Laser Physics 19.

Semiconductor lasers

Maák Pál

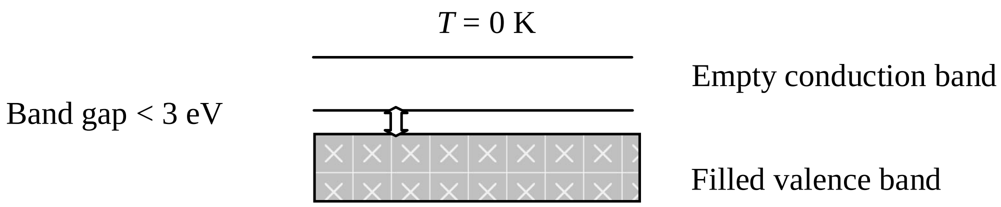
Atomic Physics Department

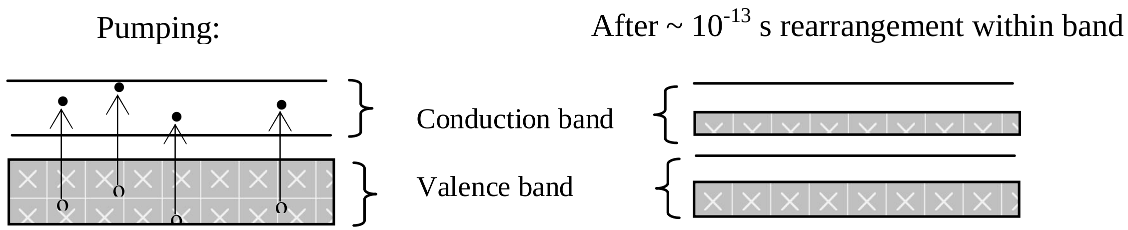
Semiconductor lasers

<u>Basic properties</u>

- Operation between conductive and valence bands of the semiconductor material
- Direct current pumping
- Efficiency typically > 30%
- Small dimensions (0.1 x 1-2 x 150-200 μm^3 volume, cross section in the range of μm^2)

<u>Semiconductor materials</u> – energy bands, charge carriers





Semiconductor lasers

Semiconductor materials – energy bands, charge carriers (cont.)

Energy of free electrons depends on $\underline{p}$:

$$E = \frac{p^2}{2m_0} = \frac{\hbar^2 k^2}{2m_0}, \quad \underline{p} = \hbar \underline{k}, \quad |\underline{k}| = \frac{2\pi}{\lambda}, \quad m_0 = 9{,}1 \cdot 10^{-31} kg$$

de Broglie wavelength

$E - k$ relation is a simple parabola!

In semiconductors electrons and holes move „freely” within the bands. Schrödinger-equation and the crystal structure determine their movements. $E - k$ is a periodic function of the $\underline{k}$ components: k_1, k_2, k_3. When a_1, a_2, a_3 are the lattice constants, the periods are π / a_1, π / a_2, π / a_3.

Close to the edges the $E - k$ function is nearly a parabola:

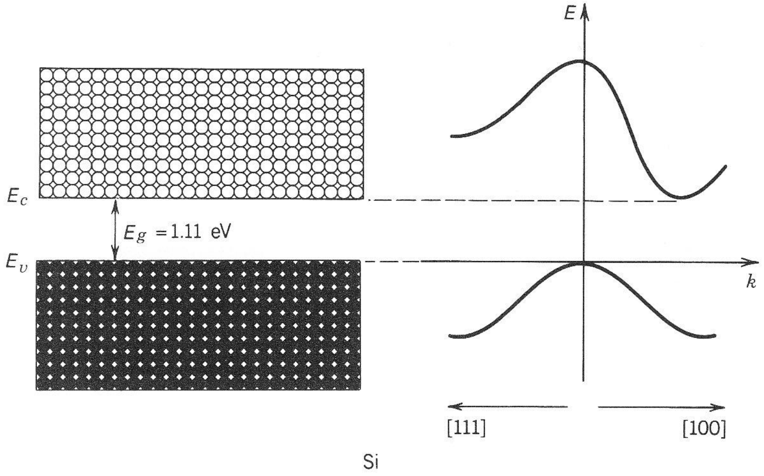
at the conduction band edge $$E = E_c + \frac{\hbar^2 k^2}{2m_c}$$

