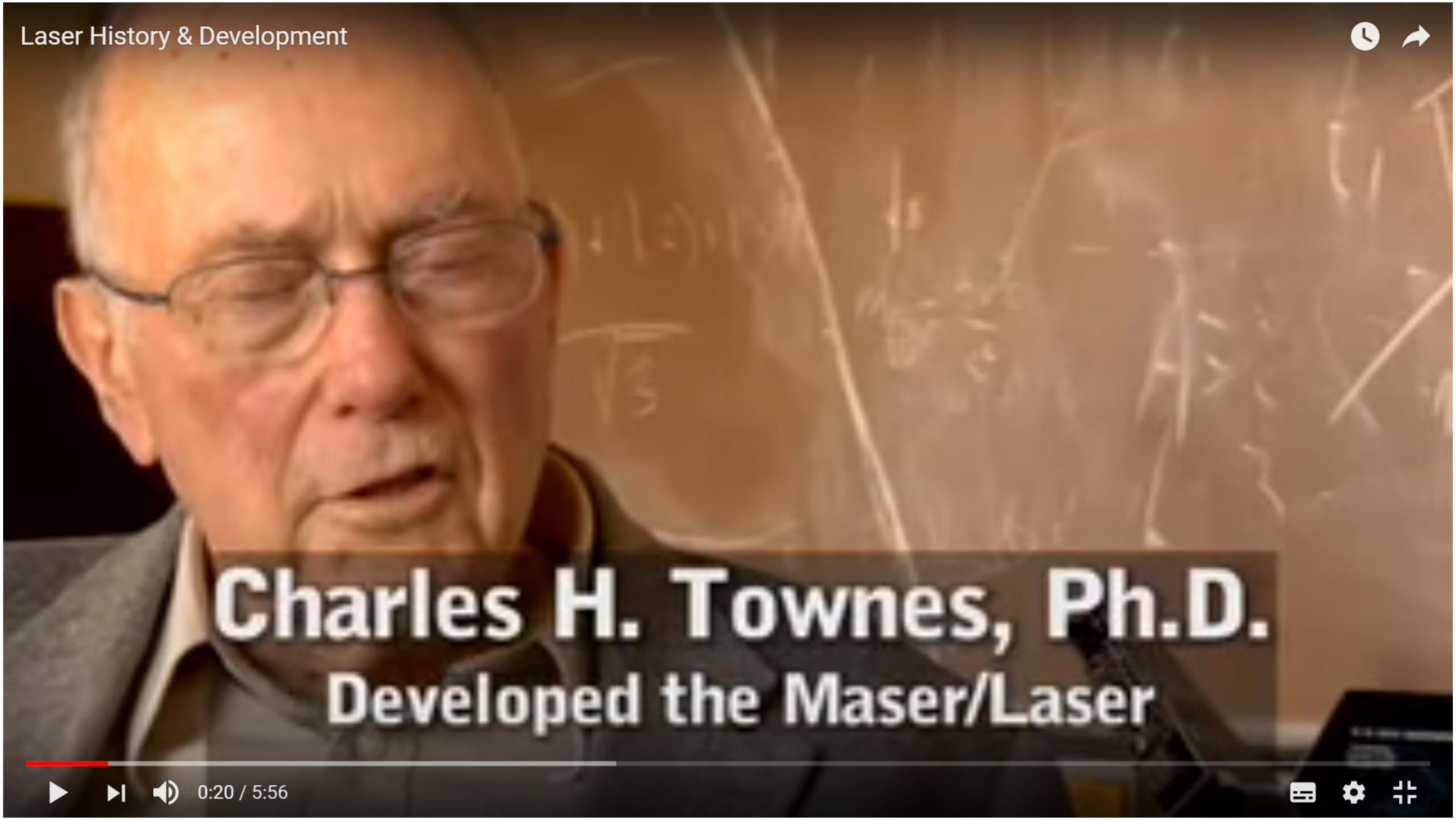
Brief History (Milestones in the history of lasers):

- **1917 Einstein's** treatment of stimulated emission. Einstein can be considered as the father of the laser.
- **Charles H. Townes** @ Columbia University, **Joseph Weber** @ University of Maryland, and **Prokhove et. al** (@ Russia) => **stimulated emission** as a mean of amplifying electromagnetic radiation in **microwave spectrum**.
- **1954 Townes et al**., using **Ammonia gas** and produced amplified Microwave radiation instead of visible light (**M**icrowave **A**mplification by the **S**timulated **E**mission of **R**adiation, **MASER**).
- **1954, Robert H. Dick** develop the ideal of using **short excitation pulse** and generate an intense burst of **amplified spontaneous emission**.

Laser Engineering, Kuhn et al.,

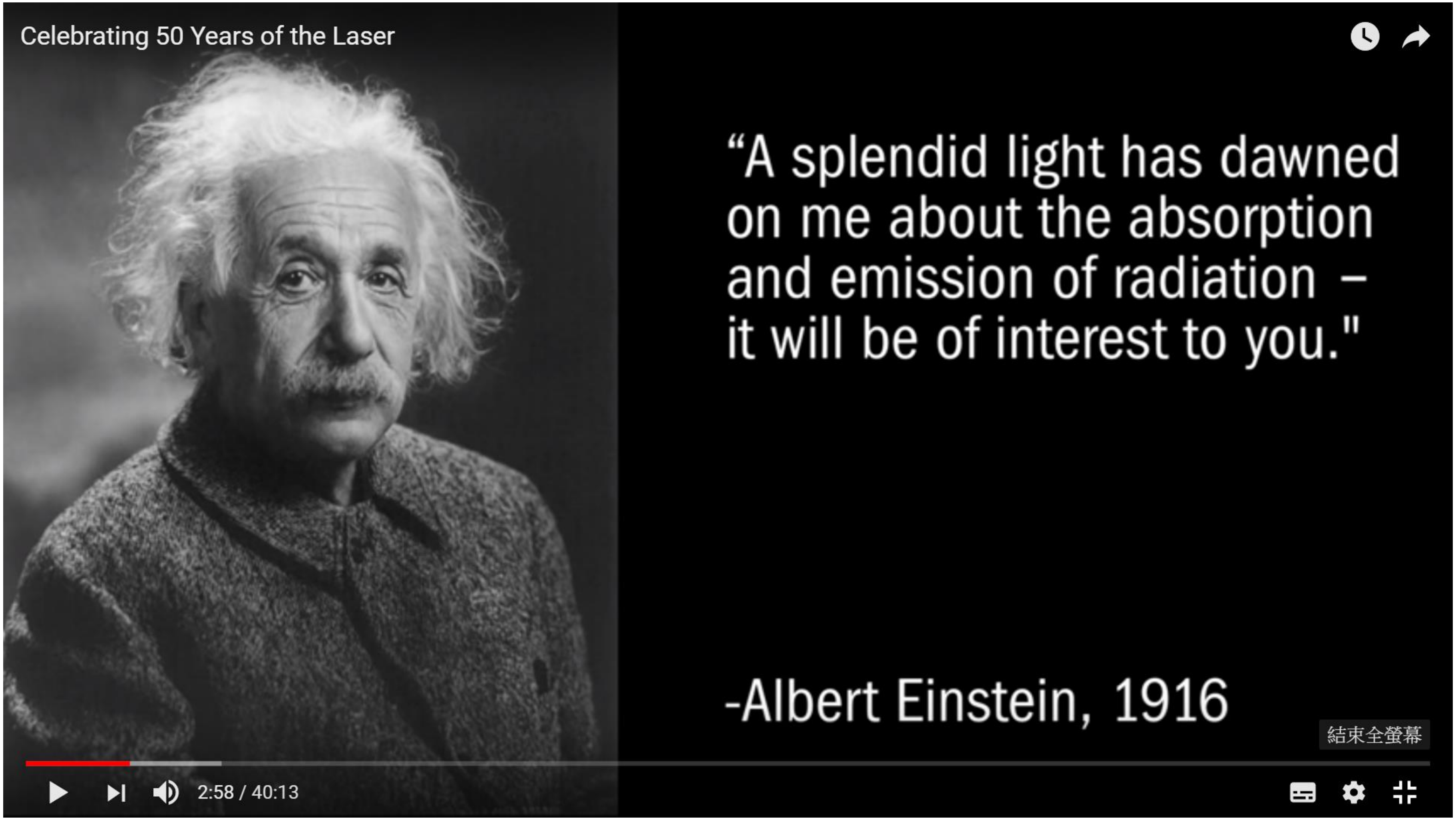
Laser History & Development

- https://www.youtube.com/watch?v=85fcjAjvhnQ



Celebrating 50 Years of the Laser

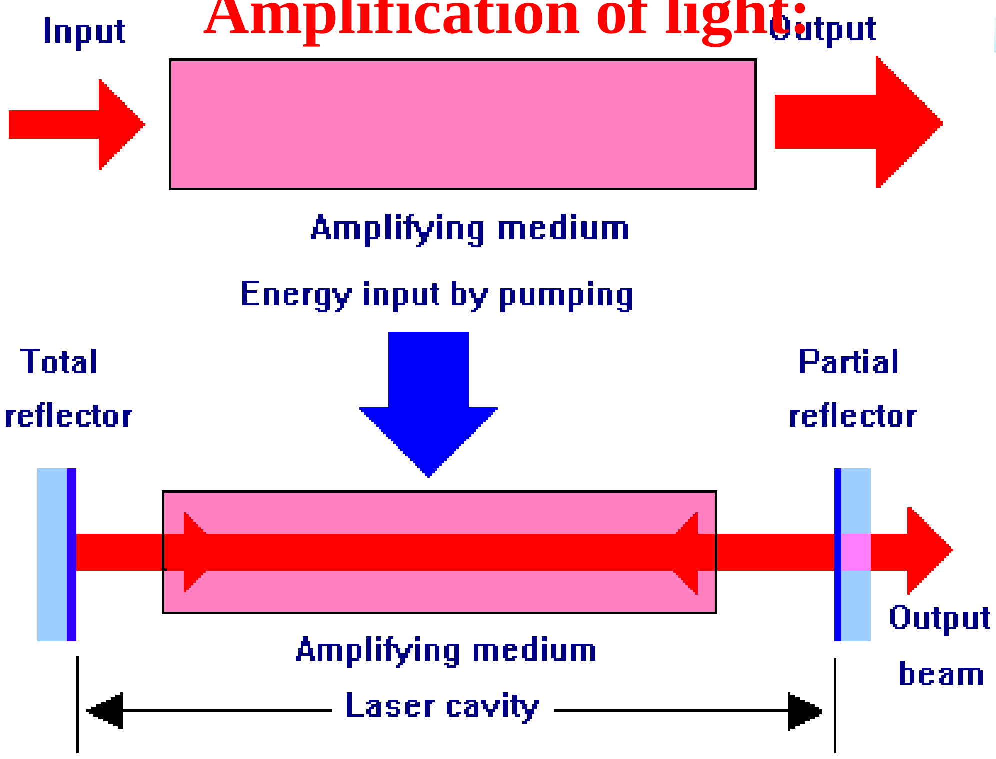
- https://www.youtube.com/watch?v=eQQeSUvgmJE



➢ 1957, Gordon Gould

- Conceive of the ideal using **Fabry-perot cavity** as a part of laser structure.
- Using the title of "**Laser**" (**L**ight **A**mplification by **s**timulated **E**mission **R**adiation) in his laboratory note book

Amplification of light:



- A laser is actually an **oscillator** rather than a simple amplifier.
- The difference is that an oscillator has **positive feedback** in addition to the amplifier.

- **1958, Schawlow** and **Townes** wrote seminal paper entitled

  "Infrared and optical masers"=> discussing the question about "pumping power requirement, **multimode cavity**, and mentioned the **three and four state laser solids state laser, linewidth and tunabitly.**

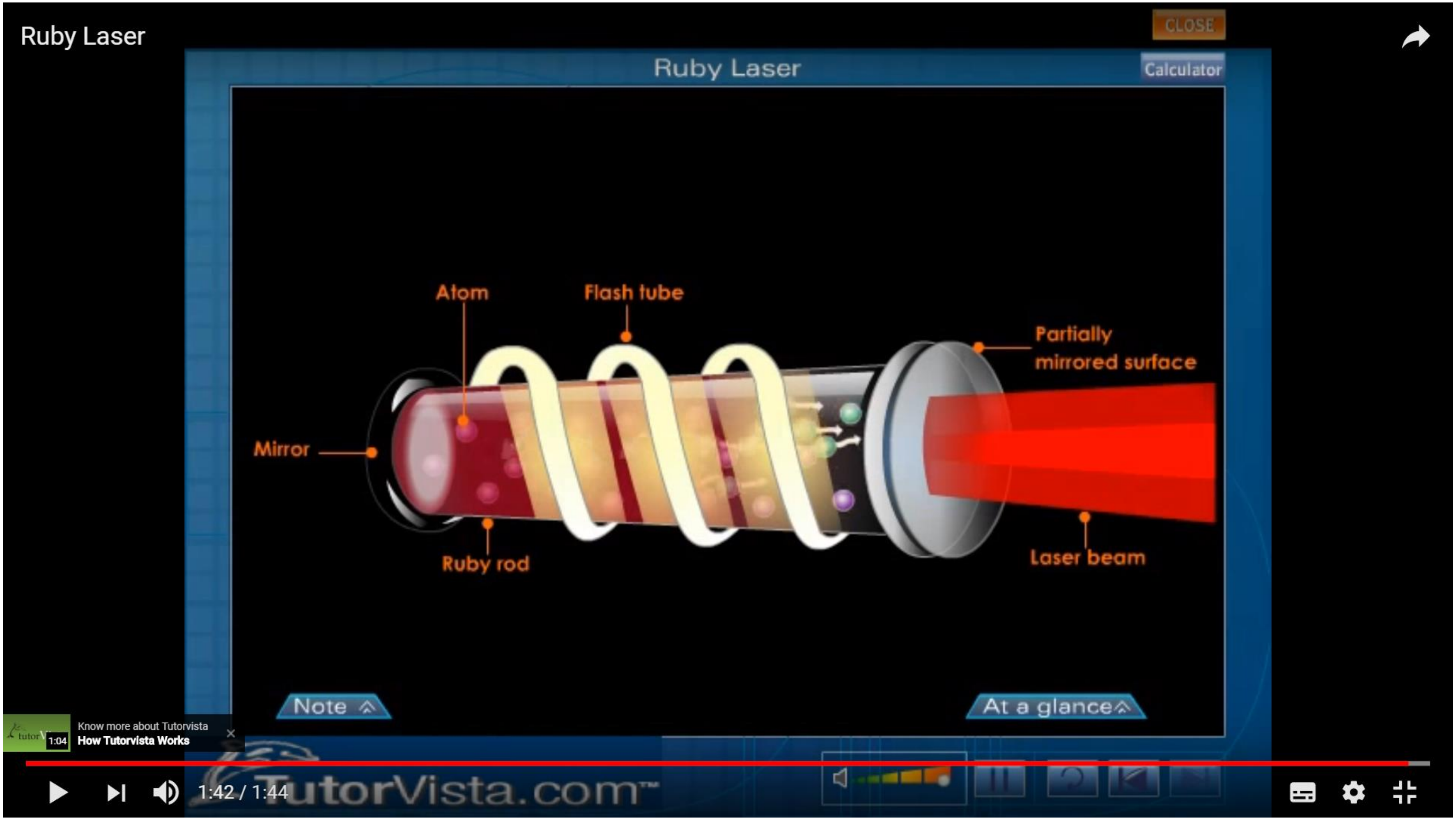
- **1960 T.H. Maiman** at Hughes Laboratories reports the first laser (**three level**): the **pulsed ruby laser** (Low chromium concentration).

How the first laser was made

- https://www.youtube.com/watch?v=Ulg_SP7HDXw

Ruby Laser

- https://www.youtube.com/watch?v=yQ0lMSNuj_o



- **1960**, Sorokin and Stevenson =>flash-lamp pump **uranium-doped calcium fluoride laser** (**first four level laser**)
- **1961** Javan et al.=> **Helium neon (He-Ne) laser** (**first continuous wave (CW) laser**).
- **1962**, **first CW semiconductor laser**.
- **1963**, Kumar et al.=> first **CO_2 laser.**
- **1964**, Geusic et al.=> **Nd:YAG laser**
- **1964**, Bridges => **Argon-ion laser (Ar^+)**.
- **1975**, the first GaAs and Excimer lasers
- **1980**, the first **CW Ti:sapphire laser**.
- **1984**, First **x-ray laser**
- **1997,** Steven Chu, Claude Cohen-Tannoudji and William D. Phillips get the Nobel Prize for “development of methods to cool an trap atoms with laser light.”

The History of Laser Light

- https://www.youtube.com/watch?v=XRLRSdgvLg0

Lasers can be divided into groups according to different criteria:

- The state of matter of the **active medium**:

  solid, liquid, gas, fiber or plasma.

- The spectral range of the **laser wavelength**:

  visible spectrum, Infra-Red (IR) spectrum, etc.

