Emitters – LASERs and LEDs

Curs 6

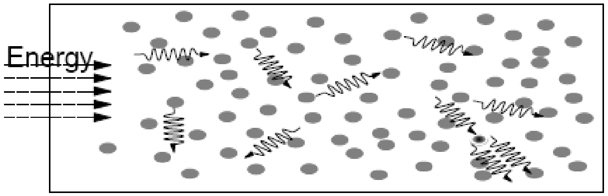
Light Sources and Transmitters

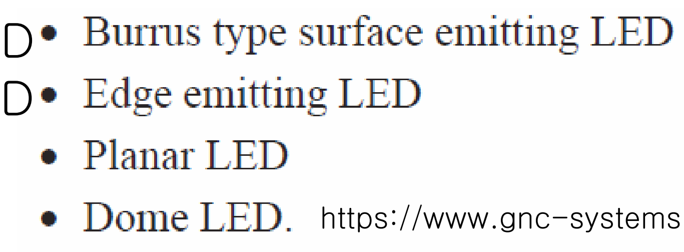
Bibliografie: Gerd Keiser, Optical Communications Essentials, 2004, McGraw-Hill

CONTENTS

- WHAT IS Emitters (LED, LASER)?
  - LED – light-emitting diode (pag77-Kasap)
  - LASER –light amplification by stimulated emission of radiation
- LED/Laser operating
- LED/Laser types
- LASER OSCILLATION CONDITION
  - Unity loop-gain condition (threshold condition)
  - Population inversion
- EXAMPLES OF LASERS
- Reference

Diferente emisia spontana (LED) si emisia stimulata (Laseri)





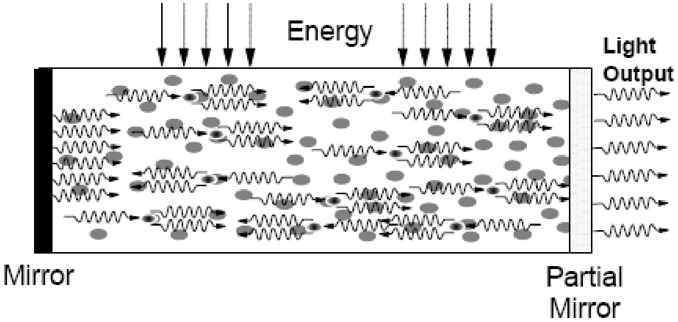
SLED • Burrus type surface emitting LED

ELED • Edge emitting LED

• Planar LED

• Dome LED. https://www.gnc-systems.com/userfiles/5.pdf

LED – emisia spontana (fluorescenta)



Laseri

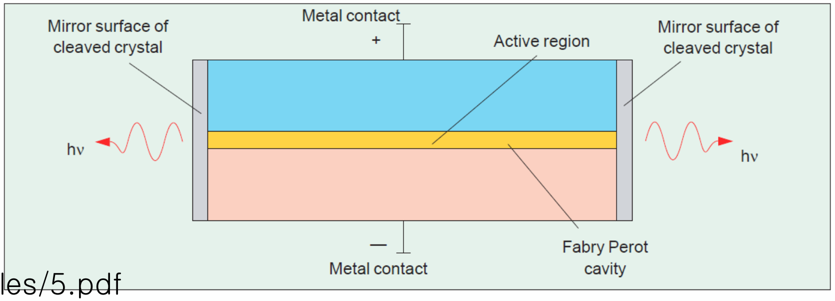


Fig. 6-22 A laser of the simplest design. This type of laser - generally known as Fabry Perot laser - has only one p-n junction. For this reason it is called a homojunction laser.

Referinte bibliografice: Gistwik – Optical Communications – cap 6 si
Optoelectronics – Borge Vinter–Cambridge press
IBM– Introduction to optical communications
Kasap – Optoelectronics and Photonics– cap 4

Nivele Fermi

LED

Laser

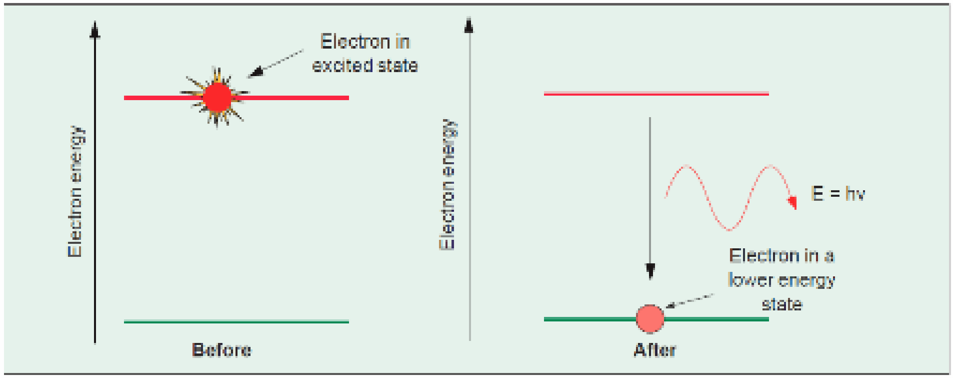


Fig. 6-17 Spontaneous emission.

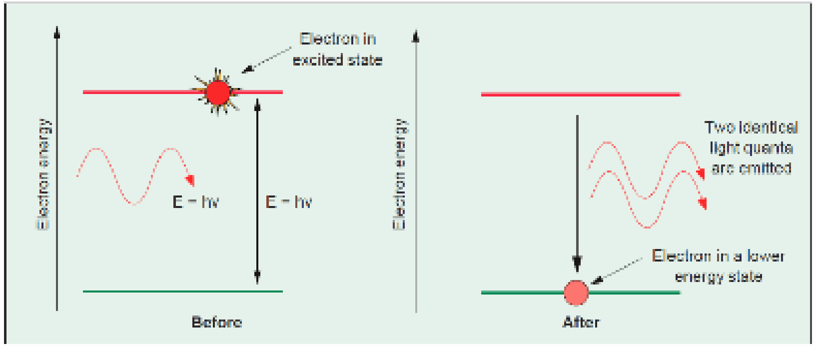
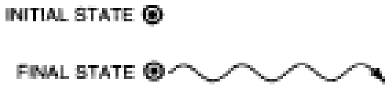
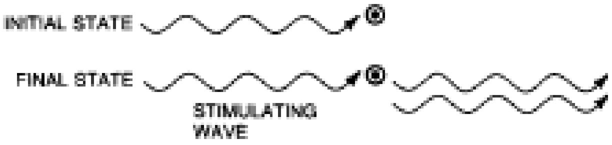


Fig. 6-18 The incident photon stimulates an electron transition that emits a photon with characteristics identical to those of the incident photon.



(A) Spontaneous emission.



(B) Stimulated emission.

Figure 2-7. Spontaneous and stimulated emission.

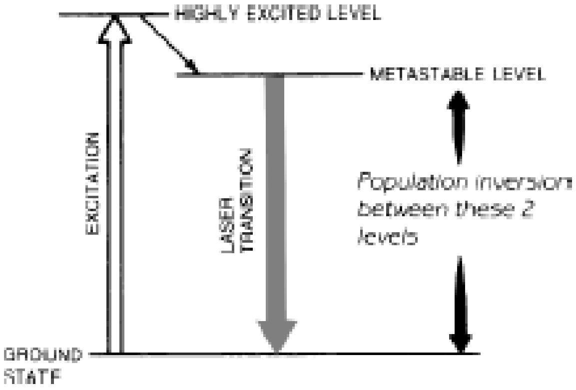
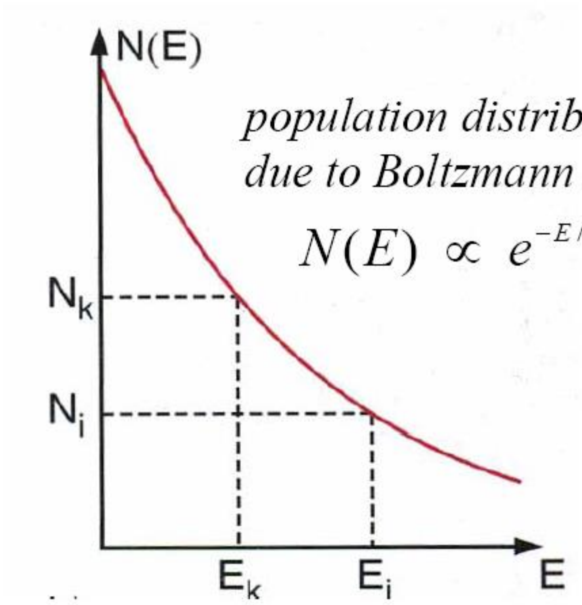


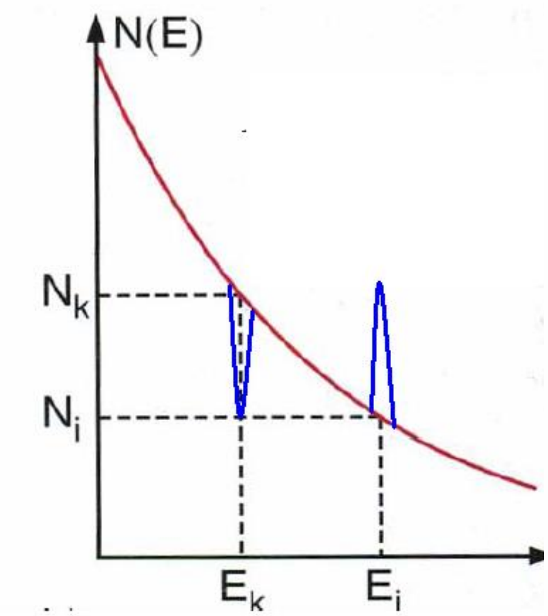
Figure 3-1. Energy levels in a three-level laser.

Inversiunea de populatie



population distribution due to Boltzmann law :

$$N(E) \propto e^{-E/kT}$$



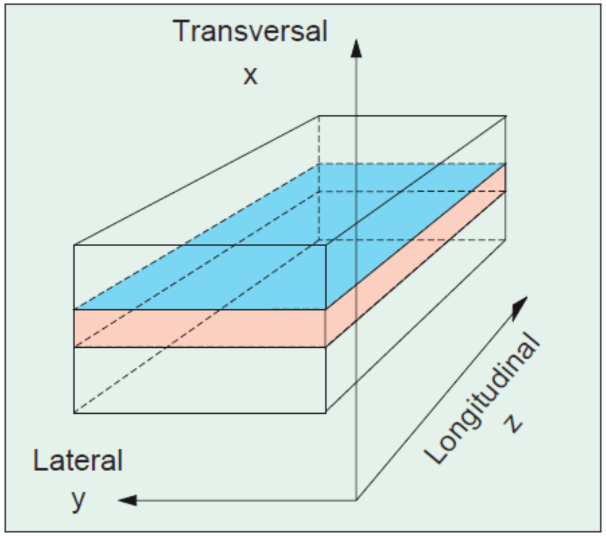


Fig. 6-23 Definition of lateral, longitudinal and transversal directions in a laser structure.

Echilibru

Tipuri de LED-uri

Output Spectrum

Burrus

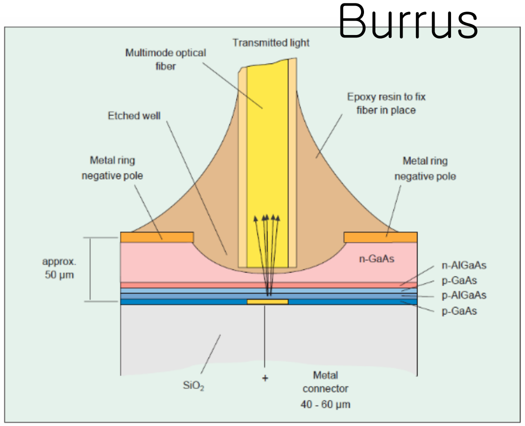
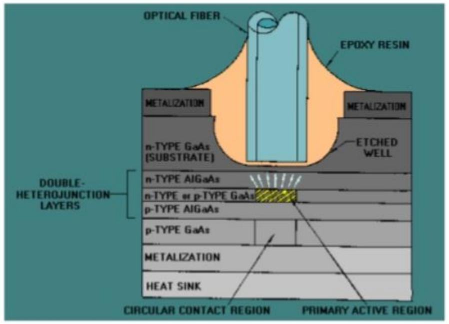
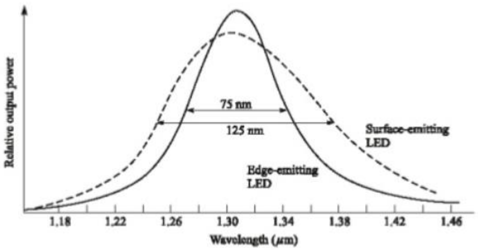
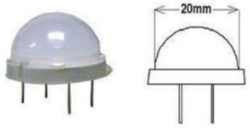


Fig. 6-29 Burrus type LED with an etched groove to minimize absorption in the n-layer of GaAs.

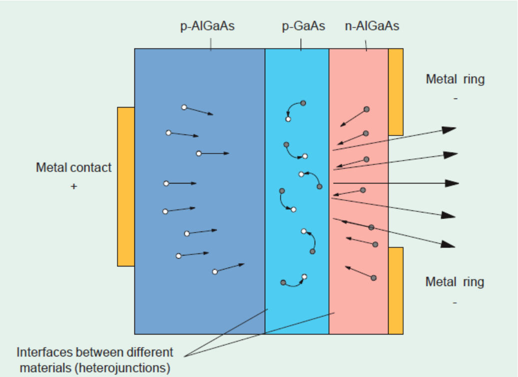
Surface Emitter LED(SLED)







Dome LED



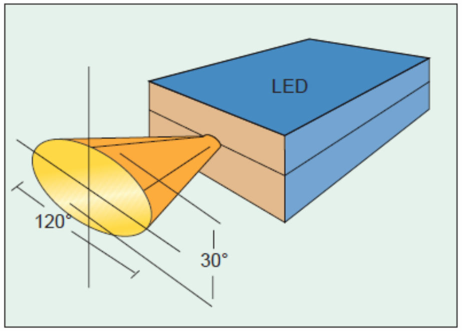
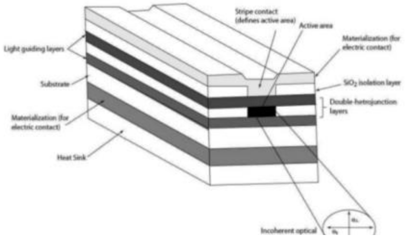


Fig. 6-30 The radiation lobe is an ellipse with an opening of around 115 - 125° in horizontal direction and 25 - 35° in vertical direction.

