Microwave Photonics

Lasers & Its Applications

Lecture #01

Fundamentals of Laser

Bikash Nakarmi

Outlines

Chapter I. Basics of Photonics & Laser

Chapter II. Types of Lasers & Output Characteristics

Chapter III. FPLD and operating Principle

Chapter IV. Lasers & Applications

Digital Photonics
Robust Radar Signal Generation
RADAR Interference and Imaging

Term paper presentation

Reference Books & Evaluation

1. Laser Electronics by Joseph T. Verdeyen
2. Optical Fiber communication by keiser
3. Selected journals

Class Participation-------------20%

Assignments---------------------25%

Quiz & Exam--------------------35%

Paper Presentation-------------20%

Lecture #01

Fundamentals of Laser

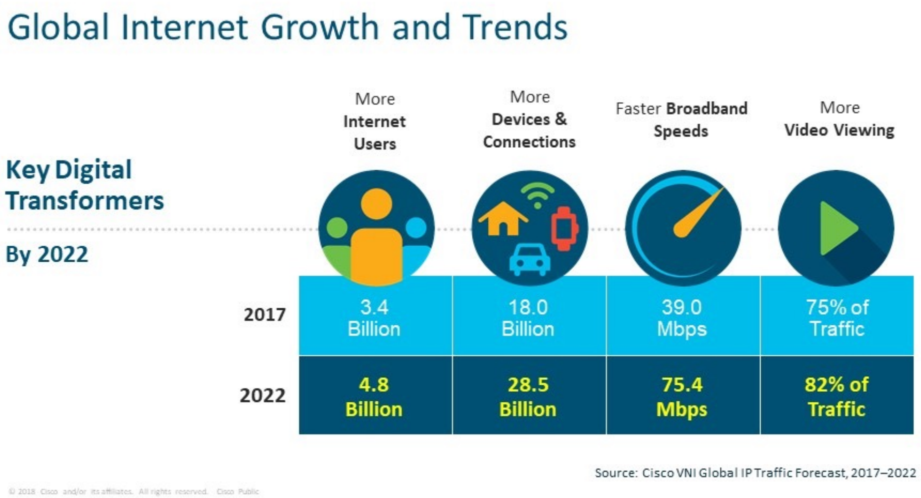
Information and Communication

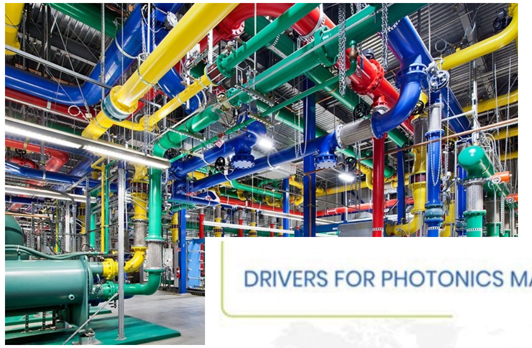
Voice, Data, or Video traffic (Multimedia)

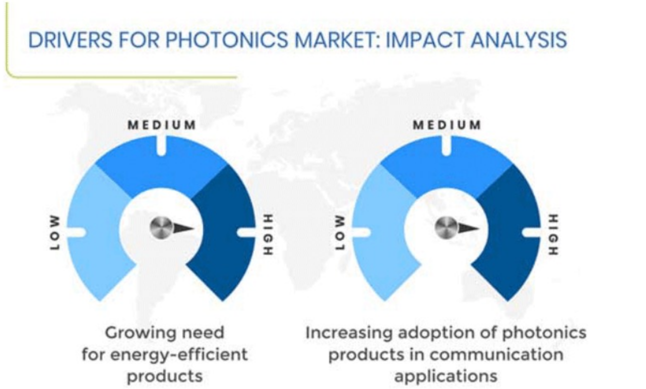
Broadband signals

(100 Mbit/s)

anyone
anytime
anywhere

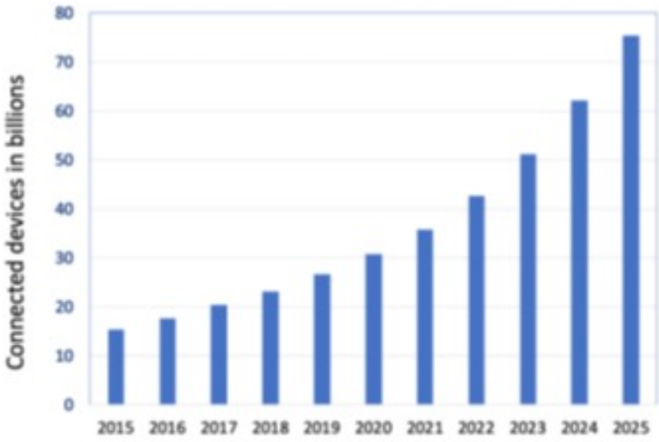


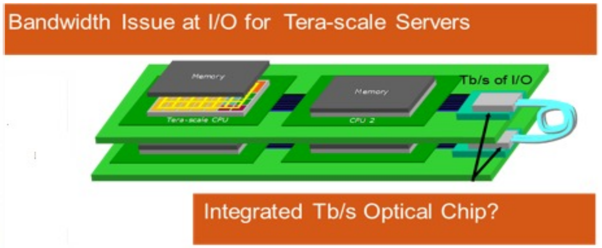


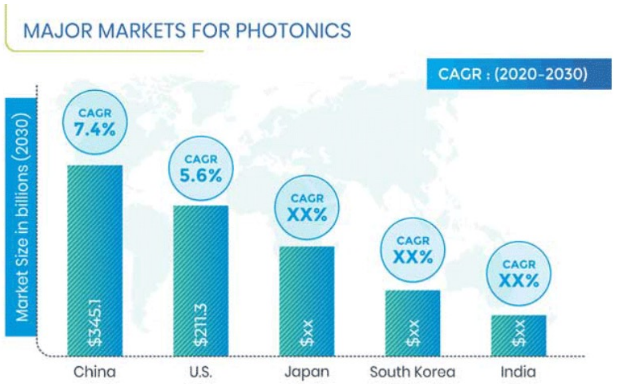


Driving forces:

- The "electronic bit-rate bottleneck"
- The demand for more bandwidth
- Power Limitations
- Widespread deployment of Dense Wavelength Division Multiplexing

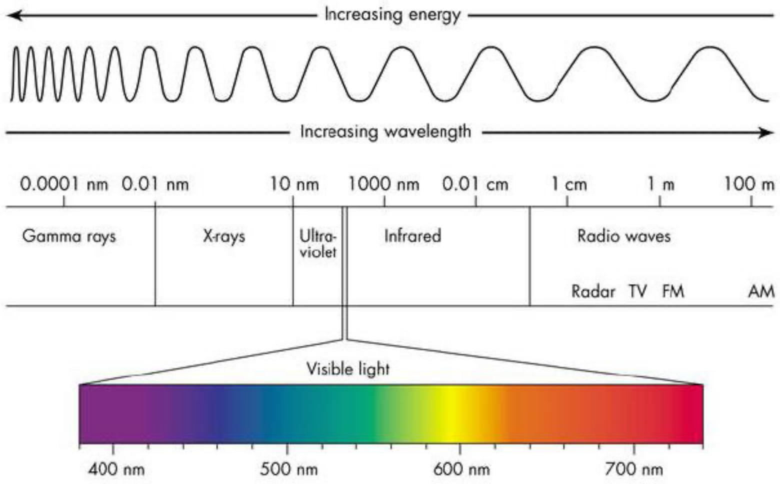


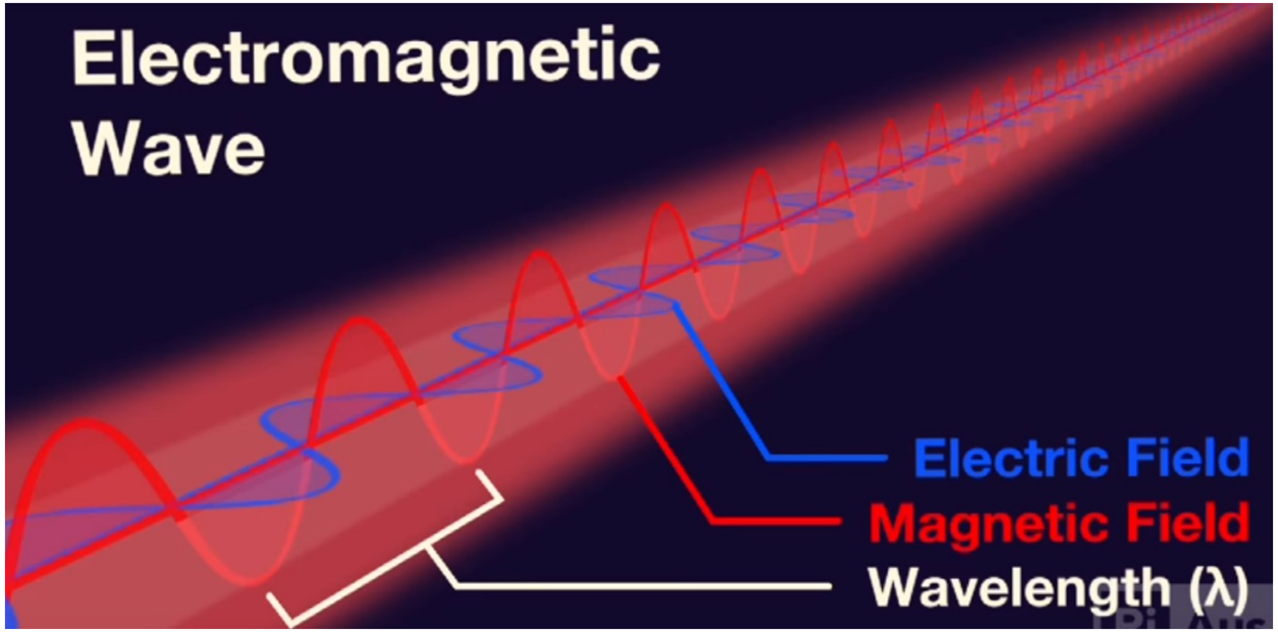




Photonics

What is light?





Increasing wavelength decreasing energy.

$$E = h\upsilon = \frac{hc}{\lambda}$$

E= Energy of a single photon

h = $6.626\times10^{-34} J.s (Plank's\ constant)$

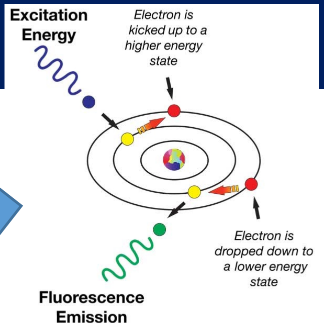
υ = frequency (Hz)

λ = wavelength (m)

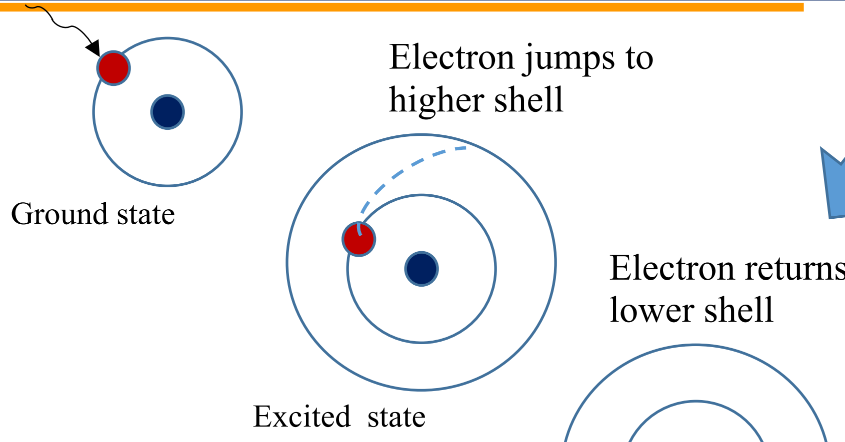
$c = 2.998\times10^{-8}$ m/s (speed of light)

Each photon have discrete energy which is shown by the equation. Photons are the fundamental building blocks of light

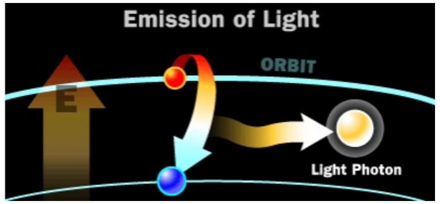
Photonics



Photonics: **“Photonics" comes from "photon"**
--the smallest unit of light.
--packet of electromagnetic energy to perform various functions in information processing systems.



"Photonics is the generation, process and manipulation of photon to achieve a certain function.

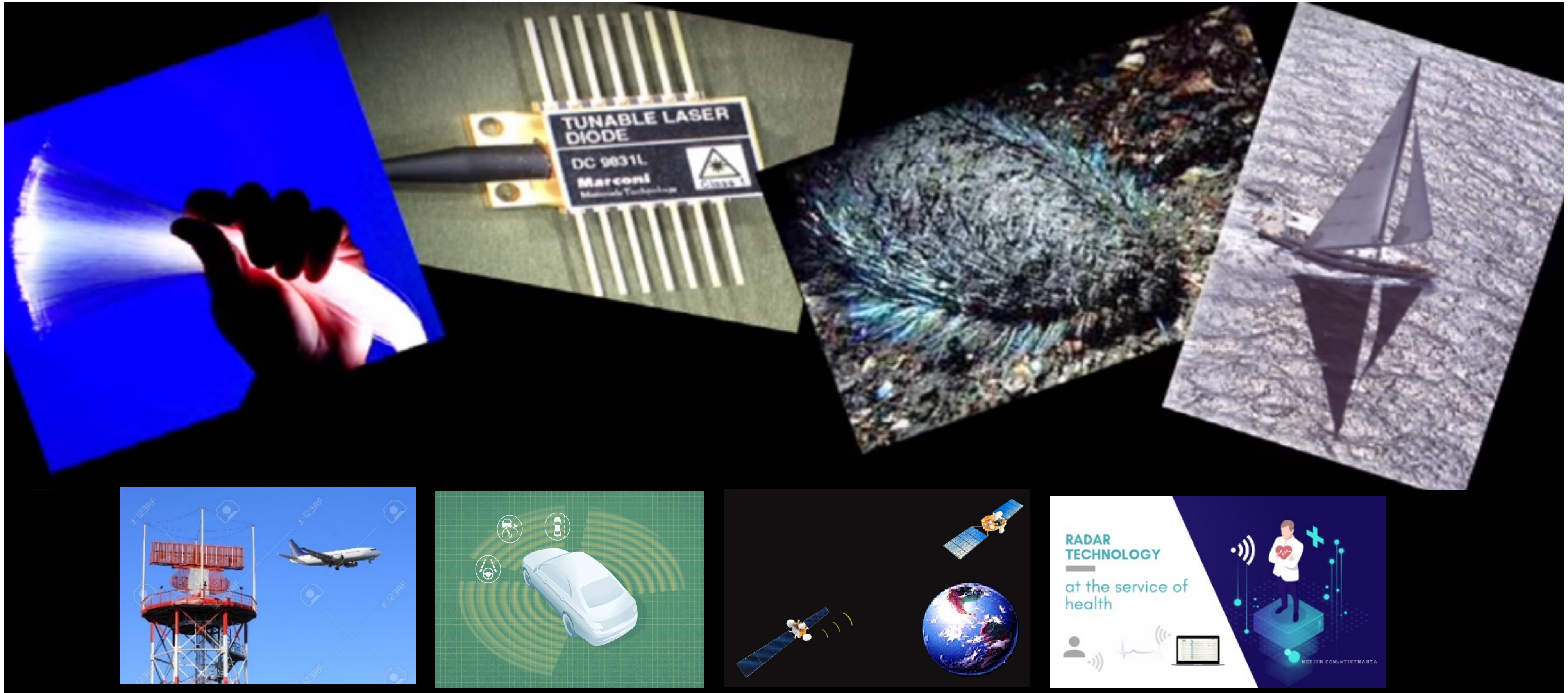


How photon produce

Four Basic Elements of Electronics and Photonics

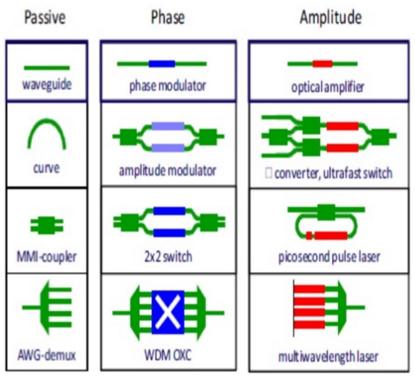
Electronics	Photonics
electrons as carrier vectors	carrier vectors can be photons, solitons, light balls, or plasmons
the generators	Lasers and spasers
transistors	plasmonsters and optical transistors
electrical cables and circuits	optical wave guides and optical fibers act as the transport cables

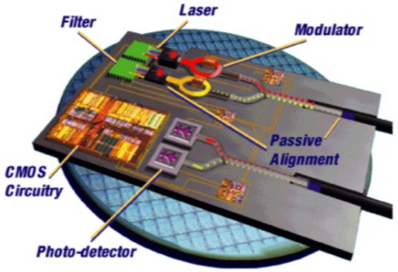
Photonics in Action



Photonics is the science of the photon,
the fundamental particle of light.