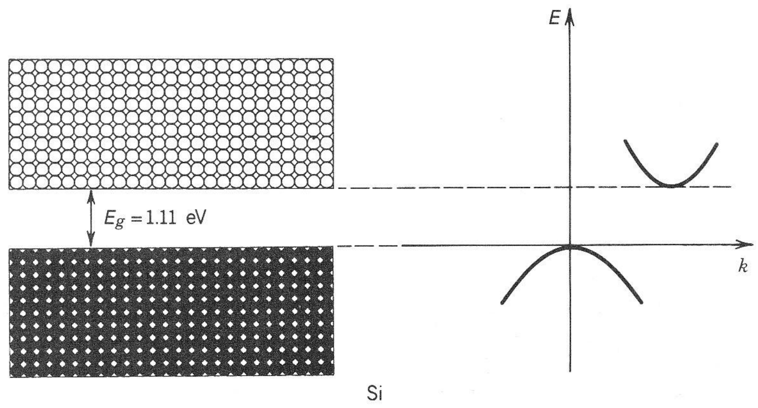
at the valence band edge $$E = E_v - \frac{\hbar^2 k^2}{2m_v}, \quad E_v = E_c - E_g$$

effective masses (c, v – conduction, valence band)

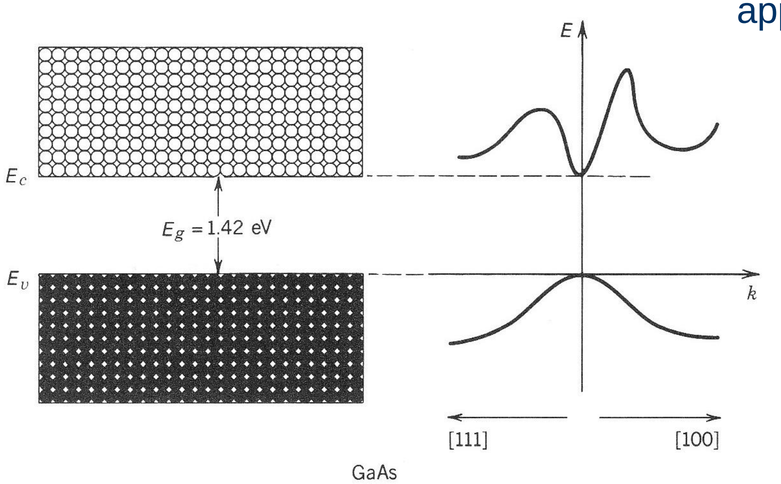
Semiconductor lasers

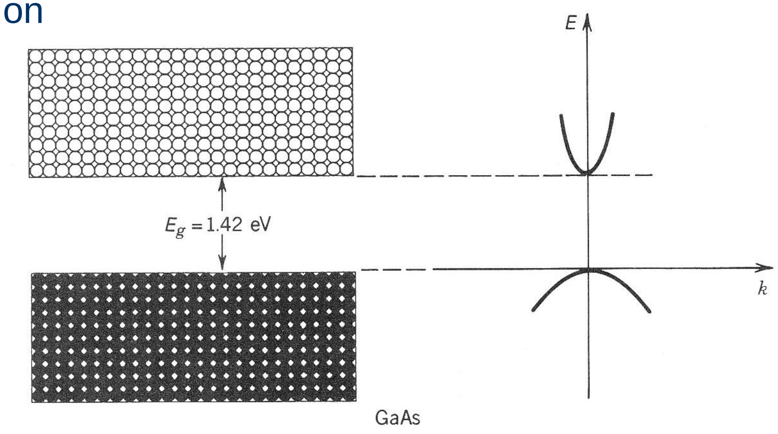
Semiconductor materials – energy bands, charge carriers (cont.)





approximation





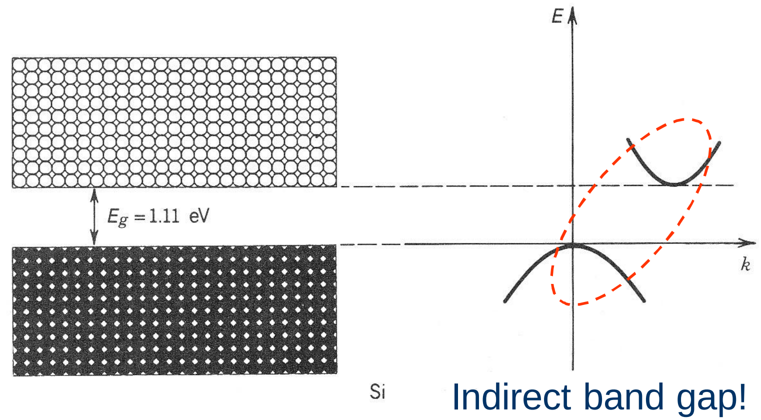
Semiconductor lasers

<u>Semiconductor materials</u> – energy bands, charge carriers (cont.)