Edge Emitting LED (ELED)



Super luminescent LED (SLD)

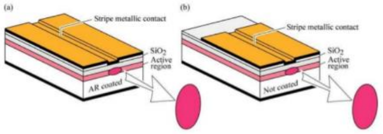


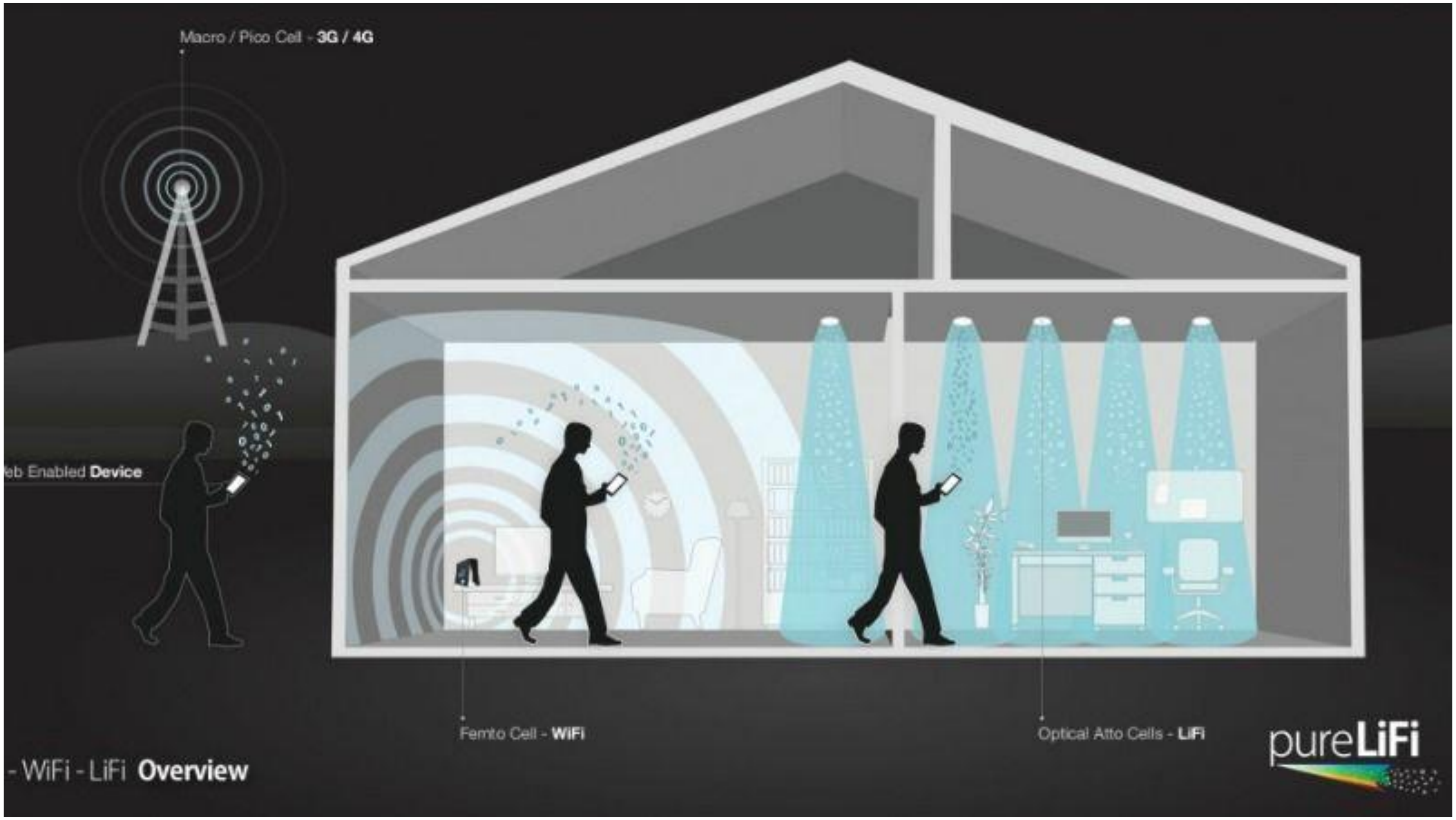
Fig. 23.9. Common structures of superluminescent diodes (SLDs). (a) SLD with cleaved facets coated with anti-reflection (AR) coatings. (b) SLD with cleaved, reflecting facets and stripe contact injecting current over the partial length of the device.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

COB MICRO SMD

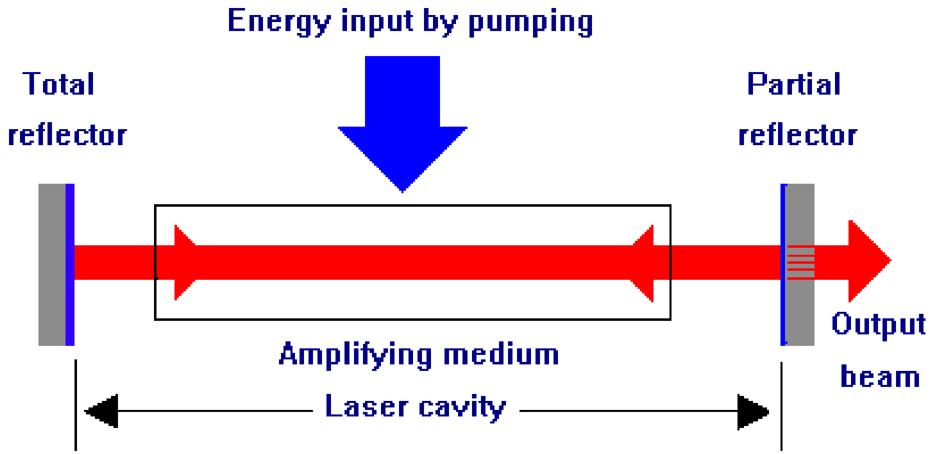
PureLifi: https://www.youtube.com/watch?v=SqtQsfe3i64

LIFI


Macro / Pico Cell - 3G / 4G
eb Enabled Device
Femto Cell - WiFi
Optical Atto Cells - LiFi
- WiFi - LiFi Overview
pureLiFi

LASER COMPONENTS

-active medium
-resonant cavity
-pumping



Stimulated Emission in a Mirrored Laser Cavity

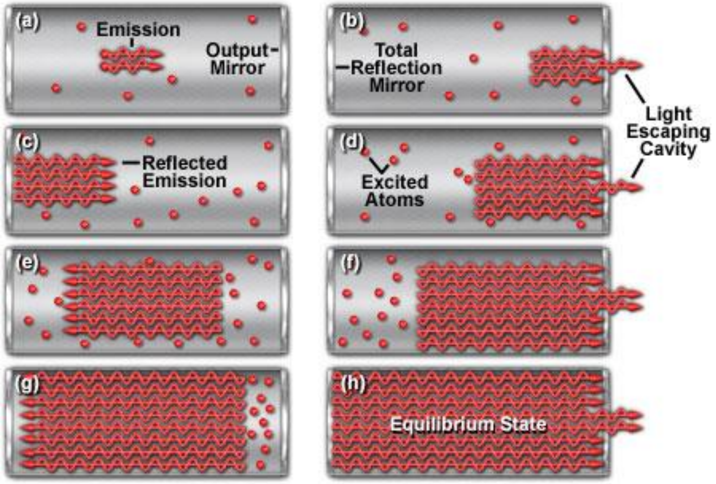
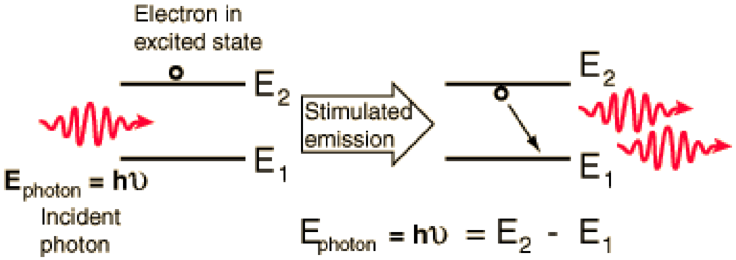
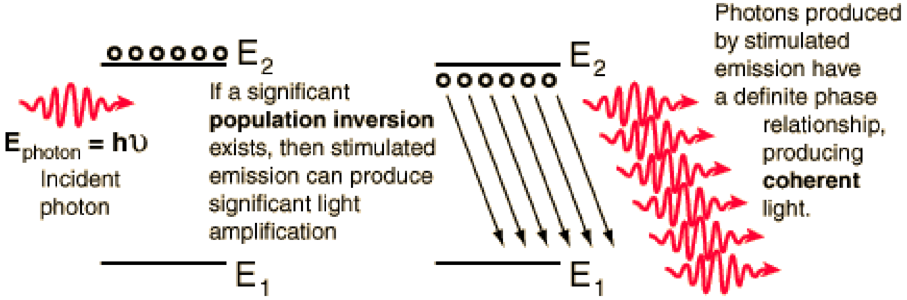


Figure 1



$E_{photon} = h\upsilon = E_2 - E_1$

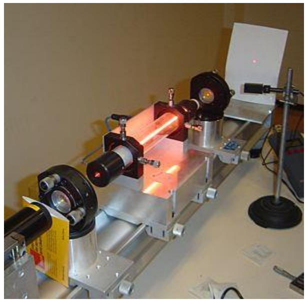


If a significant **population inversion** exists, then stimulated emission can produce significant light amplification

Photons produced by stimulated emission have a definite phase relationship, producing **coherent** light.

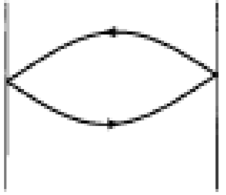
LASER- Light Amplification by Stimulated Emission of Radiation

Fabry–Perrot condition



He–Ne Laser

Power Increase = Lost Power + Output Power



ROUND TRIP IS ONE WAVELENGTH.

ROUND TRIP IS 2 WAVES.

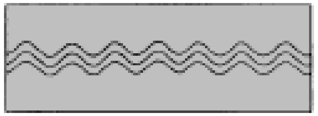
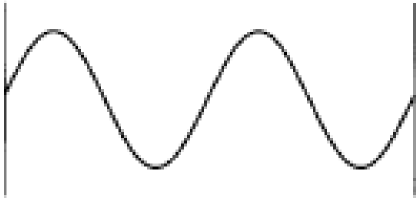


Figure 3-6. Light waves are resonant if twice the length the laser cavity equals an integral number of wavelengths.



ROUND TRIP IS 4 WAVES.

$$N\lambda = 2L$$

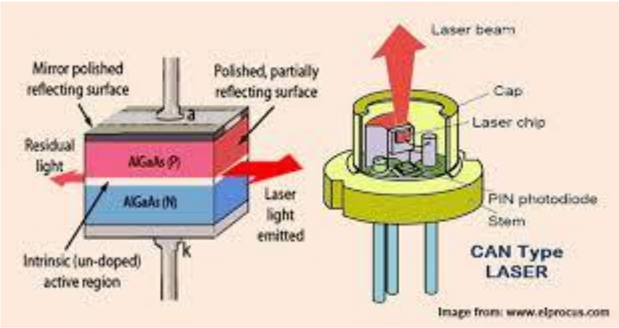
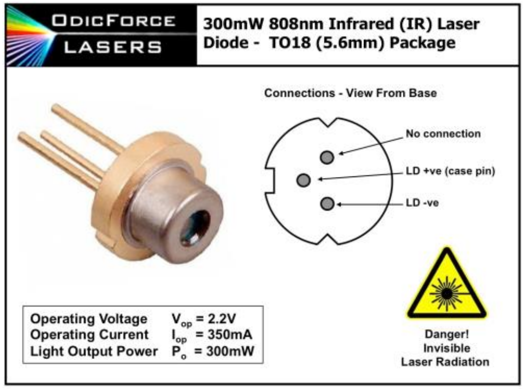


Image from: www.elprocus.com



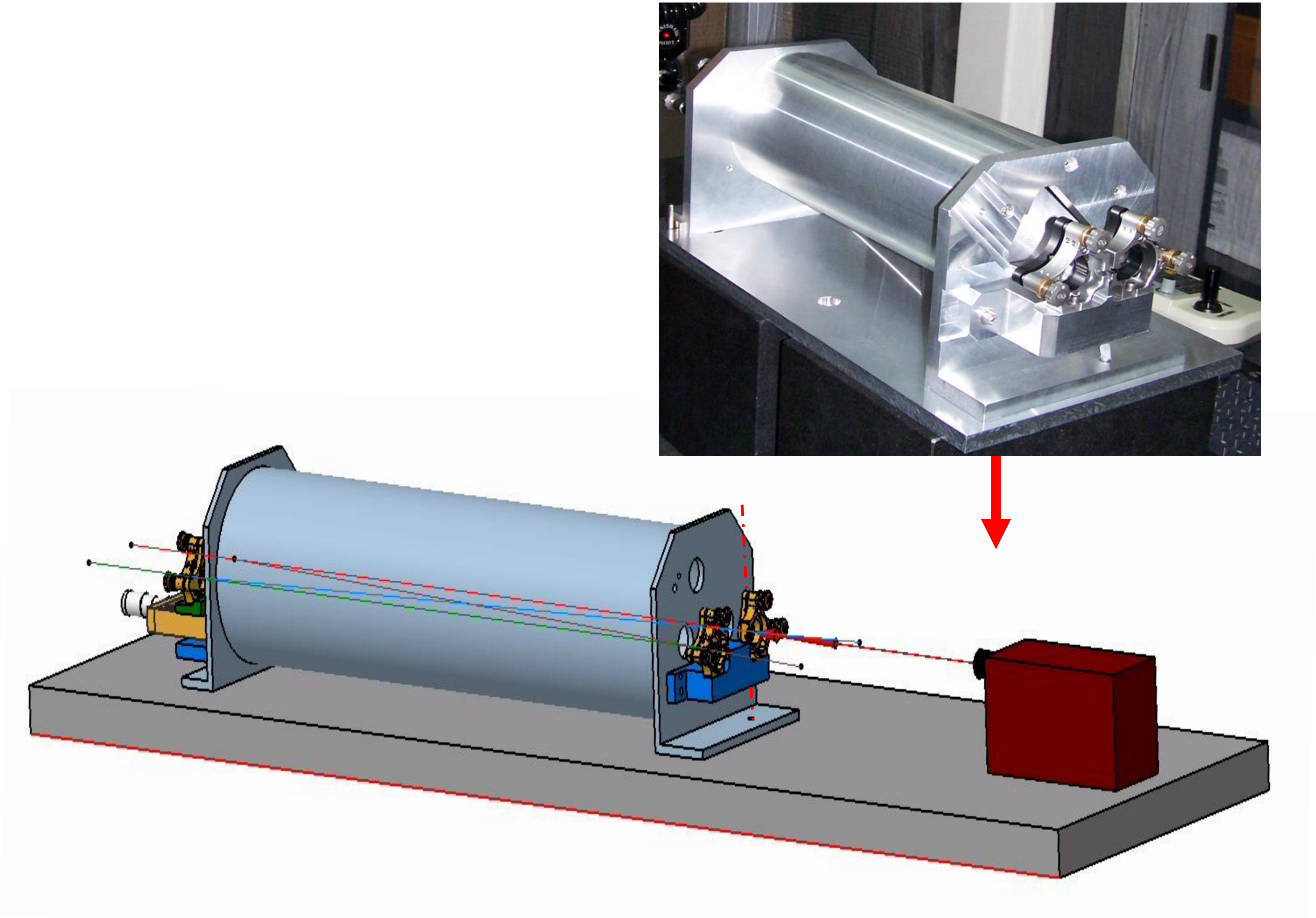
300mW 808nm Infrared (IR) Laser Diode - TO18 (5.6mm) Package

