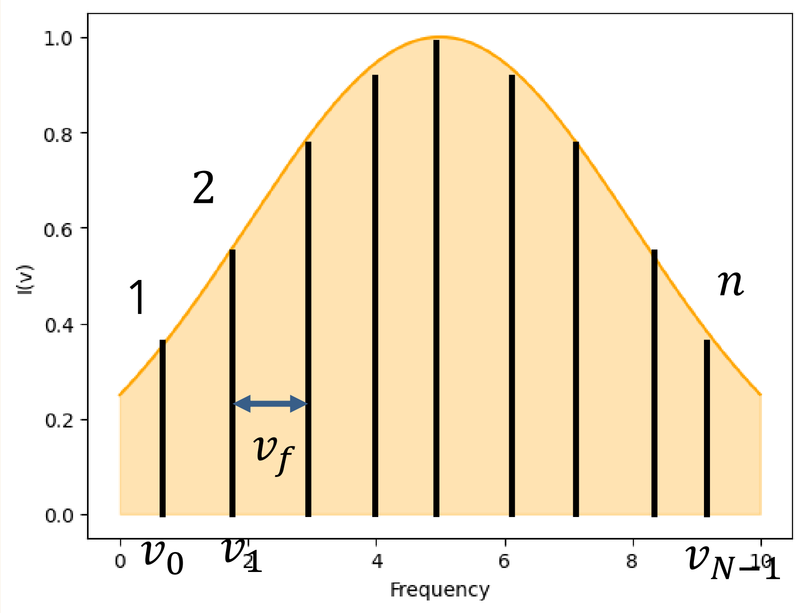
b)