How Photonics is used

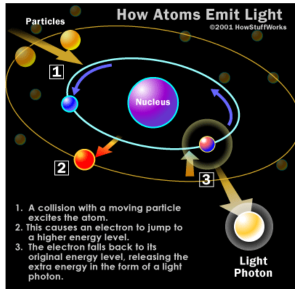


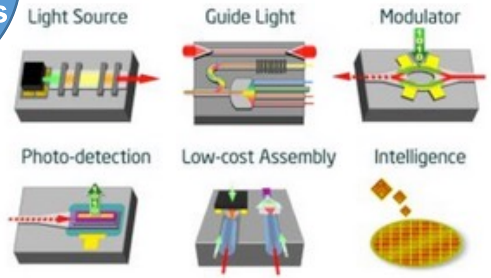


Integration and system design

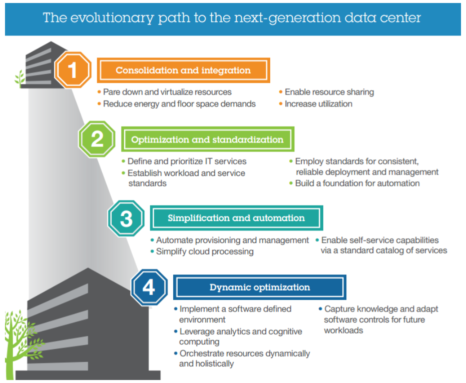
Silicon photonics and electronics

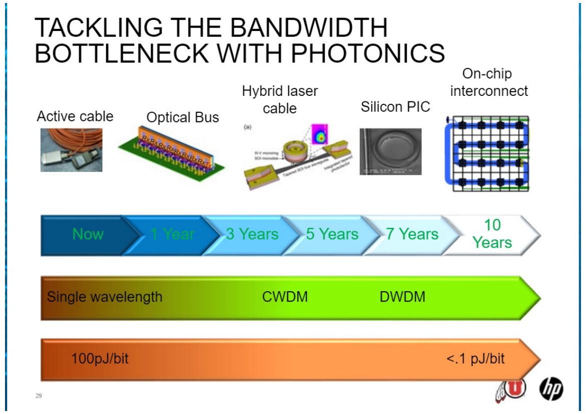
Sources and optical components

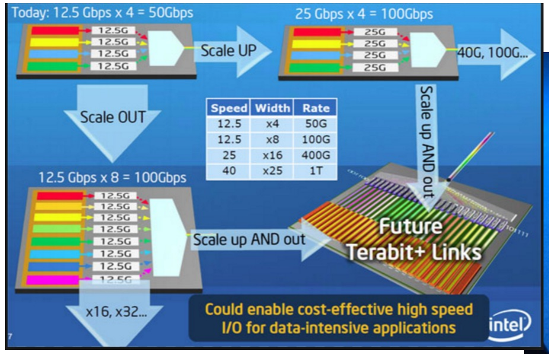




Generation of Light Photon



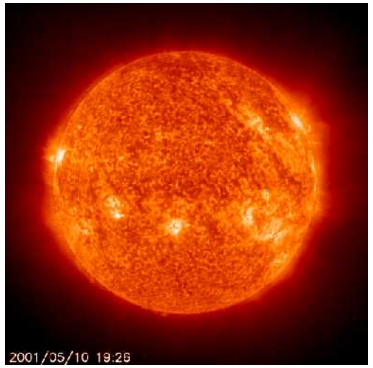




Huawei and Intel collaborate on 100 G switch

Integrated Photonics system in networking, computing, data centre, sensors

Sources of Light



Hot Objects

Natural Light Sources

Mostly used for light purposes

LED

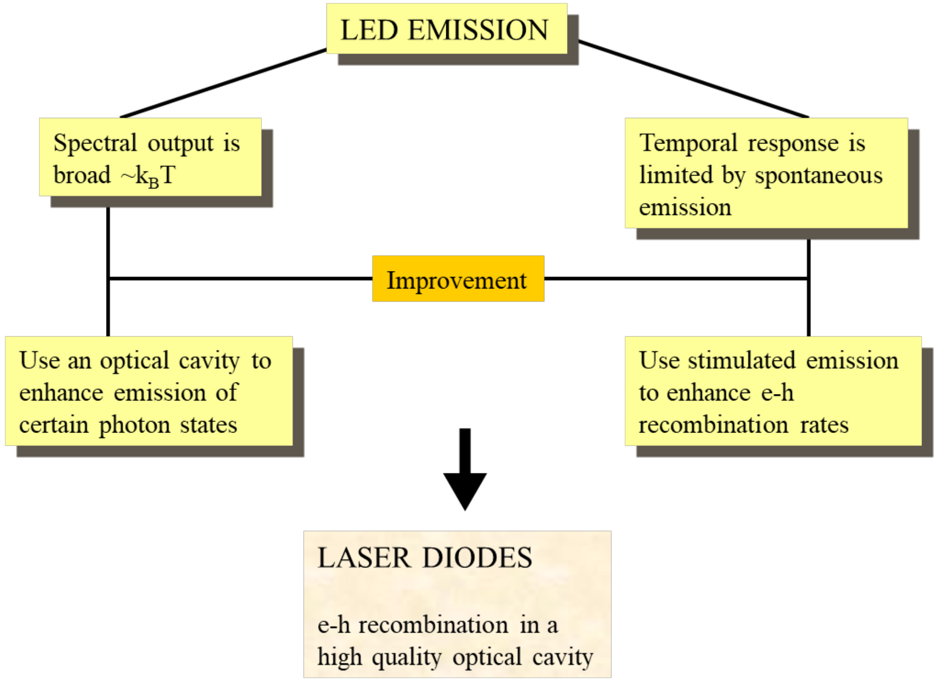
Artificial Light Sources

Semiconductor devices that emits visible light when an electric current passes through it.

Light Amplified by Stimulation Emission of Radiation, LASER

Sources of Light

	LED	LD
Beam generation	Spontaneous Emission	Stimulated Emission
Beam Directivity	No	Yes
Spectrum Width	40nm	0.01nm (single mode)
Response Time	few nsec (Not appropriate for high speed transmission)	0.01nsec
Driving Circuit	Simple	Complex, Temp Cont required, expensive
Application	Short reach and small band comm.	Long haul and broadband Transmission



Light Amplified by Stimulation Emission of Radiation, LASER

Laser Fundamentals

Why

Light Amplified by Stimulation Emission of Radiation, LASER ?

- **Lasers have unique Properties**
- **Created many devices**
- **Improved existing devices**

Laser Fundamentals: Examples of laser applications

Industrial

Automotive

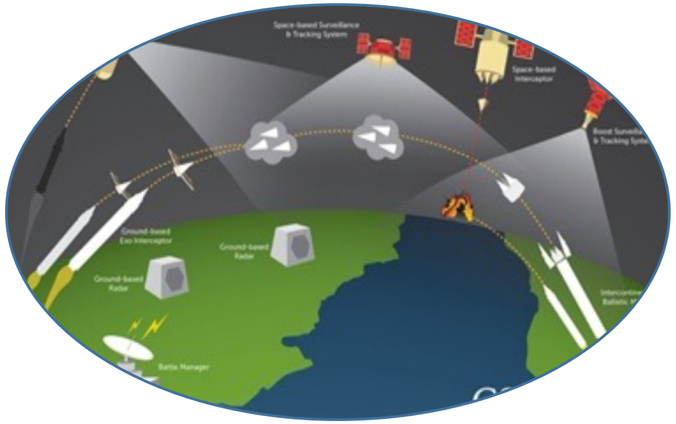
Consumer

Bio-Medical

High Energy Physics and Science

Analytical

Defense

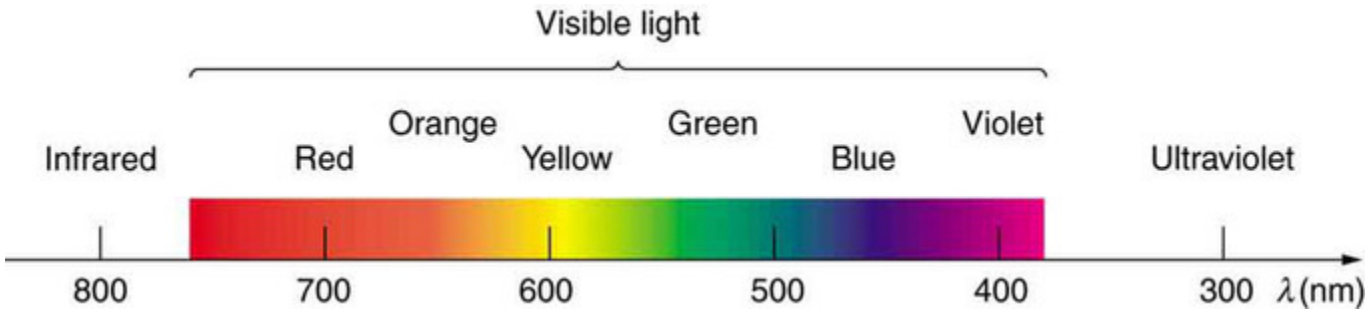


Courtesy: Hamatsu and CSIS defense project

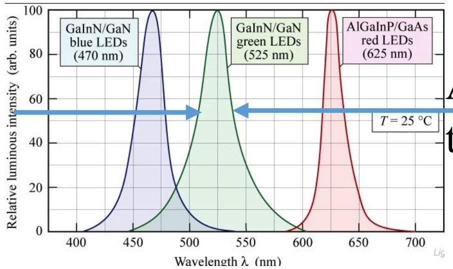
Laser Fundamentals: Property of Laser

1. High Monochromaticity / Narrow Spectral Width/ High Temporal Coherence

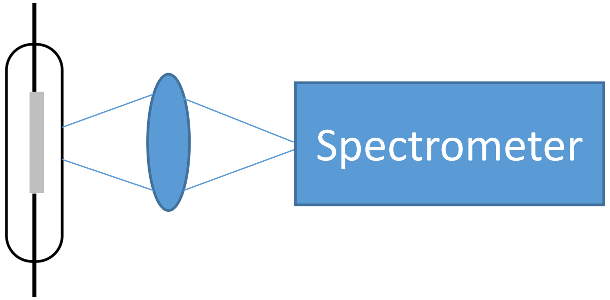
Visible Range of Light

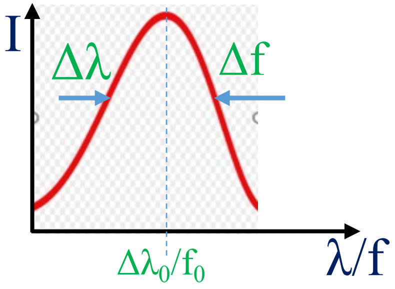


Spectrum Lamp

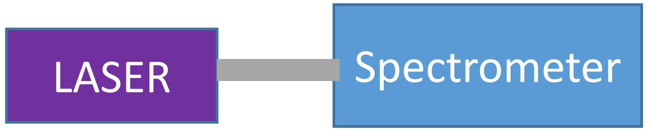


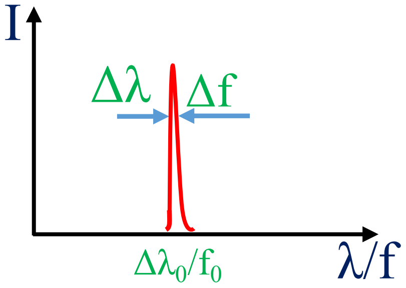
About more than 10 GHz





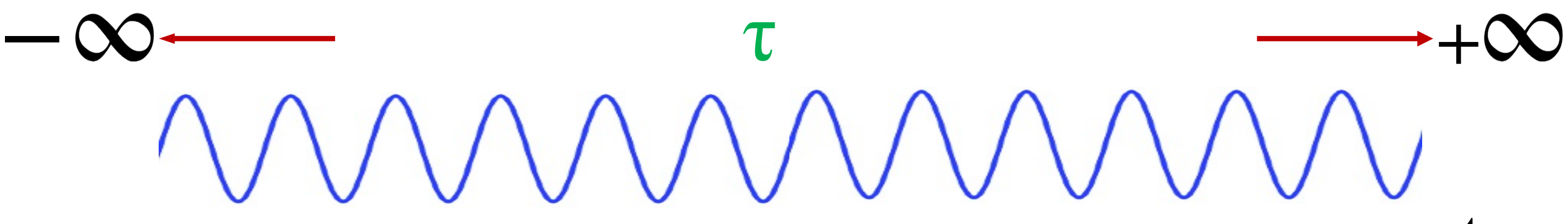
Laser



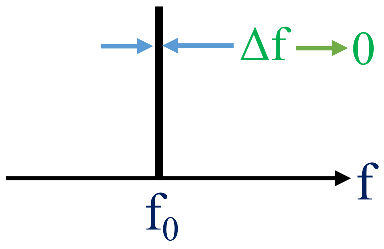


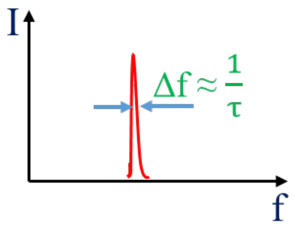
Laser Fundamentals: Property of Laser

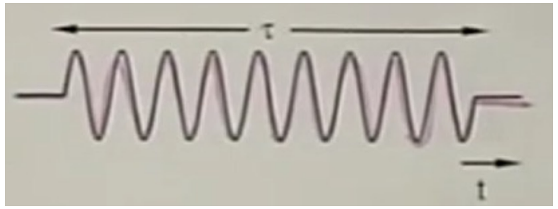
High Monochromaticity / Narrow Spectral Width / High Temporal Coherence