Connections - View From Base

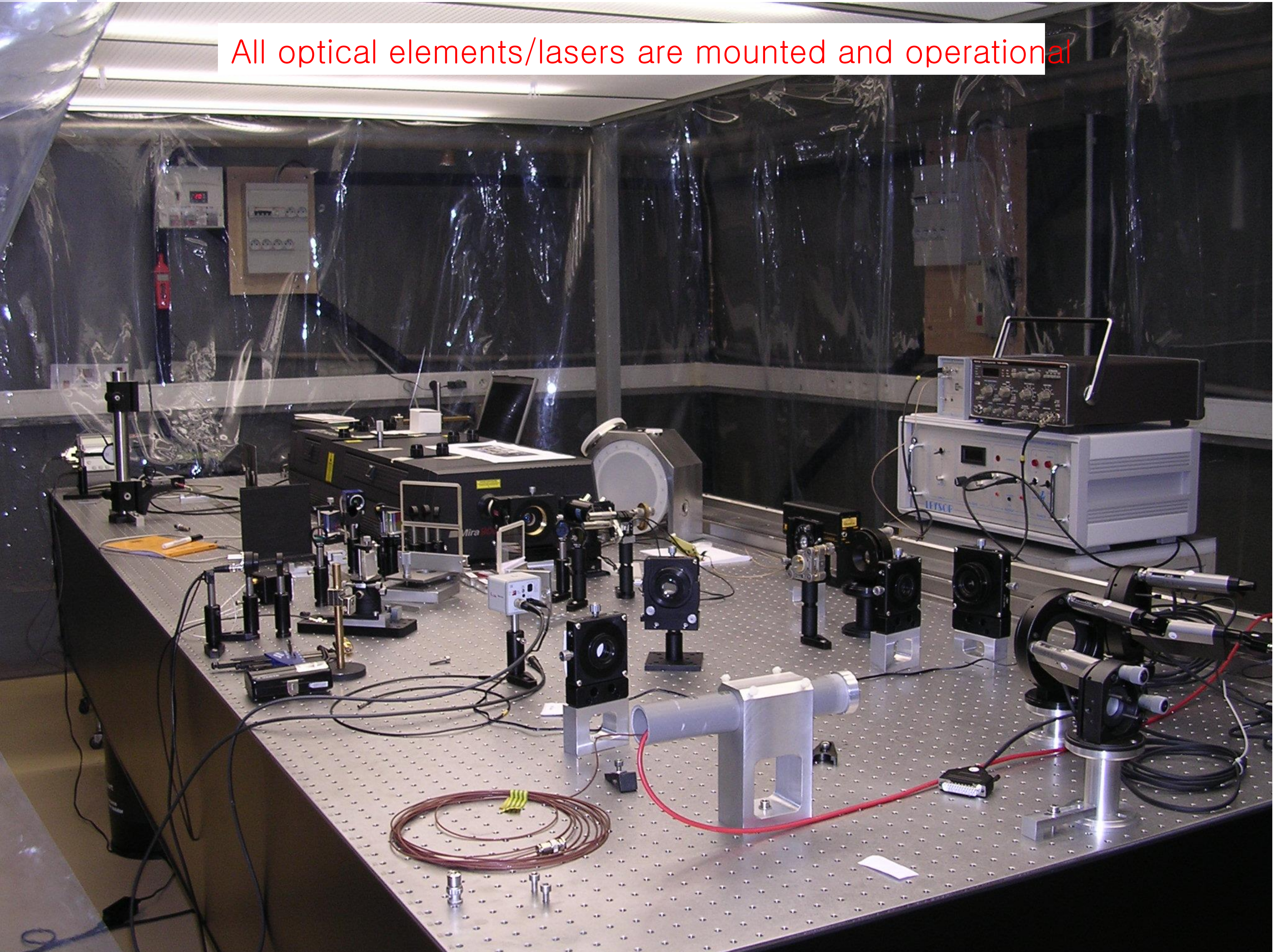
Operating Voltage	V_{op} = 2.2V
Operating Current	I_{op} = 350mA
Light Output Power	P_o = 300mW

Danger!
Invisible
Laser Radiation

LASER examples



All optical elements/lasers are mounted and operational



Buried heterojunction (BH), Ridge (RH)

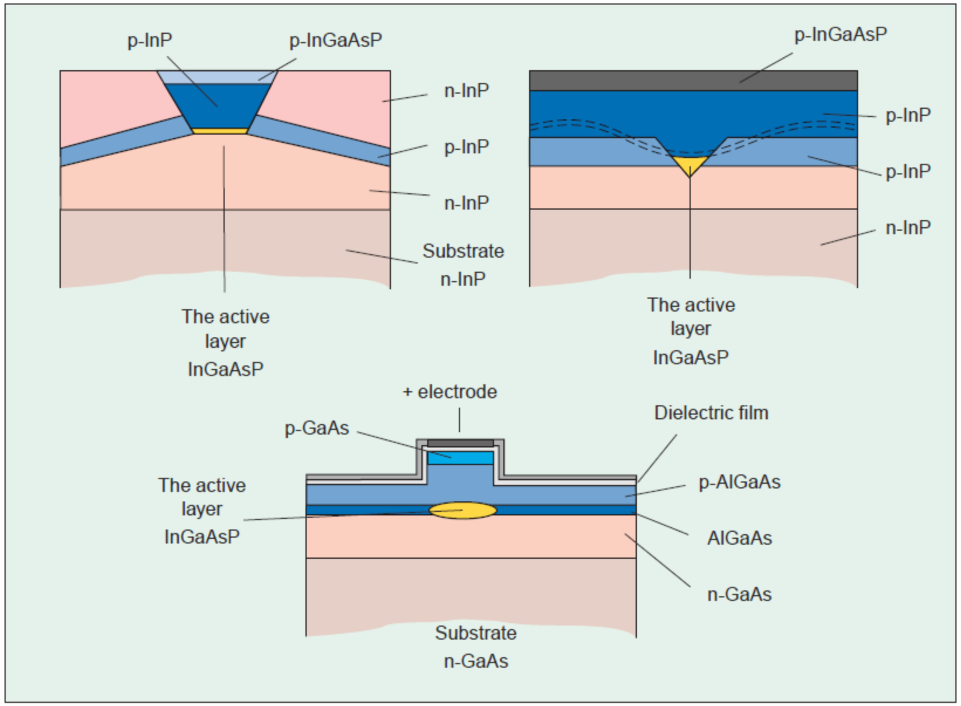


Fig. 6-24 Heterojunction laser diodes. Top left and right: two different types of BH laser diode - one planar and the other non-planar. Bottom: a ridge laser diode.

V-groove

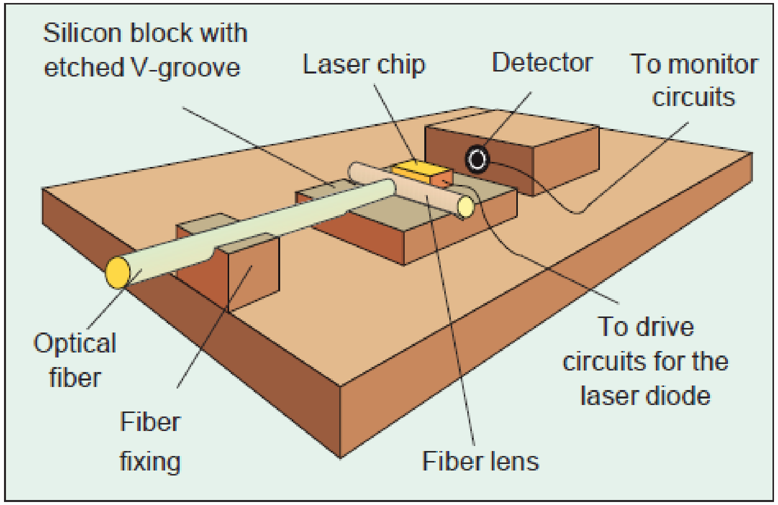


Fig. 6-25 Integrated laser chip with fixed fiber, lens system and monitoring detector.

Fibre active

4.3 Optical Fiber Amplifiers 165

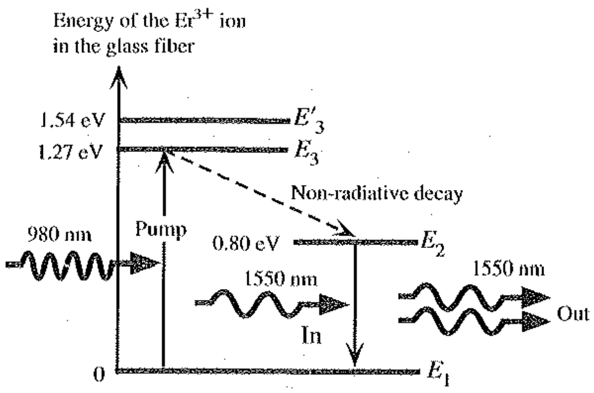
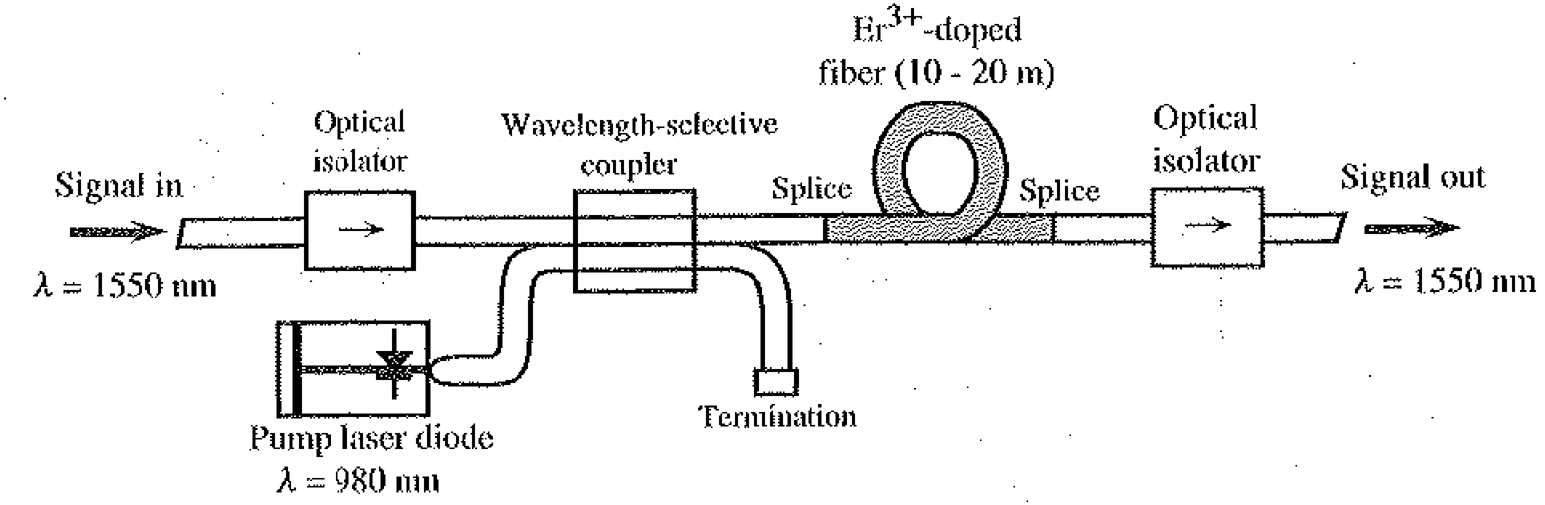


FIGURE 4.3 Energy diagram for the Er^{3+} ion in the glass fiber medium and light amplification by stimulated emission from E_2 to E_1. Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations).

Laser pe 3 niveluri

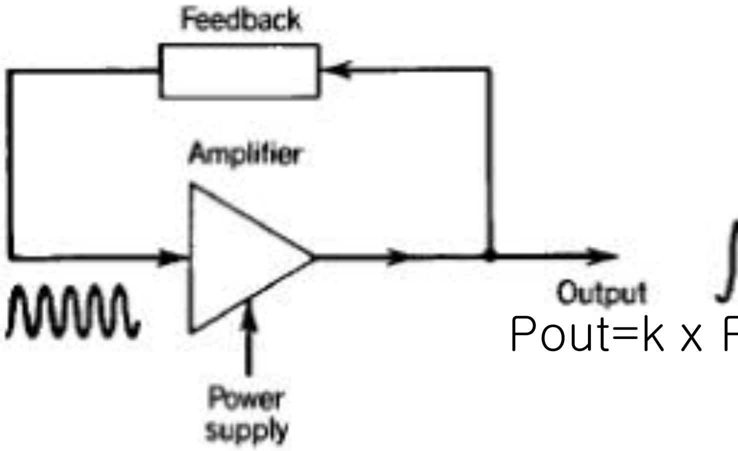


Schema echivalenta

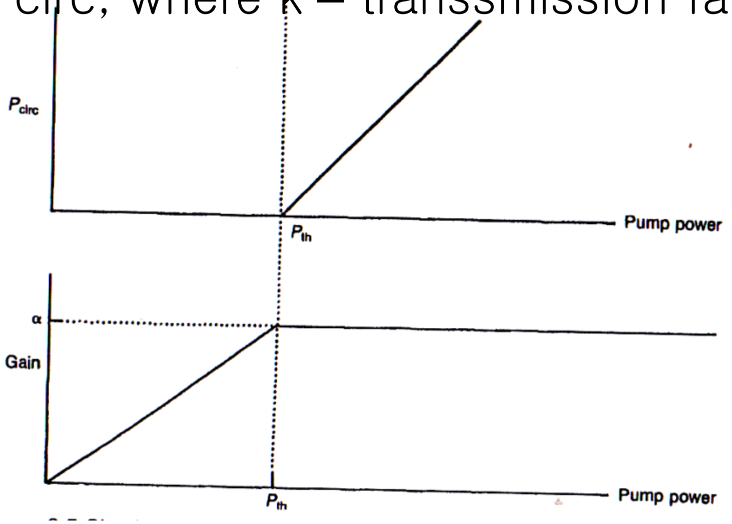
Referinta – Fundamentals of Photonics – Bahaa Saleh

- An amplifier with a gain-saturation mechanism
- A feedback system
- A frequency-selection mechanism
- An output coupling scheme

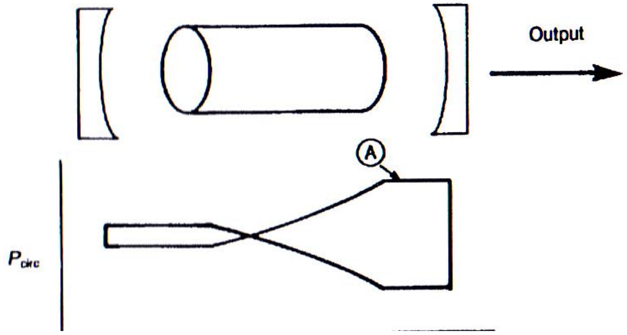
Oscillation condition:
f/(1+af)=infinit
if 1+af=0 => a=−1/f
Resonant condition
Nx lamda = 2xL



Pout=k x Pcirc, where k – transsmission factor



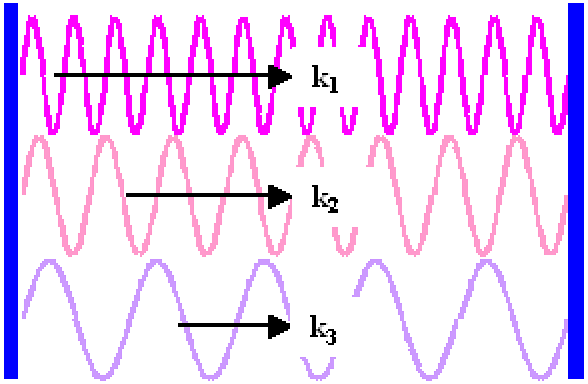
Pcirc

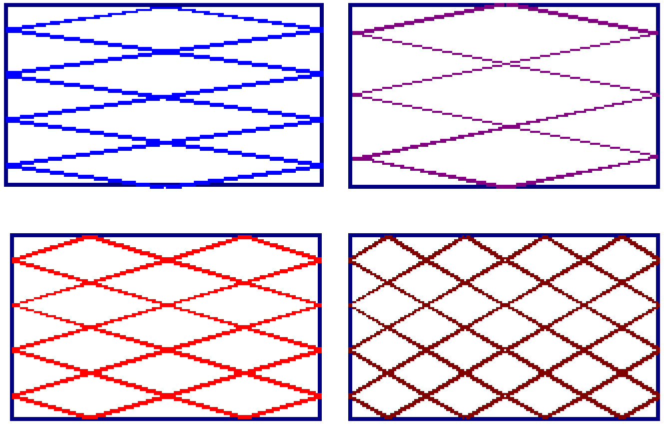


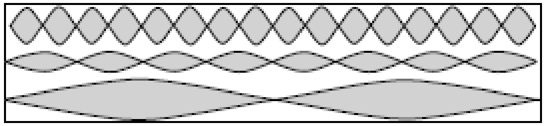
Modurile de oscilatie a unui laser

Modes- each frequency resonates on a different path within the cavity.