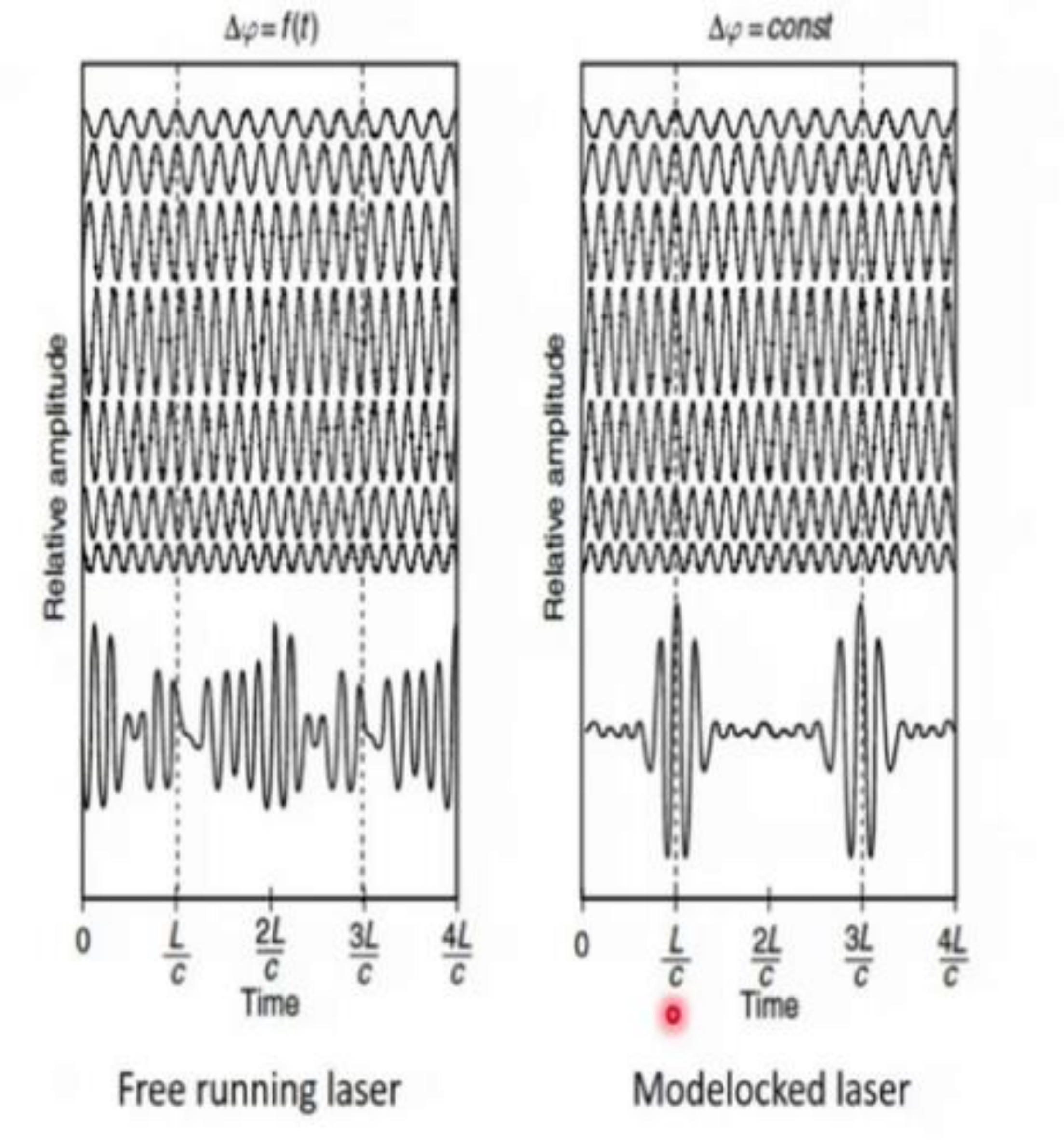
MODE LOCKING

This technique allows the generation of optical pulses as short fs, ultrashort pulses).

Mode locking is all about creating a phase relation somehow and maintaining it.

E.g. Ti: Sapphire laser





MODE LOCKING

The amplitude of the nth mode of Electric field can be written as

$$E(t) = \sum_{n=0}^{N-1} E_n e^{\iota 2\pi \nu_n t - \iota \phi_n}$$

ν_n is the frequency and ϕ_n is the initial phase

$\nu_n = \nu_0 + n\nu_f$

ν_0 is the frequency of the first mode

The combined total amplitude of the modes can be expressed as

$$E(t) = E_0 \sum_{n=0}^{N-1} e^{\iota 2\pi \nu_n t - \iota \phi_n}$$

MODE LOCKING

The difference in frequency between the modes is given by

$$v_{n+1} - v_n = \Delta v = \frac{c}{2nd}$$

The total intensity of the multi-longitudinal modes output is

$$I(t) = |E(t)|^2 = \sum_{m=0}^{N-1} E_m e^{\iota 2\pi \nu_m t - \iota \phi_n} \sum_{n=0}^{N-1} E_n^* e^{-\iota 2\pi \nu_n t + \iota \phi_n}$$

$$I(t) = \sum_n |E_0|^2 + \sum_n \sum_m E_n E_m^* e^{\iota 2\pi (v_n - v_m) t - \iota (\phi_n - \phi_m)}$$

MODE LOCKING

$$I(t) = N|E_0|^2 + |E_0|^2 \sum_n \sum_m e^{\iota 2\pi(v_n - v_m)t - \iota(\phi_n - \phi_m)}$$

The intensity is equal to N times the intensity of individual modes.

$$I(t) = N|E_0|^2$$

This value can vary if a few modes randomly phase together, But for a large value of N, it doesn’t vary significantly from the average value.

$$I(t) = N|E_0|^2 \pm |E_0|^2$$

MODE LOCKING

Let's see what will happen if we lock the phases of all the modes together; this is mode-locking.

$$\Phi_n = \phi_0 \; for \; all \; value \; of \; n$$

Then the combined total amplitude of the modes can be expressed as

$$E(t) = E_0 e^{\iota \phi_0} \sum_{n=0}^{N-1} e^{\iota 2\pi \nu_n t}$$

Since, $v_n = v_0 + n v_f$

$$E(t) = E_0 e^{\iota \phi_0} e^{\iota 2\pi \nu_o t} \sum_{n=0}^{N-1} e^{\iota 2\pi n \nu_f t}$$

MODE LOCKING

$$E(t) = E_0 e^{\iota\phi_0} e^{\iota 2\pi v_o t} \sum_{n=0}^{N-1} e^{\iota n\delta t}$$

where, $\delta = 2\pi v_f$

$$E(t) = E_0 e^{\iota\phi_0} e^{\iota 2\pi v_o t}[1 + e^{\iota\delta} + e^{\iota 2\delta} + \ldots + e^{\iota(N-1)\delta}]$$