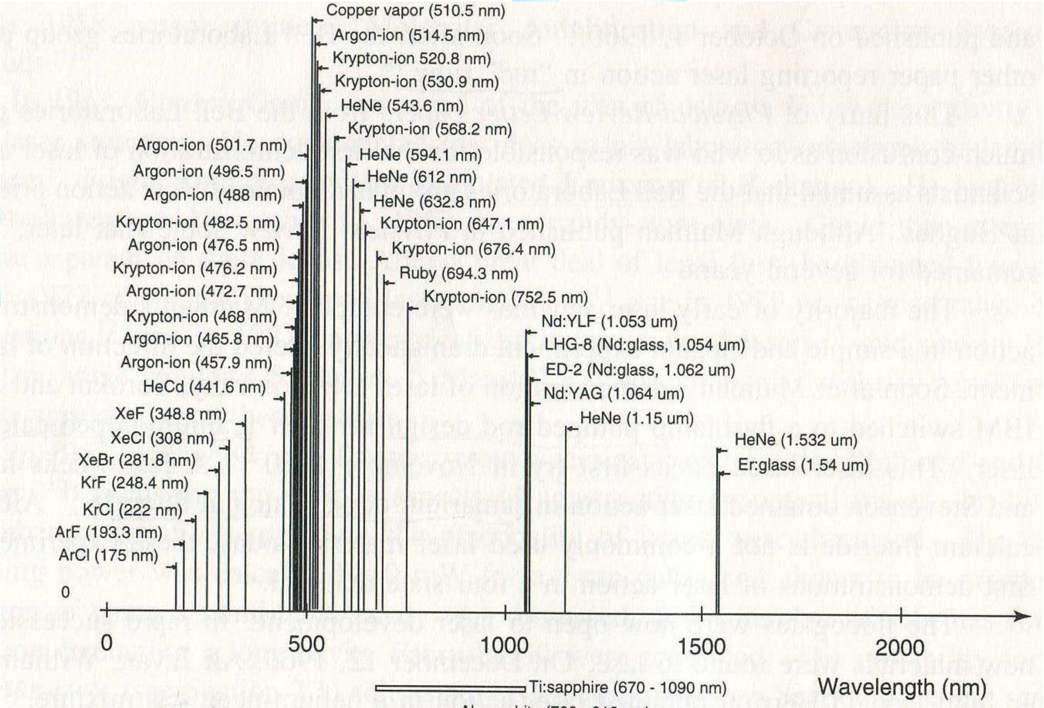
- The **excitation (pumping)** method of the active medium:

  Optic pumping, Electric pumping, etc.

- The characteristics of the radiation emitted from the laser:

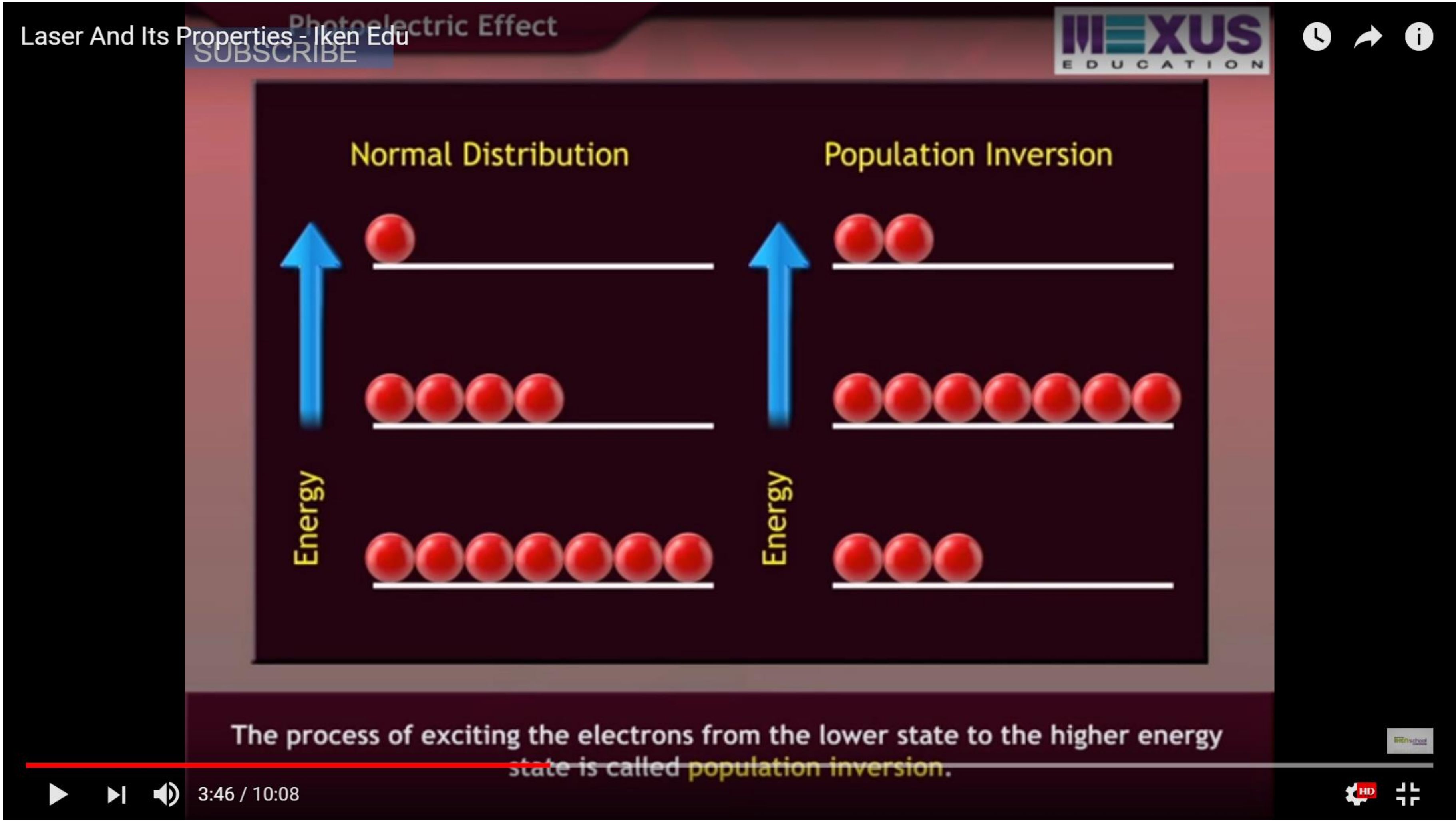
  CW, pulsed output.

- The number of energy levels which participate in the lasing process.



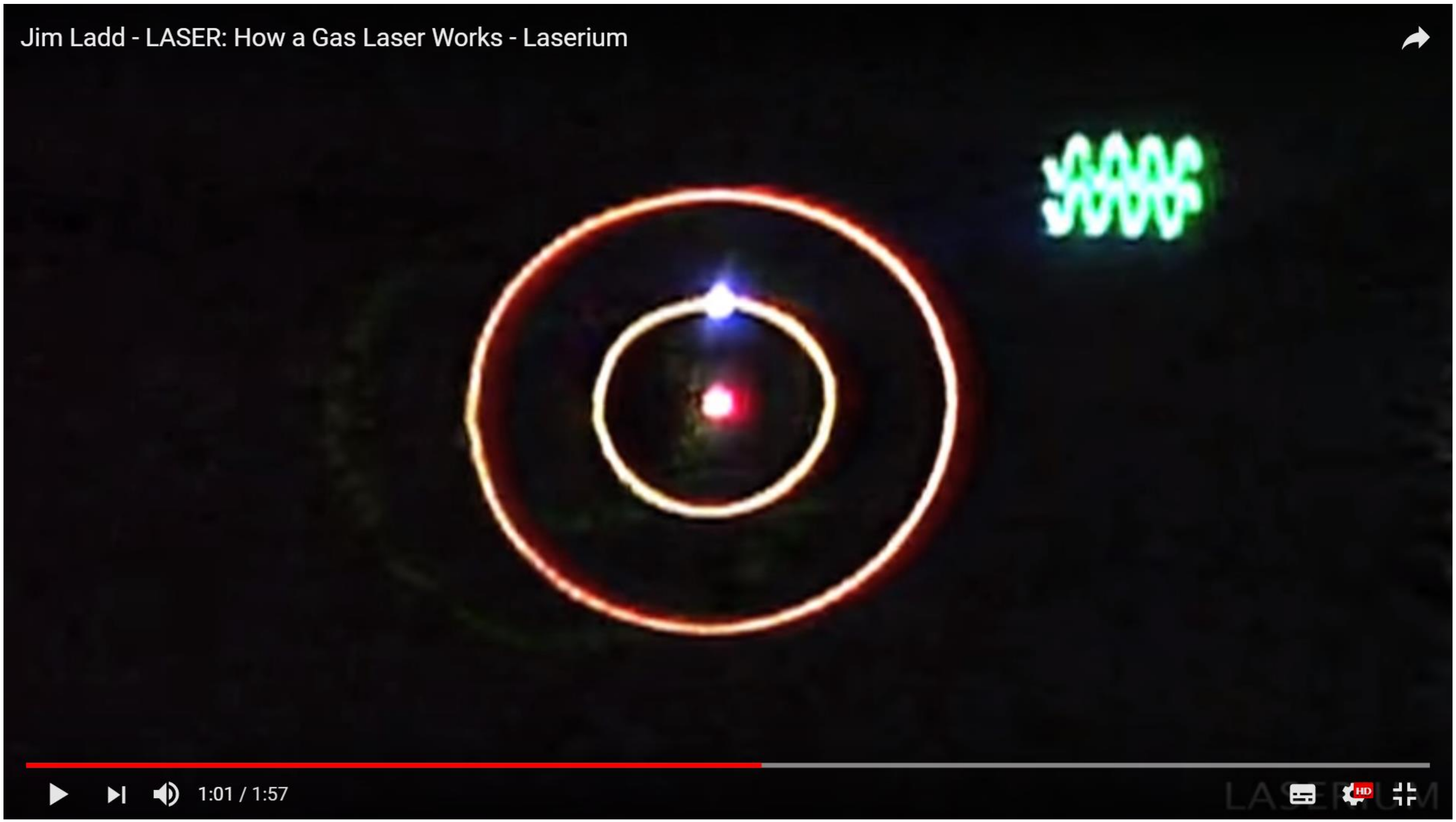
Introduction of laser

- https://www.youtube.com/watch?v=QlVDFZDL2Ho



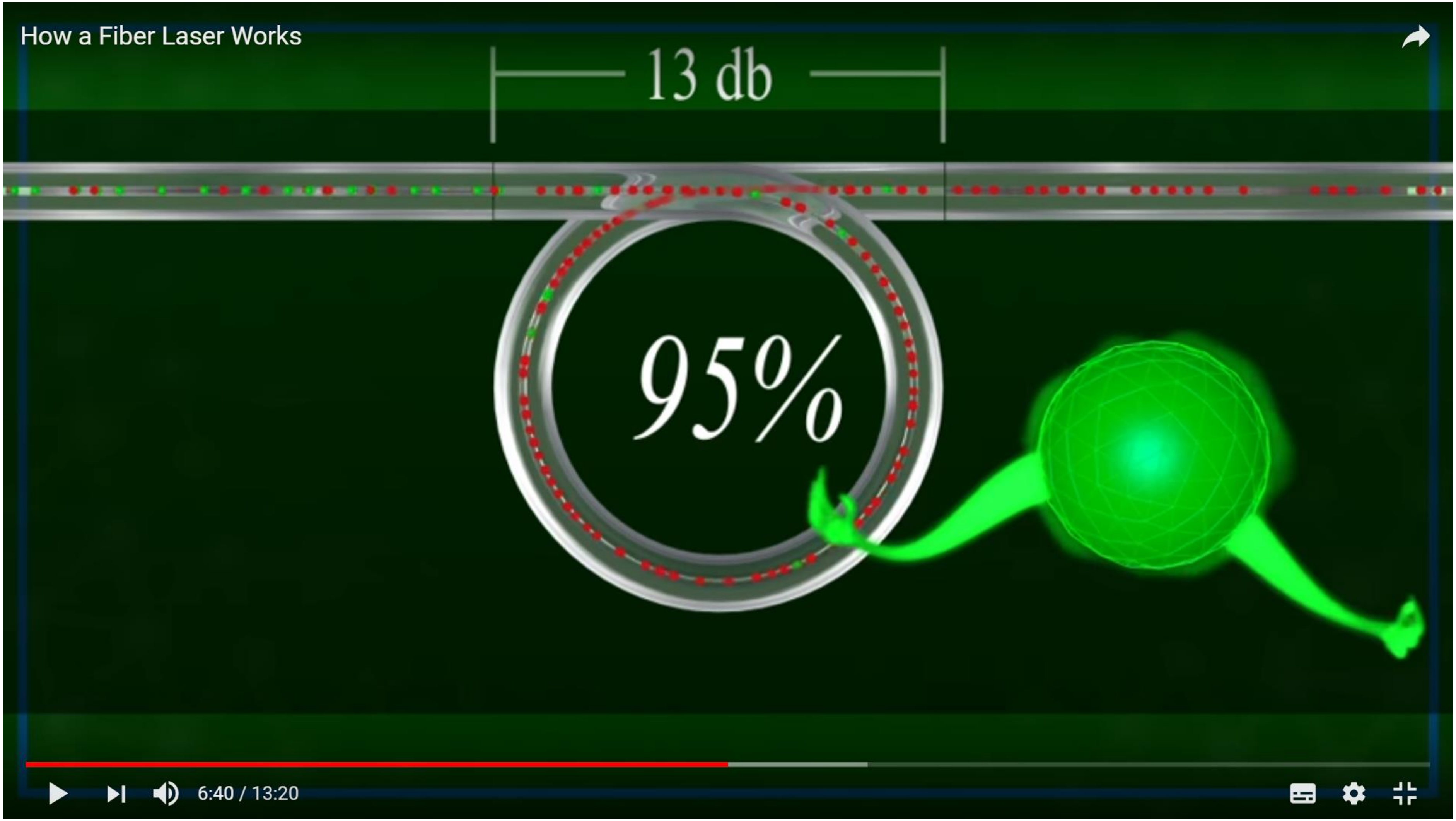
How a gas laser laser work?