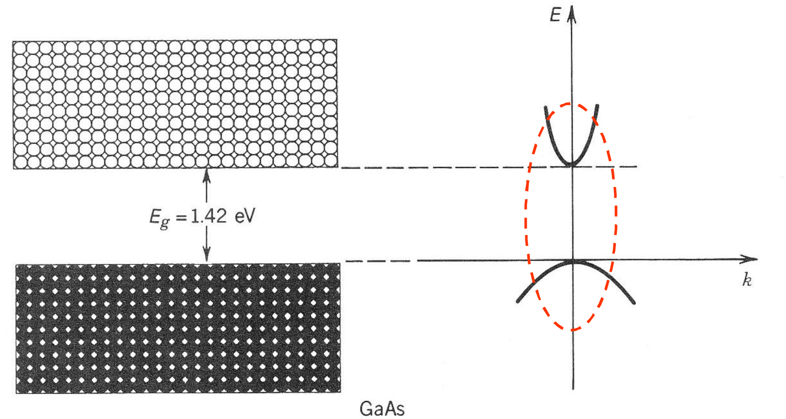
Avarage effective masses of electrons and holes		
	m_c/m_0	m_v/m_0
Si	0.33	0.5
GaAs	0.07	0.5

Basic difference between Si and GaAs considering interaction with light!

Photon momentum << electron momentum! In indirect band gap semiconductor the recombination is not possible with only a photon emission!



Indirect band gap!



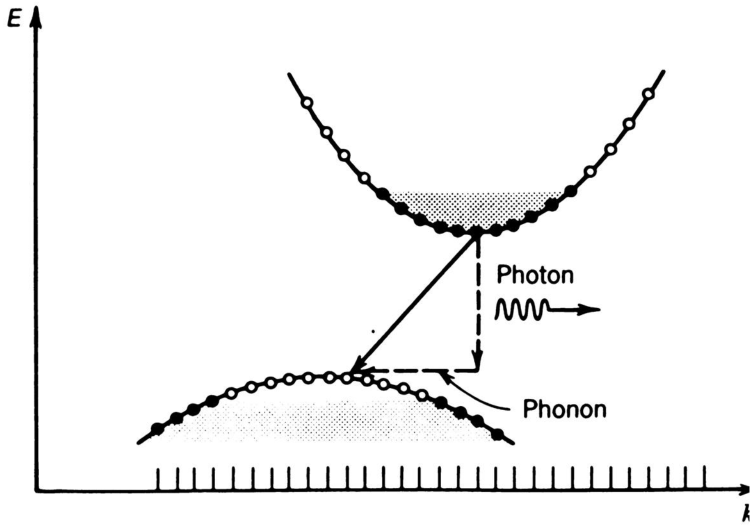
direct band gap!

Semiconductor lasers

<u>Semiconductor materials</u>

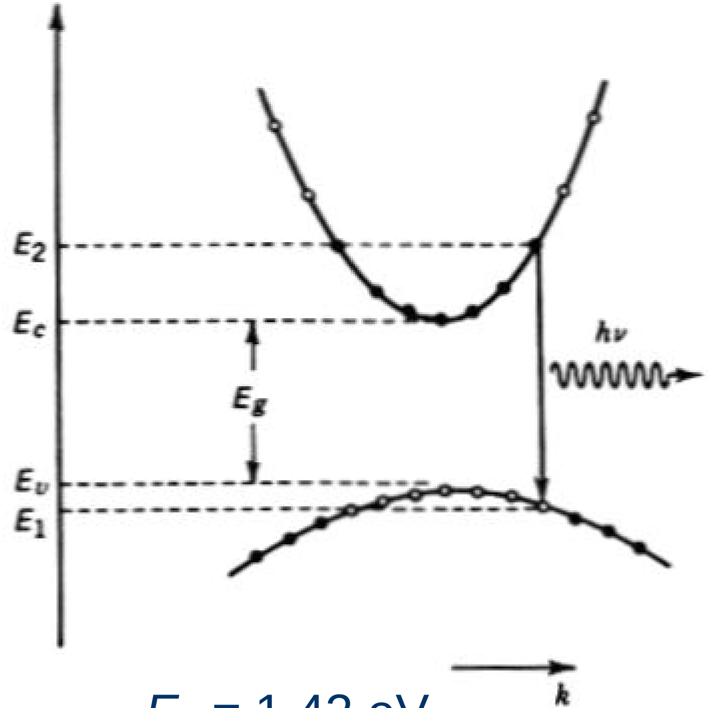
Photon emission in indirect and direct band semiconductors:

indirect transition (e.g. in Si)



Probability of transition
in silicon ~10^{-5}, E_g = 1.11 eV

direct transition (e.g. in GaAs)

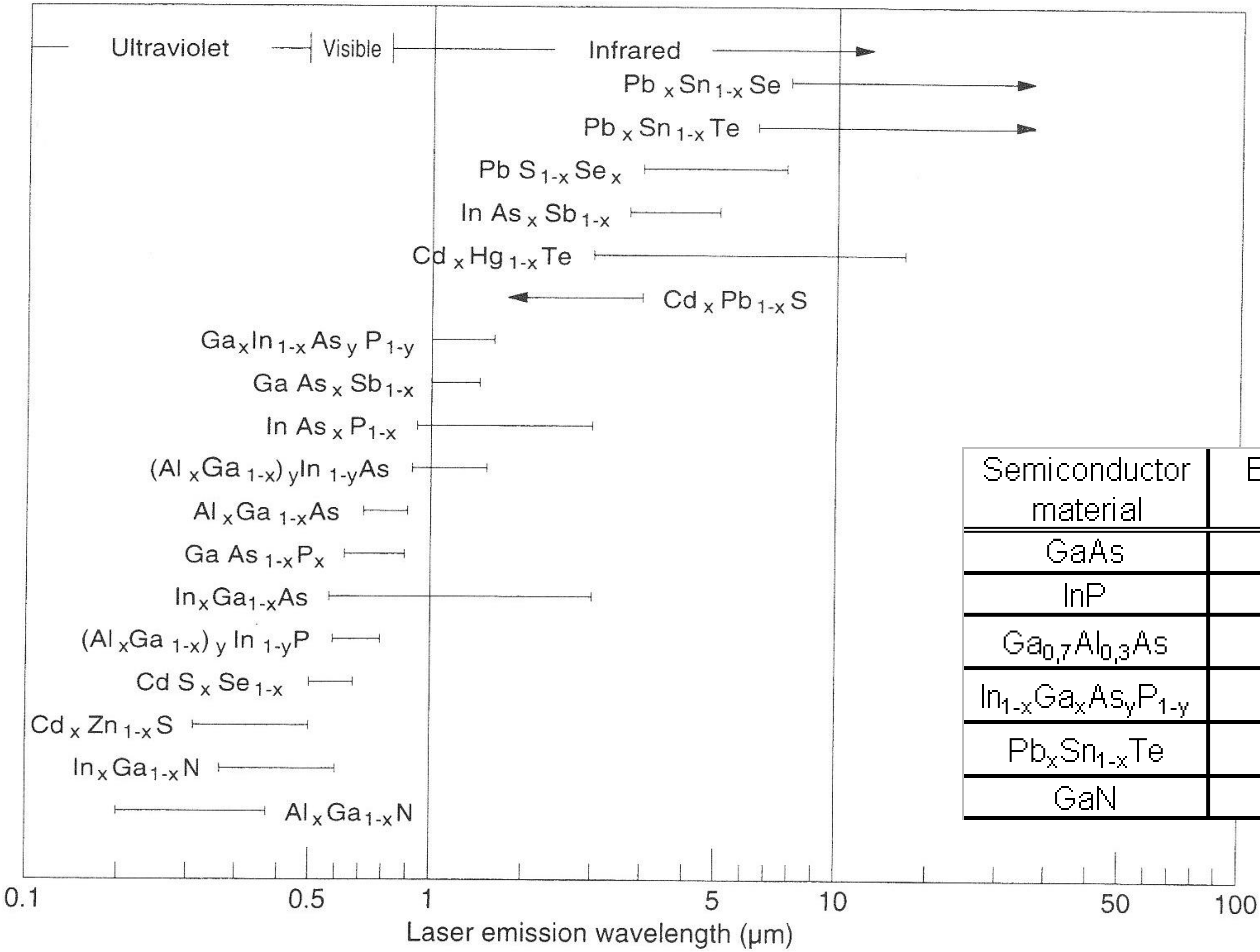


E_g = 1.42 eV

Semiconductor lasers

Materials of semiconductor lasers

Material	Bandgap (eV)	Effective mass: Electrons	Effective mass: Holes
InAs	0.36	0.023	0.40
InP	1.36	0.077	0.64
GaAs	1.43	0.067	0.48
AlAs	2.16		
GaP	2.26	0.82	
AlP	2.45		
GaN	3.39	0.19	1.4



Semiconductor material	Band gap [eV]	λ [μm]
GaAs	1.428	0.868
InP	1.351	0.918
$Ga_{0,7}Al_{0,3}As$		0.65 – 0.9