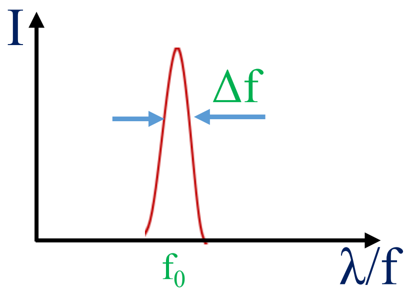


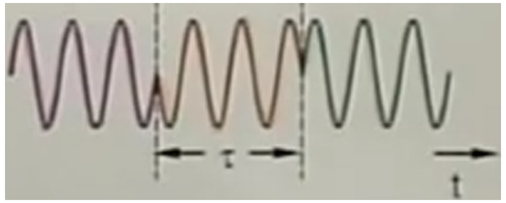
Ideal Case



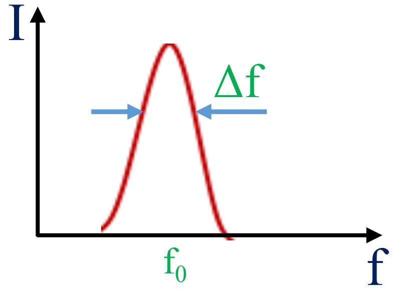


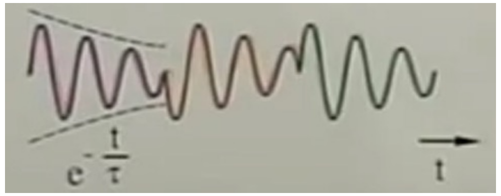






In real scenario





High Temporal Coherence

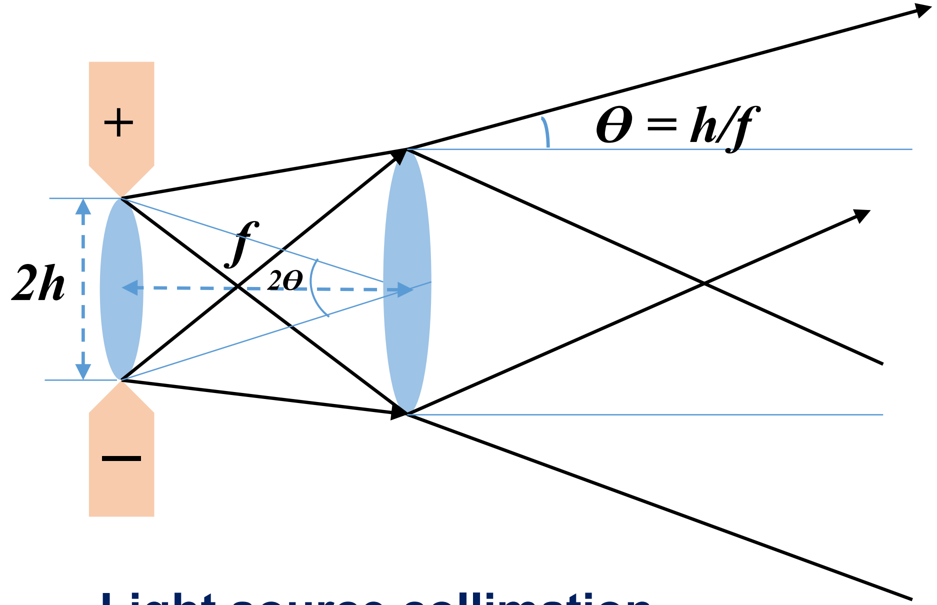
- **Radiation time without phase interruption is very high τ very long**
- **$\Delta f \approx 1/\tau$ is very small**
- **Can predict amplitude and phase at any time at a given position**

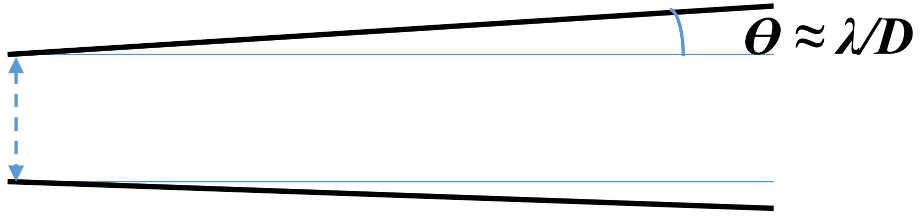
Application of narrow spectral width

- **Communication**
- **Spectroscopy**
- **Interferometry**
- **Holography**
- **Sensors**

Laser Fundamentals: Property of Laser

2. Highly Collimated (Diffraction limited) / Very small focused spot/ High Spatial Coherence





Light source collimation

Depends on h and f

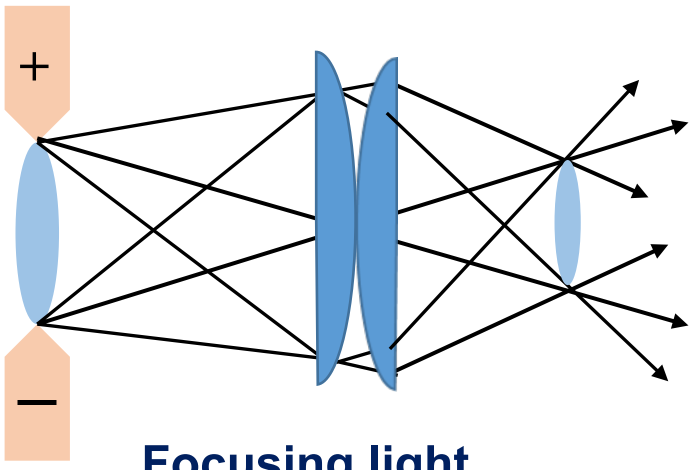
Diffraction-limited collimation

- No dependence on the source size due to basic physics of electromagnetics radiation
- only with λ *and D*

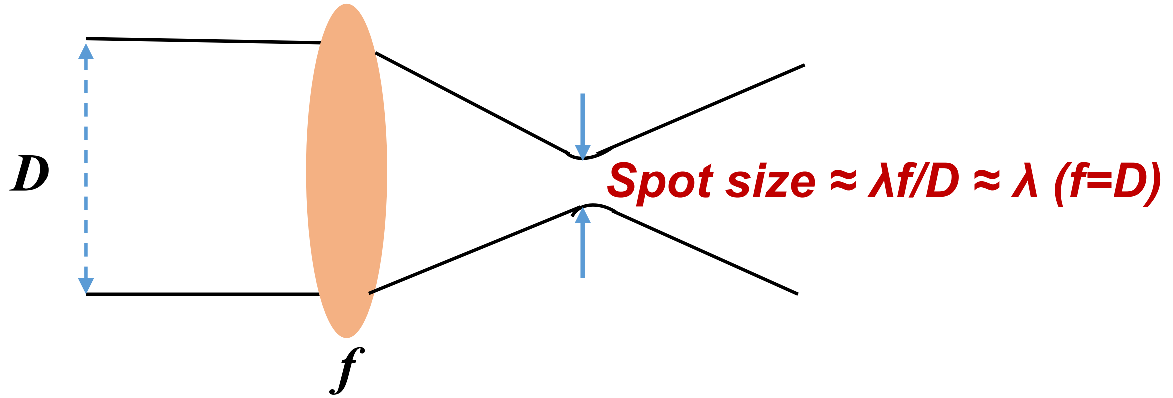
Applications: Alignment, bar code readers, communication, radar

Laser Fundamentals: Property of Laser

Highly Collimated (Diffraction limited) / Very small focused spot/ High Spatial Coherence



Focusing light



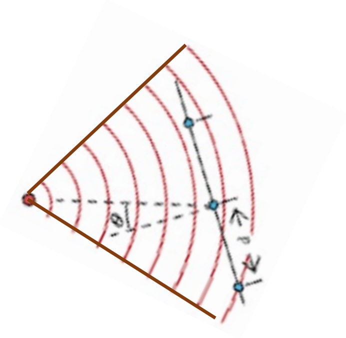
Diffraction limited focusing

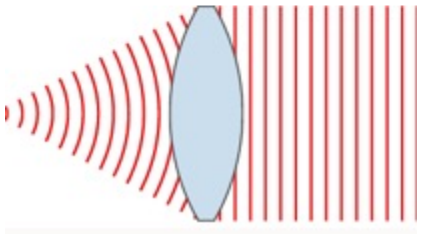
Applications: compact discs, laser printers, material processing, surgery

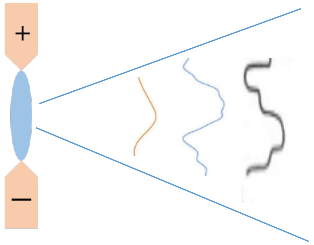
Laser Fundamentals: Property of Laser

Highly Collimated (Diffraction limited) / Very small focused spot/ High Spatial Coherence

- **Wave well behaved in space**
- **Can predict amplitude and phase at any position at a given time**







Temporal Coherence	Spatial coherence
Concerned with phase correlation of waves at a ***given point in space at two different instant of time***	Concerned with the phase correlation of ***two different points across a wave front at a given instant of time***
Coherence related with ***time***	Coherence related with ***position***
Longitudinal coherence	***Transverse*** coherence
Related to ***frequency bandwidth of the source***	Related to the ***size of the source***

Laser Fundamentals: Property of Laser

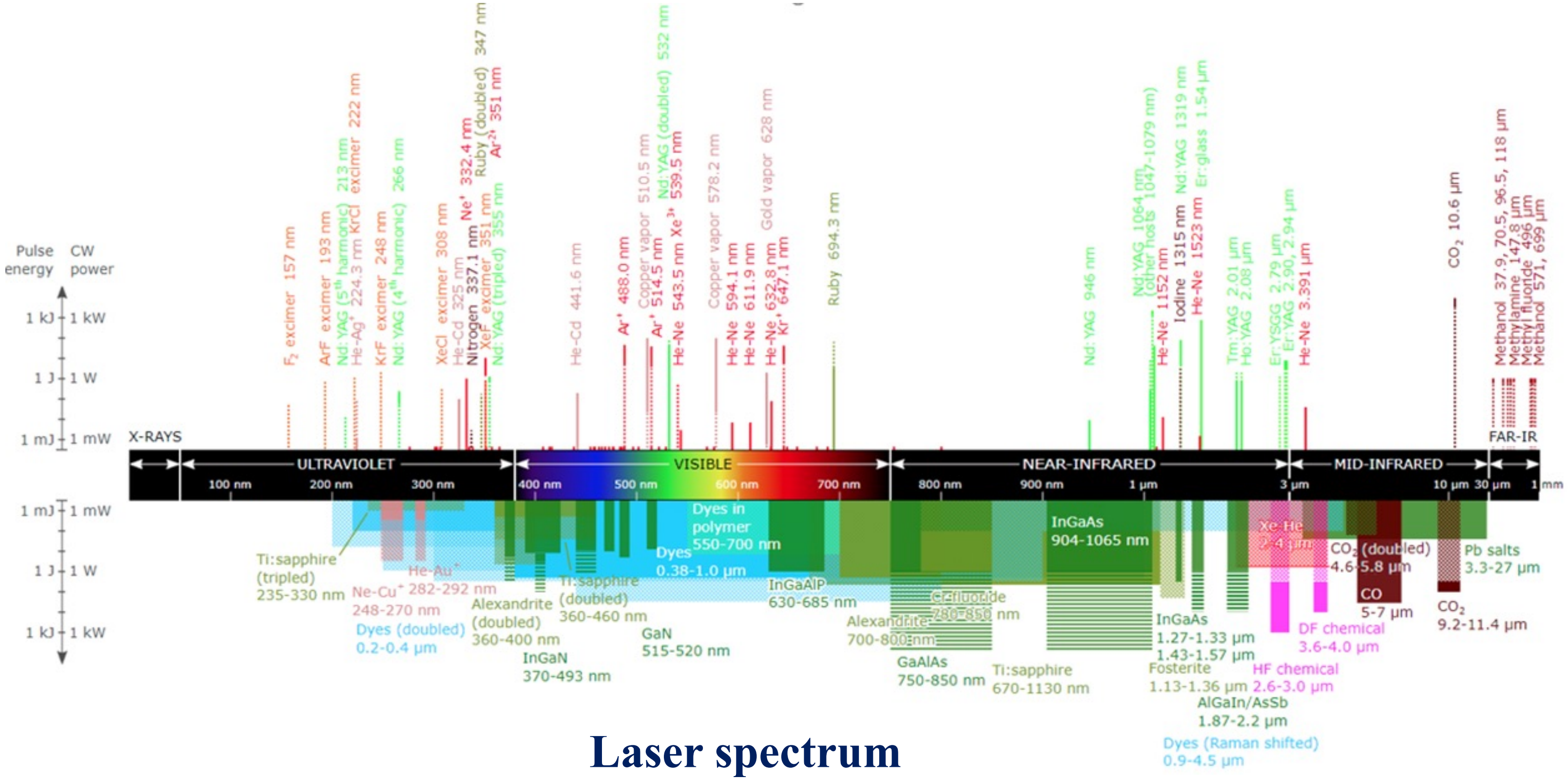
3. High Power

- CW or PULSED
- CW laser power can power from milliwatt to megawatt
- Pulsed laser can go from Giga watt to exawatt

Applications: Material processing, Fusion, Military, Nonlinear optics, and more

Laser Fundamentals: Property of Laser

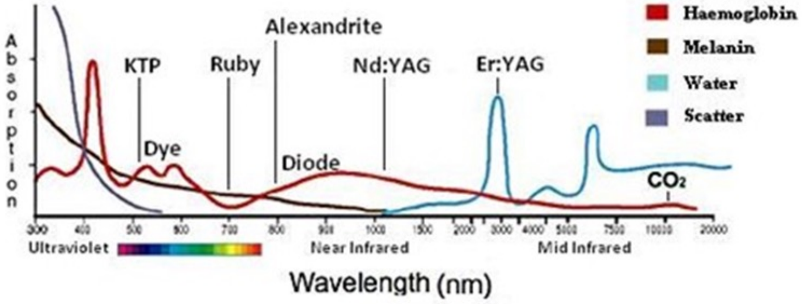
4. Wide Tuning Range



Laser spectrum

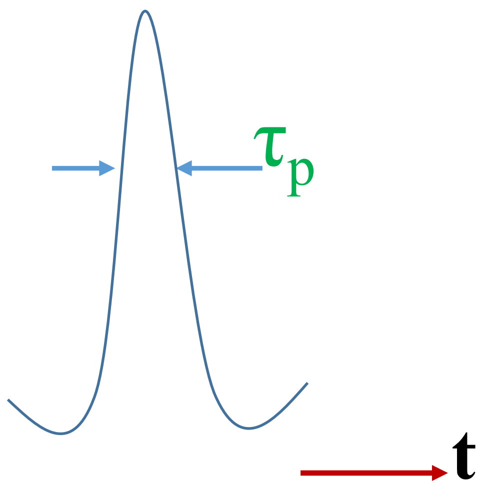
Applications:

- Interaction with specific atoms & molecules
- Spectroscopy (dye laser)
- Propagation
- Medical