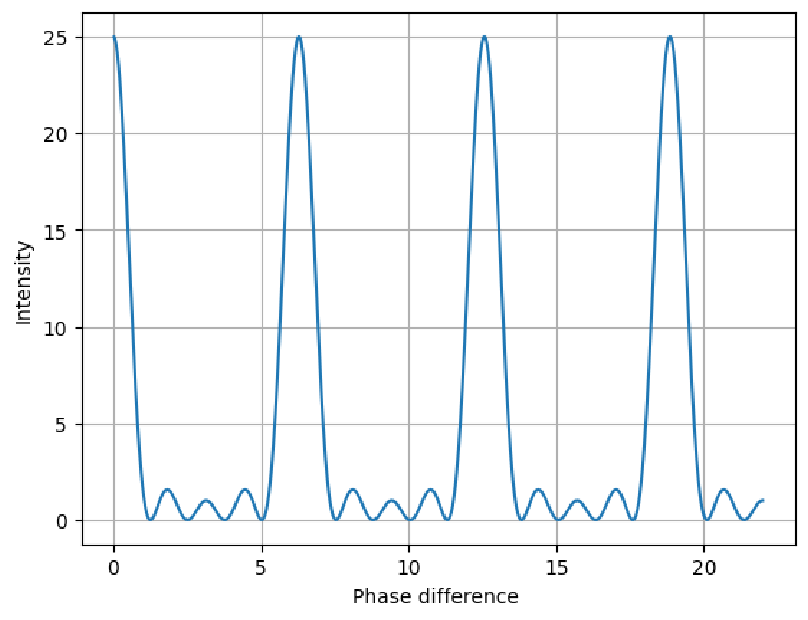
$$E(t) = E_0 e^{\iota\phi_0} e^{\iota 2\pi v_o t} \frac{[1 - e^{\iota N\delta}]}{[1 - e^{\iota\delta}]}$$

$$E(t) = E_0 e^{\iota\phi_0} e^{\iota 2\pi v_o t} \frac{e^{\frac{\iota N\delta}{2}}\left[e^{-\frac{\iota N\delta}{2}} - e^{\frac{\iota N\delta}{2}}\right]}{e^{\frac{\iota\delta}{2}}\left[e^{-\frac{\iota\delta}{2}} - e^{\frac{\iota\delta}{2}}\right]}$$

MODE LOCKING

The total intensity can be expressed as

$$I(t) = |E_0|^2 \frac{|\sin\left(\frac{N\delta}{2}\right)|^2}{|\sin\left(\frac{\delta}{2}\right)|^2}$$



Minima occur at: $\frac{N\delta}{2} = m\pi$

$\longrightarrow$ $I = 0 \; at \; \delta = \frac{2m\pi}{N}$ where m = 1,2,3 …

Maxima occur at: $\frac{\delta}{2} = m\pi$

$\longrightarrow$ By l hospital's rule $\boxed{I(t) = N^2|E_0|^2}$

METHOD OF MODE LOCKING

Active mode-locking **Passive mode-locking**

- Time gap between pulses or round trip time, $T = \frac{1}{\Delta v} = \frac{2L}{c}$,
- Pulse width $\tau = \frac{1}{N\Delta v}$
- Where N is the number of modes, and by increasing the no. of modes, one can create shorter and shorter pulses.

Before mode locking: $I = NE_0^2$

After Mode locking: $I = N^2E_0^2$

ACTIVE MODE LOCKING

The modulation frequency is adjusted to match the round-trip time of light within the cavity. This ensures that the optical modes of the laser are synchronized, causing constructive interference at specific points in time.