$In_{1-x}Ga_xAs_yP_{1-y}$		0.9 – 1.7
$Pb_xSn_{1-x}Te$		6.3 – 30
GaN	3.39	0.366

Semiconductor lasers

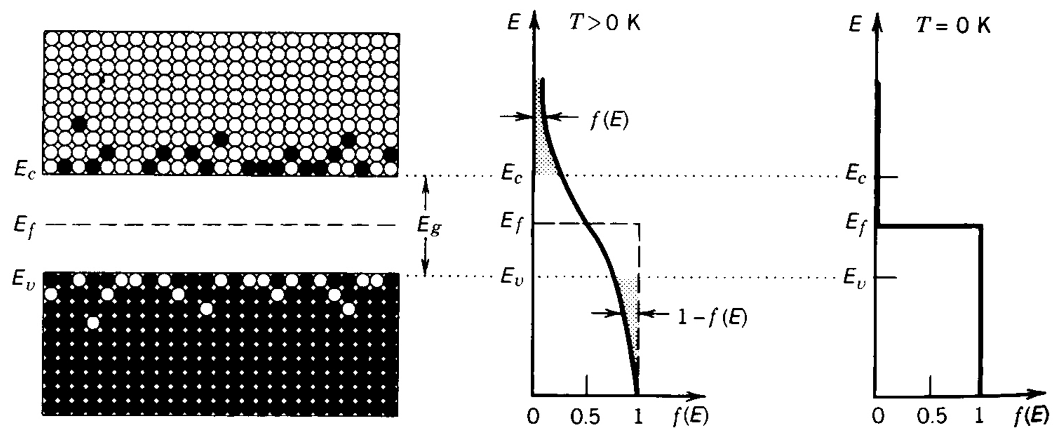
Semiconductor materials – probability of occupancy, thermal equilibrium

At T = 0 K the electrons occupy the lowest energy states (acc. Pauli exclusion principle), the valence band is completely filled, the conduction band is completely empty. With increasing T, electrons $\rightarrow$ to the conduction band, leaving empty states (holes) in the valence band.

The probability that E state is filled (Fermi function):