- https://www.youtube.com/watch?v=6l945YVDOCA



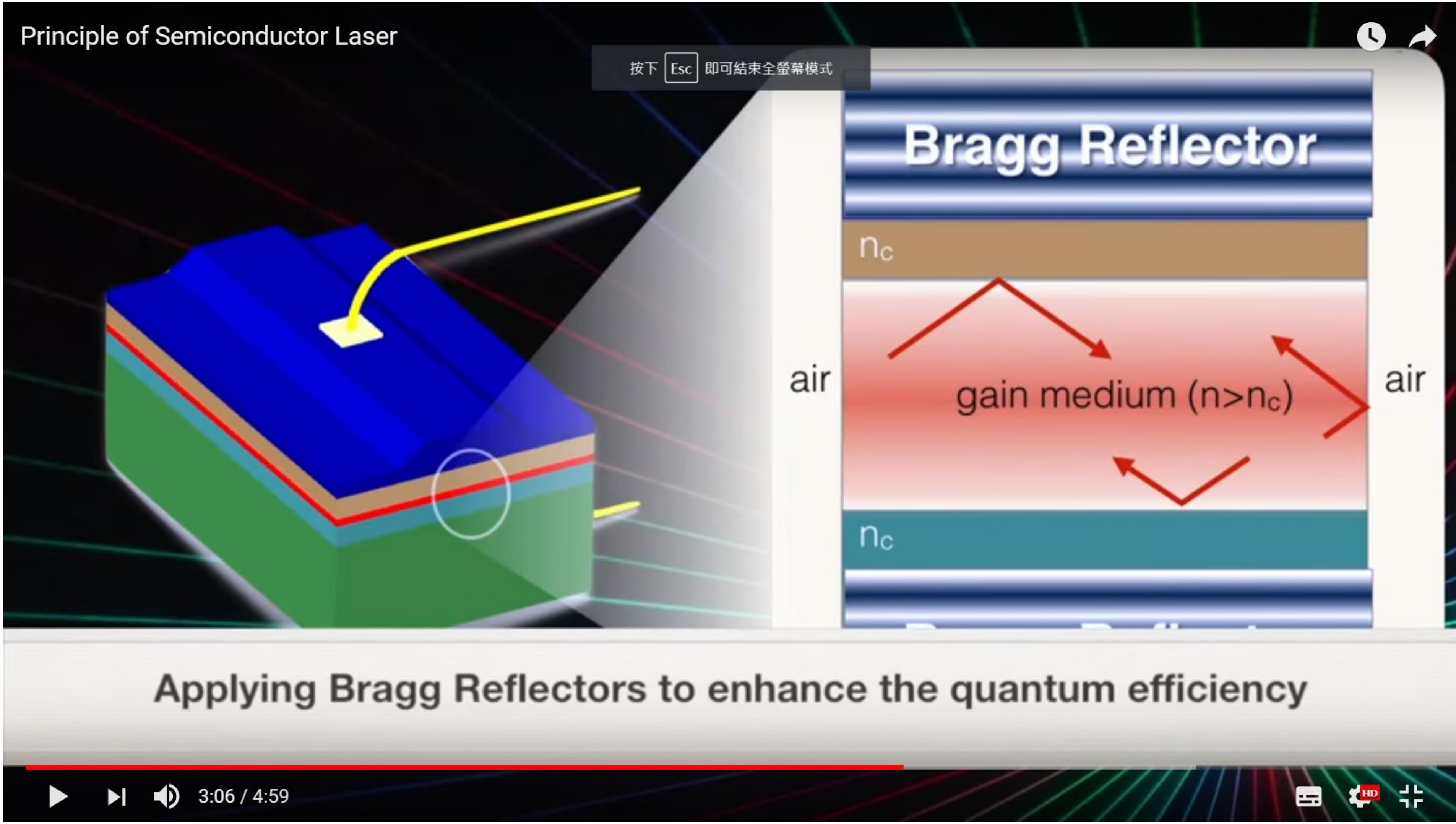
How fiber laser work

- https://www.youtube.com/watch?v=ofEqFlqkiS0



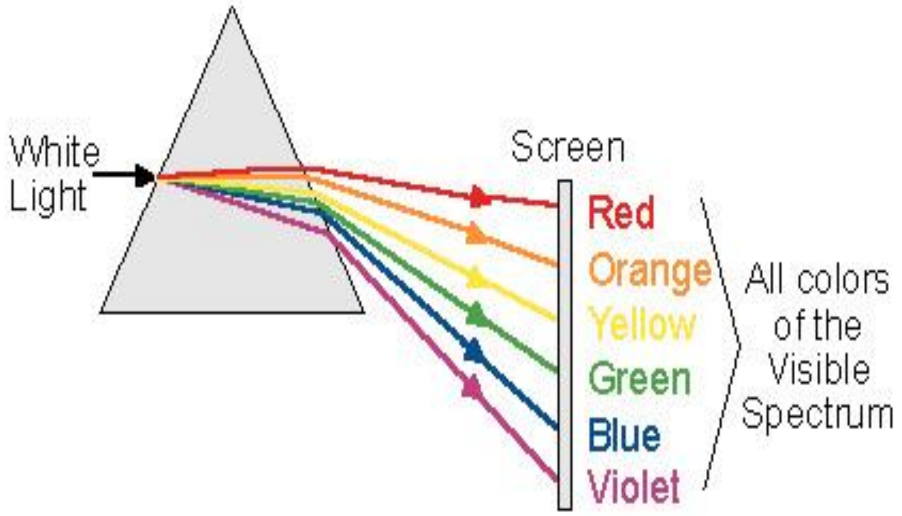
Principle of Semiconductor Laser

- https://www.youtube.com/watch?v=NpePZjTXqRw



Properties of Laser Light

- Monochromaticity
- Directionality
- Brightness
- Coherence
- Polarization



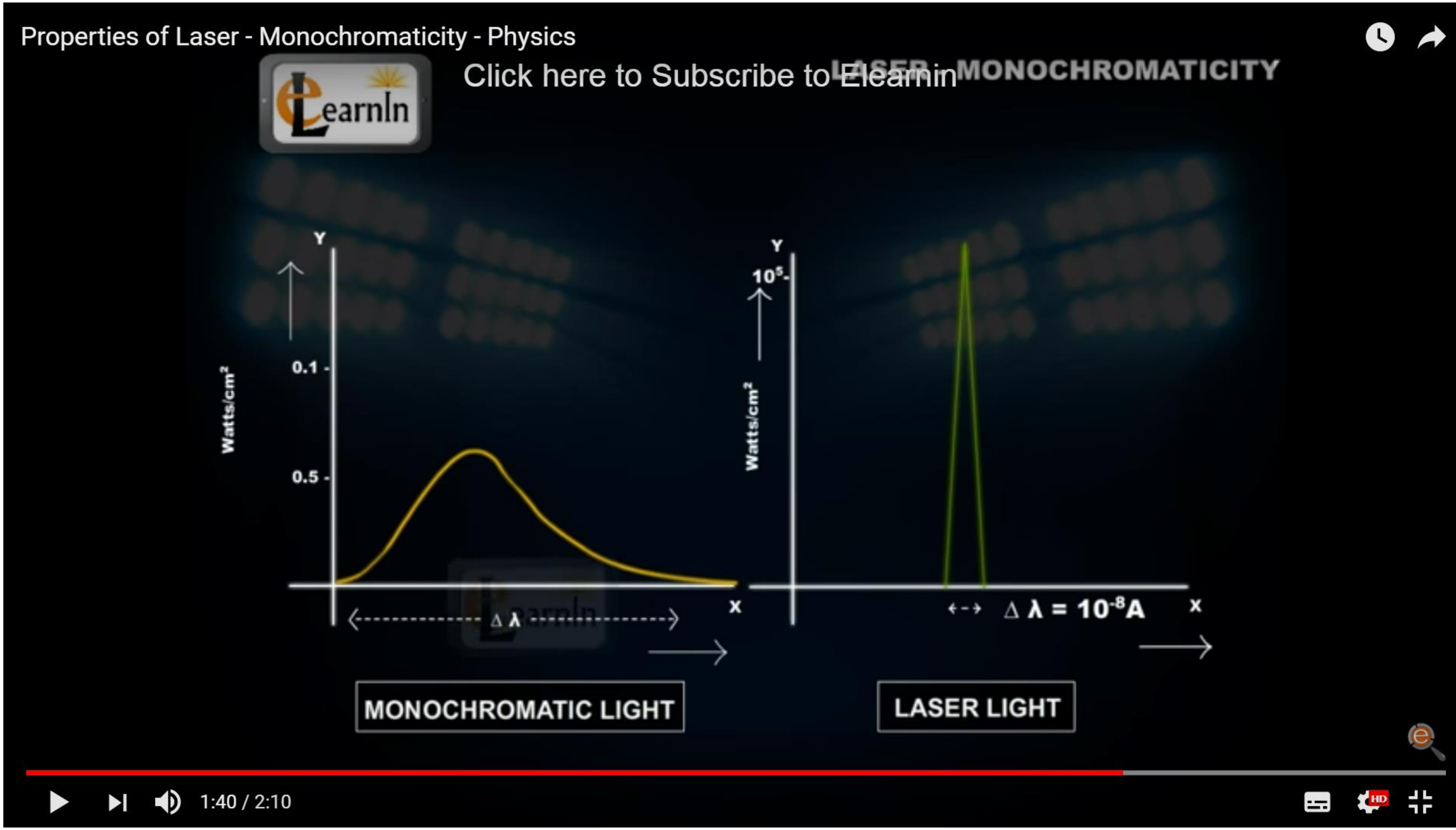
Monochromaticity

When "white light" is transmitted through a prism, it is divided into the different colors which are in it.

Monochromaticity means **"One color"** , a group of photons at exactly one **frequency**

Properties of Laser - Monochromaticity

- https://www.youtube.com/watch?v=y-JCF3K9ntc



Example

Consider a HeNe laser with a linewidth of 1.5 GHz and a center operating wavelength of 632.8 nm. What is the laser linewidth Δλ in angstroms?

$$\Delta\lambda \approx \left(\frac{c}{\nu^2}\right)\Delta\nu = \frac{\lambda^2}{c}\Delta\nu = (632.8\times10^{-9})^2\,\frac{1.5\times10^9}{3\times10^8} = 0.002004\,nm$$

Example

Consider a Nd:YAG laser with a laser linewidth of 4.5 angstroms and a center wavelength of 1.064 mm. What is the coherence length?

$$\Delta\nu \approx c\left(\frac{\Delta\lambda}{\lambda^2}\right) = 3x10^8\left(\frac{4.5\times10^{-10}}{(1.064\times10^{-6})^2}\right) = 119.17GHz$$

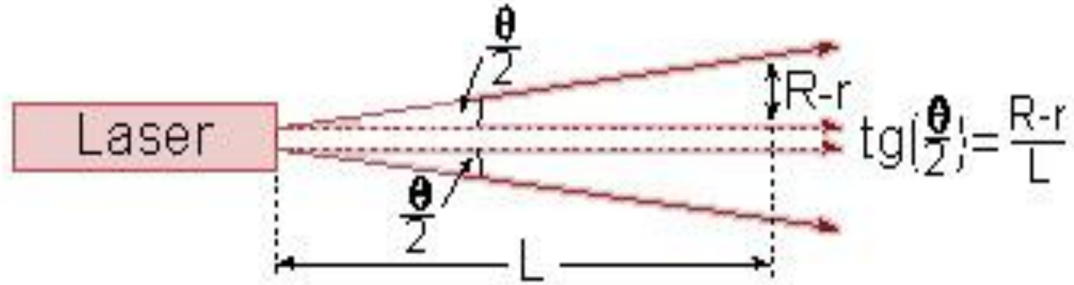
The coherent length

$$l_c = \frac{c}{\Delta\nu} = \frac{3\times10^8}{119.16} = 2.516\,mm$$

- The **spectral line width** of lasers can be much smaller than that of the **atomic transition**.
- This is because the emission is affected by the **optical cavity** and **the lasing mechanism**.
- In certain cases, the laser can be made to operate on just **one of the longitudinal modes** of the cavity.
- **Advantages of high degree of monochromaticity:**
  - **standard color source**
  - Applications in **high resolution spectroscopy**, **interferometry** and **holography**, etc, which require **high coherence**.
  - Sources for precision **measurements**
  - Increase **focusability**

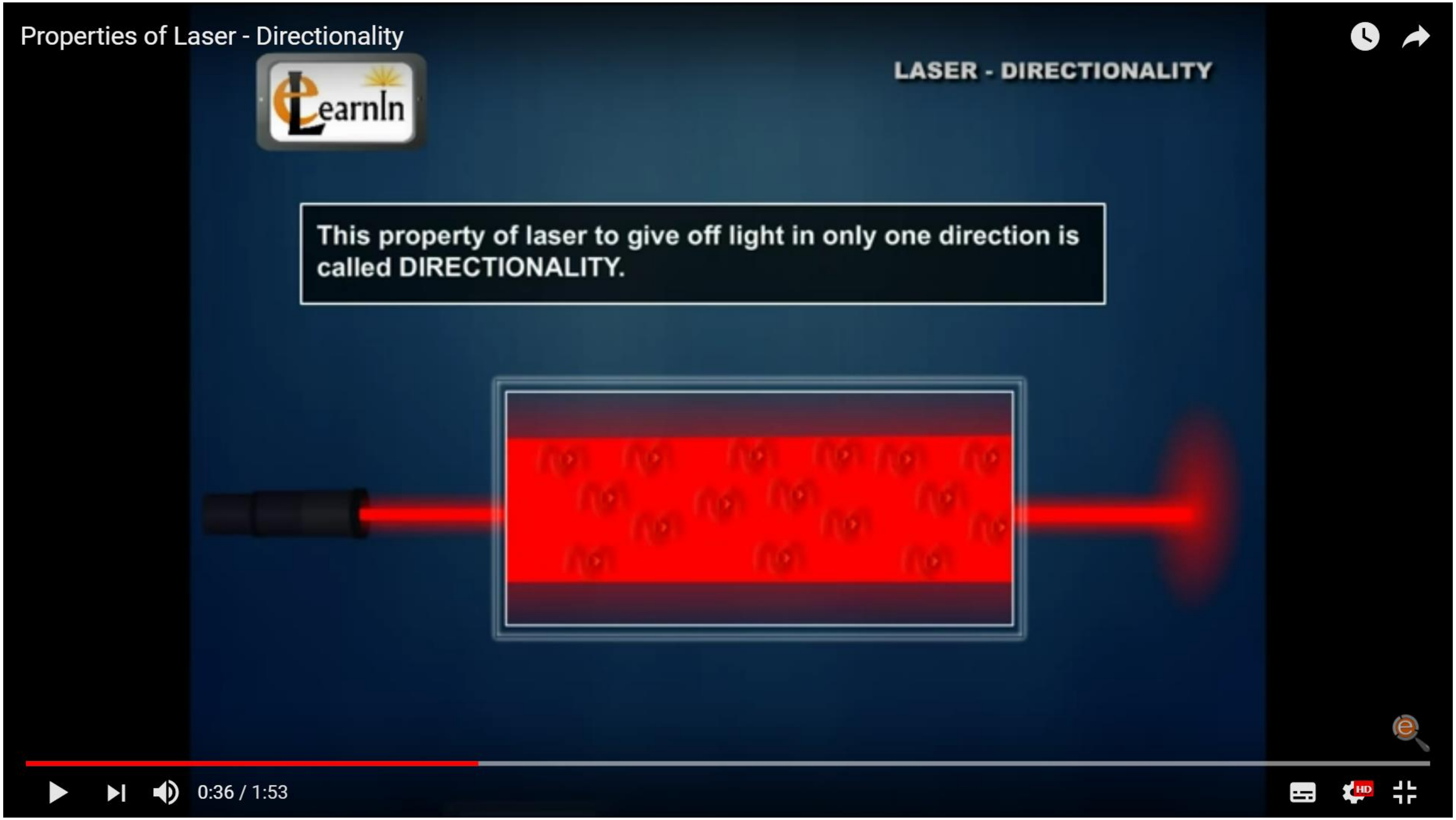
Directionality

- In contrasts with **light bulbs** and **discharge lamps**, in which the light is emitted in all directions, the light comes out as a **highly directional beam**.
- The directionality is a consequence of the **cavity**.
- Radiation comes out of the laser in a certain direction, and spreads at a defined **divergence angle** (θ).



Properties of Laser - Directionality

➢ https://www.youtube.com/watch?v=-o0Qhek38UE



This angular spreading of a laser beam is very small compared to other sources of electromagnetic radiation that can be described by:

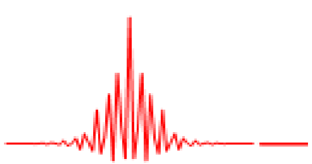
(a) From Geometric Optics point of view:

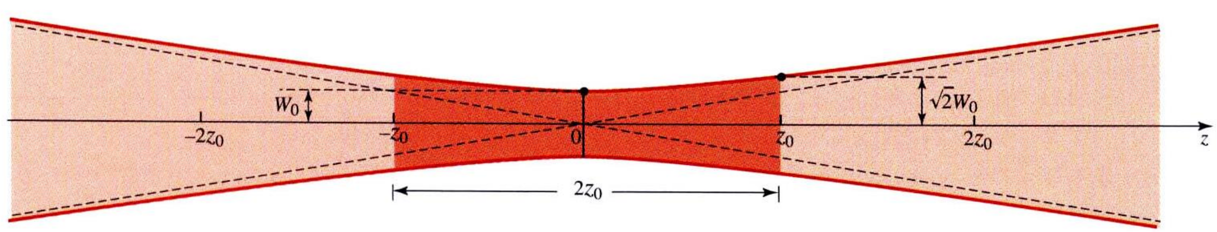
Only rays that are **closely aligned** with the resonator's **centerline** can make the required number of round trips, and these aligned rays diverge only slightly when they emerge.

(b) From Wave Optics point of view:

Beam diverges due to **diffraction** and **partial spatial coherence**. The divergence of a **TEM$_{00}$** laser beam is determined by the **intrinsic size** of beam within laser cavity (**beam waist ω_0**).

$$\varphi = 2\theta \approx \tan^{-1}\left(\frac{2\omega_0}{z_0}\right) = \tan^{-1}\left(\frac{2\lambda}{\pi\omega_0 n}\right) \approx 1.27\frac{\lambda}{2\omega_0}$$





Brightness

Brightness ≡ radiant flux (radiometry, power) or luminous flux (photometry) emitted per unit surface area (source) per unit solid angle

$$B = radiance(radiometry) = \frac{radiant\ \ flux(power)}{area \bullet solid\ angle} = \left[\frac{Watts}{m^2\Omega}\right]$$

or

$$B = luminance(photometry) = \frac{luminous\ \ flux}{area \bullet solid\ angle} = \left[\frac{lumen}{m^2\Omega}\right]$$

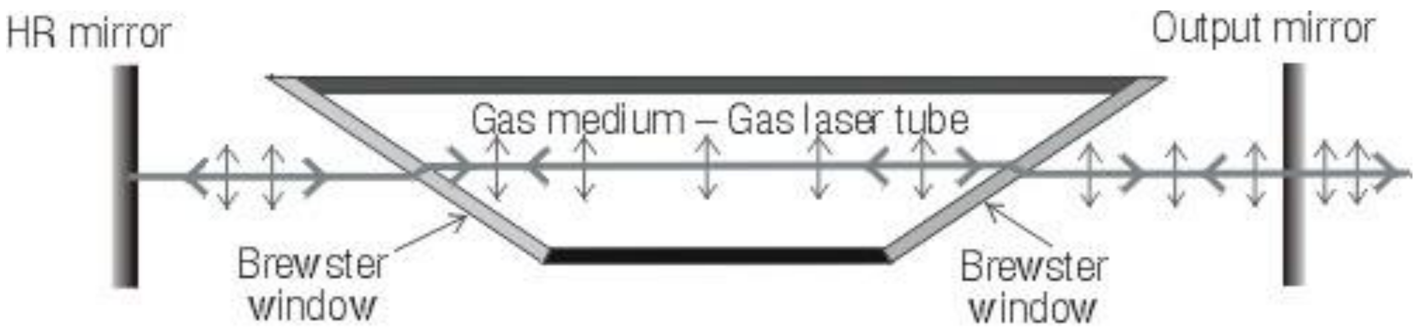
Since laser radiation divergence is of the order of milli-radians, the beam is almost **parallel**, and laser radiation can be send over **long distances**.

Advantages of high directionality and brightness:

- increase S/N ratio
- good focusability

Polarization

Figure shown below is concerned with the operation of **Brewster windows** in a gas laser to produce a polarized laser beam.



(c) Beam polarized in vertical direction after a short time, essentially no horizontal component remains

Since the laser beam reflects back and forth between the cavity mirrors, the loss of the 15% per reflection at the Brewster window quickly **wipes out** the **TE mode**, **leaving only the TM mode**

Coherent (spatial and temporal)

- In discussing the **coherence** of an optical beam, we must distinguish between **spatial** and **temporal coherence**. Laser beams have a **high degree** of both.
- **Temporal coherence** : measure the **phase correlations** at different time **at the same position**.
- Consider the electric field **at a fixed point P**, if there has a phase relationship between the two fields at time t and $t+\tau$, we say that the electric field is **temporal coherence** over time τ.
- If this occurs for any value τ, the E. M wave is said to have **perfect time coherence**.
- If this occurs for $0 < \tau < \tau_c$, it said to said **partial temporal coherence** with **coherence time** τ_c.
- It measures the **degree of monochromaticity of the light**.