Absorption spectrum

5. Short pulse widths

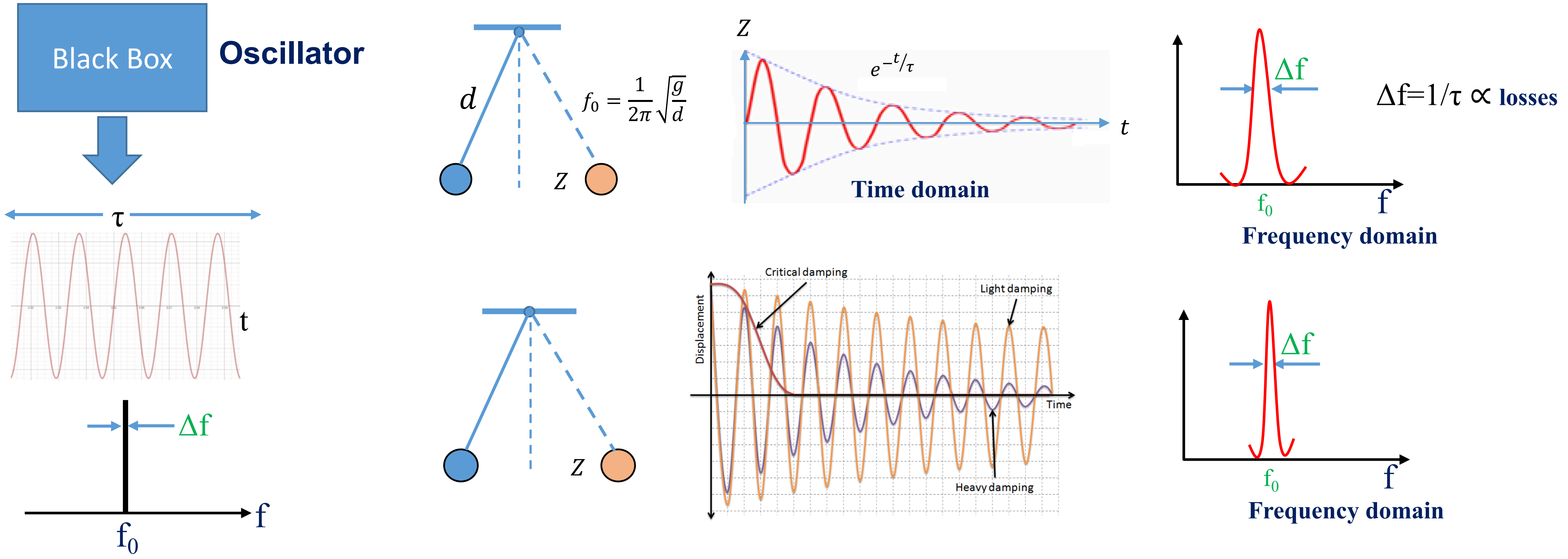


Applications:

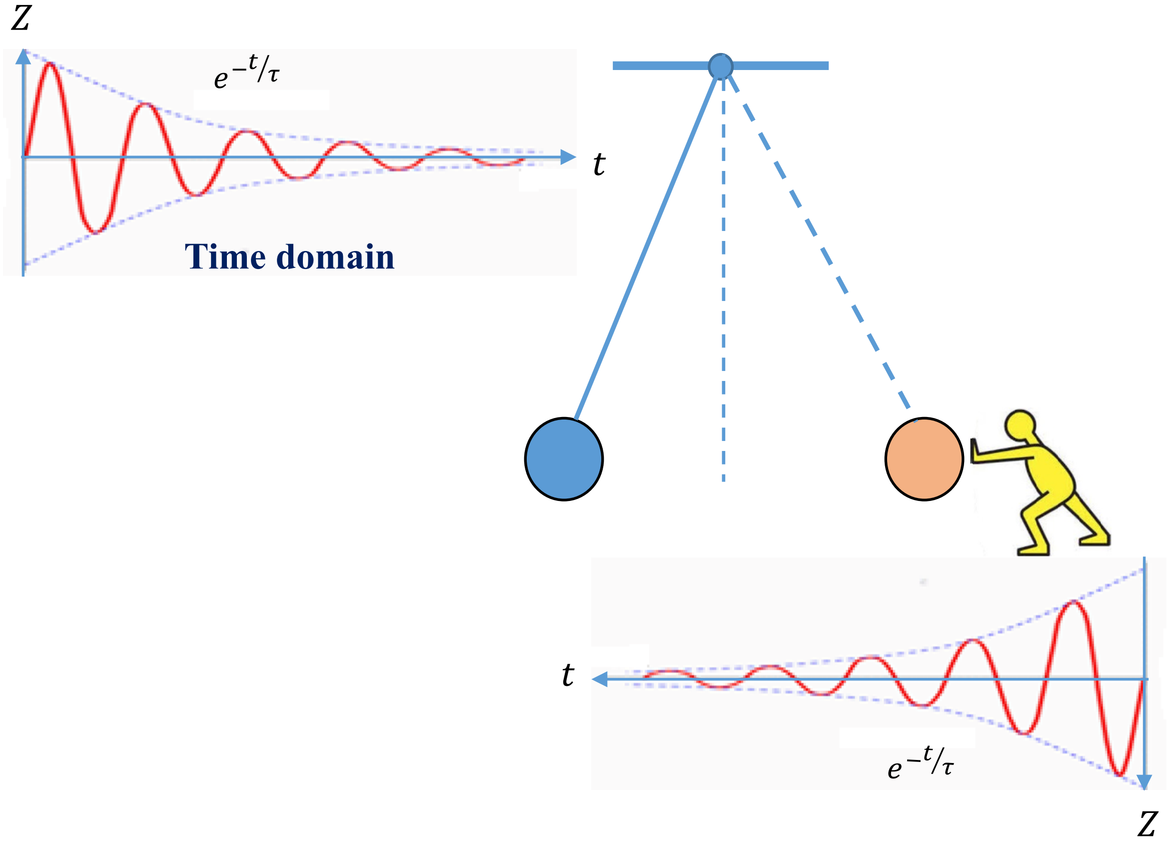
- Fast phenomena
- Optical computers
- Radar
- imaging

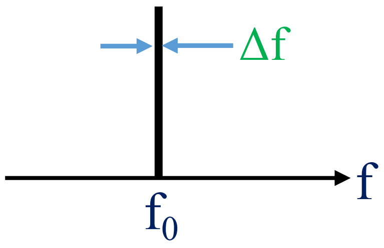
Pulse width is the time during which the laser output power remains continuously above all of its maximum value (FWHM). The pulse width can vary from nanosecond to picosecond to femtosecond.

Laser Fundamentals: Oscillator (1)



Laser Fundamentals: Property of Laser



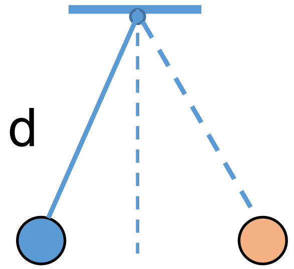


Frequency domain

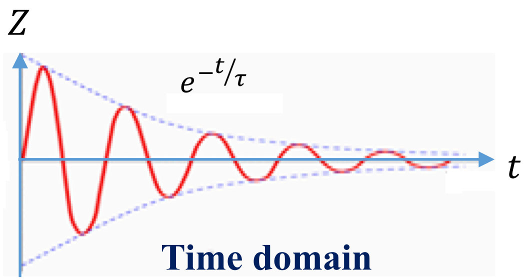
Need things for oscillator:

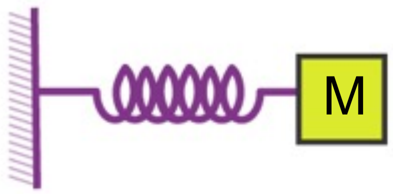
- Low loss resonator , resonator gives the required frequency of oscillation
- A means to overcome the loss at resonance frequency

Laser Fundamentals: Property of Laser

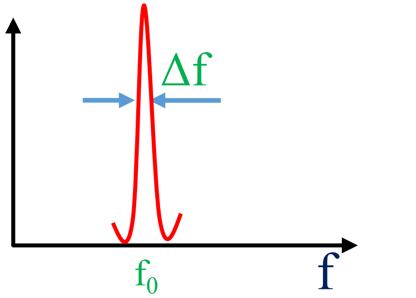


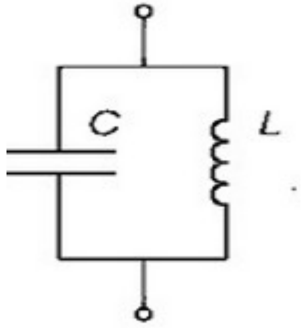
$$f_0 = \frac{1}{2\pi}\sqrt{g/d}$$





$$f_0 = \frac{1}{2\pi}\sqrt{k/M}$$





$$f_0 = \frac{1}{2\pi}\sqrt{1/LC}$$

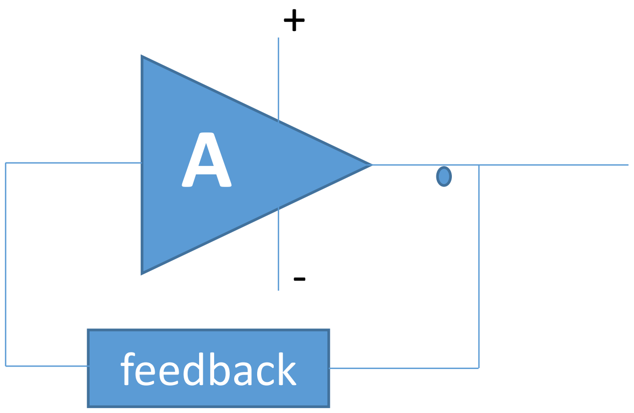
$\Delta f = 1/\tau \propto$ **losses**

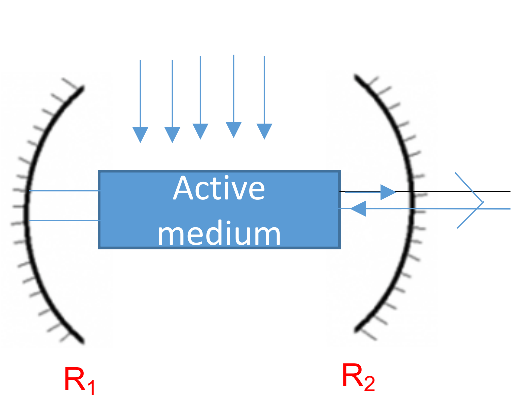
Laser Fundamentals: Property of Laser

Light Amplified by Stimulation Emission of Radiation, LASER

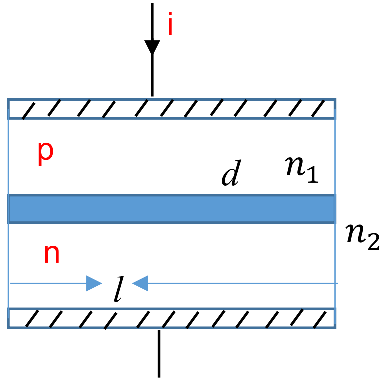
is

analogues to the oscillator and oscillator is generally an amplifier with a feedback





Bulk laser



Semiconductor laser

$$\Delta n = \frac{(i/e)\tau}{l \times w \times d}$$

$$E_{fc} - E_{fv} > E_g$$

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

So in general 3 components of laser is

- gain medium --- active device
- Pump or power supply
- Optical feedback- optical resonator

E_2 ———— N_2

E_1 ———— N_1

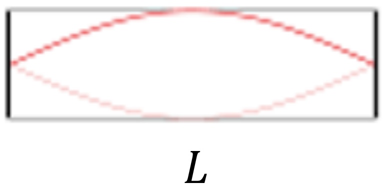
$$N_2 > N_1$$

Population inversion

Laser Fundamentals: Resonator

Optical Resonator determines

- Longitudinal Mode → Resonance frequency
- Transverse mode → Field Distribution

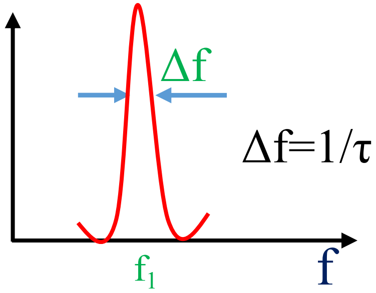


$$k_1 n \times 2L = q \times 2\pi$$

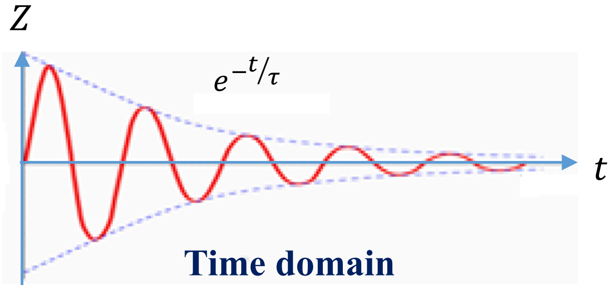
$$\frac{2\pi}{\lambda_1} n \times 2L = q \times 2\pi$$

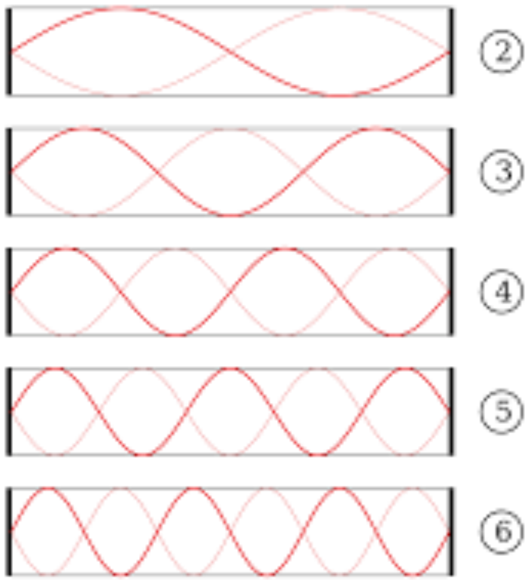
$$L = \frac{\lambda_1}{2} \qquad \lambda f = c$$

$$\lambda_1 = 2L \qquad f_1 = \frac{C}{2L}$$

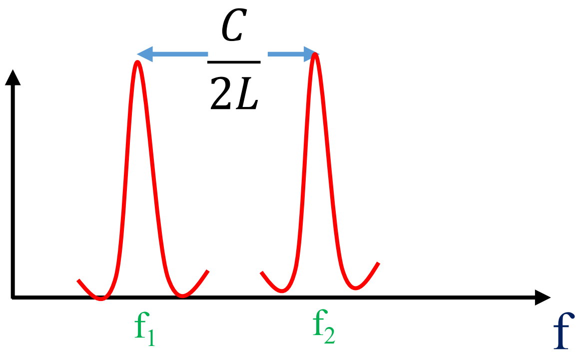


$\Delta f = 1/\tau \propto$ losses



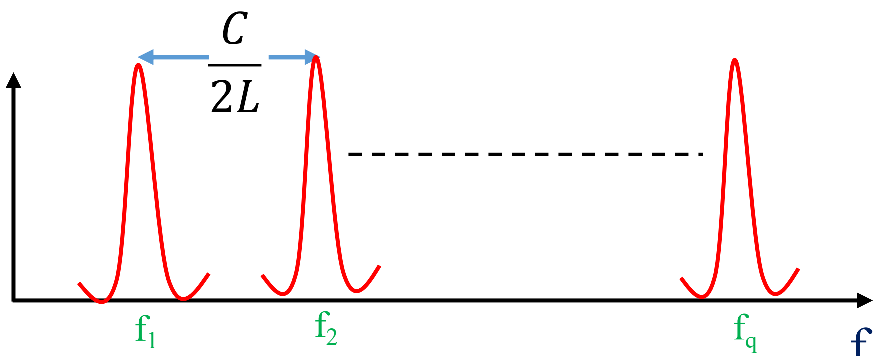


$$\lambda_2 = \frac{2L}{2} \qquad f_2 = 2\frac{c}{2L}$$

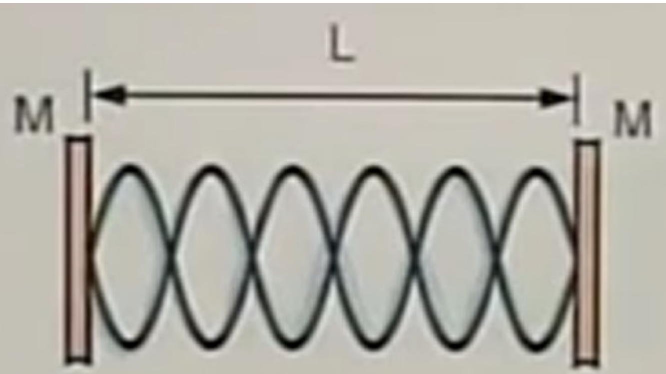


$$\lambda_q = \frac{2L}{q}$$

$$f_q = q\frac{c}{2L}$$

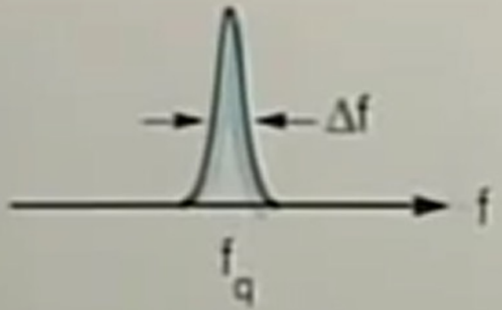


Laser Fundamentals: Resonator



$$\lambda_q = \frac{2L}{q}$$

$$f_q = q\frac{c}{2L}$$



e.g.