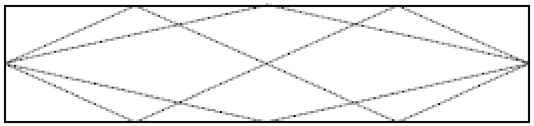
- **axial** or **longitudinal modes (fig a.)**
- **transverse** modes (fig b.)





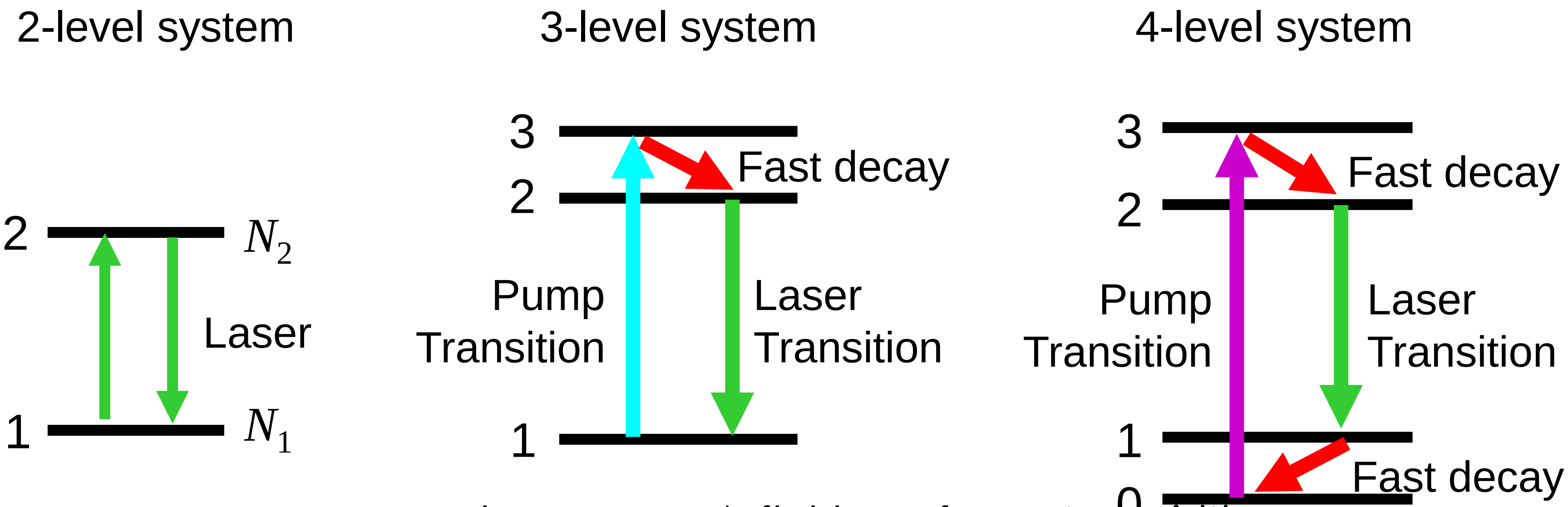


Longitudinal Modes



Lateral Modes

Inversiunea de populatie



2-level system

3-level system

4-level system

A common definition of **spectral width** is the full **width** at half maximum (FWHM)

https://en.wikipedia.org/wiki/Full_width_at_half_maximum

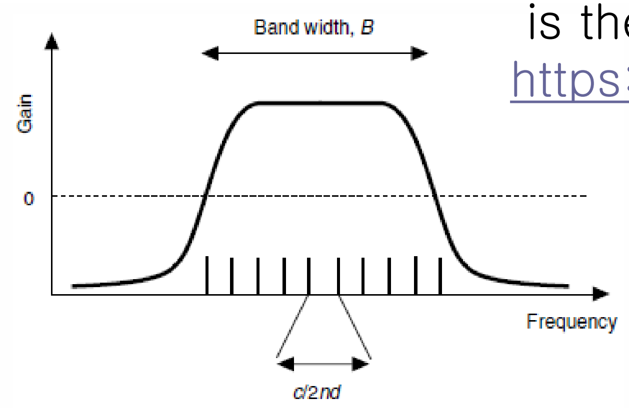


Fig. 4.9. The maximum number of modes which may be supported in a cavity is given by the ratio of the spectral bandwidth to the modal frequency spacing.

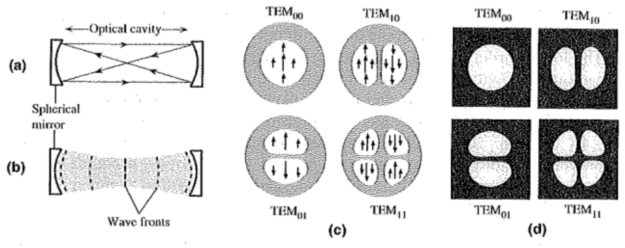


FIGURE 4.13 Laser Modes (a) An off-axis transverse mode is able to self-replicate after one round trip. (b) Wavefronts in a self-replicating wave (c) Four possible modes low order transverse cavity modes and their fields. (d) Intensity patterns in the modes of (c). (For rectangular symmetry.)

Referinta – Optoelectronics, p139

Check of the laser diode operation: 1D cavity modes

Current modulation of the laser diode

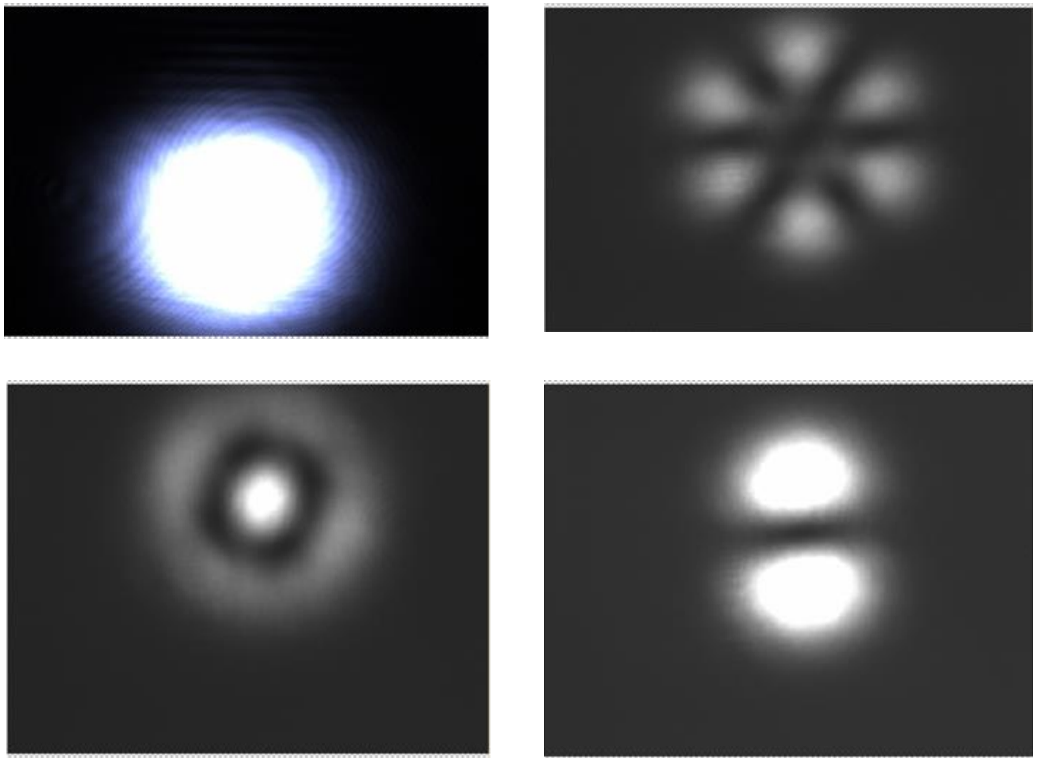
Cavity=2 mirrors

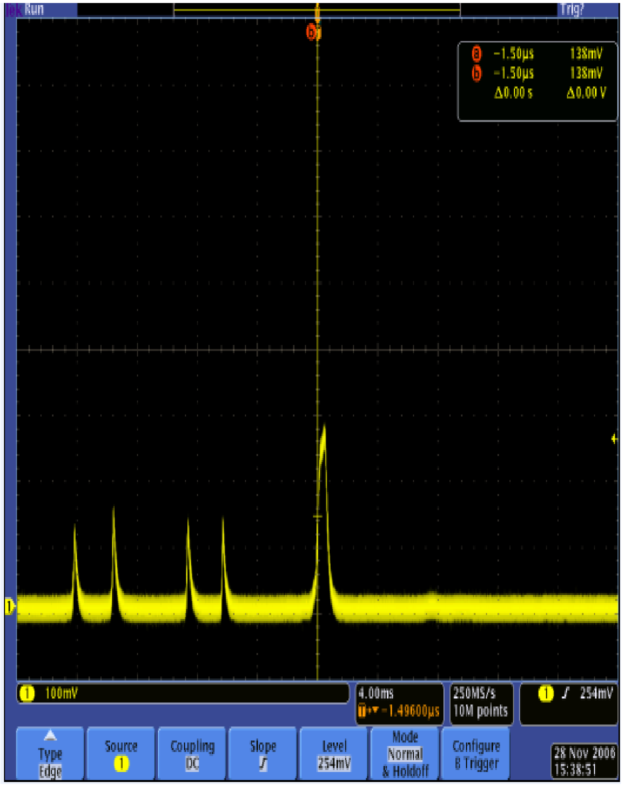
photodiode

CCD

Transmitted power

modes

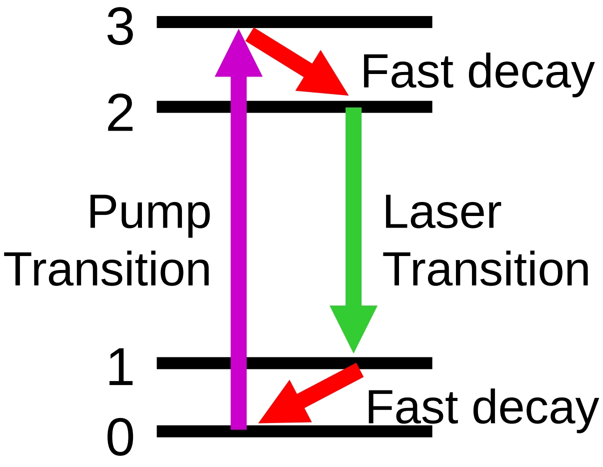




Type Edge
Source 1
Coupling DC
Slope ƒ
Level 254mV
Mode Normal & Holdoff
Configure B Trigger

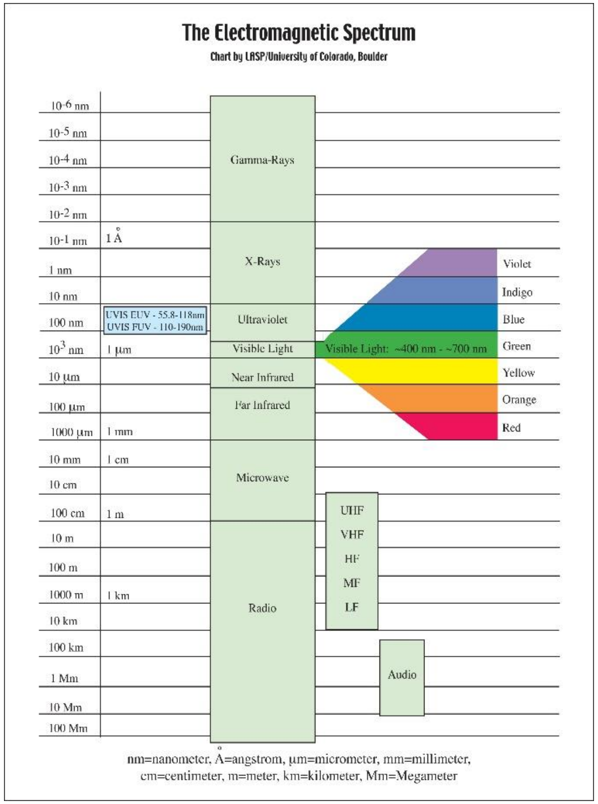
Summary – Basic Laser

- Source light
- Reflective Mirrors (cavity)
- Gain Media
    - ☐ Energy Level Structure
    - ☐ Population Inversion



Laser light properties

- Monochromatic
- Temporal and spatial coherence
- High light intensity
- Short Pulse duration (fsLaser)
- Spectra :
    - Far infrared (IR) – (10–1000 micro m)
    - Middle IR – (1–10 micro m)
    - Near IR –(0.7–1 micro m)
    - Visible (V) – (400–700nm)
    - Ultraviolet (UV) – (200–400nm)
    - Vacuum ultraviolet (VUV) – (100–200nm)
    - Extreme ultraviolet (EUV) – (10–100nm)
    - Soft X-ray – (20–30nm)

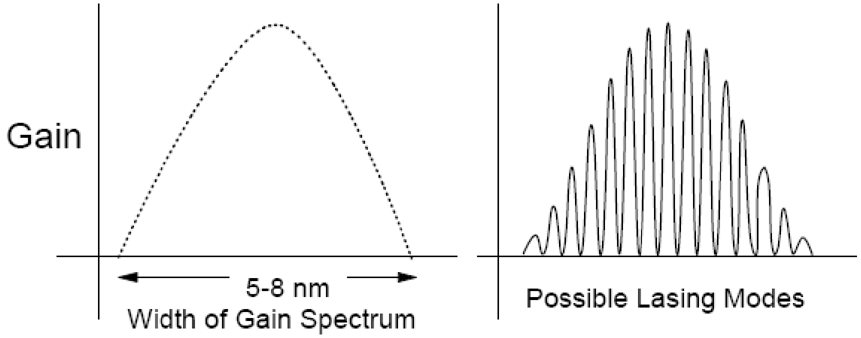


Parametrii tehnici

- Spectral width
- Linewidth
- Coherence time and length
- Power
- Operating wavelength
- Wavelength (frequency) stability
- Switching time and modulation
- Tuning range and speed

Spectral width (FWHM)-

It is a fact that most simple semiconductor lasers do not produce a single wavelength of light. They produce instead a range of wavelengths. This range of wavelengths is called the “spectral width” of the laser. This seems to contradict the basic principle of laser operation. However, it is not so. In a semiconductor laser, a mirrored cavity is used to build up the light. By mechanical necessity, the cavity is long enough for several wavelengths to be produced It is interesting that these different wavelengths (modes) are not produced simultaneously – or rather their strength varies widely. So spectral width is usually quoted as the FWHM (Full Width Half Maximum). FWHM is measured between the points on the curve where power has decayed to one half of the peak. Thus in some contexts it is also called the “3-dB point”.