Electric field of one mode:

$$E(t) = E_0 cos2\pi v_1 t$$

Electric field after modulation:

$$E(t) = (E_0 + E_0 cos2\pi v_f t) cos2\pi v_1 t$$

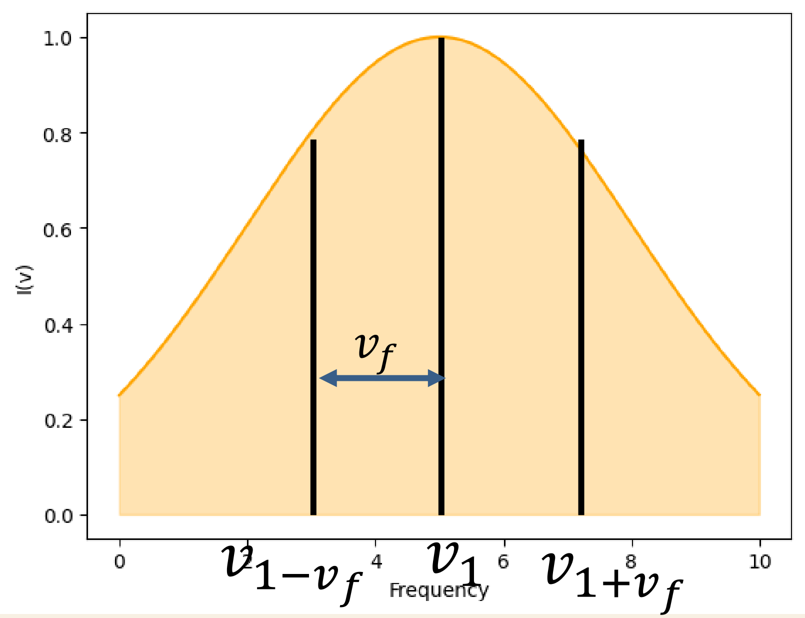
$$E(t) = E_0 cos2\pi v_1 t + \frac{E_0}{2}\left(cos2\pi\left(v_1 + v_f\right) + cos2\pi\left(v_1 - v_f\right)\right)$$

ACTIVE MODE LOCKING

$$E(t) = E_0 cos2\pi v_1 t + \frac{E_0}{2}\left(cos2\pi\left(v_1 + v_f\right) + cos2\pi\left(v_1 - v_f\right)\right)$$

The modulation in the frequency of the longitudinal modes leads to the generation of sidebands; the frequency of this sideband is equal to the frequency of the neighboring longitudinal modes.

The generated side bands are in the same phase, and other modes will also be modulated will result in the generation of the side bands in the same phase, enforcing other modes to oscillate in the same phase and resulting in mode locking.



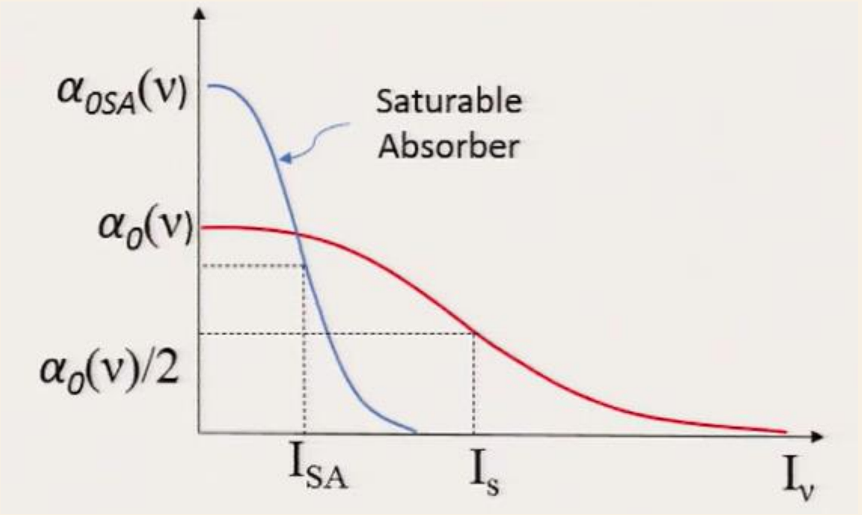
PASSIVE MODE LOCKING

The saturable absorber is used for the passive mode locking.