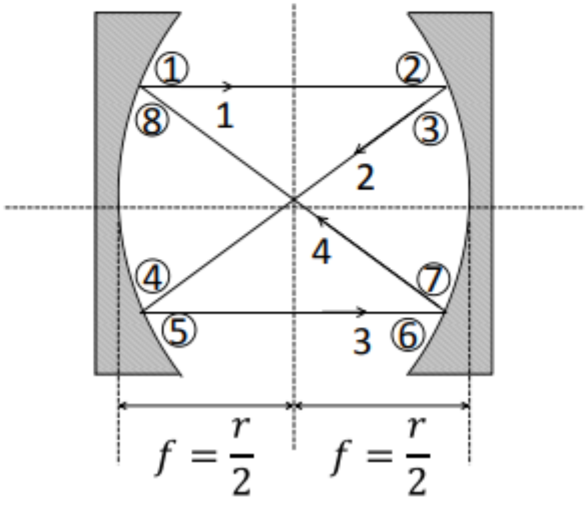
$L = 100\,\text{cm}$

$\lambda = 0.5\,\mu\text{m} = 5\text{x}10^{-5}\,\text{cm}$

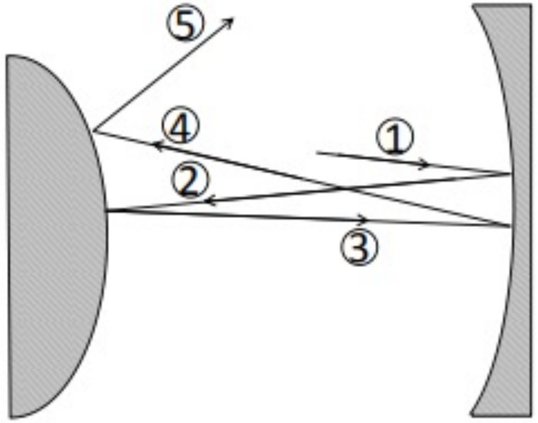
$$q = \frac{2L}{\lambda} = \frac{200}{5\text{x}10^{-5}} = 4\text{x}10^{6}$$

$f_q = 6\text{x}10^{14}\,\text{Hz}$

Laser Fundamentals: Stability



Stable Cavity

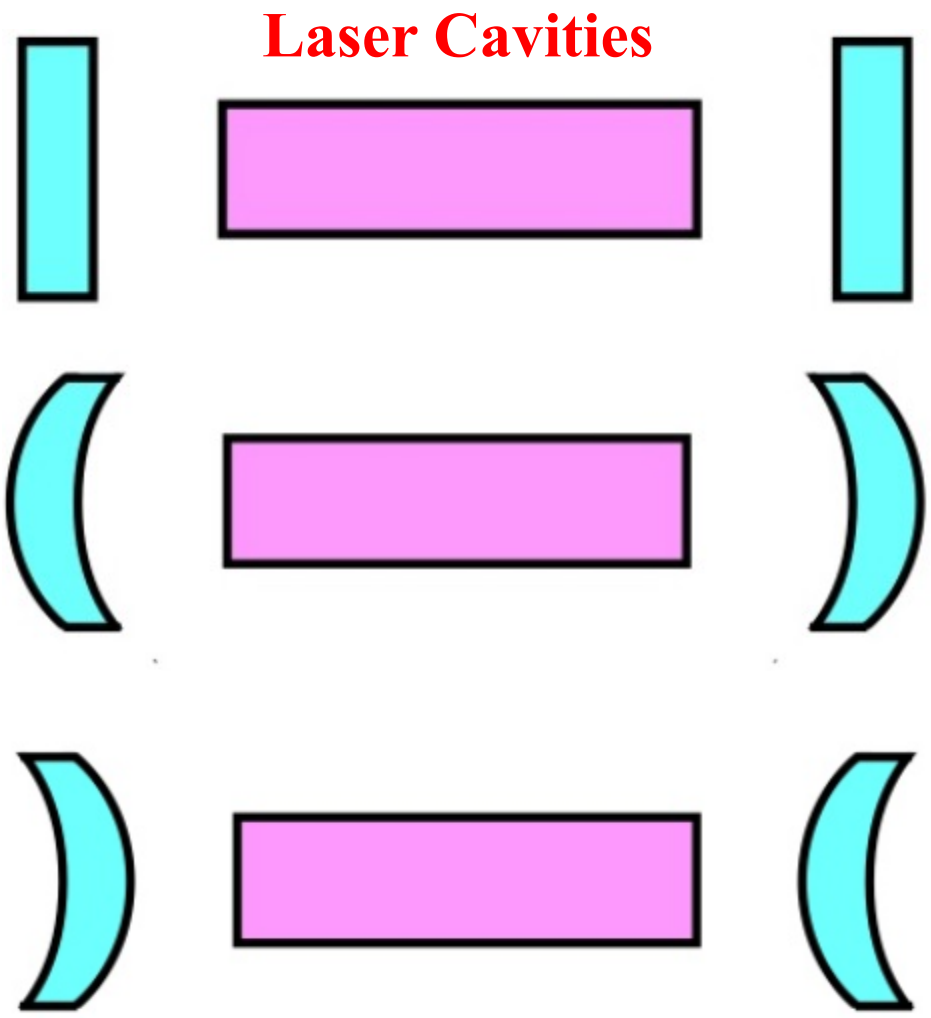


unstable Cavity

- A stable optical cavity consists of two or more optical elements (usually mirrors) in which *a ray will eventually replicate itself*
- Have low diffraction loss
- Stable cavities have smaller mode volume
- Useful for low-gain, low-volume lasers

- In an unstable cavity, *rays do not replicate themselves*
- Each trip through the cavity will take the ray further from the optic axis, resulting in high diffraction losses
- Useful for high-gain, high-volume lasers

Laser Fundamentals: Stability



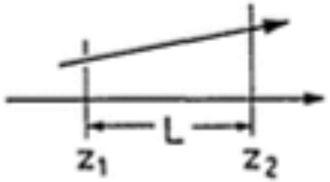
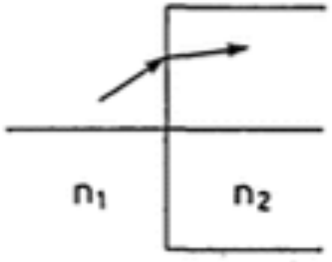
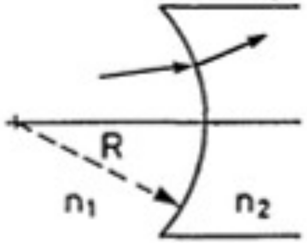
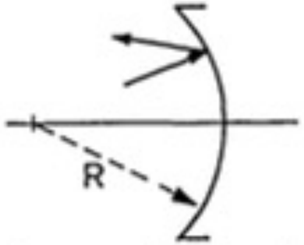
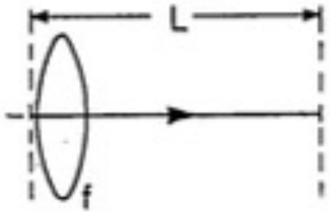
Two flat mirrors, the flat-flat laser cavity, is difficult to align and maintain aligned.

Two concave curved mirrors, the usually stable laser cavity, is generally easy to align and maintain aligned

Two convex mirrors, the unstable laser cavity, is impossible to align

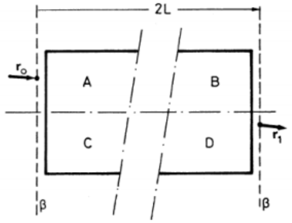
Laser Fundamentals: Ray Matrix

Table 1. Ray Matrices for Various Simple Optical Elements[a]

Structure	Diagram	Matrix
Straight section (length L)		$\begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$
Thin lens [focal length f: ($f > 0$, converging; $f < 0$, diverging)]		$\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$
Flat dielectric interface (refractive indices n_1, n_2)		$\begin{bmatrix} 1 & 0 \\ 0 & n_1/n_2 \end{bmatrix}$
Curved dielectric interface (radius R)		$\begin{bmatrix} 1 & 0 \\ \frac{n_2 - n_1}{n_2 R} & \frac{n_1}{n_2} \end{bmatrix}$
Curved mirror (radius of curvature R)		$\begin{bmatrix} 1 & 0 \\ -2/R & 1 \end{bmatrix}$
Thin lens (focal length f followed by a distance L)		$\begin{bmatrix} 1 - \frac{L}{f} & L \\ -\frac{1}{f} & 1 \end{bmatrix}$

Laser Fundamentals: Stability

Employ the ABCD-matrix approach, in which case the cavity is stable if



Modes: TEM transverse modes

ABCD law of Gaussian beam propagation $q = \frac{A\,q_1 + B}{C\,q_1 + D}$

q must repeat itself after a round trip:

$$q = \frac{Aq + B}{Cq + D} \longrightarrow Cq^2 + (D - A)q - B = 0$$

q must be complex, hence $(D - A)^2 + 4BC < 0$

Since AD-BC=1 $(D + A)^2 < 4$

Stability condition: $-1 < \left(\frac{A + D}{2}\right) < 1$ (re-derived)

$$0 \le \frac{A + D + 2}{4} \le 1$$

$$0 \le g_1 g_2 \le 1$$

Where,

$$g_1 = 1 - \frac{d}{R_1} \;; \quad g_2 = 1 - \frac{d}{R_2}$$

The ABCD matrix for a round trip of a cavity comprising two mirrors with radii R1 and R2 separated by a distance d

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{2}{R_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{2}{R_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 - \frac{2d}{R_2} & 2d - \frac{2d^2}{R_2} \\ \frac{4d}{R_1 R_2} - \frac{2}{R_1} - \frac{2}{R_2} & 1 + \frac{4d^2}{R_1 R_2} - \frac{4d}{R_1} - \frac{2d}{R_2} \end{bmatrix}$$

If d is the mirror separation and the mirror's radii of curvature are R1 and R2, then the cavity will be stable if and only if

$$0 \le \frac{\left(1 - \frac{2d}{R_2}\right) + \left(1 + \frac{4d^2}{R_1 R_2} - \frac{4d}{R_1} - \frac{2d}{R_2}\right) + 2}{4} \le 1$$

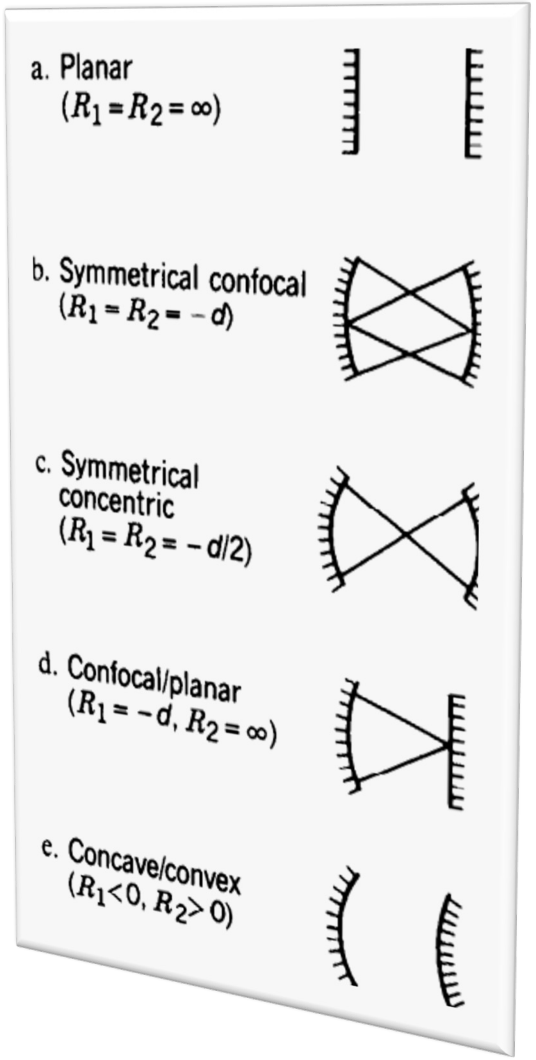
When simplified, this expression becomes

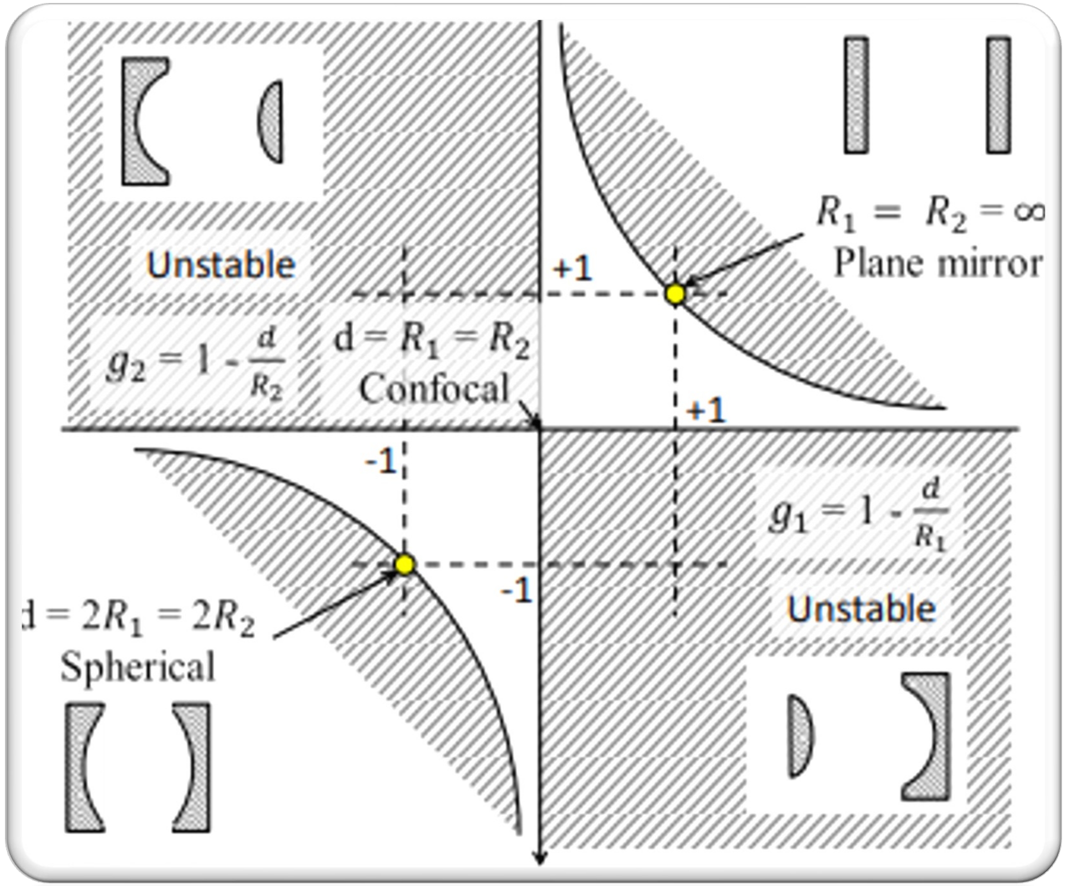
$$0 \le \left(1 - \frac{d}{R_1}\right)\left(1 - \frac{d}{R_2}\right) \le 1 \quad \Rightarrow \quad 0 \le g_1 g_2 \le 1$$

$$g_1 \equiv 1 - \frac{d}{R_1} \quad \text{and} \quad g_2 \equiv 1 - \frac{d}{R_2}$$