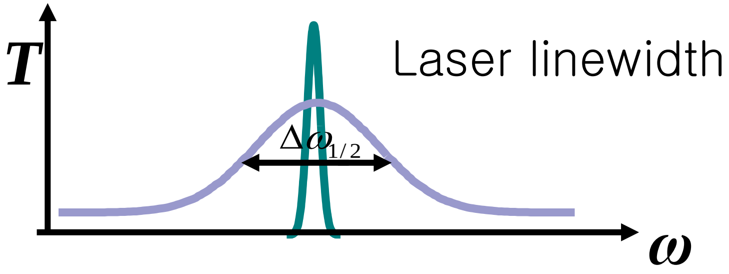


Importance:

1. FWHM hight-the more dispersion the signal will suffer when travelling on the fibre
2. FWHM mic-maximizare WDM channel
3. FWHM mic – efecte neliniare (SBS – stimulated brillouin scattering) nedorite
4. FWHM – efect asupra tehnicilor de modulatie

Linewidth

A particular laser line is emitted at a very specific wavelength corresponding to one mode (light path) in the laser's cavity. Over time this wavelength varies somewhat around a center wavelength (the amount of variation is the linewidth)



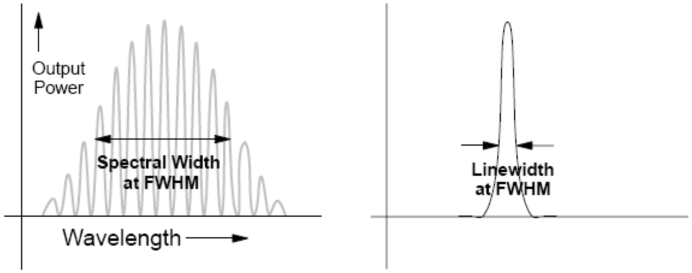


Figure 70. Spectral Width and Linewidth. These are usually measured as the width at half the maximum signal amplitude. That is at FWHM (Full Width Half Maximum).

Instead of producing a continuous range of wavelengths over their spectral width, semiconductor lasers produce a series of “lines” at a number of discrete wavelengths. Lines themselves vary in width (in different types of lasers) very significantly. The linewidth is inversely proportional to the coherence length of the laser.

http://www.rp-photonics.com/linewidth.html

Temporal and spatial coerence (IBM)

- The length of time that coherence is maintained is called the “coherence time”.
- The length that the signal could travel in a vacuum during that time is called the coherence length.
- Ex: LED – coherence time half a picosecond and its coherence length is around 15 microns

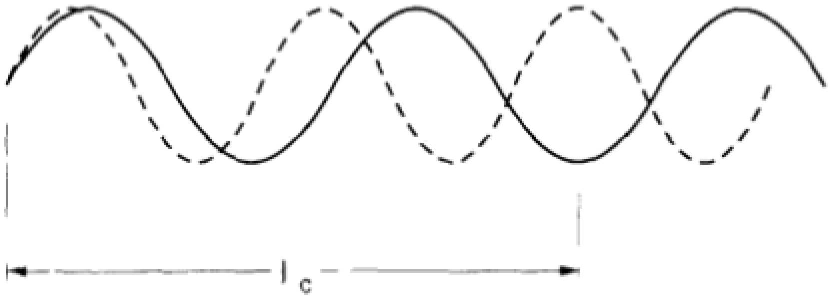
  LASER – good quality, narrow linewidth – coherence time of perhaps a microsecond and a coherence length of up to 200 meters.

$$\text{Length}_{coherence} = c \times \text{Time}_{coherence} = \frac{\lambda^2}{\Delta\lambda}$$

Where $\Delta\lambda$ = Linewidth and λ = Centre Wavelength.

Coherence

- Another important consideration in the study of lasers is the interaction of two electromagnetic waves that have only slightly different frequencies (coerenta temporala), or that originate from points only slightly separated spatially (coerenta spatiala) – for example, two closely located but separate laser beams or a single beam illuminating two closely positioned apertures. In such instances the two distinct waves or beams will interfere with each other to produce, in some cases, very dramatic effects.
- When the waves do not interfere – incoherent
- Exista si partial coerent – exista o oarecare interferenta



Coerenta temporala–
Lungime de coerenta(lc)

- Power
- Operating wavelength – material used for lasing and geometry of the laser cavity
- Wavelength (frequency) stability – wavelength variaza cu temperatura n(t)– important in WDM techniques, each laser must keep within its allocated wavelength
- Switching time and modulation – how fast they can operate–> tehnici de modulatie (OOK, FSK), altfel modulator extern (external modulator to be placed into the light beam after it is generated)
- Tuning range and speed – sisteme WDM – switched between different wavelengths (channels). Tunable lasers are seldom capable of continuous tuning over an unbroken range of wavelengths. When they are tuned they “jump” from one wavelength to another (corresponding to the resonance modes of the laser cavity)

Laser operation

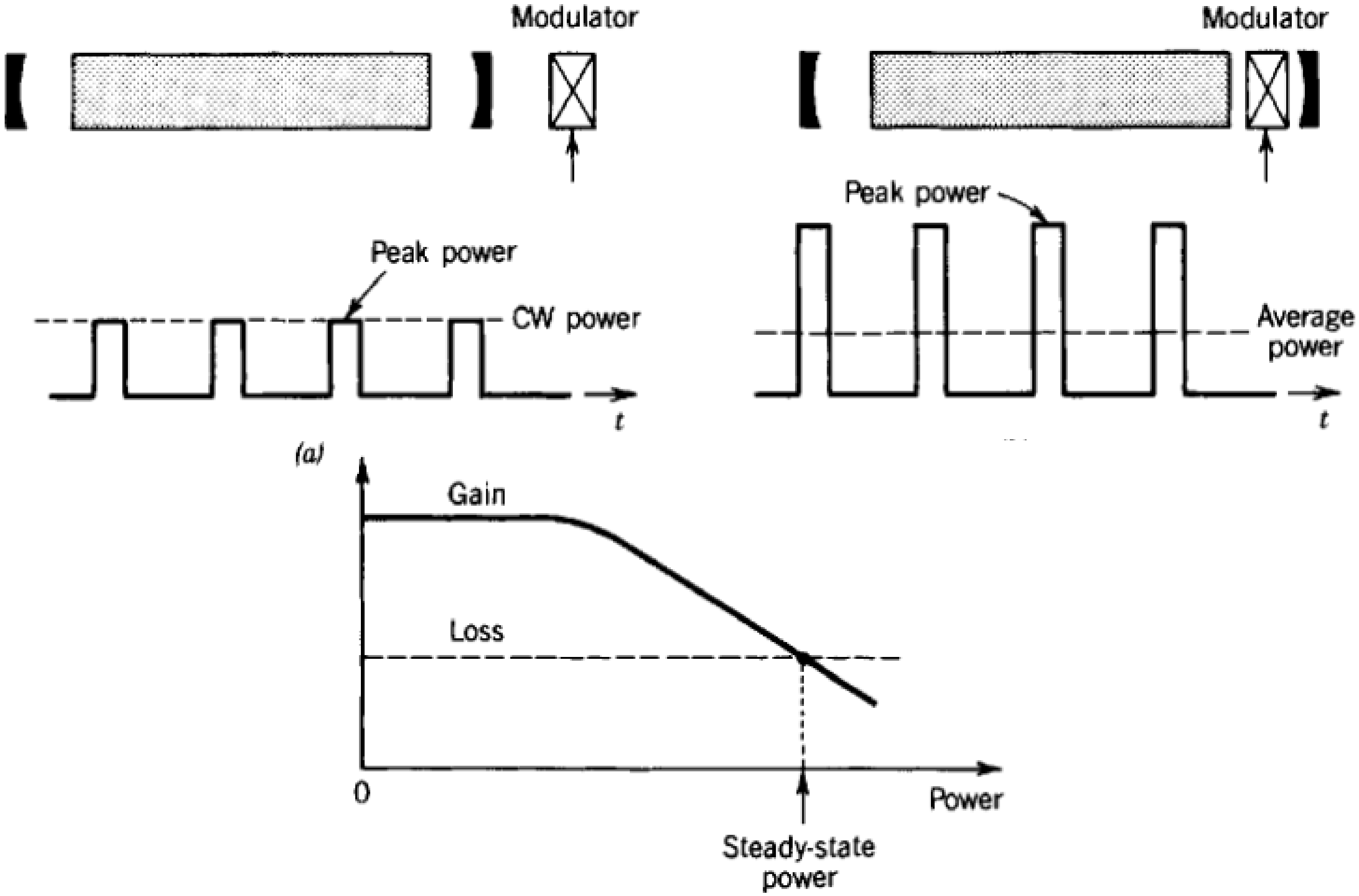
- CW – continuu
- Pulses

- Intern cavity
- Extern cavity

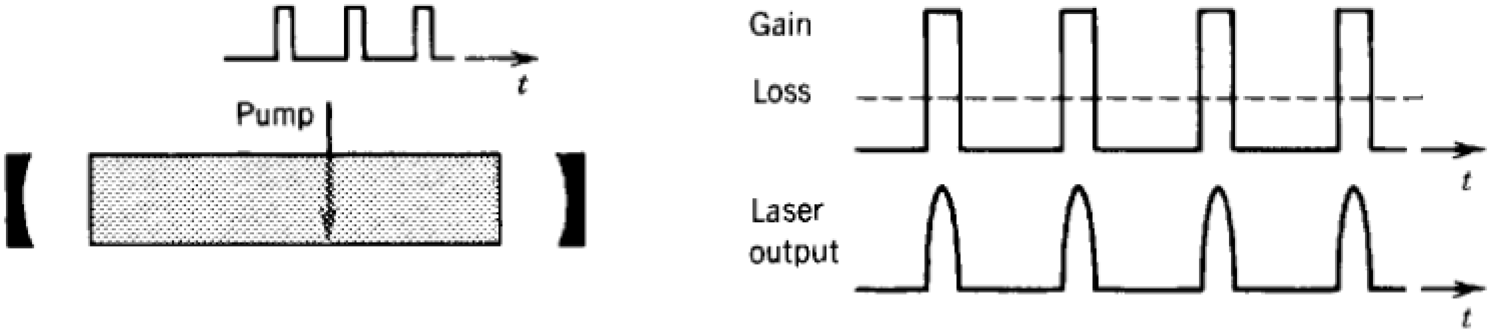
- Below treshold
- Just above treshold
- Full power

- Laser types
    - gas laser
    - solid laser
    - semiconductor laser
    - dye laser

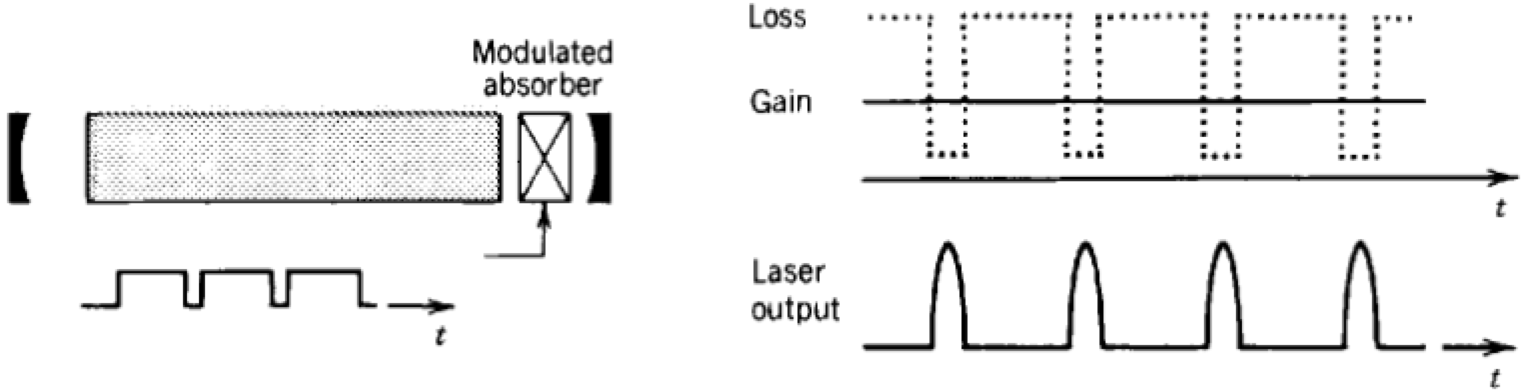
Pulse lasers



Gain switching



Q- switching



Q-switching operating

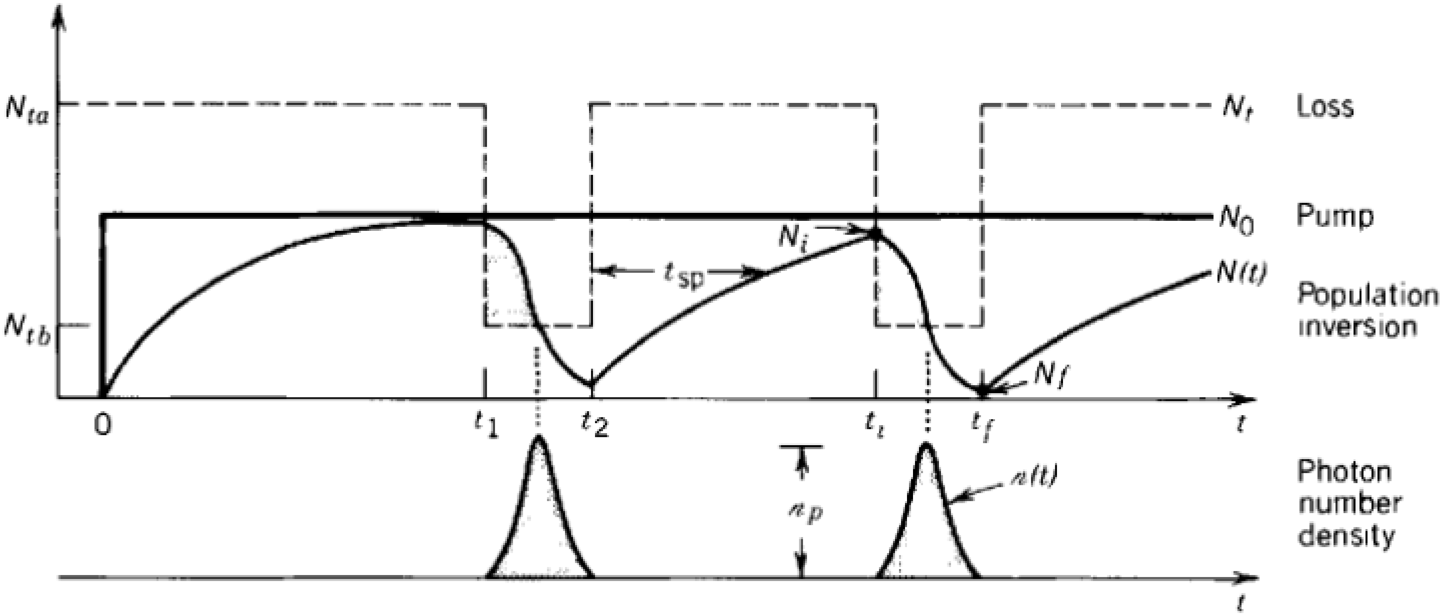
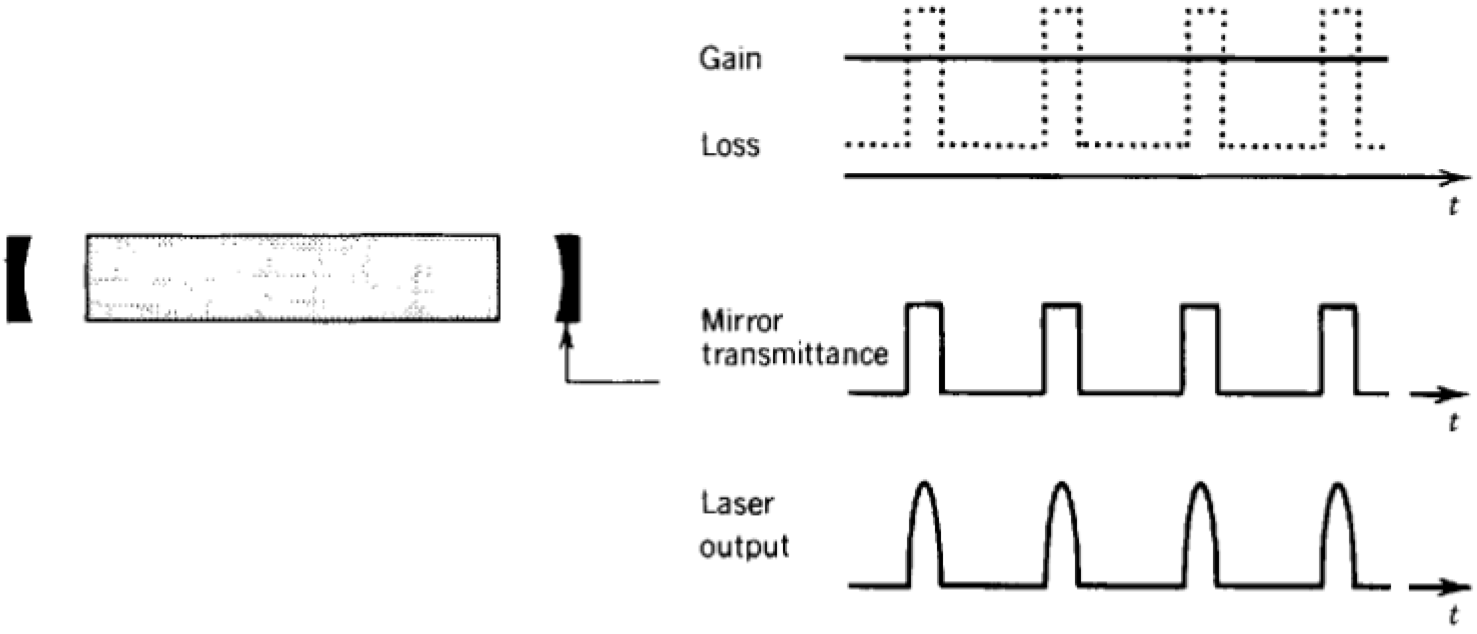


Figure 14.3-6 Operation of a *Q*-switched laser. Variation of the population threshold N_t (which is proportional to the resonator loss), the pump parameter N_0, the population difference $N(t)$, and the photon number $n(t)$.