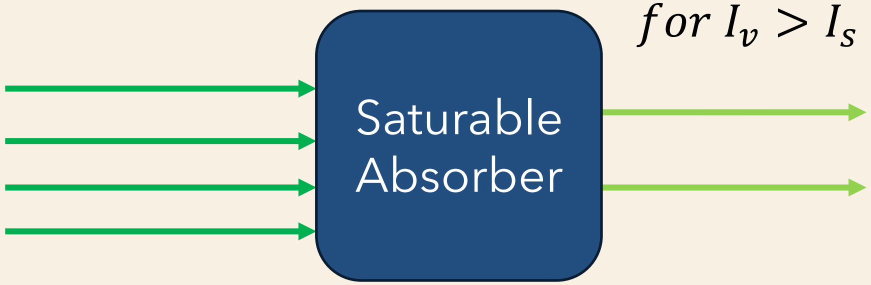
The material which have small value of I_s and large value of $\alpha_0(v)$ can act as a saturable absorber.

Saturated Absorption coefficient: $$\alpha(v) = \frac{\alpha_0(v)}{1 + \frac{I_v}{I_s}}$$

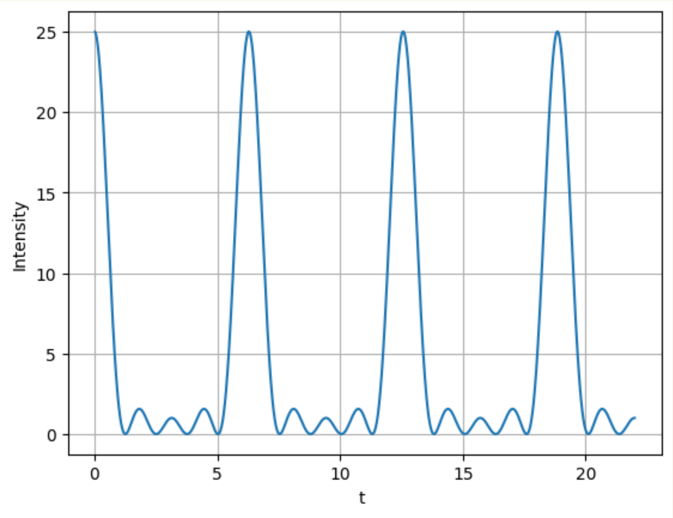
Where $\alpha_0(v)$ is small signal absorption coefficient.

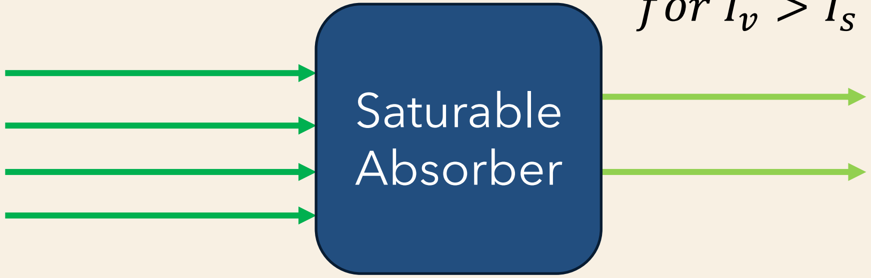


$for\ I_v > I_s$

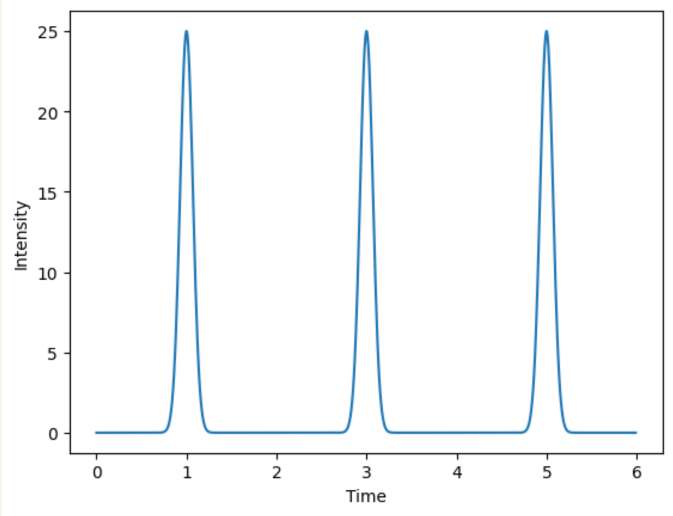


SATURABLE ABSORBER FOR PULSE CLEANING





$for\ I_v > I_s$



Saturable Absorber example: Methylene blue, Crypto cyanine

REFRENCES

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THANK YOU

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