The two mirror cavity stability criteria

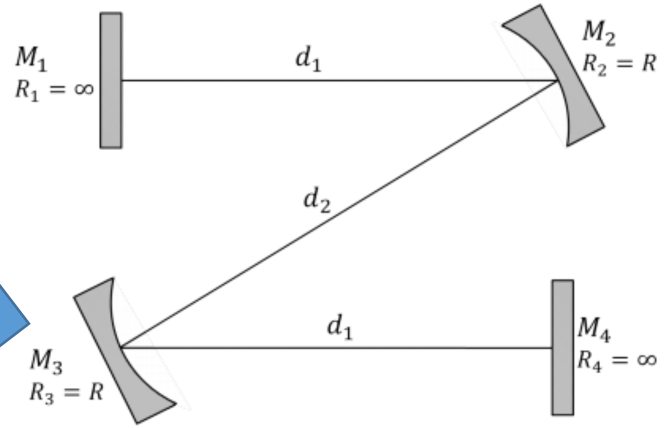
Laser Fundamentals: Stability





Laser Fundamentals: Stability

Solution: The first step is to unwrap the cavity. Due to the symmetry of this cavity, it is only necessary to go from M_1 to M_4 before an equivalent position is reached.

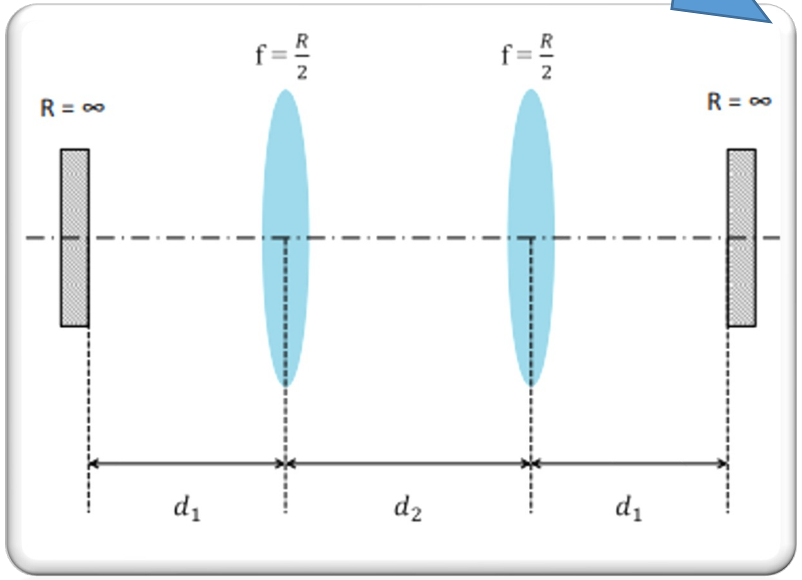


The ABCD matrix for this half traversal of the cavity is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{1/2} = \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{1/2} = \begin{bmatrix} 1 - \frac{4d_1+2d_2}{R} + \frac{4d_1 d_2}{R^2} & \\ & 1 - \frac{4d_1+2d_2}{R} + \frac{4d_1 d_2}{R^2} \end{bmatrix}$$

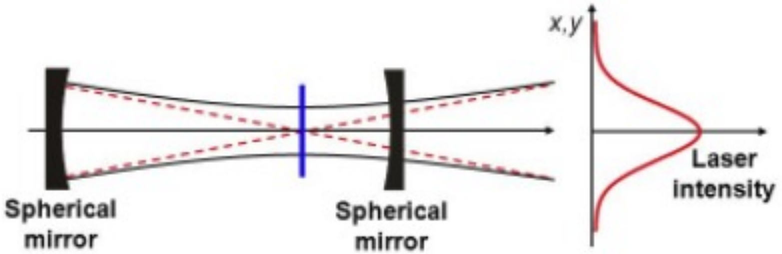
$$\left| \frac{R^2 - (4d_1 + 2d_2)R + 4d_1 d_2}{R^2} \right| \leq 1$$

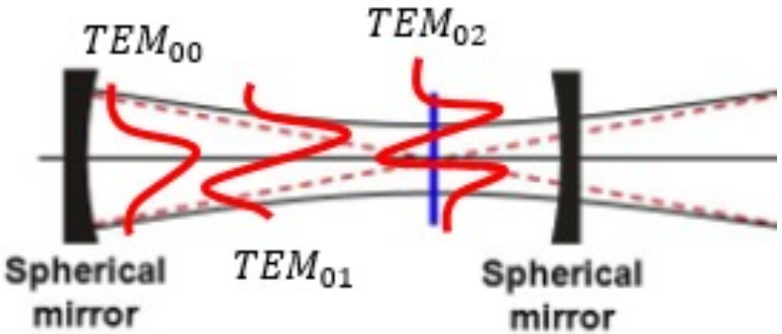


Laser Fundamentals:

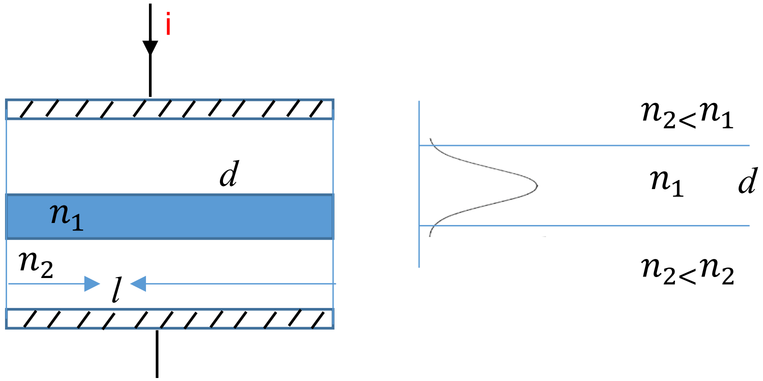
Transverse mode: Field Distribution

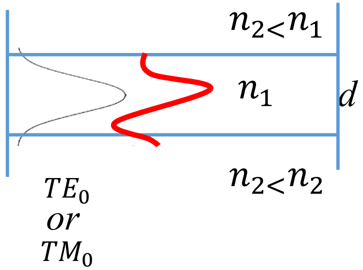
Bulk laser





Semiconductor laser





$$V = \frac{2\pi}{\lambda} d \sqrt{n_1^2 - n_2^2}$$

V parameter

Need things for oscillator:

- Low loss resonator , resonator gives the required frequency of oscillation
- A means to overcome the loss at resonance frequency

Laser Fundamentals: Gaussian Beam

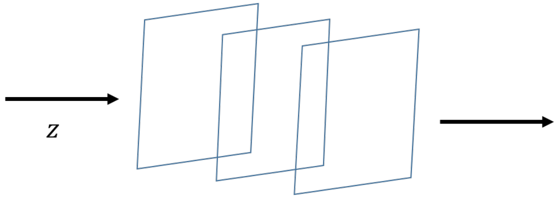
Gaussian beam wave equation to our concept and assumption

Plane Wave

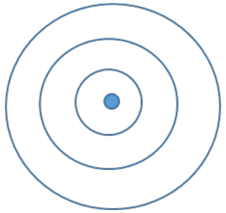
Propagation direction, frequency

$$A exp\, j(Kz - wt)$$

amplitude, phase



spherical wave)



$$\frac{A}{r} e^{jkr}$$

$$Ae^{-\frac{x^2+y^2}{w^2}}\, exp\, j(Kz - wt) e^{jk\frac{x^2+y^2}{2z^2}}$$

Actual Gaussian Beam Equation

$$\frac{E_0(x,y,z)}{E_A} \square \left\{ \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w^2(z)} \right] \right\} \exp\square - i[kz - \tan^{-1}(z/z_0)\square \exp\left[-i\frac{kr^2}{2R(z)} \right]$$

amplitude factor which limits the beam “spot size

Almost a plane wave with respect to longitudinal phase

describes wavefront curvature (radial phase)

Laser Fundamentals: Gaussian Beam

$$\frac{E(x,y,z)}{E_0} = \frac{w_0}{w(z)}\exp\left[-\frac{r^2}{w^2(z)}\right]$$

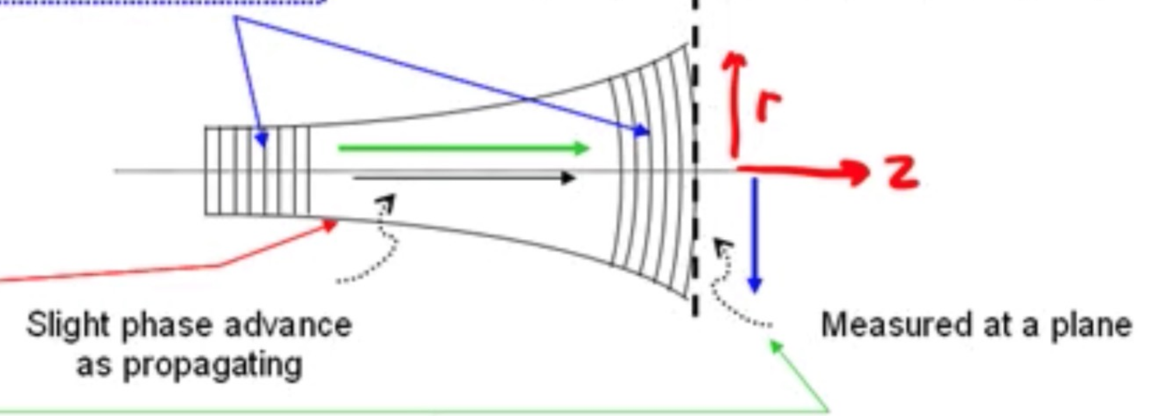
Amplitude Factor: Describes beam spread (pure real)

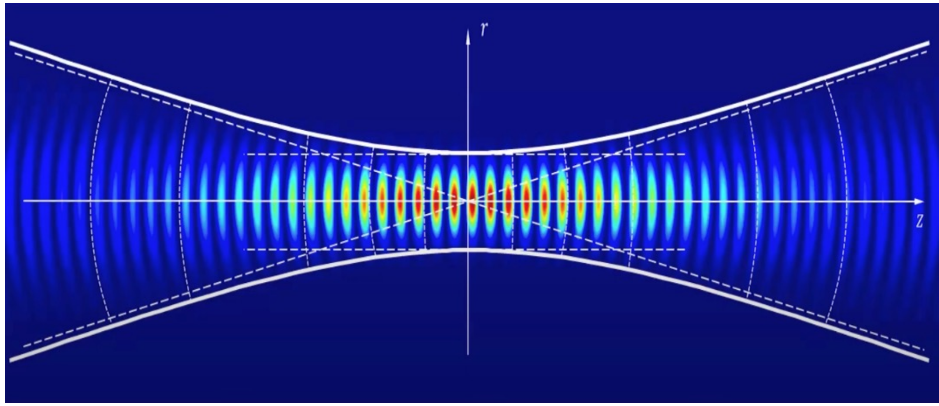
$$\times\exp\left\{-j\left[kz - \tan^{-1}\left(\frac{z}{z_0}\right)\right]\right\}$$

Longitudinal Phase Factor: Describes shift from plane wave to spherical wave behavior

$$\times\exp\left[-j\frac{kr^2}{2R(z)}\right]$$

Radial Phase Factor: Accounts for phase shifts due to measuring a spherical surface along a plane





Laser Fundamentals: Gaussian Beam

Gaussian Beam Spot, Radius and Phase

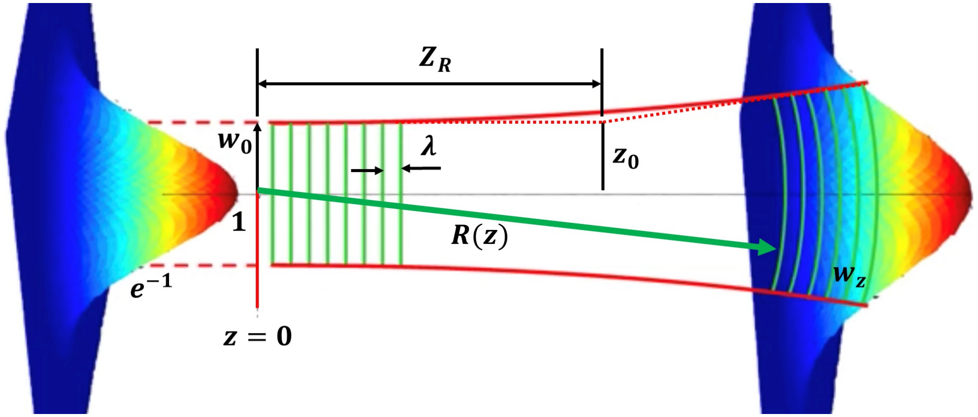
$w(Z)$: Gaussian beam width at distance z along the beam

w_0: Beam waist;

b: depth of focus;

Z_R: Rayleigh range;