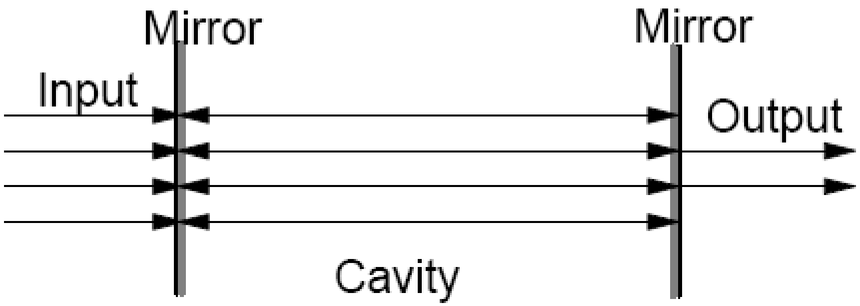
Cavity dumping



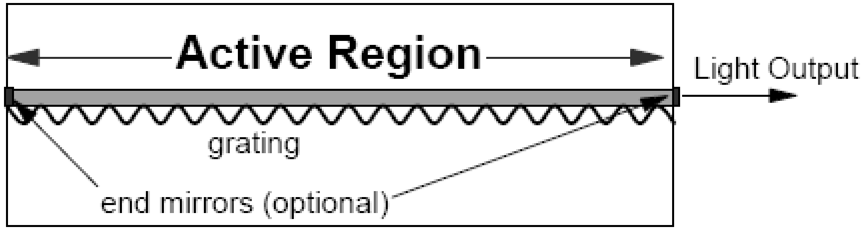
Laser types (IBM)- Generating Pulses

- Semiconductor Laser diodes
- Fabry-Perrot
- DFB (distributed feedback laser)
- Q-switching
- Mode Locking
- DBR (distributed bragg reflector laser)
- Quantum-weels
- Tunable Laser (DBR)
- Multi-Wavelength
- VCSEL (Vertical cavity surface emitting lasers)
- Fibre ring Lasers
- Double pumping/free electrons

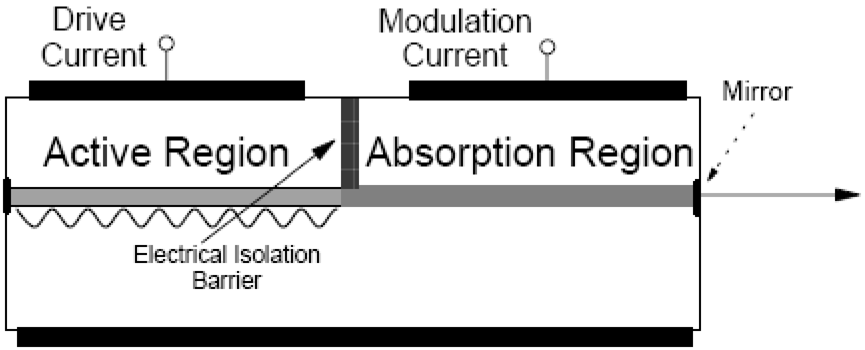
Fabry Perot



DFB



Q-switch =
DFB cu modulator electro-abs in cavit



Mode-locking

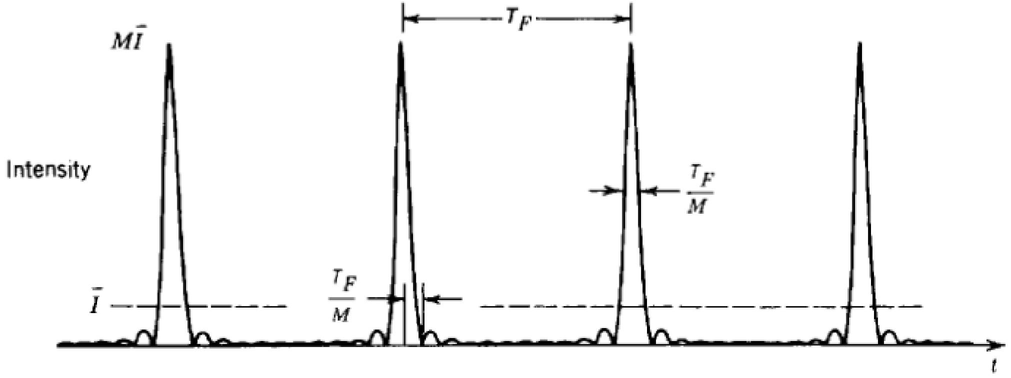


Figure 14.3-9 Intensity of the periodic pulse train resulting from the sum of M laser modes of equal magnitudes and phases. Each pulse has a width that is M times smaller than the period T_F and a peak intensity that is M times greater than the mean intensity.

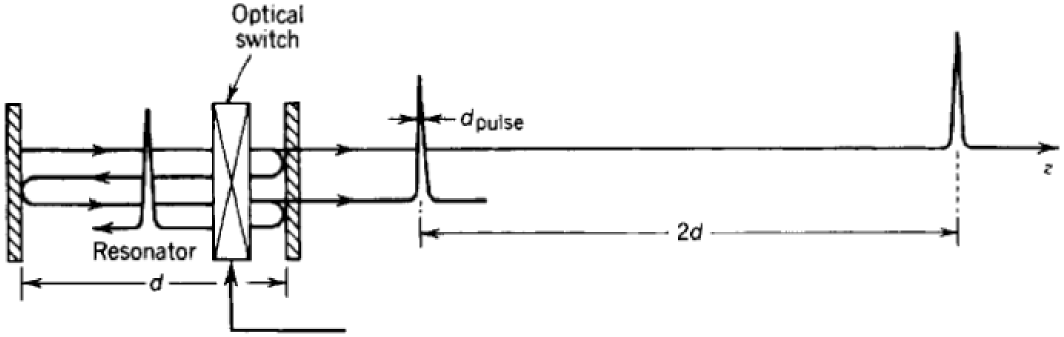
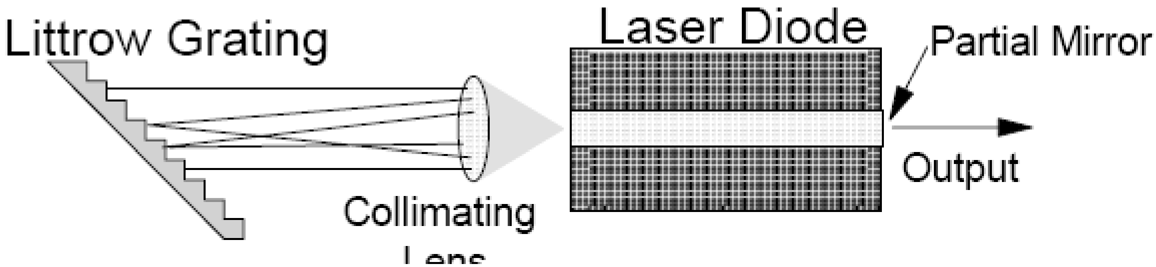
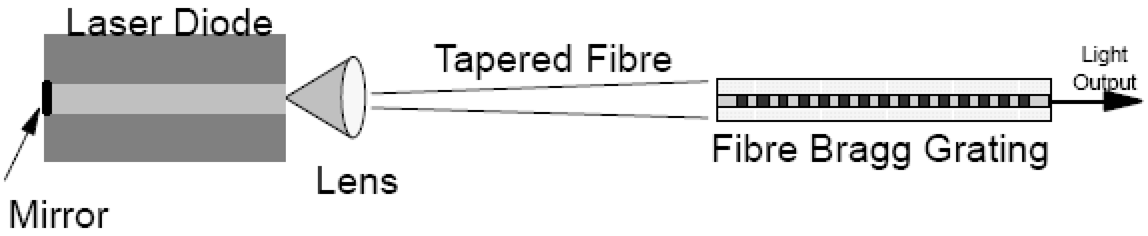


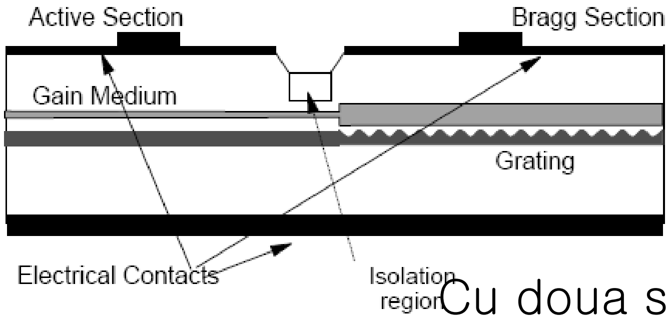
Figure 14.3-10 The mode-locked laser pulse reflects back and forth between the mirrors of the resonator. Each time it reaches the output mirror it transmits a short optical pulse. The transmitted pulses are separated by the distance $2d$ and travel with velocity c. The switch opens only when the pulse reaches it and only for the duration of the pulse. The periodic pulse train is therefore unaffected by the presence of the switch. Other wave patterns, however, suffer losses and are not permitted to oscillate.

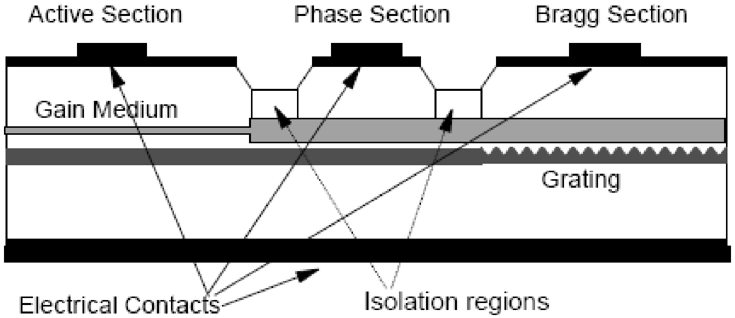
DBR



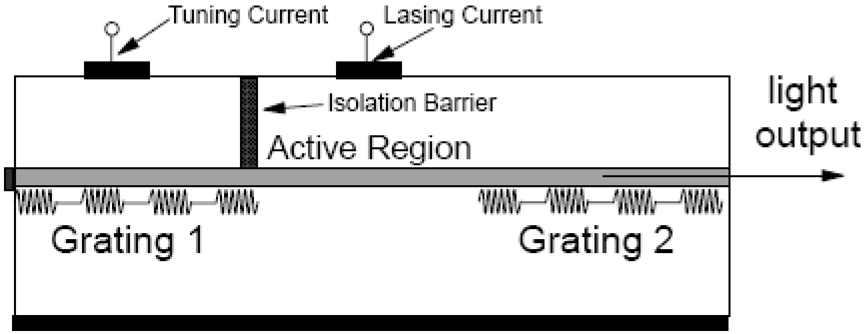


Laseri acordabili

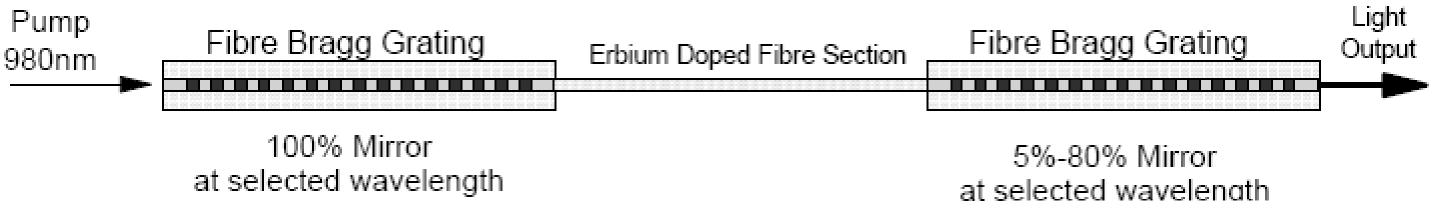




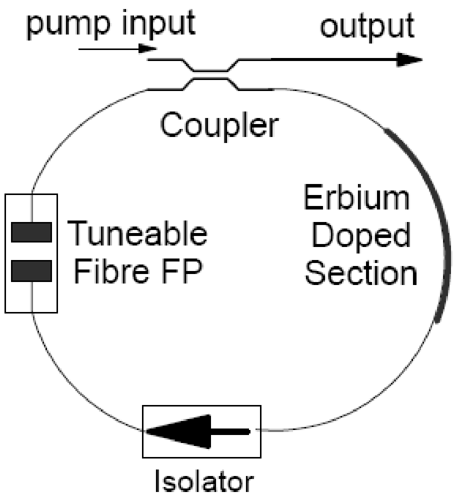
Cu doua si cu trei sectiuni



In fiber



Ring



VCSEL

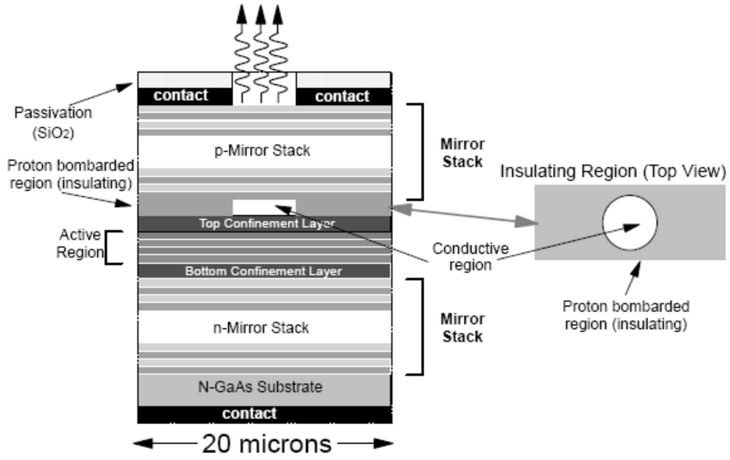
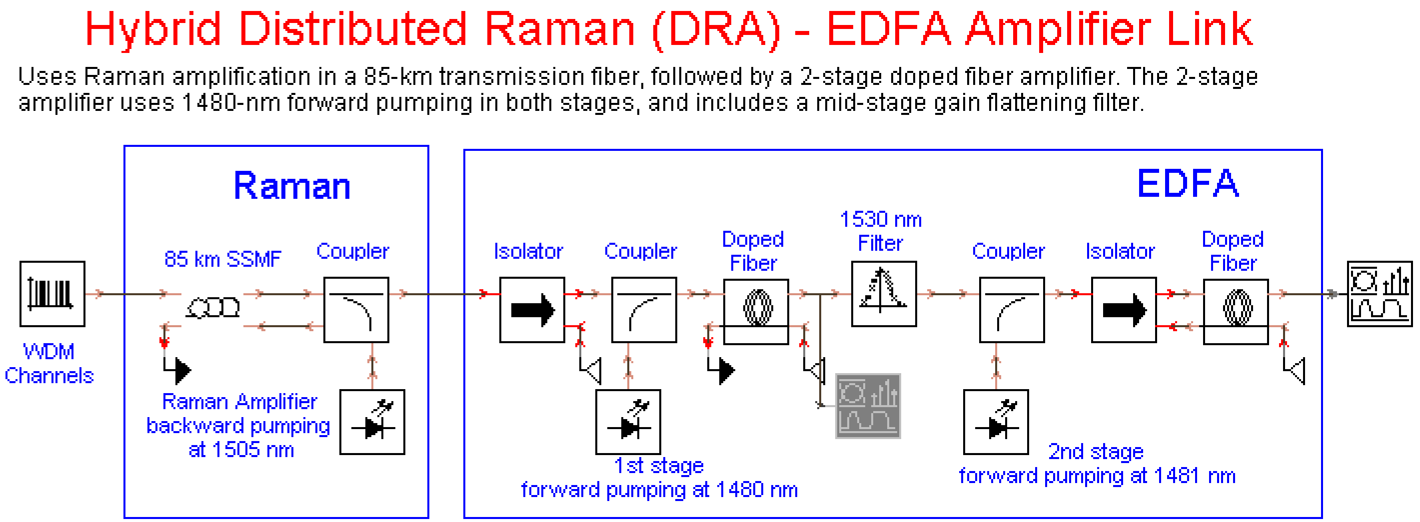