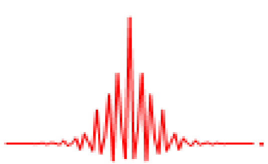
- Let us consider two linearly polarized wave of the **same frequency** ω

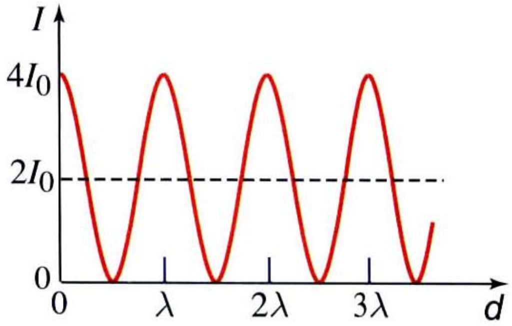
$$E_1 = E_{10} \exp i(k_1 \cdot r - \omega t + \phi_1)$$
$$E_2 = E_{20} \exp i(k_2 \cdot r - \omega t + \phi_2)$$

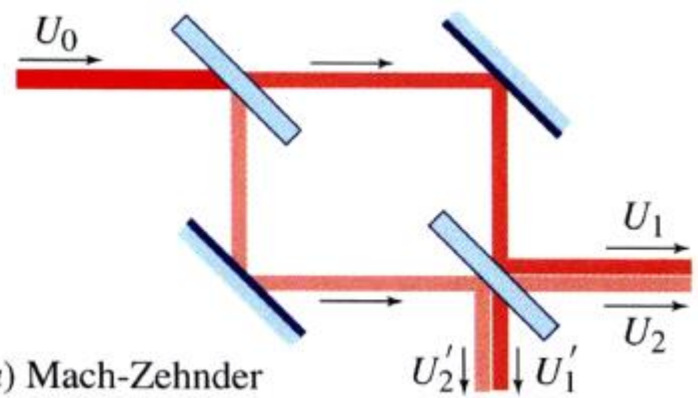
- The superposition of the two plane wave, results in an irradiance function

$$I = |E|^2 = E \cdot E^* = (E_1 + E_2)\cdot(E^*_1 + E^*_2)$$
$$= |E_1|^2 + |E_2|^2 + 2E_1 \cdot E_2 cos\theta$$
$$where\ \theta = k_1 \cdot r - k_2 \cdot r + \phi_1 - \phi_2$$

- If the phase difference is constant, the two source are said to be mutually coherent. If the phase difference varies with time, the interference will be destroyed.



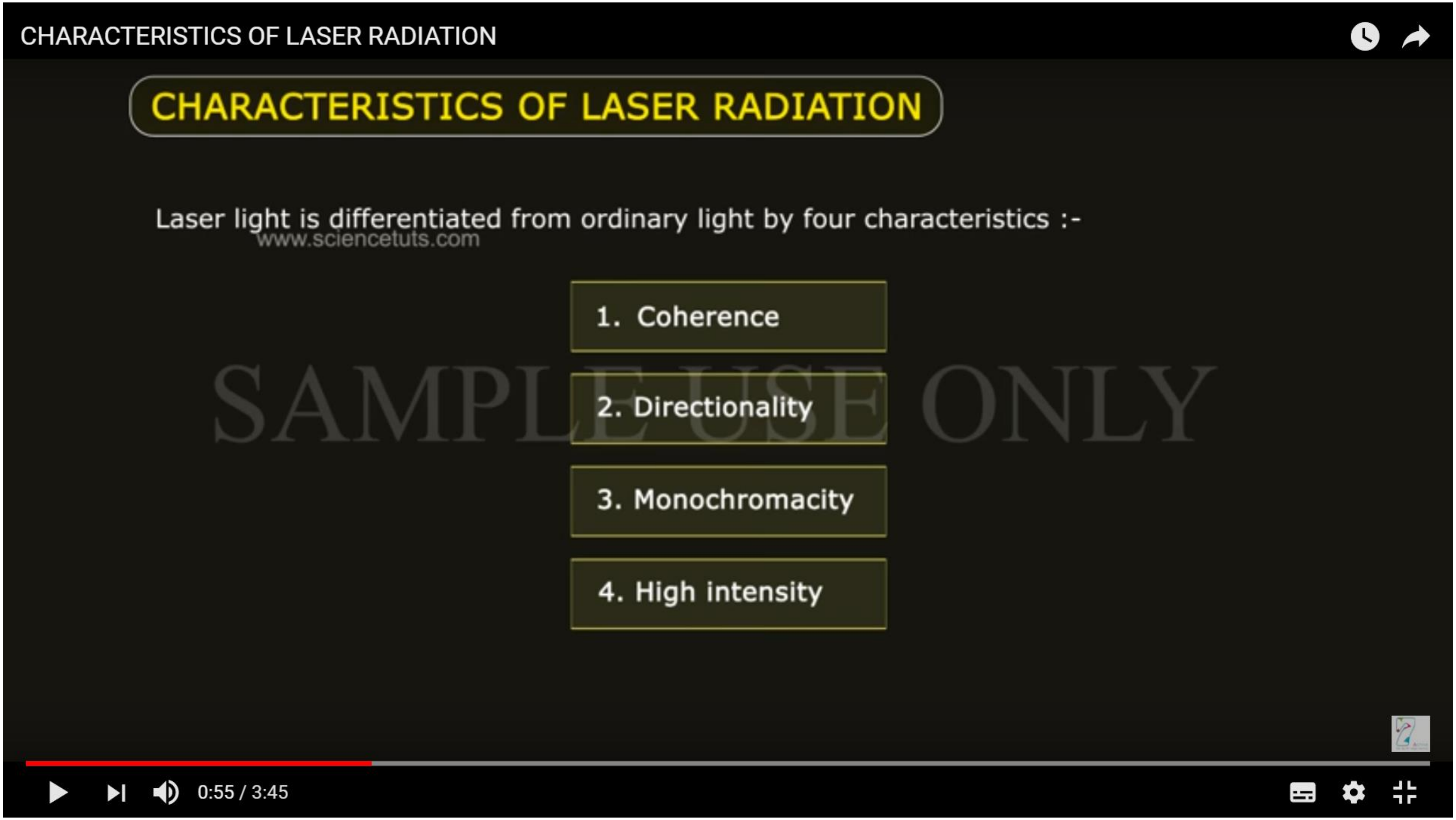




(a) Mach-Zehnder

Property of laser

- https://www.youtube.com/watch?v=BKVMw4jpDZw



Coherence length

- In general, the **temporal coherence time** τ_c is given by the reciprocal of the spectral line width.
- Coherence length $l_c = c\,\tau_c = c/\Delta\nu = \lambda^2/\Delta\lambda$

For example

Typical values of the **coherence length** for a number of light sources are given in Table.

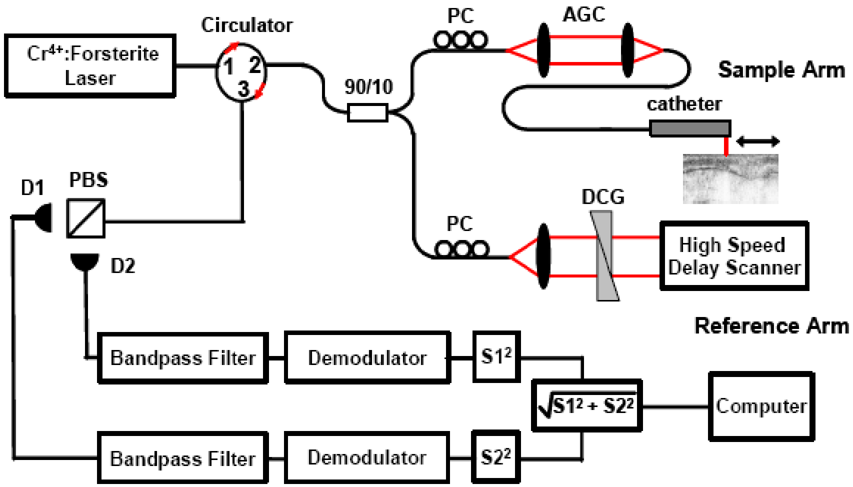
White light $\Delta\nu = 5\times10^{14}$ *Hz*, $\Delta\lambda = 300$ *nm* $\lambda_{av} \sim 550$ *nm*

$\Rightarrow l_c \sim 1000\ nm \sim 2\lambda_{av}$

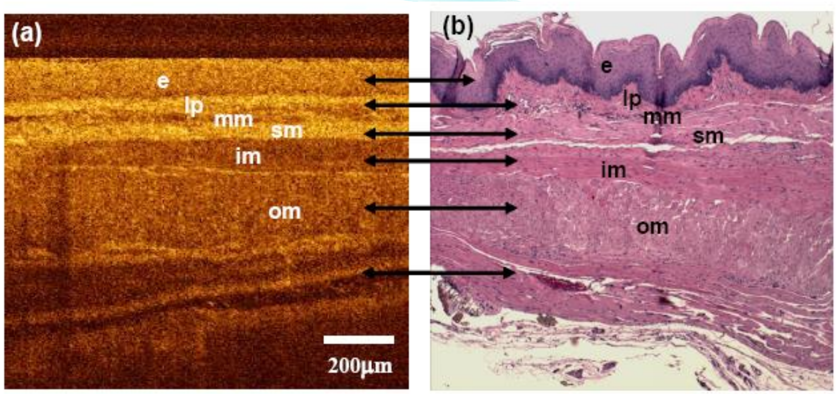
Source	$\Delta\nu_c$ (Hz)	$\tau_c = 1/\Delta\nu_c$	$l_c = c\tau_c$
Filtered sunlight ($\lambda_o = 0.4$–$0.8\ \mu$m)	3.74×10^{14}	2.67 fs	800 nm
Light-emitting diode ($\lambda_o = 1\ \mu$m, $\Delta\lambda_o = 50$ nm)	1.5×10^{13}	67 fs	20 μm
Low-pressure sodium lamp	5×10^{11}	2 ps	600 μm
Multimode He–Ne laser ($\lambda_o = 633$ nm)	1.5×10^{9}	0.67 ns	20 cm
Single-mode He–Ne laser ($\lambda_o = 633$ nm)	1×10^{6}	1 μs	300 m

Broadband spectrum (good spatial resolution)

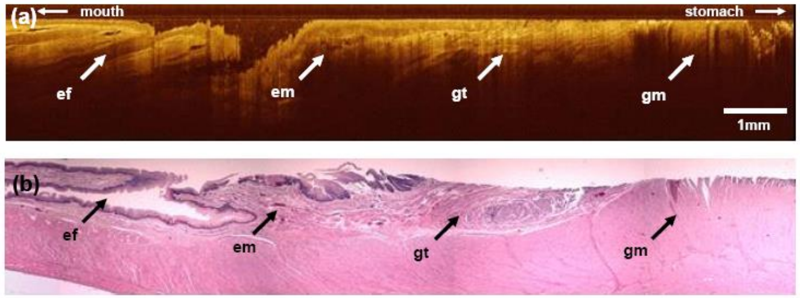
Optical coherent tomography measurement (OCT)



- **Non-invasive** cross-sectional imaging in biological systems.
- Uses **low coherence interferometry** to produce a two-dimensional (2D) image of optical scattering from internal tissue microstructures;
- Similar to that of **ultrasonic pulse–echo imaging**.
- The axial image resolution, Δz, is determined by **$z = 2\ln(2)/\pi](\lambda^2_0/\Delta\lambda)$**, $\Delta\lambda$: bandwidth, λ_0 : center wavelength

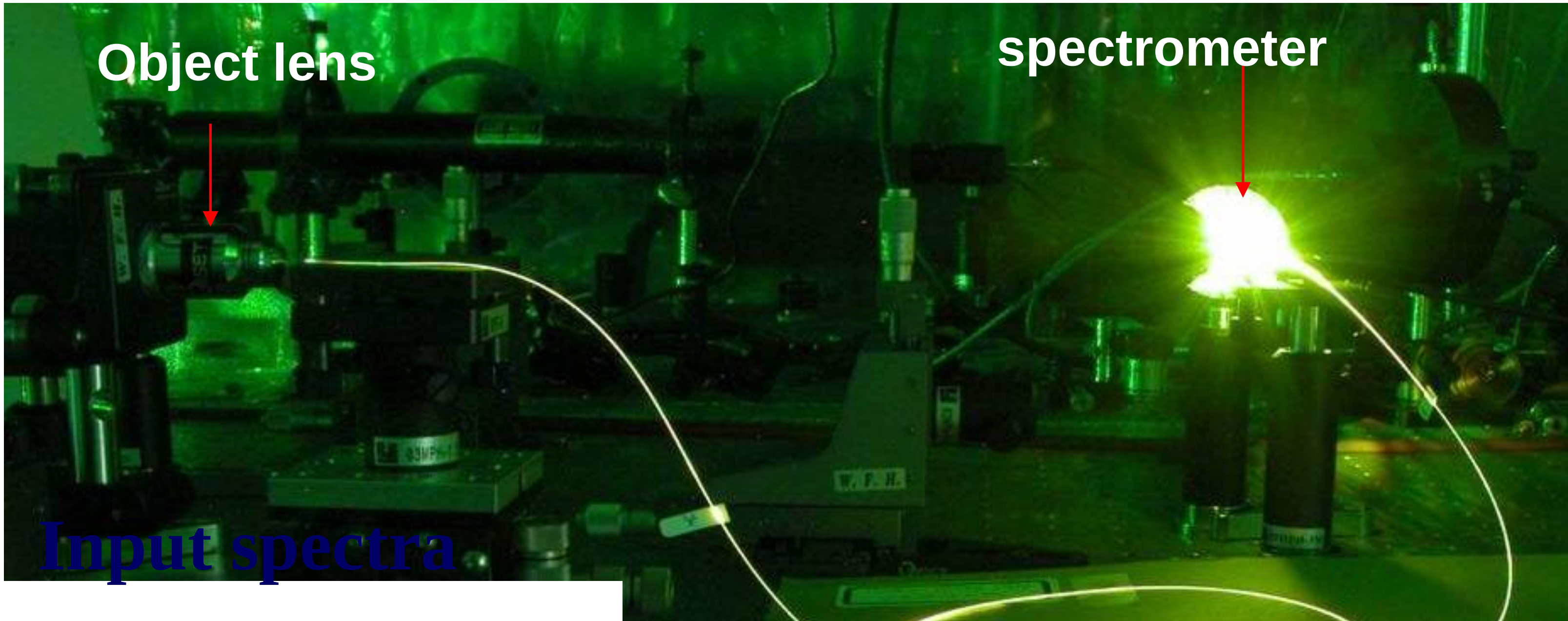


Rabbit esophagus

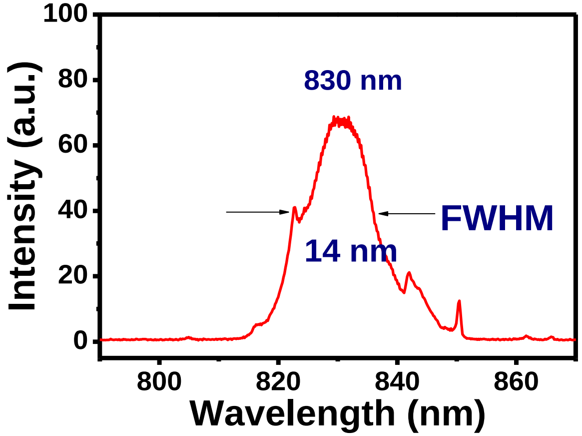


Science, 254,P1178 (1991), Science, 276, 2037 (1997). Opt. Express, 11, 3290 (2003), Opt. Express,12, 3532 (2004), Opt. Express, 12, 5287 (2004).