Θ: Total angular spread

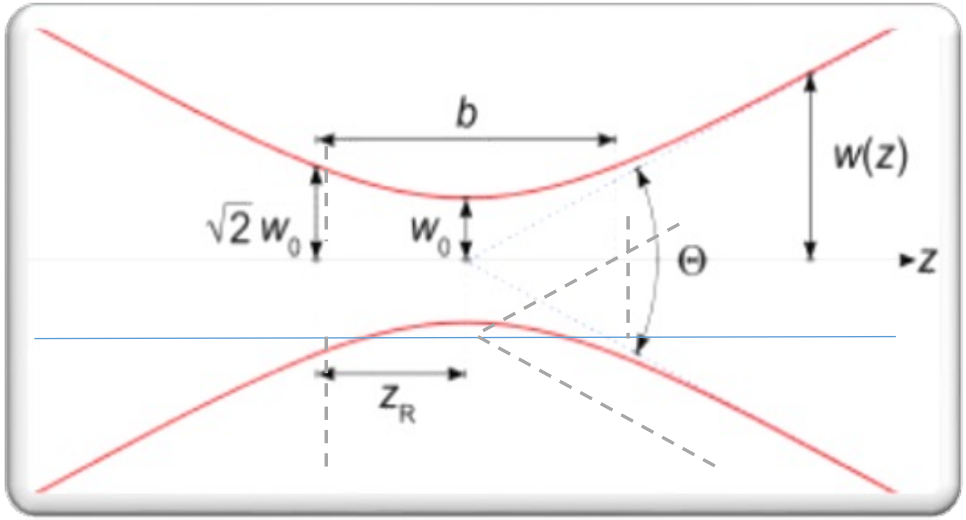


The expressions for the spot size, radius of curvature, and phase shift:

$$w(z) = w_0\sqrt{1 + \left(Z/Z_R\right)^2}$$

$$R(z) = Z + {Z_R}^2/Z$$

$$\psi(z) = \arctan\left(Z/Z_R\right)$$

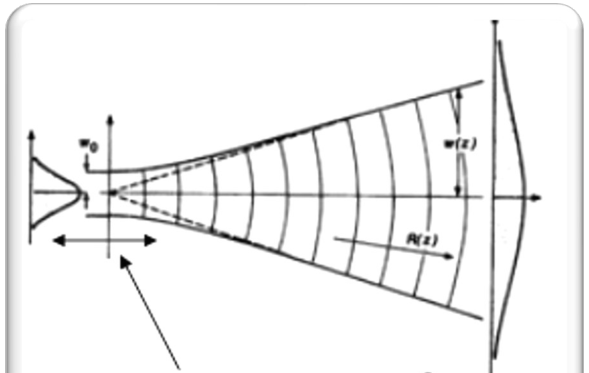


where:

Z_R the Rayleigh Range (the distance over which the beam remains about the same diameter), and it's given by $Z_R = \pi w_0^2/\lambda$

Gaussian Beam Collimation

Twice the Rayleigh range is the distance over which the beam remains about the same size, that is, remains “collimated.”



$$2z_R = 2\pi w_0^2 / \lambda$$

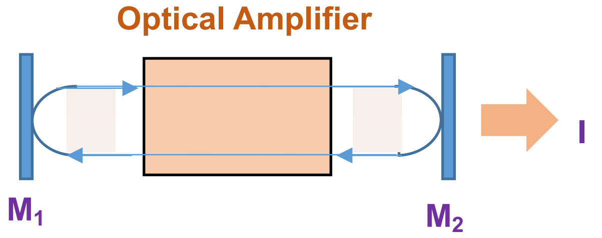
Waist spot size w_0	Collimation Distance $\lambda = 10.6\ \mu m$	Collimation Distance $\lambda = 0.633\ \mu m$
.225 cm	0.003 km	0.045 km
2.25 cm	0.3 km	5 km
22.5 cm	30 km	500 km

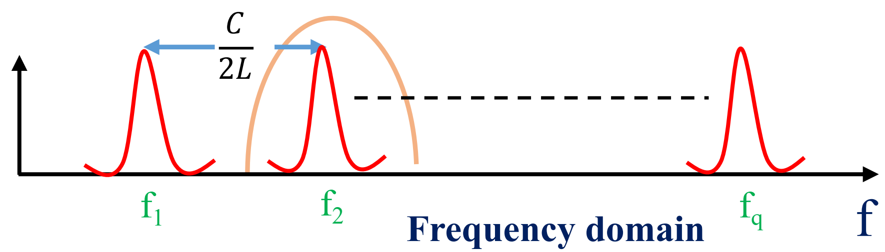
Tightly focused laser beams expand quickly. Weakly focused beams expand less quickly, but still expand. As a result, it's very difficult to shoot down a missile with a laser.

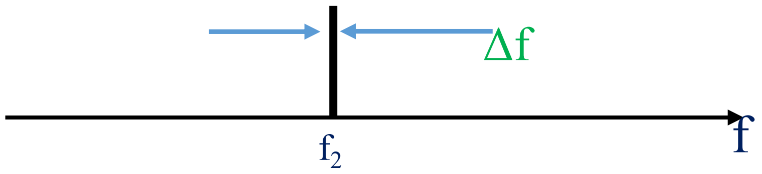
Longer wavelengths expand faster than shorter ones.

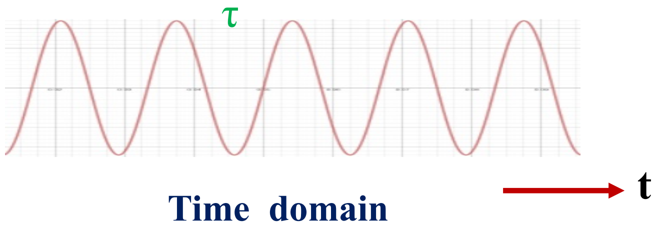
Laser Fundamentals: Optical Amplifier

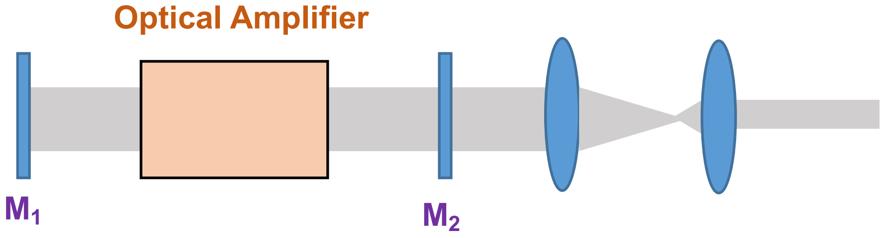
A means to overcome the loss at resonance frequency

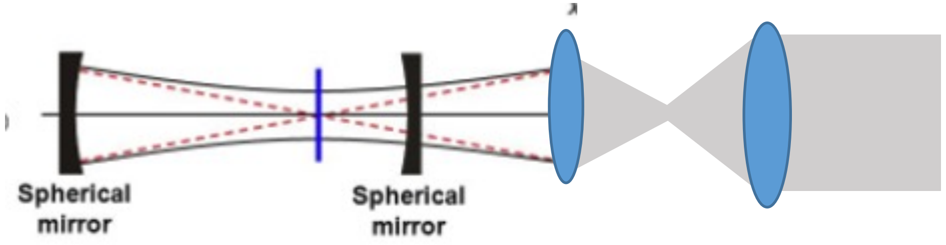




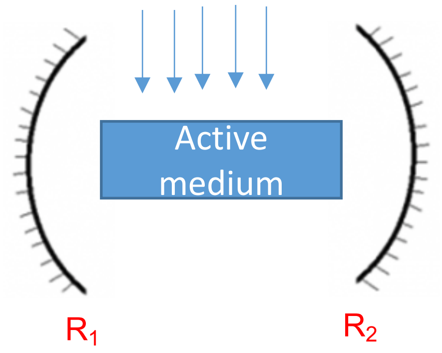








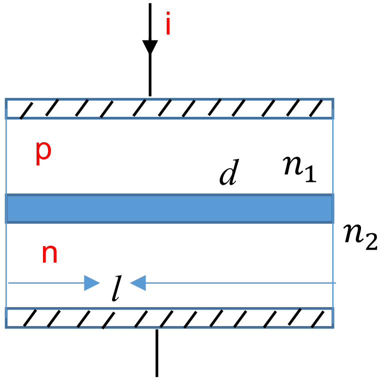
Laser Fundamentals: Optical Amplifier



Bulk laser

Active medium becomes gain medium when

$$E_{fc} - E_{fv} > E_g$$



Semiconductor laser

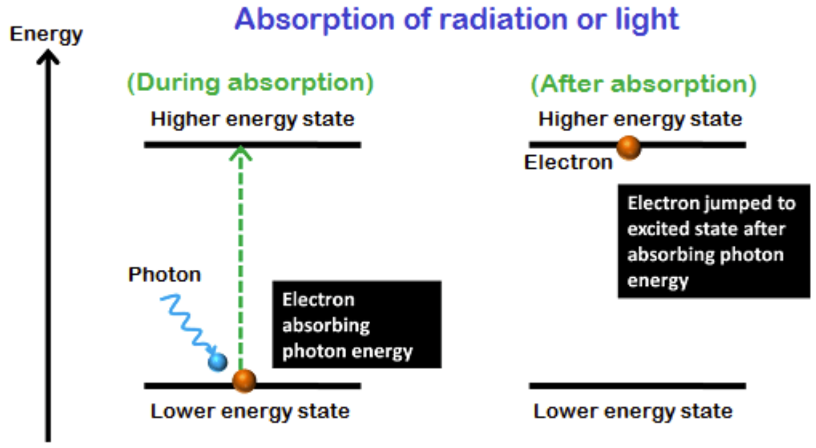
$$\Delta n = \frac{(i/e)\tau}{l \times w \times d}$$

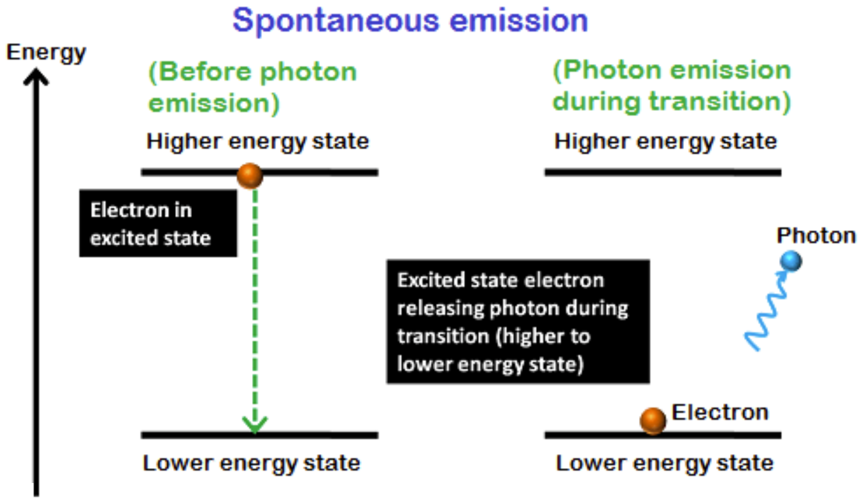
$$E_{fc} - E_{fv} > E_g$$

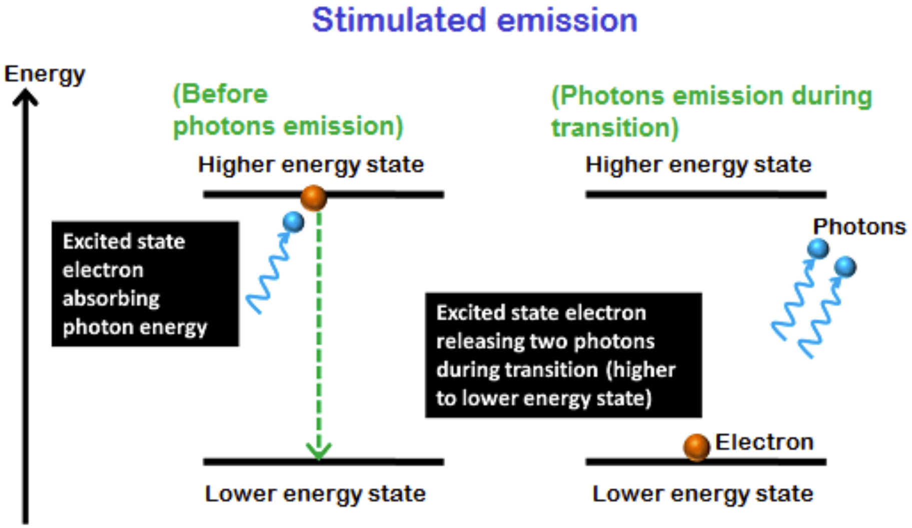
Photons are interacted in 3 different ways with the atoms