Figure 92. VCSEL Structure

Fibra activa

- EDFA
- Raman



Hybrid Distributed Raman (DRA) - EDFA Amplifier Link

Uses Raman amplification in a 85-km transmission fiber, followed by a 2-stage doped fiber amplifier. The 2-stage amplifier uses 1480-nm forward pumping in both stages, and includes a mid-stage gain flattening filter.

LASER OSCILLATION CONDITION

- Unity loop-gain condition

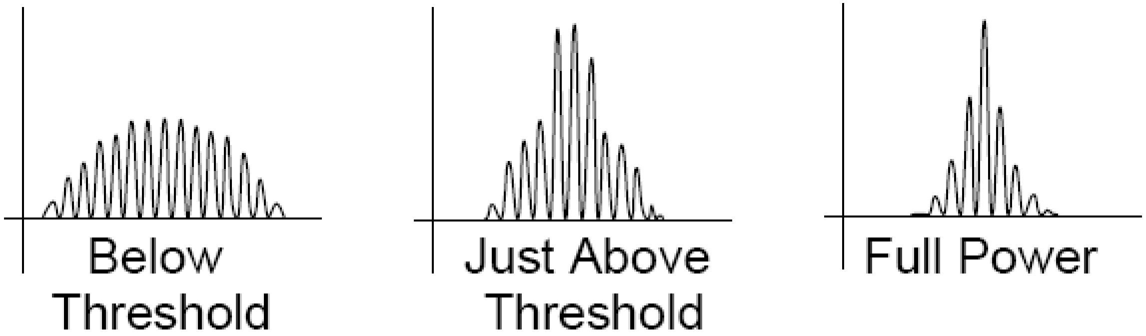
→ threshold gain

：required minimum gain for laser action
and the gain under steady state laser operation
(Amplification = Loss)

- Population inversion

：necessary but not sufficient condition for laser action
(additional gain needed to overcome the loss)

Operates

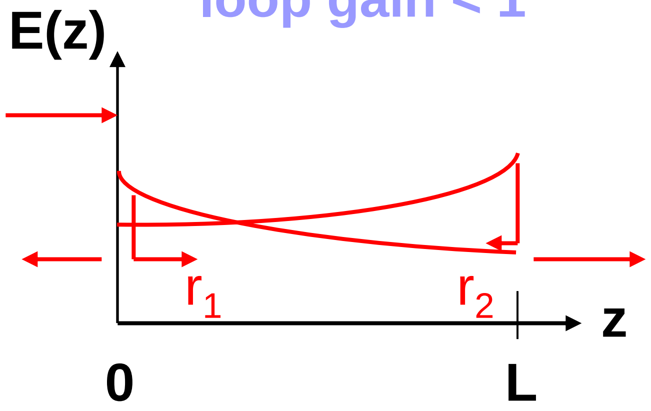


LASER OSCILLATION CONDITION

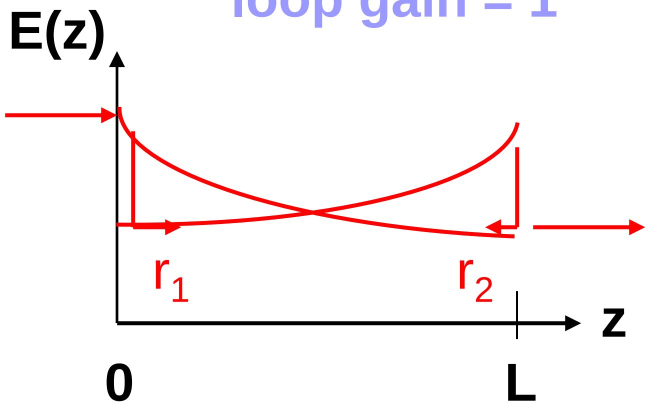
- Threshold condition
  - round trip gain (or loop-gain)
  - G = $\dfrac{irradiance\ after\ a\ round\ trip}{initial\ \ irradiance}$
    - G>1 : oscillation grows – initial stage of the laser action
    - G=1 : threshold condition – steady oscillation
    - G<1 : oscillation die out

CW LASER OSCILLATION CONDITION

Oscillation Condition: Threshold Gain & Lasing Wavelength



Below threshold
loop gain < 1



At the threshold
loop gain = 1

Unity loop gain

$$r_1 r_2 \exp[(g - \alpha_i)L] \exp(j4\pi nL/\lambda_0) = 1$$

Threshold condition

$$g_{th} = \alpha_i + (1/L) \ln(1/r_1 r_2)$$

$$\lambda_{0,m} = n\,L\,/\,2\,m$$

CW LASER OSCILLATION CONDITION

- Laser losses
  - transmission at the mirrors → output : mirror loss
    → the other mirror highly reflective
  - absorption and scattering at the mirrors
  - diffraction loss at the laser mirrors due to the finite size of the mirrors
    → part of radiation spread out beyond the mirror edge
    → use of concave mirrors to reduce the diffraction losses
  - absorption in the laser medium by transitions other than the desired one

CW LASER OSCILLATION CONDITION

- Unity loop-gain condition

→ threshold gain

: required minimum gain for laser action
and the gain under steady state laser operation
(Amplification = Loss)

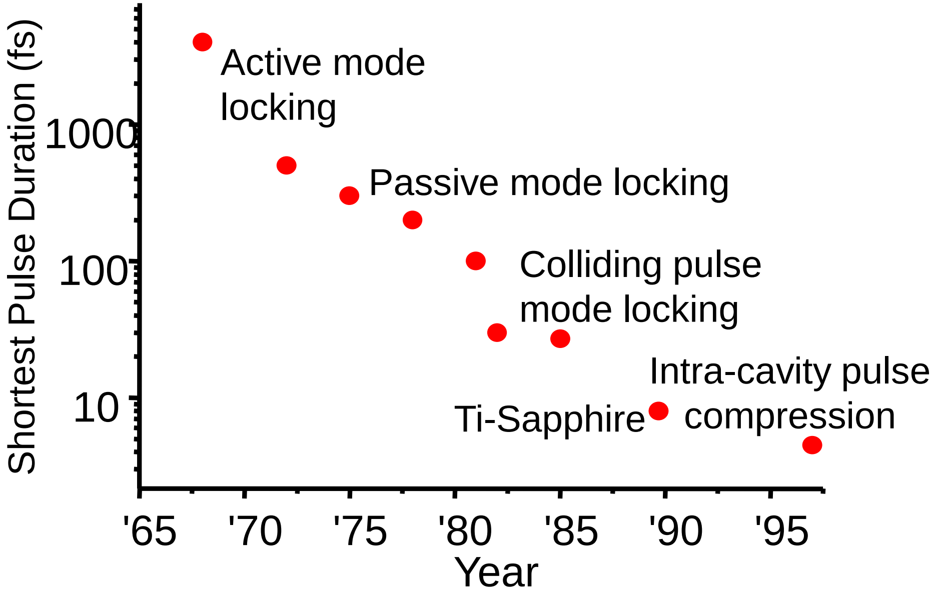
- Population inversion

: necessary but not sufficient condition for laser action
(additional gain needed to overcome the loss)

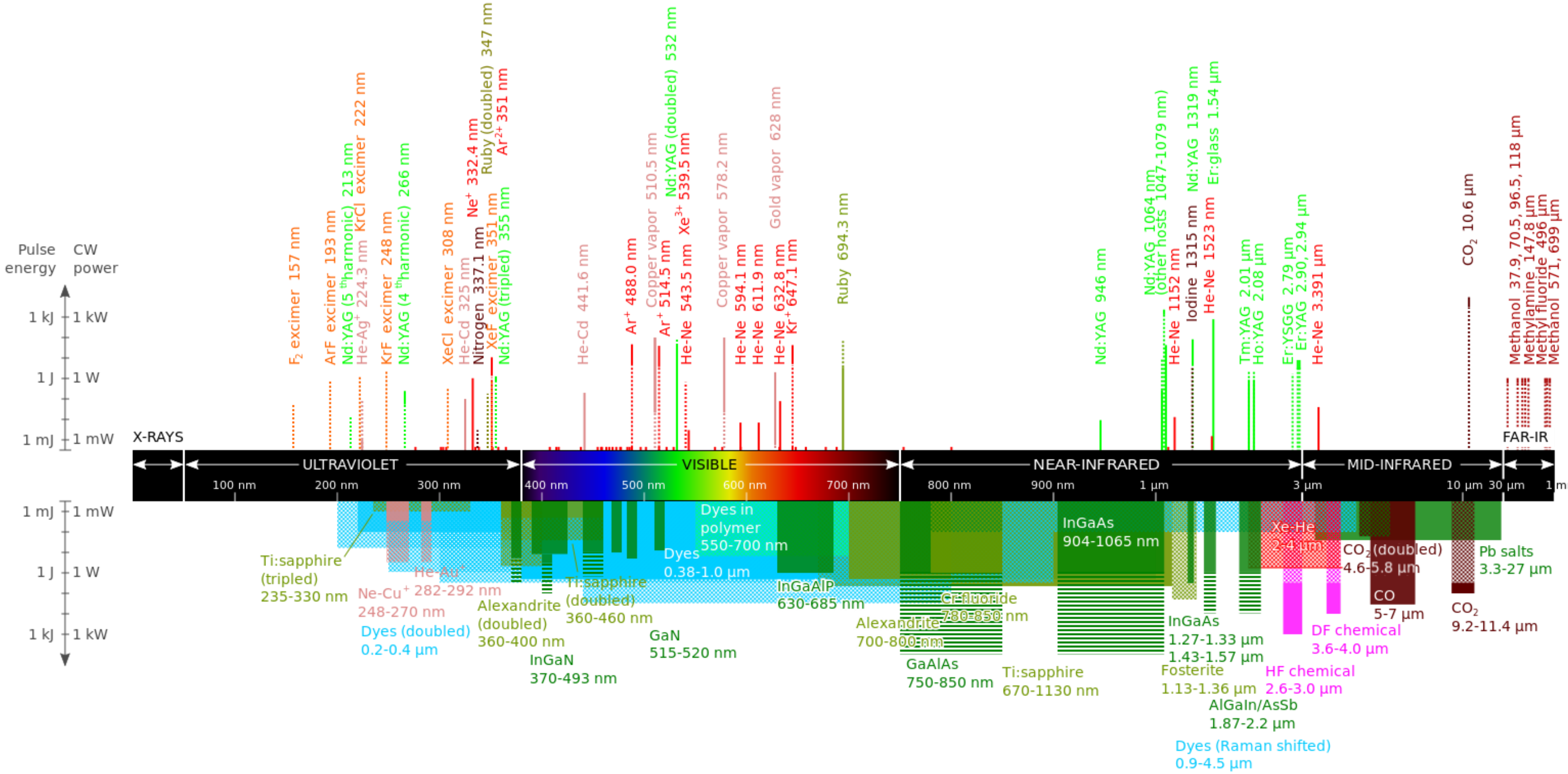
효과적인 population inversion을 위해선 4-level system이 적합함

Mode-Locking Methods

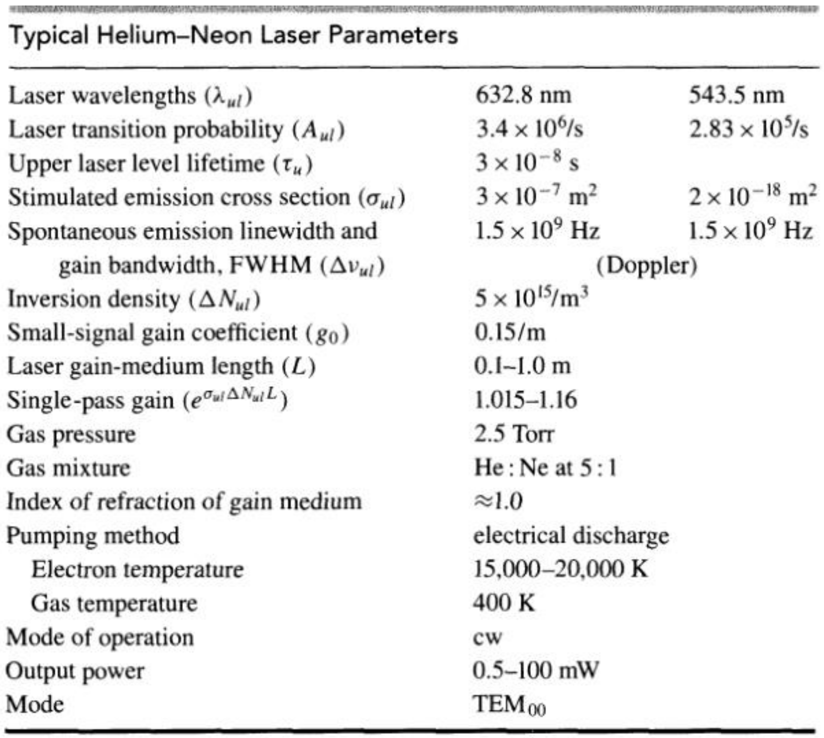
- Active – Mechanical Shutters
  - Acousto-Optic Switches (low gain lasers)
  - Synchronous Pumping
- Passive
  - Colliding Pulse
  - Additive Pulse
  - Kerr Lens