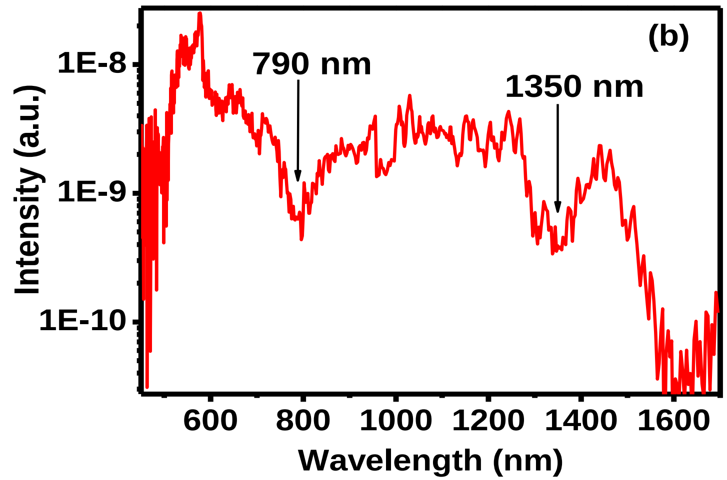
Photography and spectrum of SC from the



Input spectra

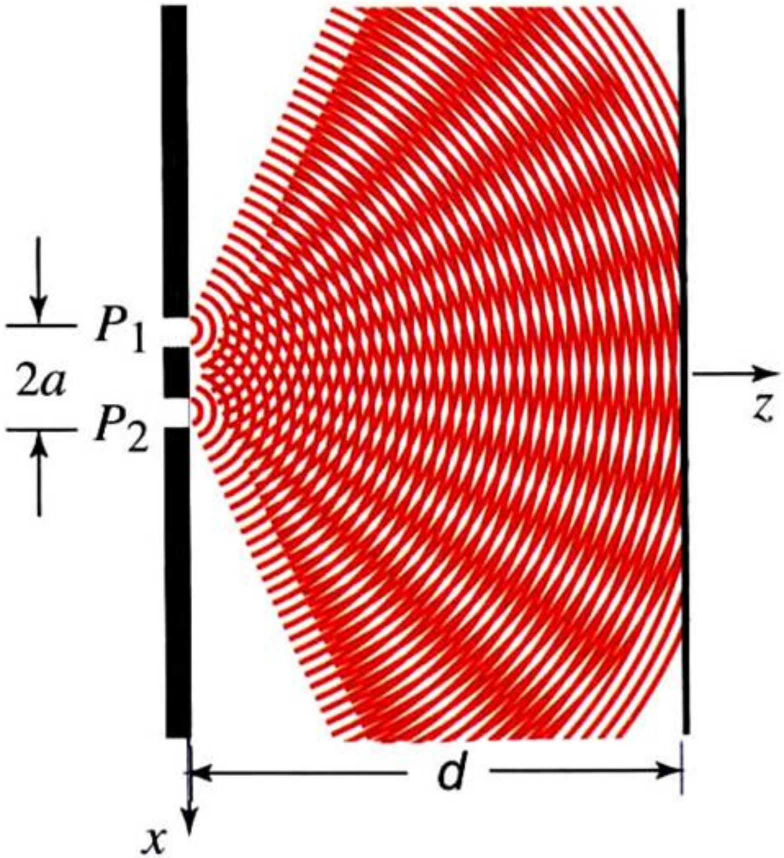


supercontinuum



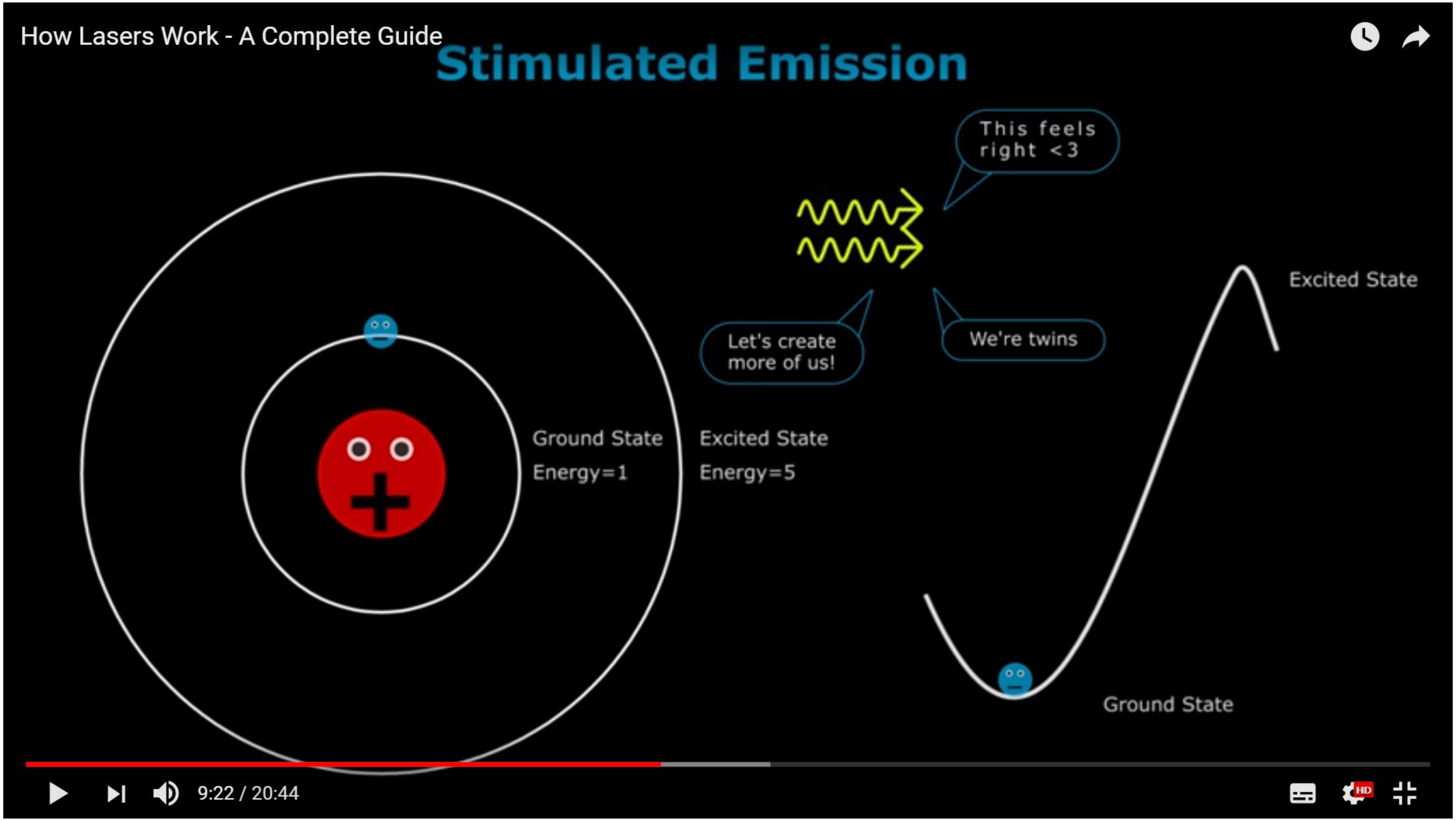
Spatial Coherence

- Consider P_1 and P_2 located on the same wavefront, the distance between P_1 and P_2 is $2a$.
- If there has a **phase relationship** between the two fields at P_1 and P_2, for any value of $2a$, the wave is said to have **perfect spatial coherence**.
- In practice, P_2 must lie within some finite area around P_1 to have good phase relation, this wave is **partial spatial coherence**.
- It measures the **uniformity** of phase across the optical wavefront and depends on the **length of the light source**.



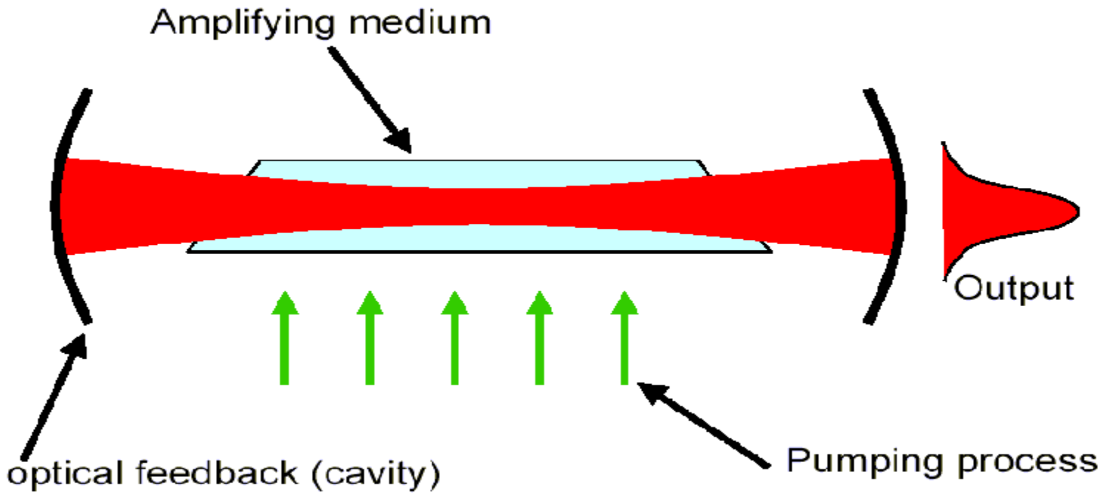
How Lasers Work - A Complete Guide

- https://www.youtube.com/watch?v=_JOchLyNO_w



Essential elements of a laser

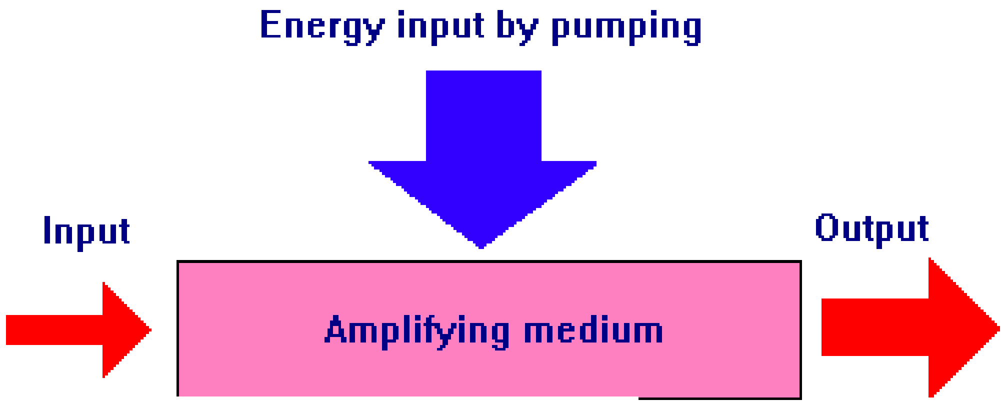
1. Gain or laser medium (active medium)
2. Pump or energy source (excitation)
3. Optical feedback (cavity or resonator)



- Pumping process prepares amplifying medium in suitable state
- Optical power increases on each pass through amplifying medium
- If gain exceeds loss, device will oscillate, generating a *coherent* output

Pumping source

- In laser terminology, the process of energizing the amplifying medium => "**pumping**" or "**excitation**".
- The **atoms** in the active medium is raises into their excited state, thus creating **population inversion**.
- In accordance to the law of **conservation of energy**, the electromagnetic radiation out of the laser < the input excitation energy.

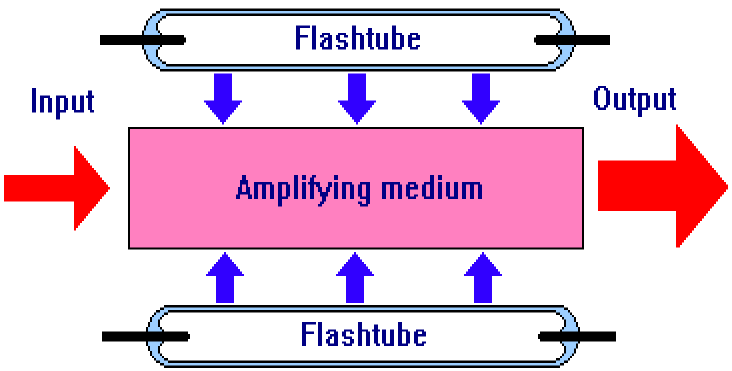


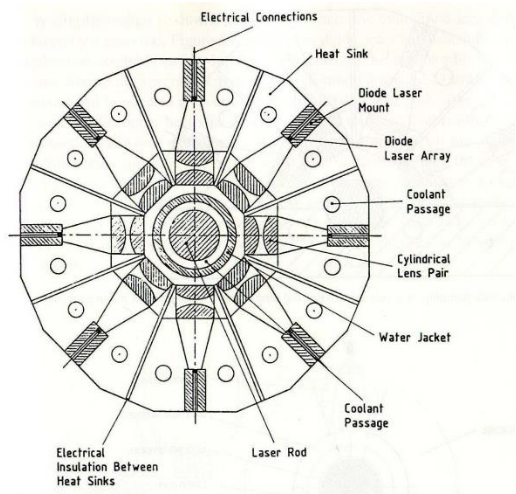
There are few types of excitation mechanisms:

(a) Optical pumping - Excitation by photons:

In **solid or liquid** active medium, the form of excitation energy =>

electromagnetic radiation (photons)

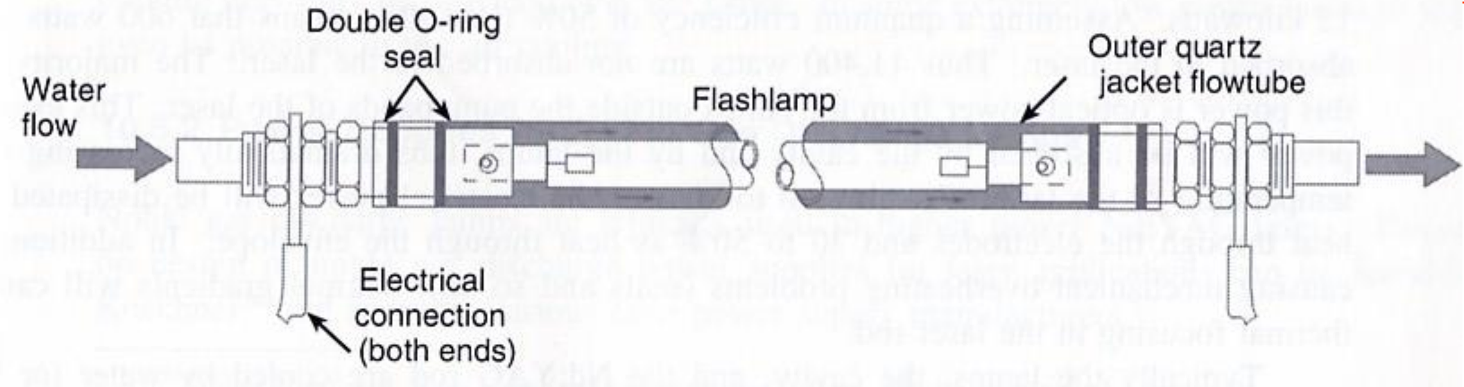




The electromagnetic radiation source can be of different kinds:

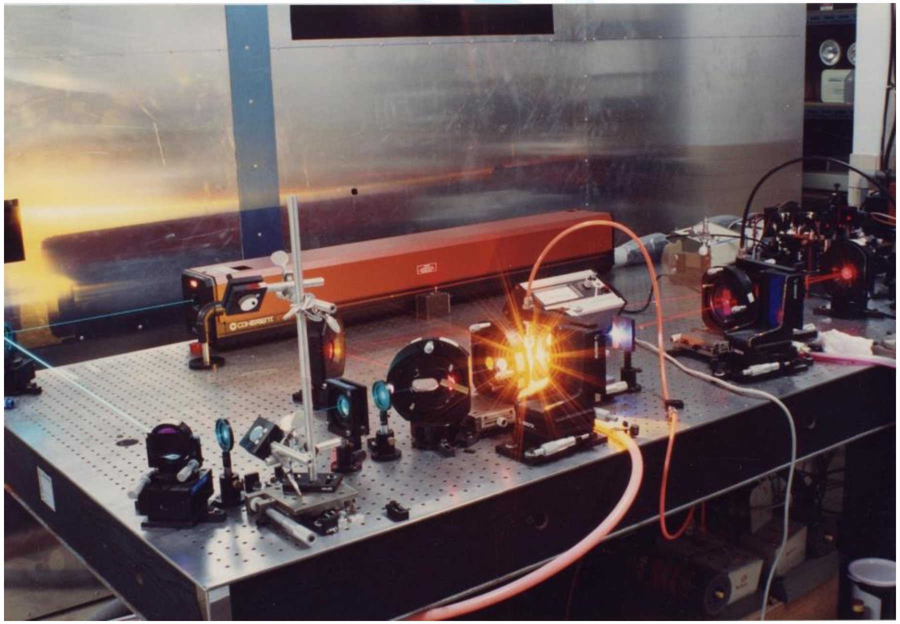
(b) Flash lamps

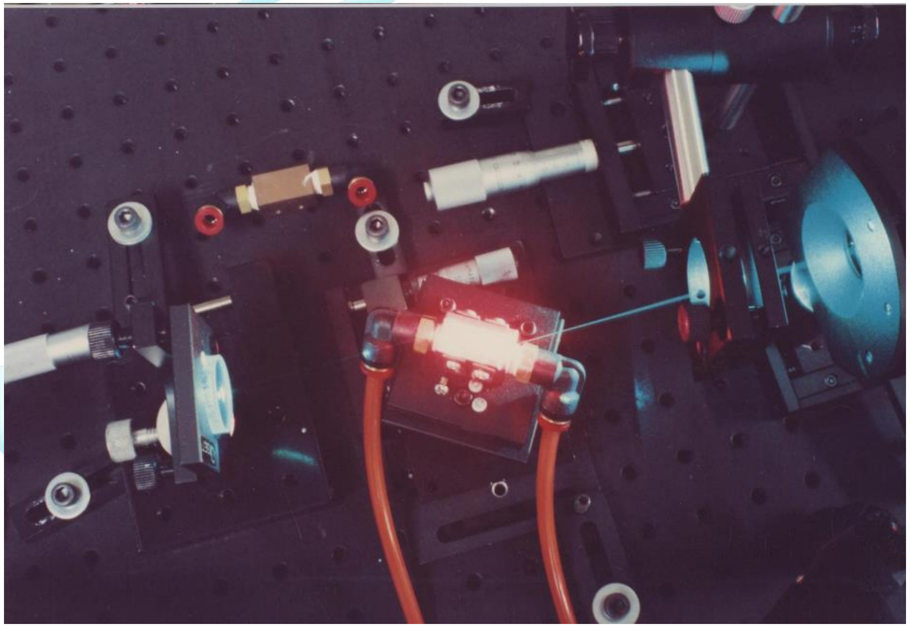
- They are build from a **quartz tube** filled with gas at **low pressure**.
- Usually **Xenon (氙) gas** is used, but sometimes when higher energy is required, other noble gasses with lower atomic weights such as **Krypton (氪)** or **Helium** are used.