- Absorption of the radiation
- Spontaneous emission
- Stimulated emission

Laser Fundamentals: Optical Amplifier

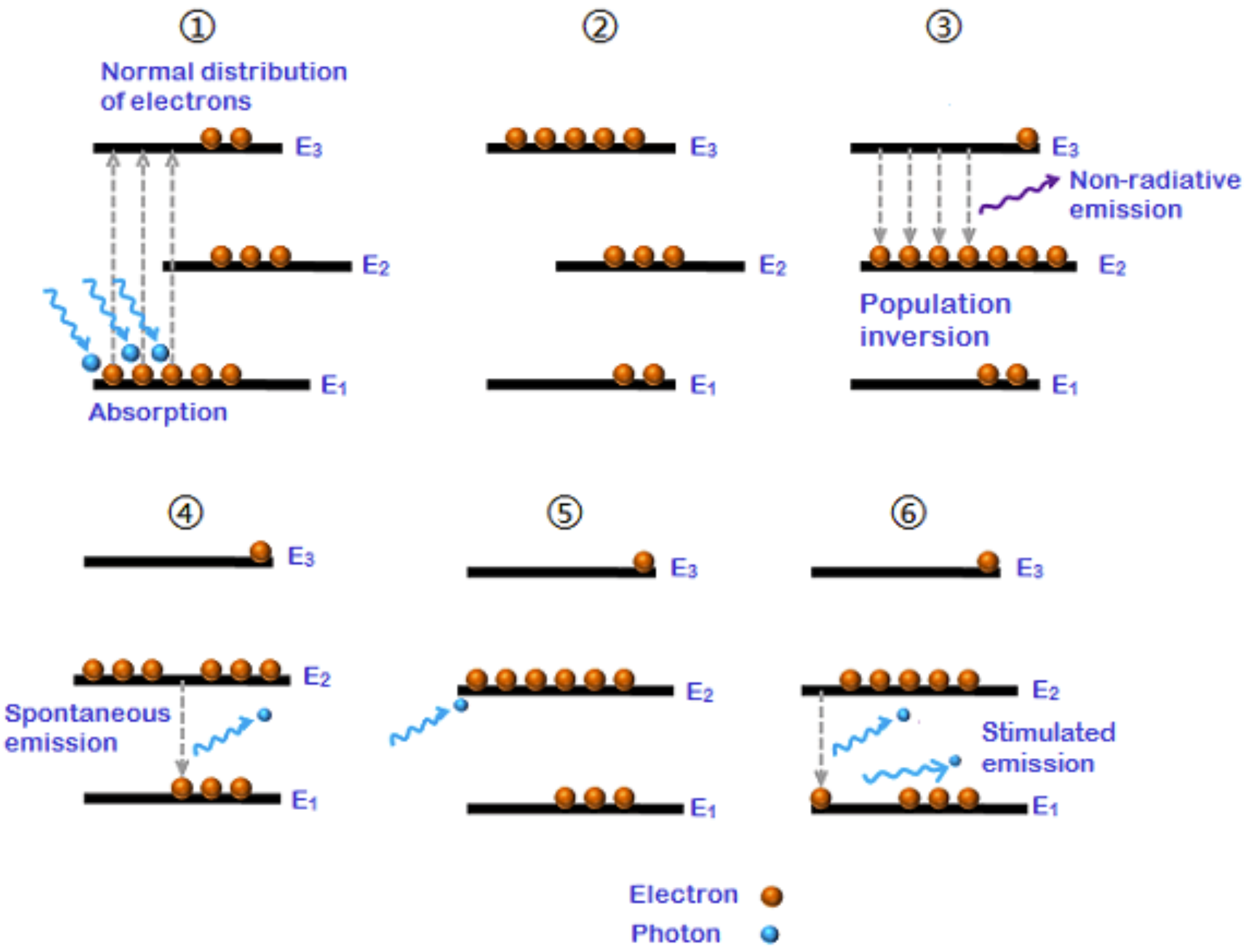






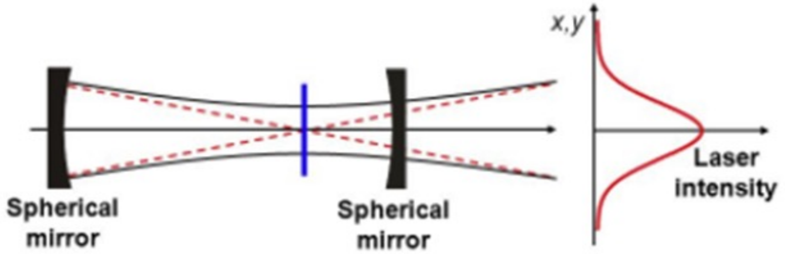
Laser Fundamentals: Optical Amplifier

Population inversion in 3-level laser

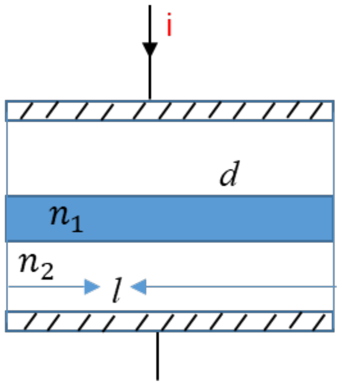


Population inversion in 4-level laser

Laser dynamics at steady state

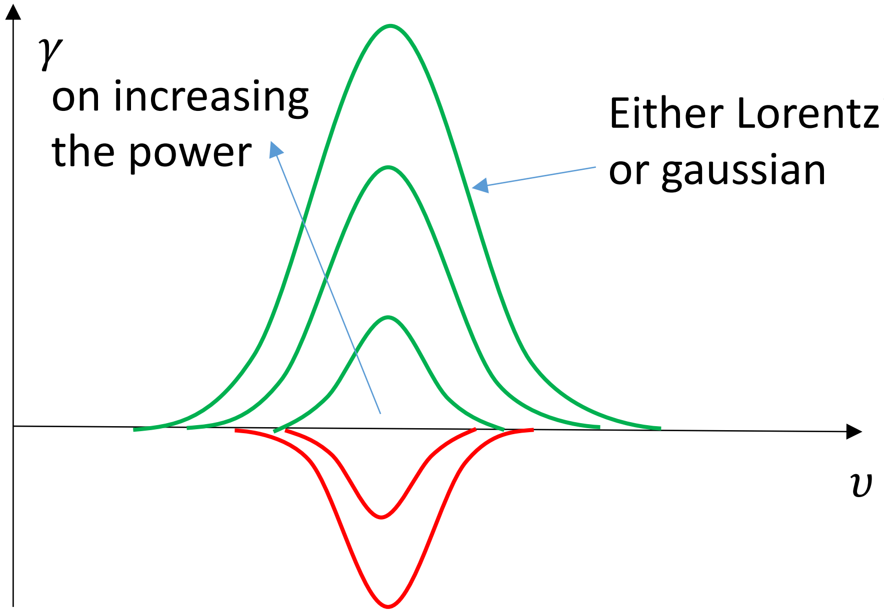


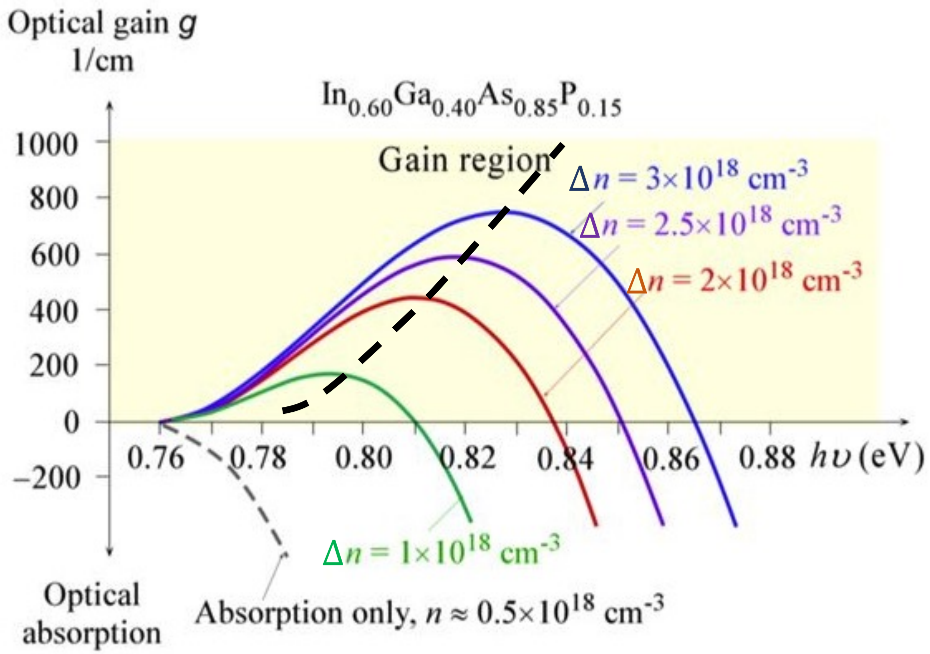
Gain = Loss



$$\Delta n = \frac{(i/e)\tau}{l \times w \times d}$$

$$E_{fc} - E_{fv} > E_g$$

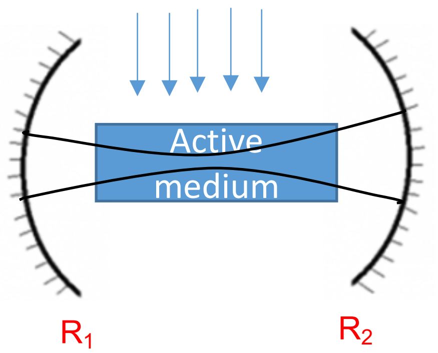




Δn on creasing, *i* increasing

Laser Fundamentals: Optical Amplifier

Gain = Loss



Bulk laser

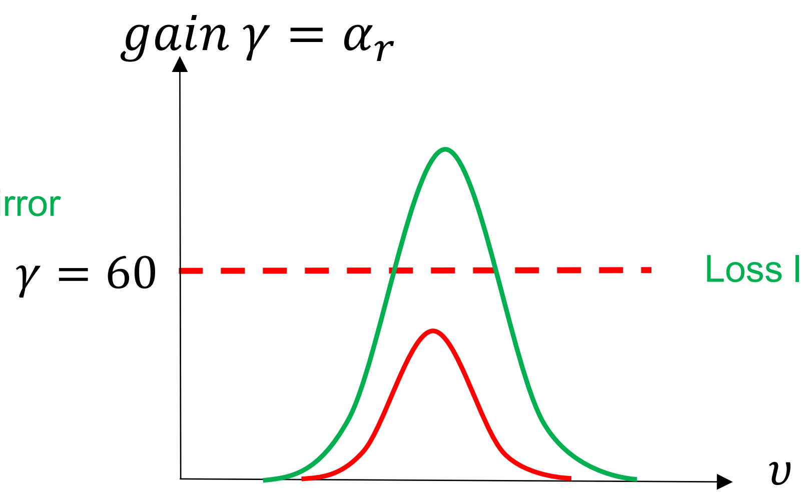
$$resonator\ loss, \alpha_r = \alpha_s + \alpha_m$$
$$= \alpha_s + \frac{1}{2L} ln\left(\frac{1}{R_1 R_2}\right)$$

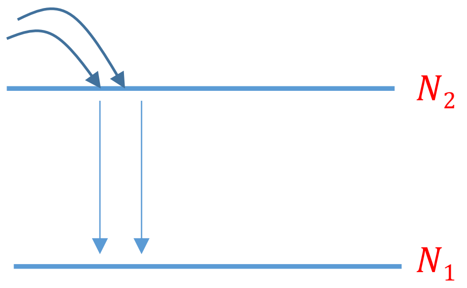
In semiconductor loss

- α_s 10 to 50 cm-1
- α_m= 38 cm-1 for 0.32 reflectivity and 300
- And resonator loss is about α_r60 cm-1 for 22 scattering loss

Loss in resonator

- Scattering loss in the medium
- Diffraction losses
- Losses due to the finite reflectivity of the mirror





$$\gamma = (N_2 - N_1)$$

"Gain Saturation"

The important thing is in steady state gain coefficient equals to loss coefficient

Laser Fundamentals:

Gain and Loss plot on steady state

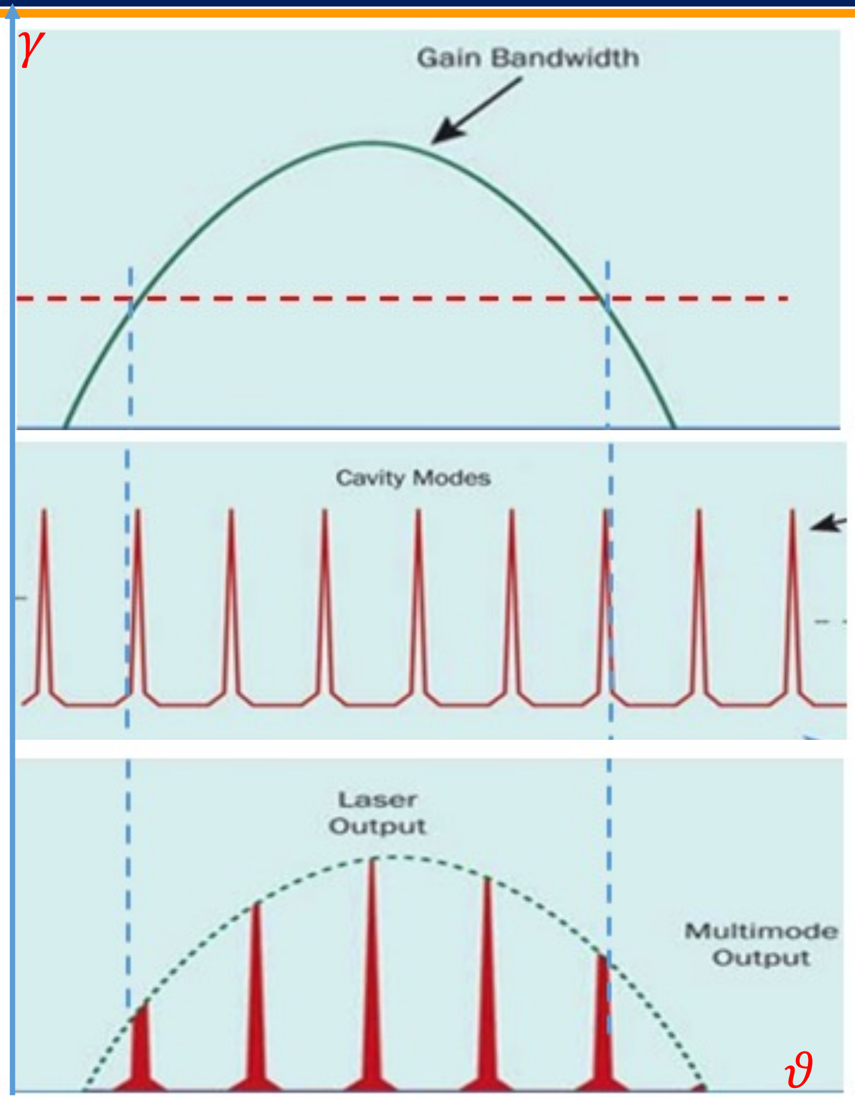
Laser Fundamentals:

Assignment # 01

1. How the short pulse can be obtained?

2. Discuss Gain saturation in the laser dynamics

Laser Fundamentals

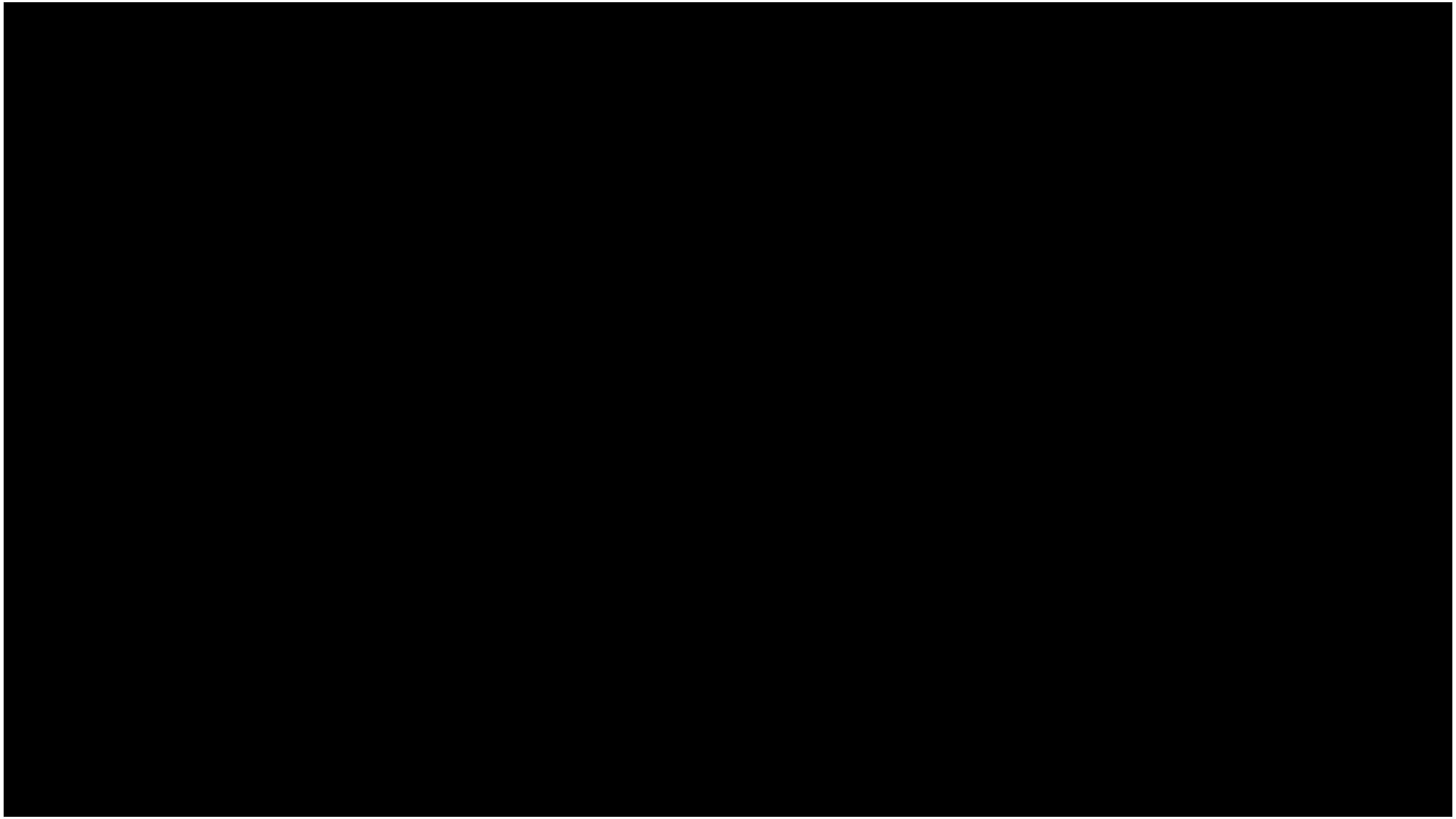


Gain plot due to the active medium pumping power

Longitudinal Mode defined by the resonator

Laser output power

Laser Fundamentals: Summary video



Any Queries

College of Electronics
and
Information Engineering ,
Room #120
Bikash@nuaa.edu.cn