Wikipedia – tipuri de laseri

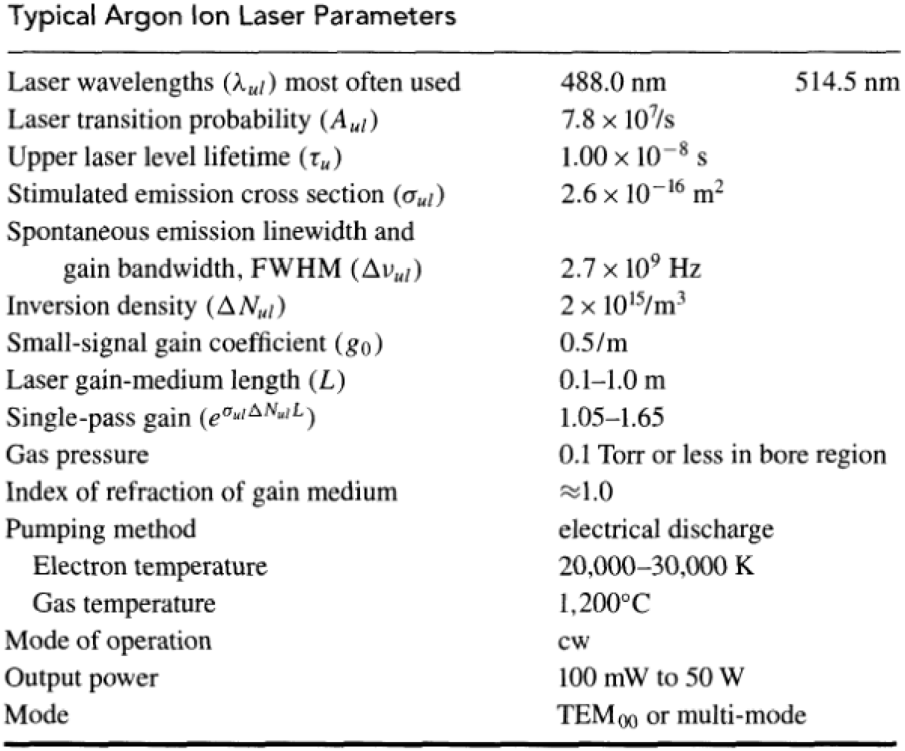


Laser types– Examples



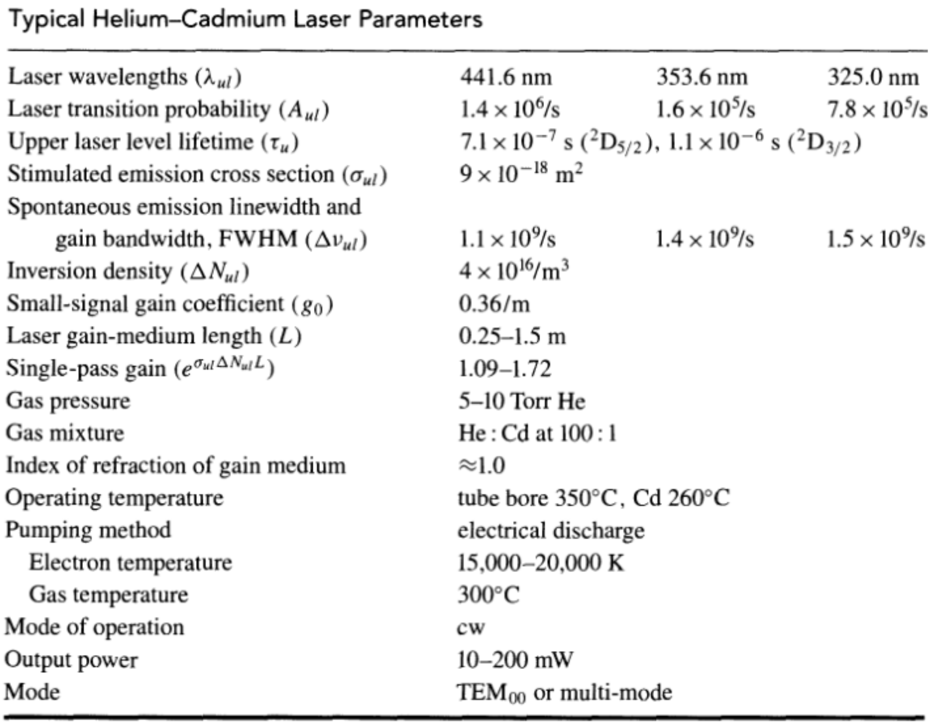
Typical Helium–Neon Laser Parameters

Laser wavelengths (λ_{ul})	632.8 nm	543.5 nm
Laser transition probability (A_{ul})	3.4×10^6/s	2.83×10^5/s
Upper laser level lifetime (τ_u)	3×10^{-8} s	
Stimulated emission cross section (σ_{ul})	3×10^{-7} m^2	2×10^{-18} m^2
Spontaneous emission linewidth and gain bandwidth, FWHM ($\Delta\nu_{ul}$)	1.5×10^9 Hz (Doppler)	1.5×10^9 Hz
Inversion density (ΔN_{ul})	5×10^{15}/m^3	
Small-signal gain coefficient (g_0)	0.15/m	
Laser gain-medium length (L)	0.1–1.0 m	
Single-pass gain ($e^{\sigma_{ul}\Delta N_{ul}L}$)	1.015–1.16	
Gas pressure	2.5 Torr	
Gas mixture	He : Ne at 5 : 1	
Index of refraction of gain medium	≈1.0	
Pumping method	electrical discharge	
Electron temperature	15,000–20,000 K	
Gas temperature	400 K	
Mode of operation	cw	
Output power	0.5–100 mW	
Mode	TEM$_{00}$	



Typical Argon Ion Laser Parameters

Laser wavelengths (λ_{ul}) most often used	488.0 nm	514.5 nm
Laser transition probability (A_{ul})	7.8×10^7/s	
Upper laser level lifetime (τ_u)	1.00×10^{-8} s	
Stimulated emission cross section (σ_{ul})	2.6×10^{-16} m^2	
Spontaneous emission linewidth and gain bandwidth, FWHM ($\Delta\nu_{ul}$)	2.7×10^9 Hz	
Inversion density (ΔN_{ul})	2×10^{15}/m^3	
Small-signal gain coefficient (g_0)	0.5/m	
Laser gain-medium length (L)	0.1–1.0 m	
Single-pass gain ($e^{\sigma_{ul}\Delta N_{ul}L}$)	1.05–1.65	
Gas pressure	0.1 Torr or less in bore region	
Index of refraction of gain medium	≈1.0	
Pumping method	electrical discharge	
Electron temperature	20,000–30,000 K	
Gas temperature	1,200°C	
Mode of operation	cw	
Output power	100 mW to 50 W	
Mode	TEM$_{00}$ or multi-mode	



Typical Helium–Cadmium Laser Parameters

Laser wavelengths (λ_{ul})	441.6 nm	353.6 nm	325.0 nm
Laser transition probability (A_{ul})	1.4×10^6/s	1.6×10^5/s	7.8×10^5/s
Upper laser level lifetime (τ_u)	7.1×10^{-7} s ($^2D_{5/2}$), 1.1×10^{-6} s ($^2D_{3/2}$)		
Stimulated emission cross section (σ_{ul})	9×10^{-18} m^2		
Spontaneous emission linewidth and gain bandwidth, FWHM ($\Delta\nu_{ul}$)	1.1×10^9/s	1.4×10^9/s	1.5×10^9/s
Inversion density (ΔN_{ul})	4×10^{16}/m^3		
Small-signal gain coefficient (g_0)	0.36/m		
Laser gain-medium length (L)	0.25–1.5 m		
Single-pass gain ($e^{\sigma_{ul}\Delta N_{ul}L}$)	1.09–1.72		
Gas pressure	5–10 Torr He		
Gas mixture	He : Cd at 100 : 1		
Index of refraction of gain medium	≈1.0		
Operating temperature	tube bore 350°C, Cd 260°C		
Pumping method	electrical discharge		
Electron temperature	15,000–20,000 K		
Gas temperature	300°C		
Mode of operation	cw		
Output power	10–200 mW		
Mode	TEM$_{00}$ or multi-mode		

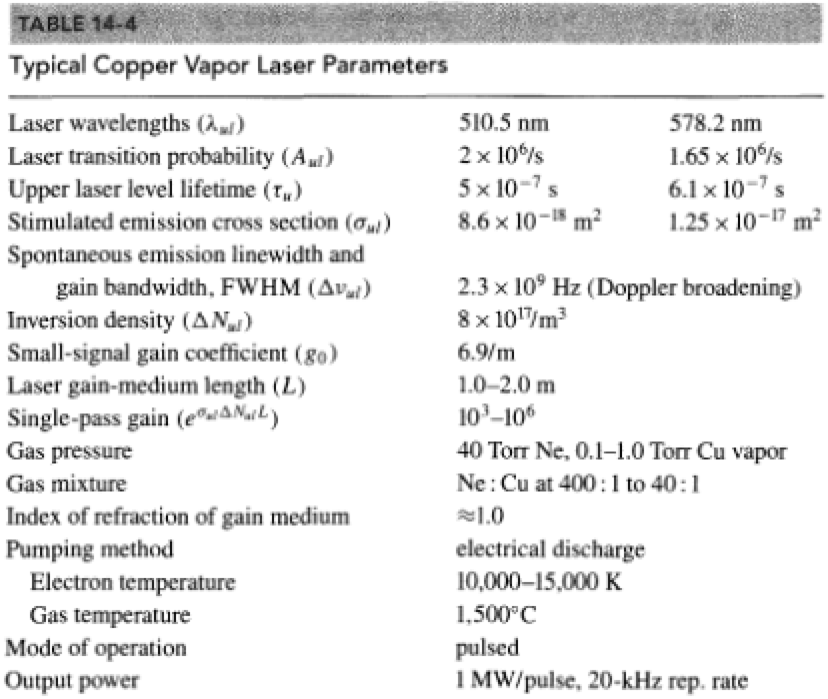
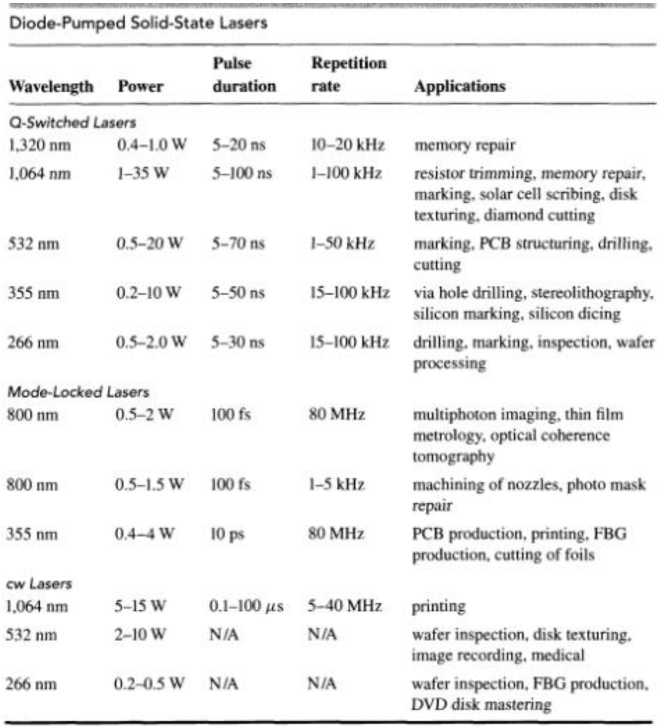


TABLE 14-4

Typical Copper Vapor Laser Parameters

Laser wavelengths (λ_{ul})	510.5 nm	578.2 nm
Laser transition probability (A_{ul})	2×10^6/s	1.65×10^6/s
Upper laser level lifetime (τ_u)	5×10^{-7} s	6.1×10^{-7} s
Stimulated emission cross section (σ_{ul})	8.6×10^{-18} m^2	1.25×10^{-17} m^2
Spontaneous emission linewidth and gain bandwidth, FWHM ($\Delta\nu_{ul}$)	2.3×10^9 Hz (Doppler broadening)	
Inversion density (ΔN_{ul})	8×10^{17}/m^3	
Small-signal gain coefficient (g_0)	6.9/m	
Laser gain-medium length (L)	1.0–2.0 m	
Single-pass gain ($e^{\sigma_{ul}\Delta N_{ul}L}$)	10^3–10^6	
Gas pressure	40 Torr Ne, 0.1–1.0 Torr Cu vapor	
Gas mixture	Ne : Cu at 400 : 1 to 40 : 1	
Index of refraction of gain medium	≈1.0	
Pumping method	electrical discharge	
Electron temperature	10,000–15,000 K	
Gas temperature	1,500°C	
Mode of operation	pulsed	
Output power	1 MW/pulse, 20-kHz rep. rate	
Mode		



Diode-Pumped Solid-State Lasers

Wavelength	Power	Pulse duration	Repetition rate	Applications
Q-Switched Lasers				
1,320 nm	0.4–1.0 W	5–20 ns	10–20 kHz	memory repair
1,064 nm	1–35 W	5–100 ns	1–100 kHz	resistor trimming, memory repair, marking, solar cell scribing, disk texturing, diamond cutting
532 nm	0.5–20 W	5–70 ns	1–50 kHz	marking, PCB structuring, drilling, cutting
355 nm	0.2–10 W	5–50 ns	15–100 kHz	via hole drilling, stereolithography, silicon marking, silicon dicing
266 nm	0.5–2.0 W	5–30 ns	15–100 kHz	drilling, marking, inspection, wafer processing
Mode-Locked Lasers				
800 nm	0.5–2 W	100 fs	80 MHz	multiphoton imaging, thin film metrology, optical coherence tomography
800 nm	0.5–1.5 W	100 fs	1–5 kHz	machining of nozzles, photo mask repair
355 nm	0.4–4 W	10 ps	80 MHz	PCB production, printing, FBG production, cutting of foils
cw Lasers				
1,064 nm	5–15 W	0.1–100 μs	5–40 MHz	printing
532 nm	2–10 W	N/A	N/A	wafer inspection, disk texturing, image recording, medical
266 nm	0.2–0.5 W	N/A	N/A	wafer inspection, FBG production, DVD disk mastering

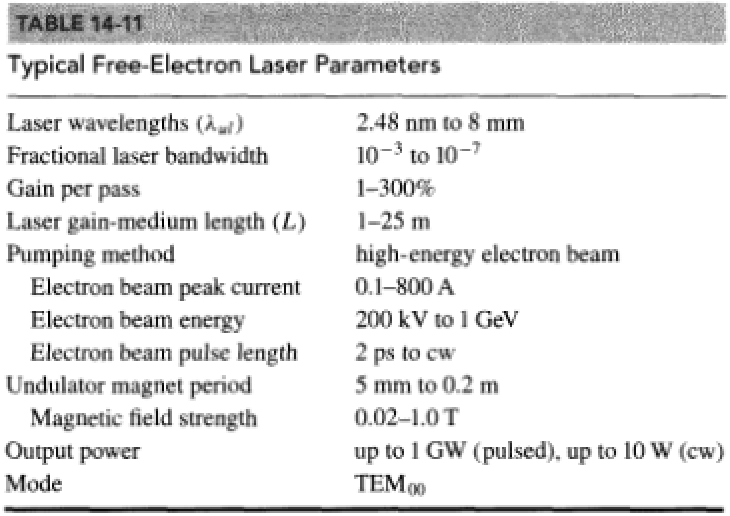


TABLE 14-11

Typical Free-Electron Laser Parameters

Laser wavelengths (λ_{ul})	2.48 nm to 8 mm
Fractional laser bandwidth	10^{-3} to 10^{-7}
Gain per pass	1–300%
Laser gain-medium length (L)	1–25 m
Pumping method	high-energy electron beam
Electron beam peak current	0.1–800 A
Electron beam energy	200 kV to 1 GeV
Electron beam pulse length	2 ps to cw
Undulator magnet period	5 mm to 0.2 m
Magnetic field strength	0.02–1.0 T
Output power	up to 1 GW (pulsed), up to 10 W (cw)
Mode	TEM$_{00}$