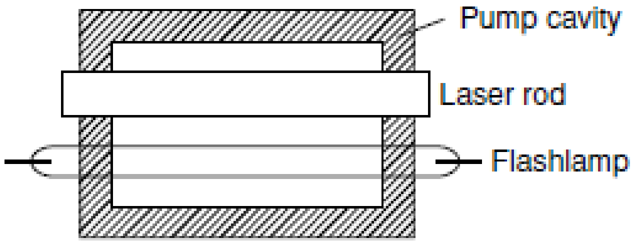
Ar ion lasers → Dye or Ti-sapphire lasers

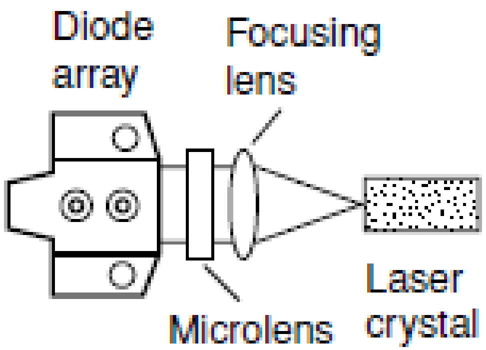
Laser diodes → Nd: YLF or Yb:YAG lasers

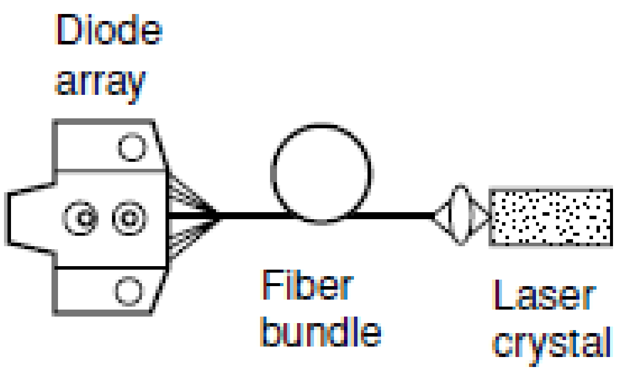


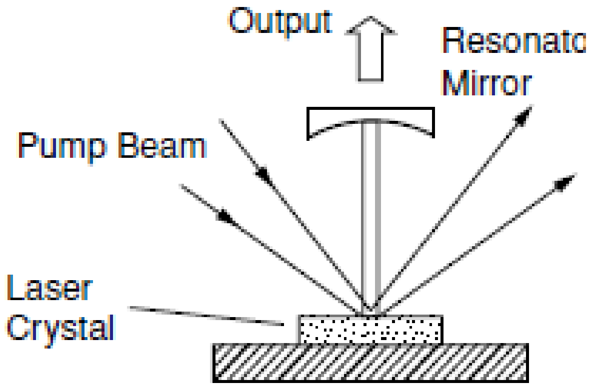


An argon laser pumps a CPM Dye laser.

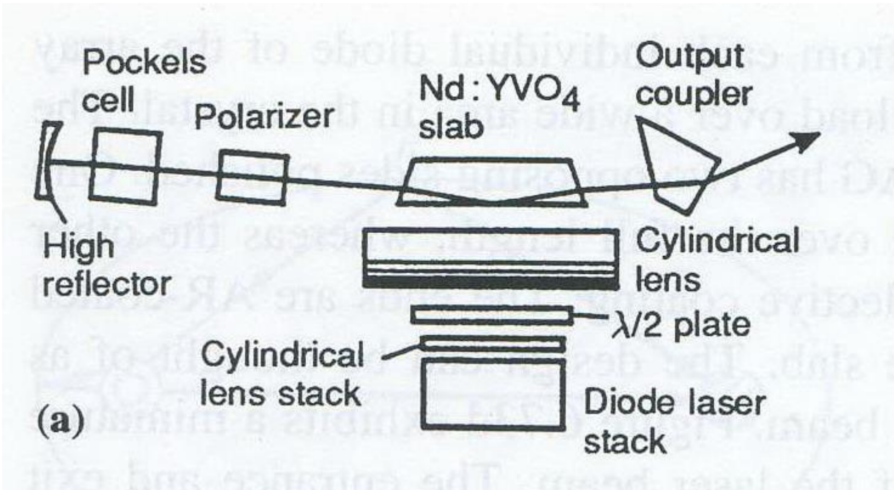

Pump cavity
Laser rod
Flashlamp


Diode array
Focusing lens
Microlens
Laser crystal

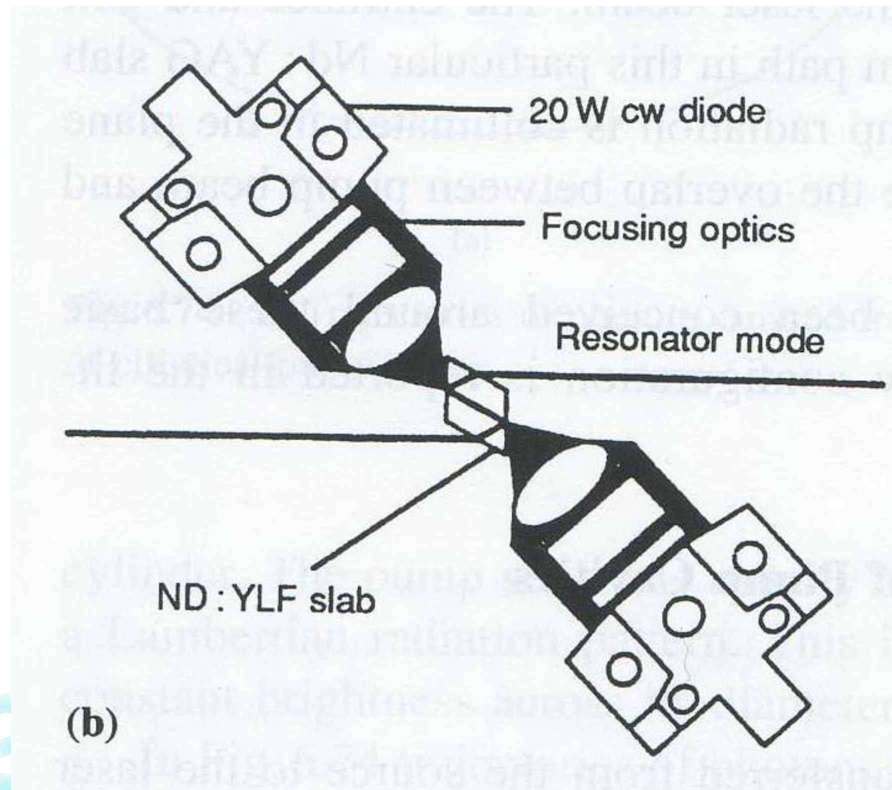

Diode array
Fiber bundle
Laser crystal


Output
Resonatc Mirror
Pump Beam
Laser Crystal

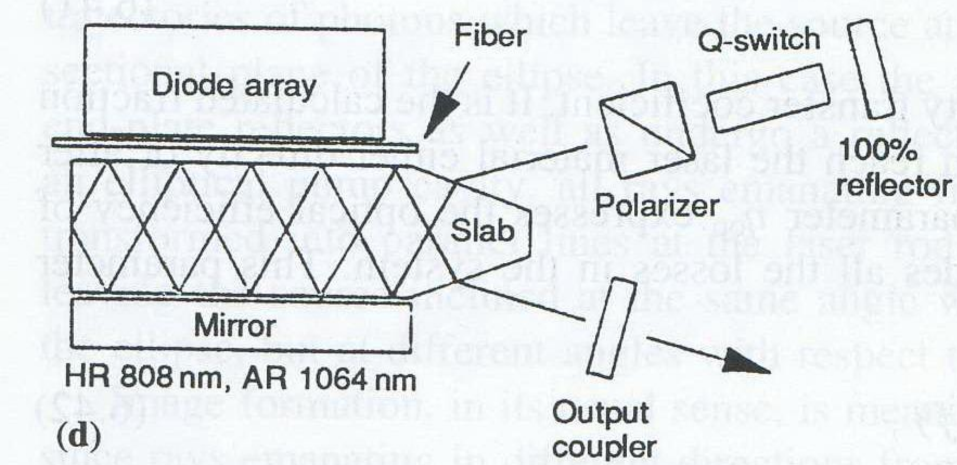
Pump configuration based on internal reflectance of the laser beam



Slab with grazing angle at the pump face



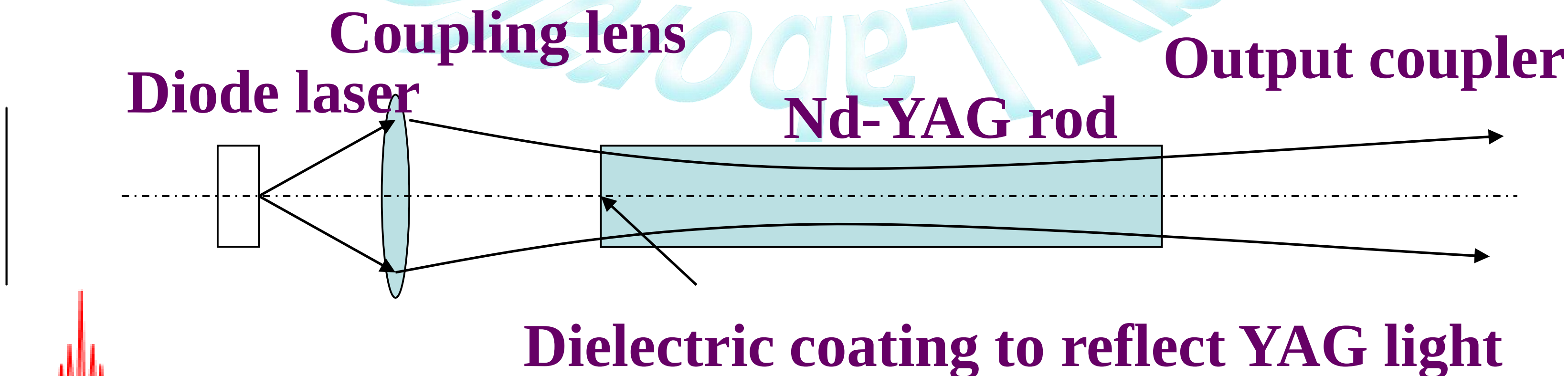
Rhombic shaped slab pumped from both side



Slab with folded zig-zag path

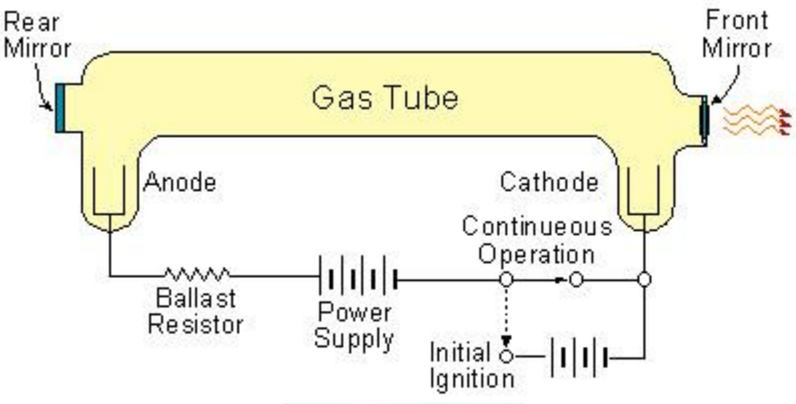
Diode Pumping of Lasers

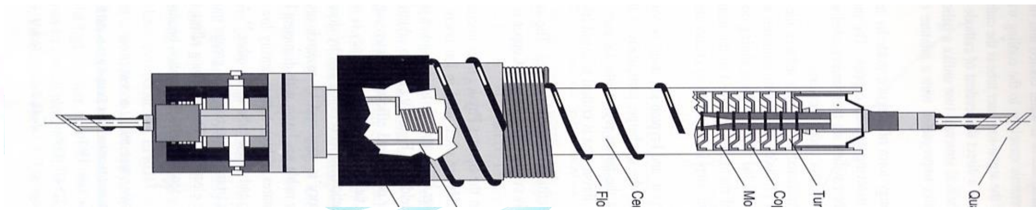
- Diode lasers can be used as pump sources for solid state lasers
  - Diode pumped solid state laser (**DPSSL**)
  - **simply, compactness, long lifetime, and portable for various application**
  - Wavelength of diode laser can be tuned by temperature or doping
  - Made to coincide with absorption peak of solid state laser
    - e.g. 807 nm for **Nd-doped medium** , 976 nm for **Yb-doped medium**
  - High efficiency
    - up to 25% of diode output to laser output



(b) Electrical excitation of a gas:

The best excitation for **gas** is by **electrical discharge.**





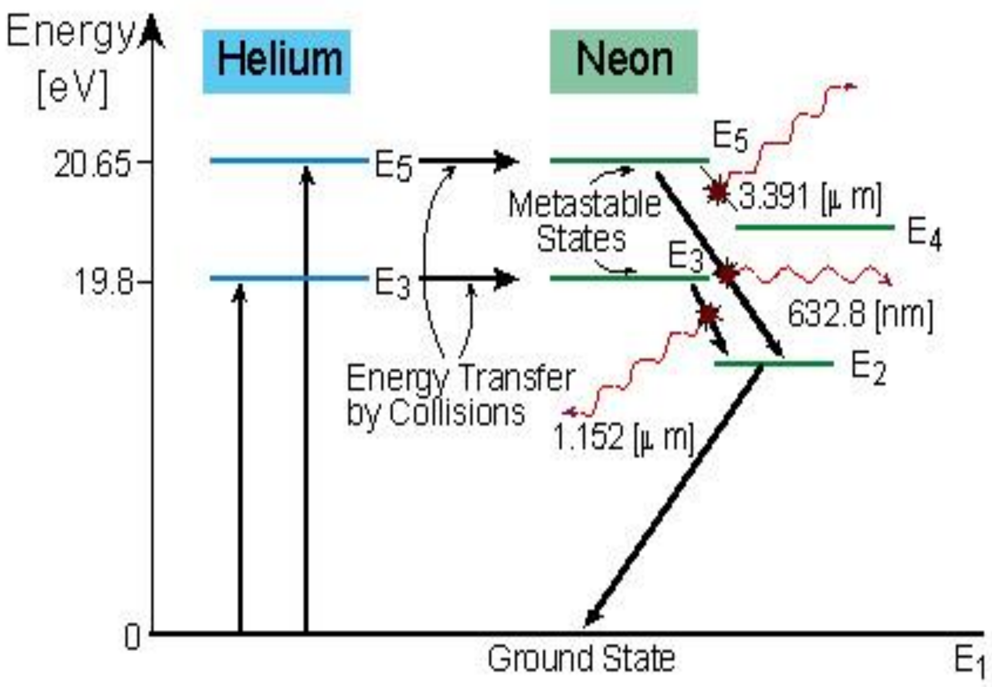
Spectra-physics argon-ion laser tube

- The gas in the tube => **electrically neutral** and most of the molecules are in the **ground state** (no external energy is applied,).
- When the **high electrical voltage** is applied => **electrons** are released from the **cathode** and accelerated toward the **anode**.
- These electrons collide with the **gas molecules** and transfer energy to them => gas molecules are raised to **excited state.**

(c) Collisions with atoms (He-Ne and CO2 laser)

At least two gasses are inside the laser tube.

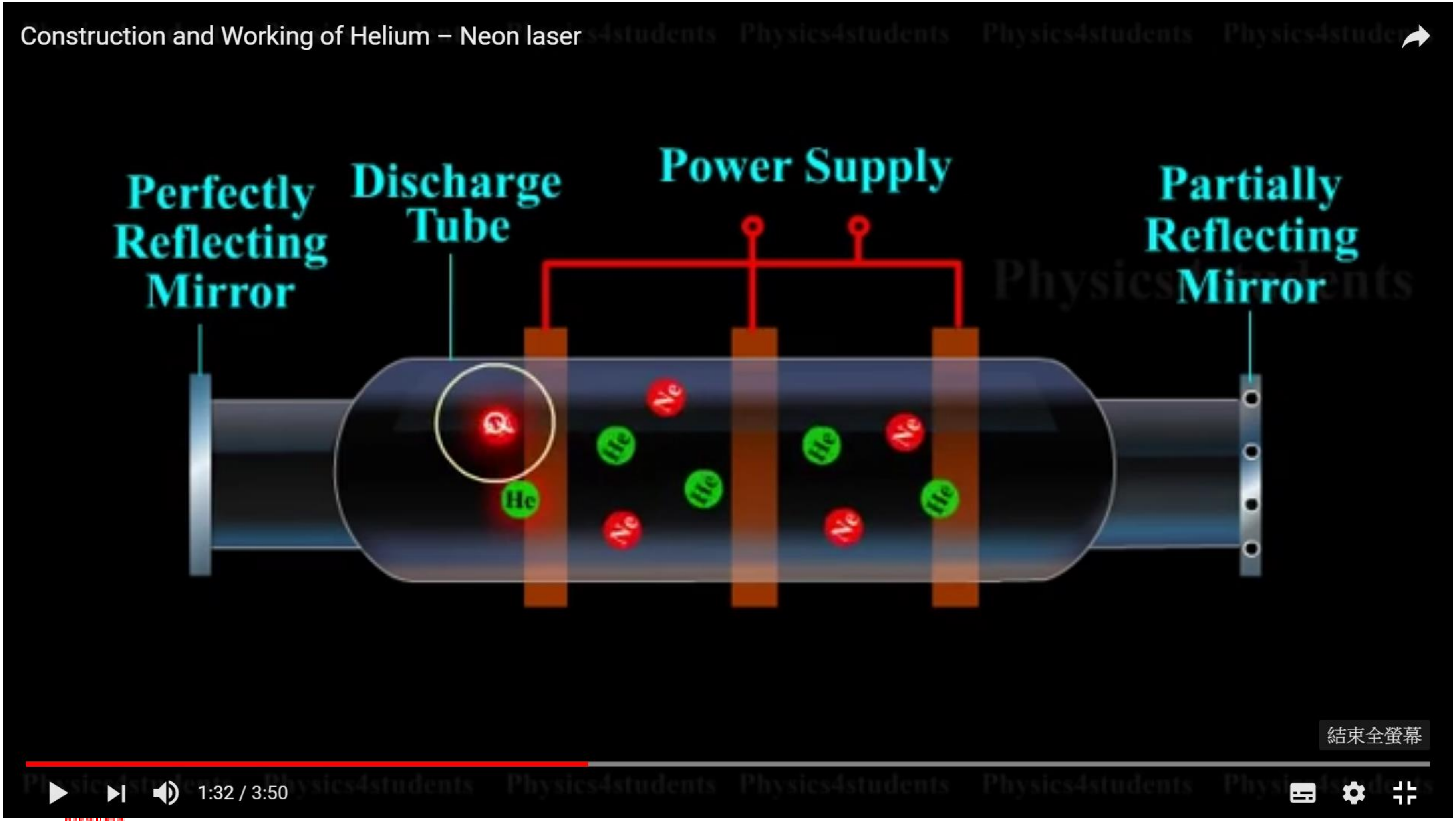
- One gas receives the energy from the collision with the accelerated free electrons.
- The second gas receives energy from collisions with the **excited molecules** of the first gas.



Helium-Neon Laser

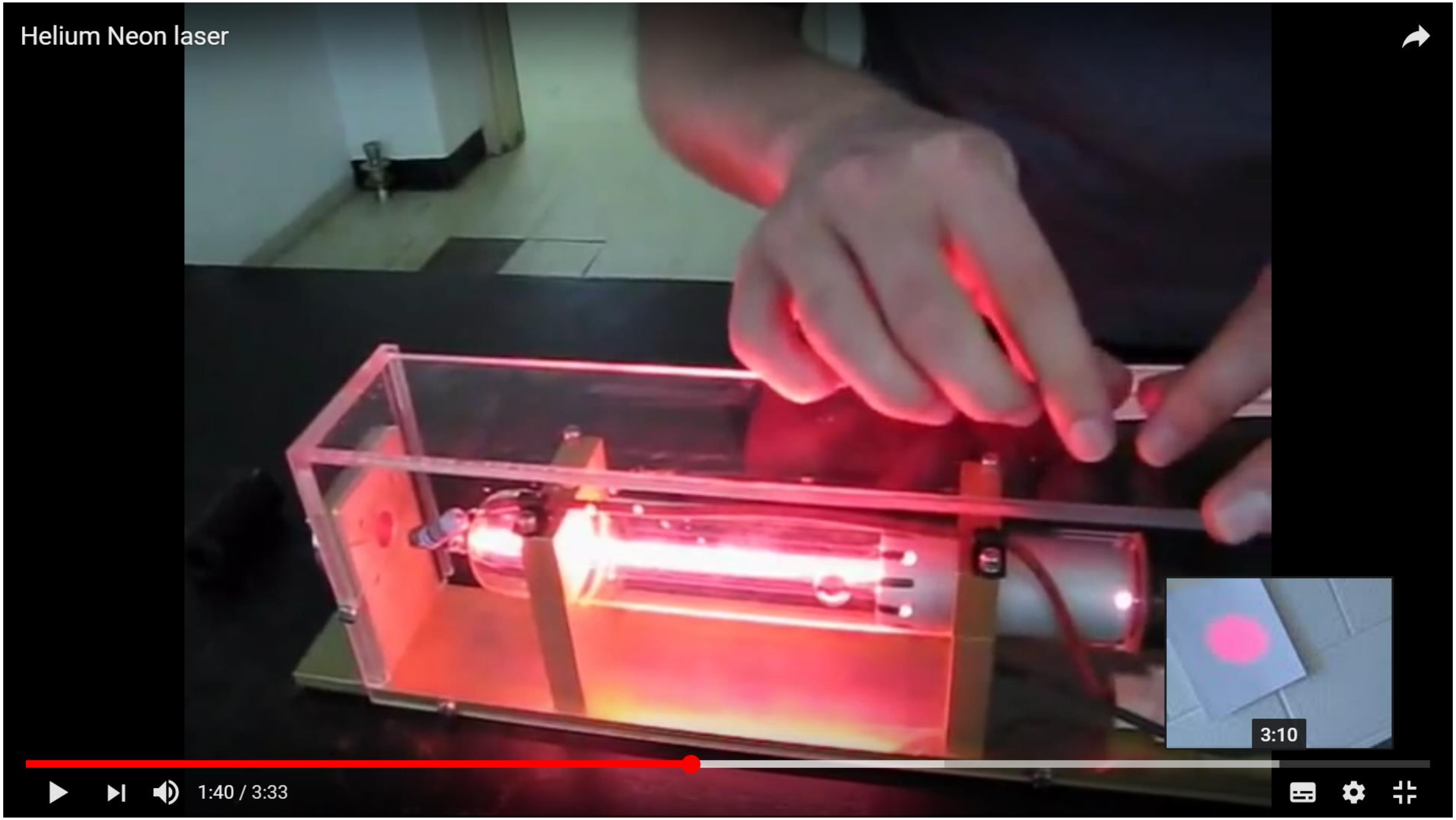
Construction and Working of Helium – Neon laser

➤ https://www.youtube.com/watch?v=RyY4PEpV2RQ



He-Ne laser

- https://www.youtube.com/watch?v=S_J1tkB0RKE



CO2 laser

- https://www.youtube.com/watch?v=tYDHQ_mH1Bc

(e) Electric current in diode lasers.

- A **forward voltage** is applied @ **p-n junction** => A significant increase in the concentration of electrons in the conduction band near the junction on the n-side and the concentration of holes in the valence band near the junction on the p-side.
- The electrons and holes **recombine** => photons (the energy of the photon is equal to the energy gap).

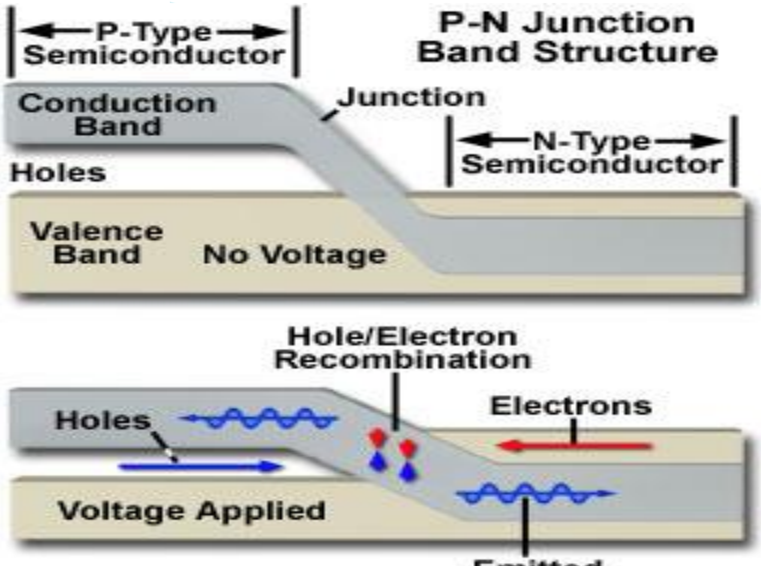
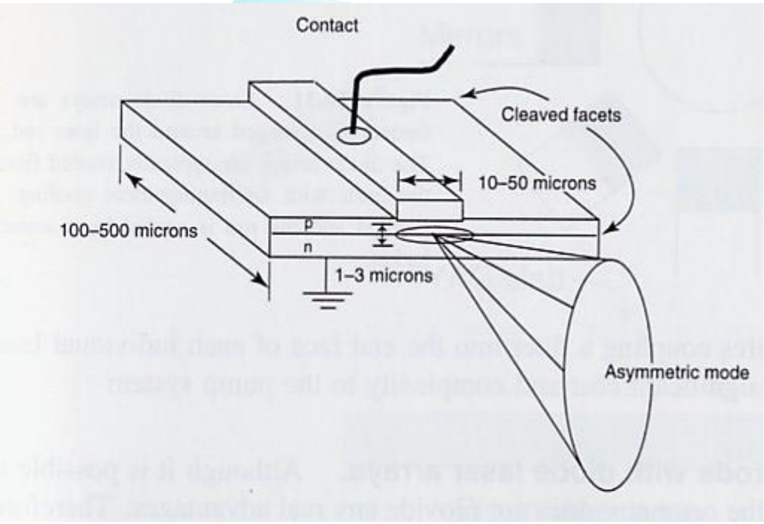


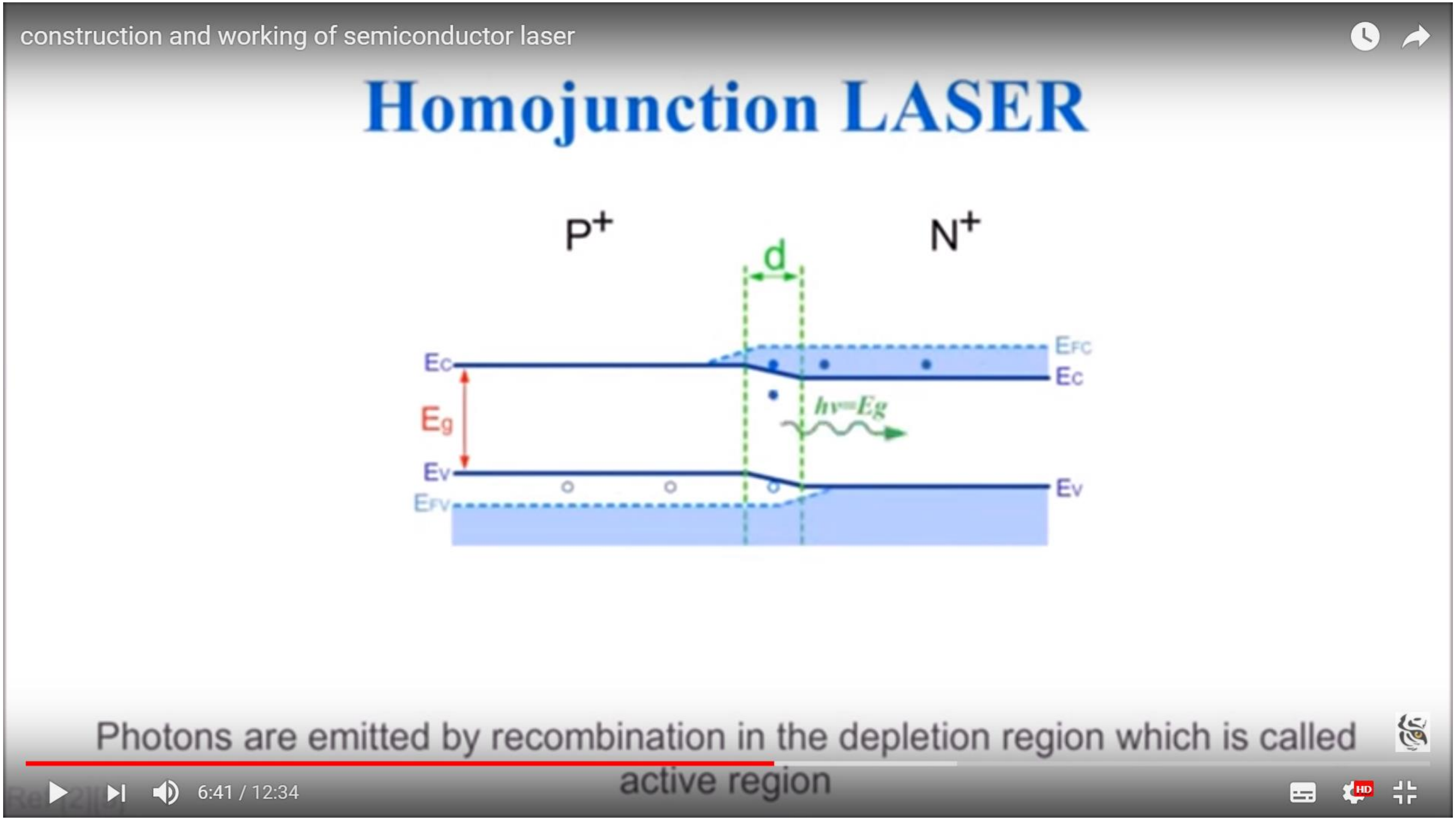
Figure 3



(e) Electric current in diode lasers.

Semiconductor laser

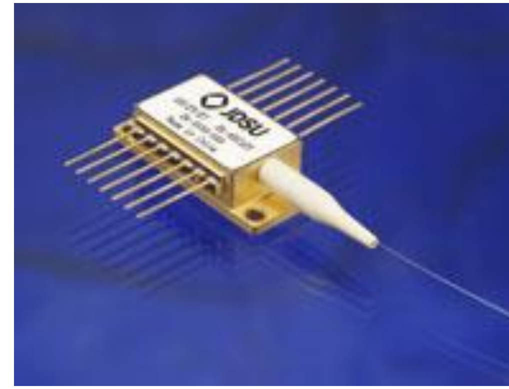
- https://www.youtube.com/watch?v=Ih0G46AiP-M



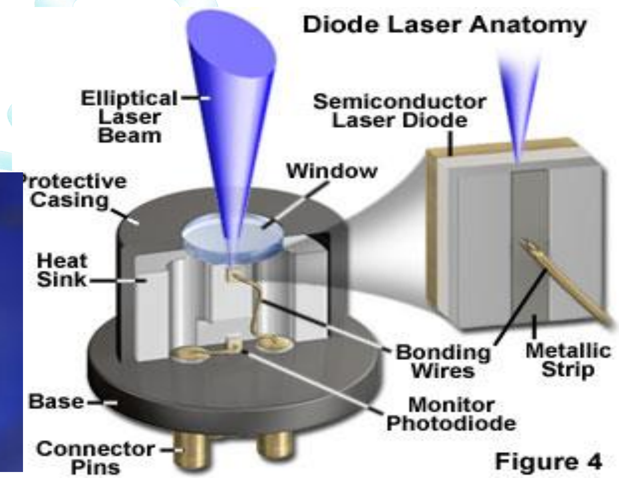
High Power Direct Diode Laser

Laser:	**Nuvonyx**
Type:	ISL 4000 L
Power:	4000 W
Wavelength:	805 +/- 10 nm
Mode:	CW and pulsed
Single lensing	
Working distance:	90 mm
Spot size:	12 mm x 0.5 mm
Intensity:	66 kW/cm^2
Double lensing	
Working distance:	40 mm
Spot size:	6 mm x 0.3 mm
Intensity:	222 kW/cm^2

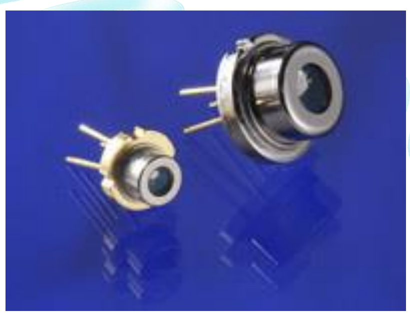
Fraunhofer USA
Center for Laser Technology
ALCAN
NUVONYX



Butterfly fiber pig tail



Open heat sink

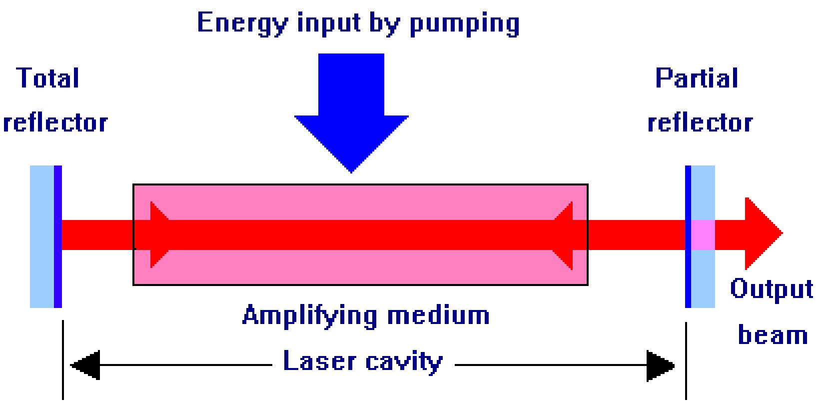


Sot-148 windows

Multi mode high power

Optical feedback

- The purpose of the mirrors is to provide => 'positive feedback'. An amplifier with positive feedback is known as an ***oscillator***.
- Except in a few exceptional cases (such as ***X-ray*** **laser**, poor beam), light amplifiers would **not** be regarded as lasers.
- A pumped **amplifying medium** positioned between mirrors(such as two mirror indicated below).
- One mirror is 100% reflecting @ lasing wavelength, the other mirror is partially reflecting @ lasing wavelength
- The part of the radiation transmitted out optical cavity => laser output.



Two mirror resonators

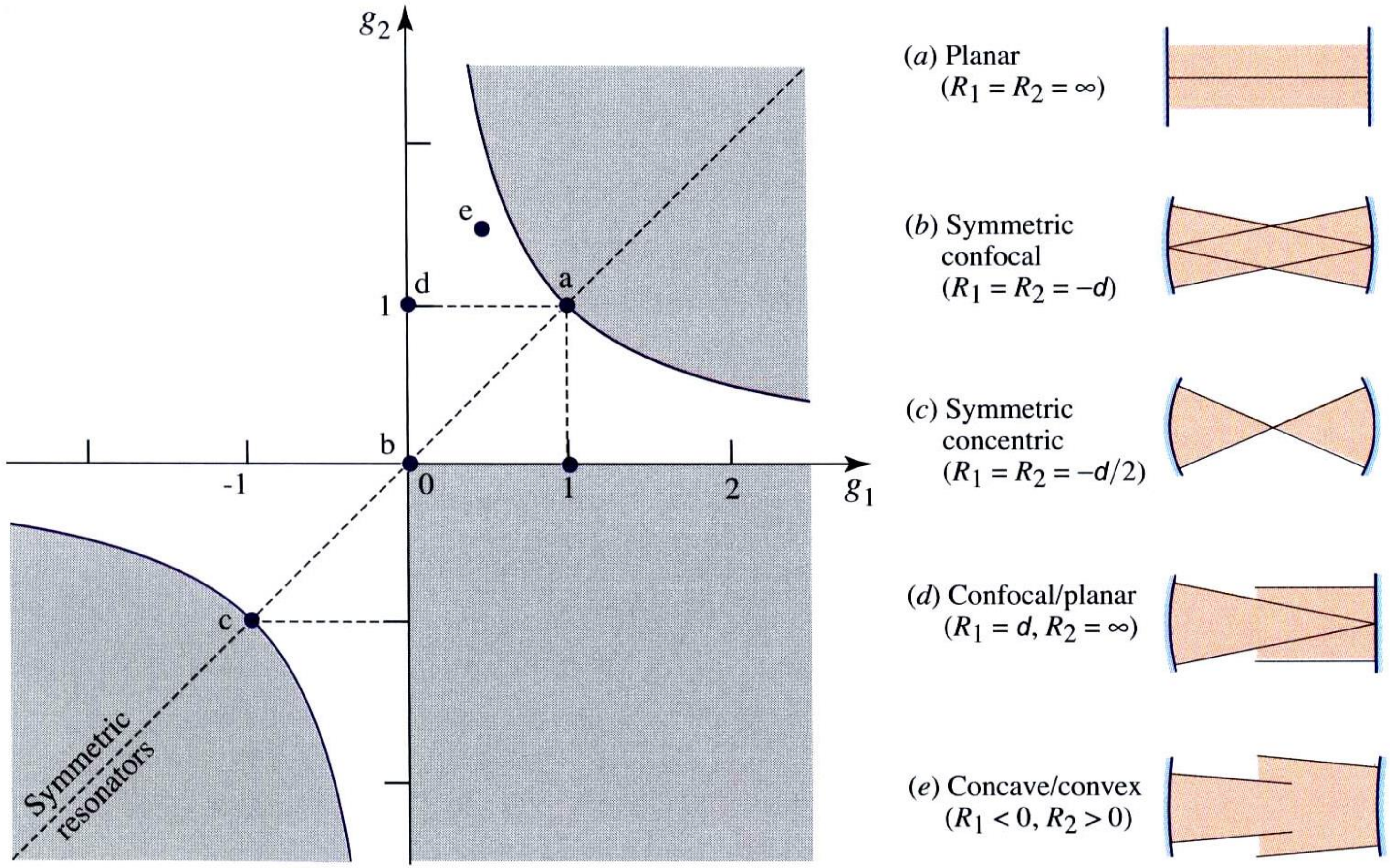
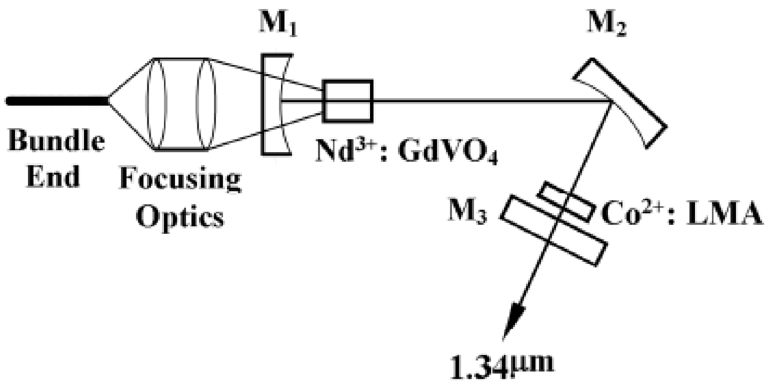


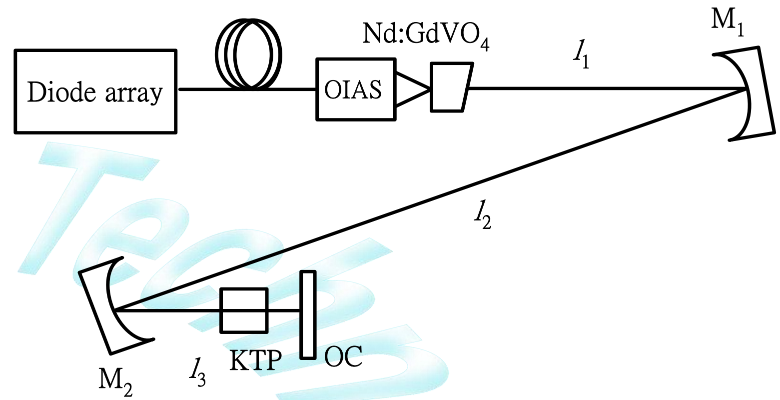
Figure 10.2-3 Resonator stability diagram. A spherical-mirror resonator is stable if the parameters $g_1 = 1 + d/R_1$ and $g_2 = 1 + d/R_2$ lie in the unshaded regions, which are bounded by the lines $g_1 = 0$ and $g_2 = 0$, and the hyperbola $g_2 = 1/g_1$. R is negative for a concave mirror and positive for a convex mirror. Commonly used resonator configurations are indicated by letters and sketched at the right. All symmetric resonators lie along the line $g_2 = g_1$.

Standing wave cavity

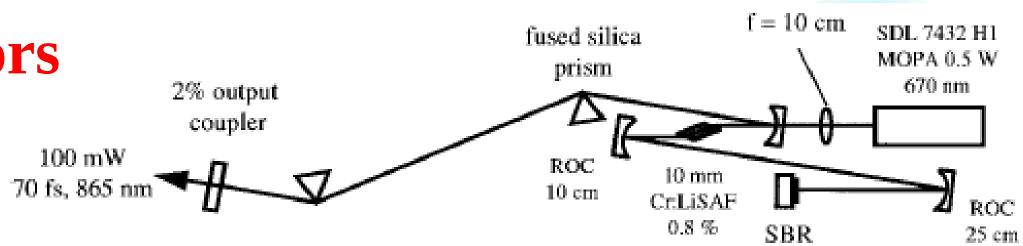
(a) Three mirrors



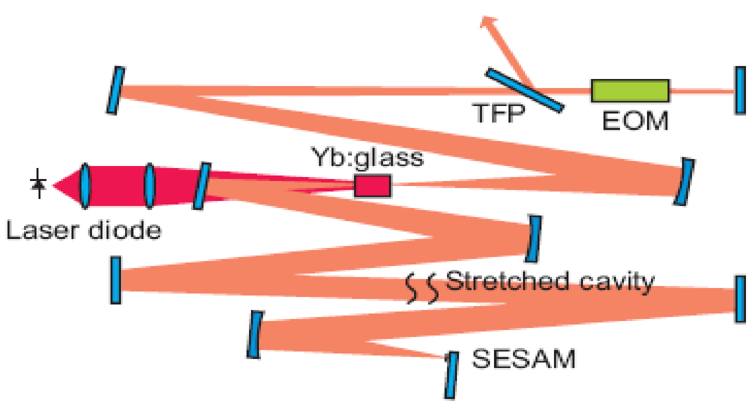
(b) Four mirrors



(c) Five mirrors

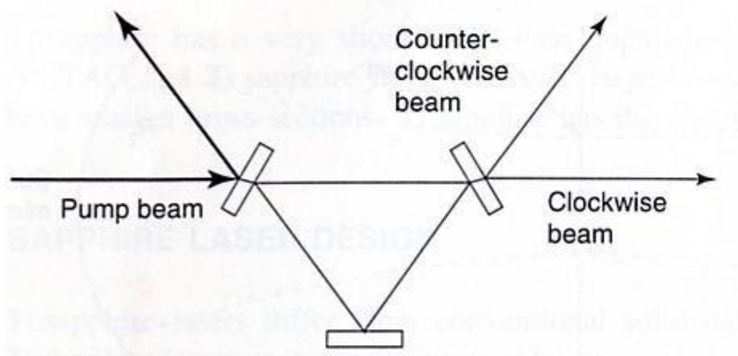


(d) Multi-mirrors



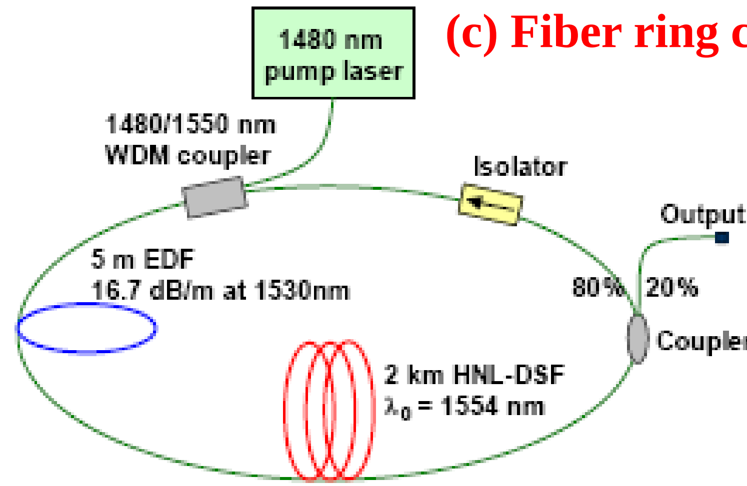
Ring Cavity (traveling wave):

To reduce the spatial hole burning from the standing wave laser.

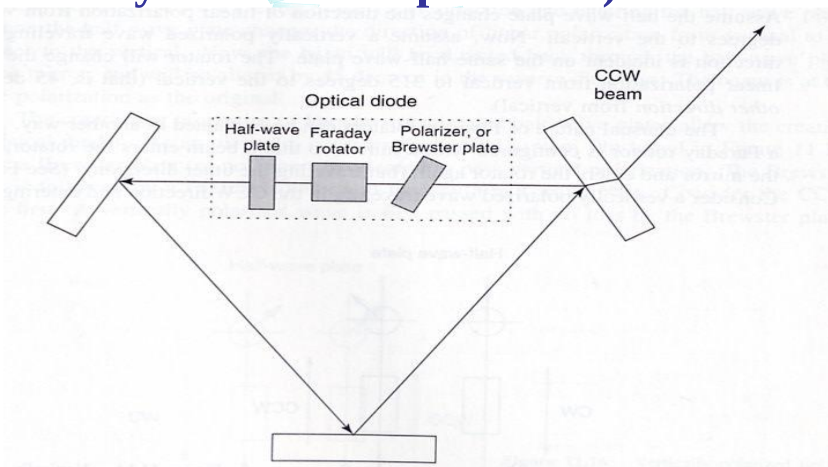


(a) Three mirror cavity (Two direction propagation)

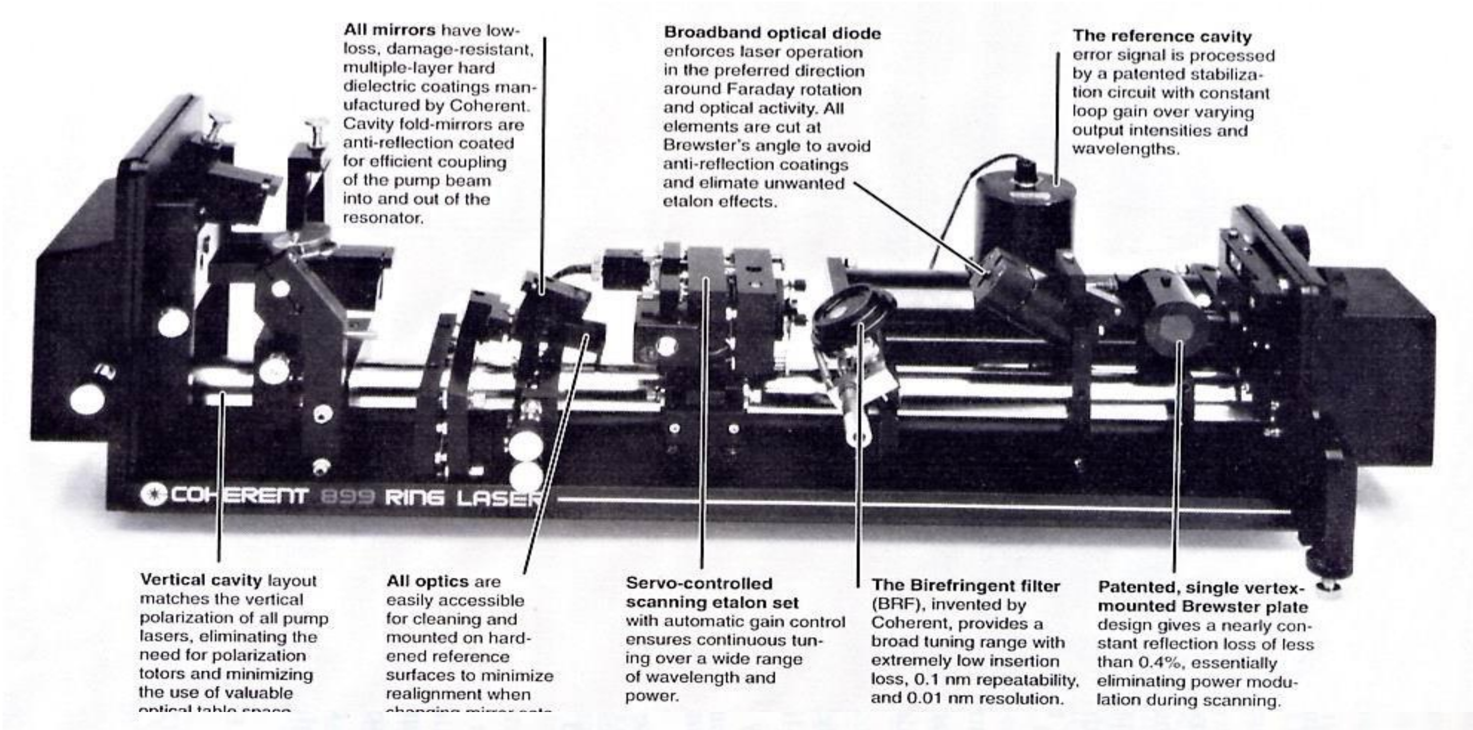
(c) Fiber ring cavity

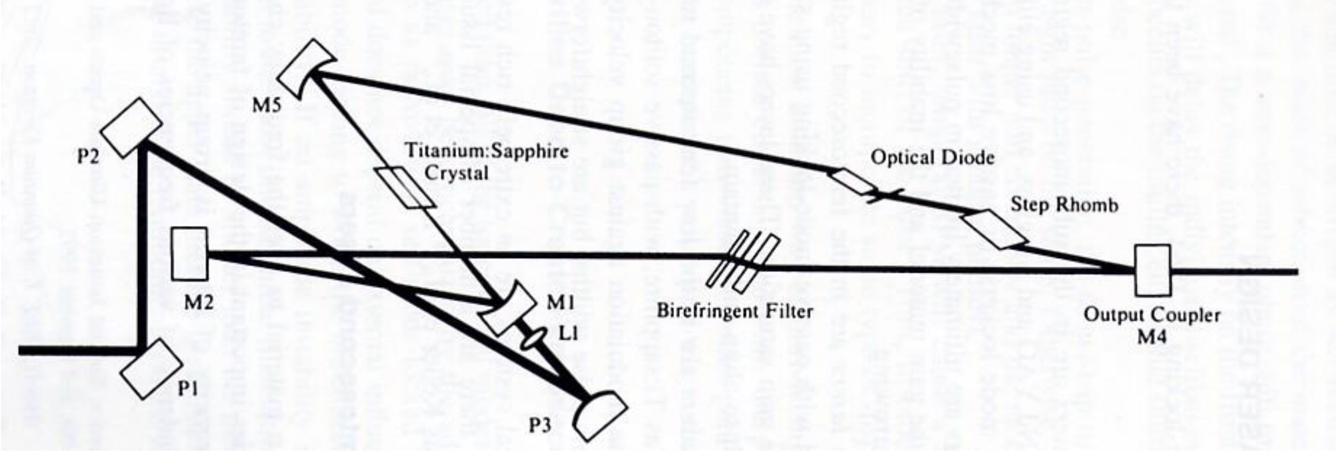


(b) Three mirror with the isolator (unidirectional oscillation- λ/2 plate, Faraday rotator and polarizer)



Coherent model 899





Several important functions of laser cavity :

a) **Rapidly building up of the light intensity**

The light intensity is increased (through stimulated emission) by multiple passes through the amplifying medium. In the absence of cavity mirrors, the oscillation would not occur.

b) **Highly direction and small divergence of the beam**

The direction of the beam is the consequence of the cavity. The divergence of a beam is determined by the intrinsic characteristic of beam (TEM_{00}) within laser cavity.

c) **Improves the spectral purity of the laser beam.**

   a) By the coating of mirror, only particular wavelengths of light can undergo repeated reflection up and down the cavity.

   b) The cavity length => number of longitudinal modes.

d) **Improves the coherence of the laser beam**

Understanding Lasers

- https://www.youtube.com/watch?v=saVE7pMhaxk