$$f(E) = \frac{1}{exp[(E - E_f)/k_B T] + 1},$$

The probability that E is empty: $1 - f(E)$

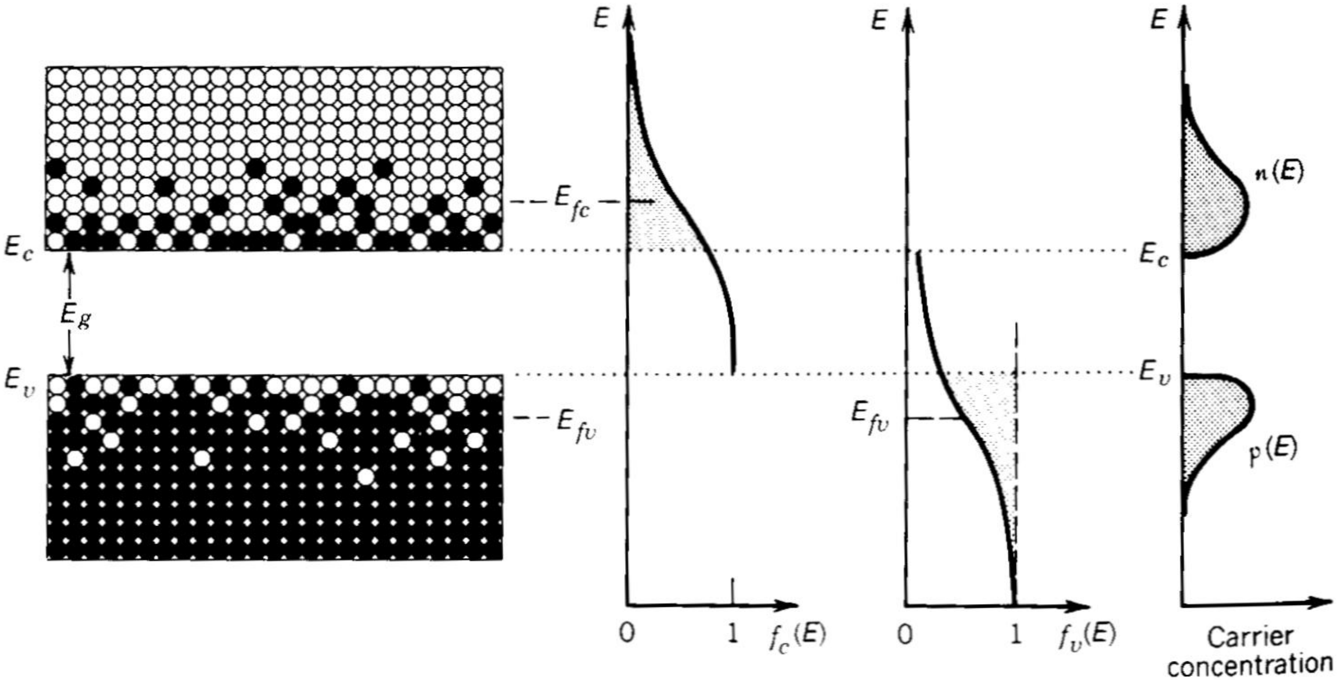


E_f is the Fermi energy, at T = 0 K is the limit of filled and unfilled levels. At any other temperature the probability of occupancy at the Fermi energy is $f(E_f)$ = ½. In semiconductors without doping the Fermi energy is approximately in the middle of the band gap in thermal equilibrium.

Semiconductor lasers

Quasi-equilibrium carrier concentrations

An external electric current or photon-flux density causes band-to-band transitions, and then quasi-equilibrium evolves in both the conduction and valence band due to interband transitions, the intraband relaxation time is ~10^{-13} s (the radiative electron-hole recombination time is 10^{-9} s). Two separate Fermi levels can be used for each band: E_{fc} és E_{fv}.



Semiconductor lasers

Absorption, emission, and gain condition

Excited direct band semiconductor in quasi-equilibrium with two Fermi level. $E_2 - E_1 = h\nu$ is the transition, where E_2 and E_1 are in the conduction and valence band, resp.

Emission condition: E_2 is filled, E_1 is empty

Absorption condition: E_2 is empty, E_1 is filled

$$f_e(\nu) = f_c(E_2)[1 - f_v(E_1)]$$

$$f_a(\nu) = [1 - f_c(E_2)] f_v(E_1)$$

The emission will be dominant, if

$$f_e(\nu) - f_a(\nu) > 0$$

$$f_c(E_2)[1 - f_v(E_1)] - [1 - f_c(E_2)] f_v(E_1) = f_c(E_2) - f_v(E_1) > 0$$

$$\frac{1}{exp[(E_2 - E_{fc})/k_B T] + 1} > \frac{1}{exp[(E_1 - E_{fv})/k_B T] + 1}$$

$$E_1 - E_{fv} > E_2 - E_{fc}$$

$$E_2 - E_1 < E_{fc} - E_{fv}$$

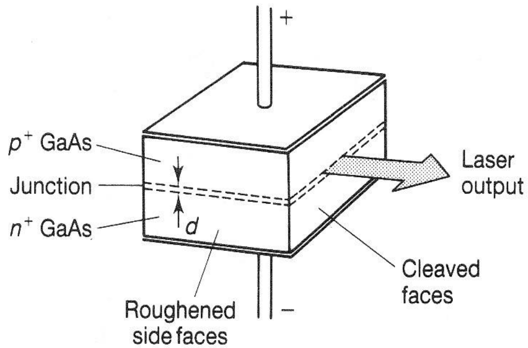
$$\boxed{E_g < h\nu < E_{fc} - E_{fv}}$$

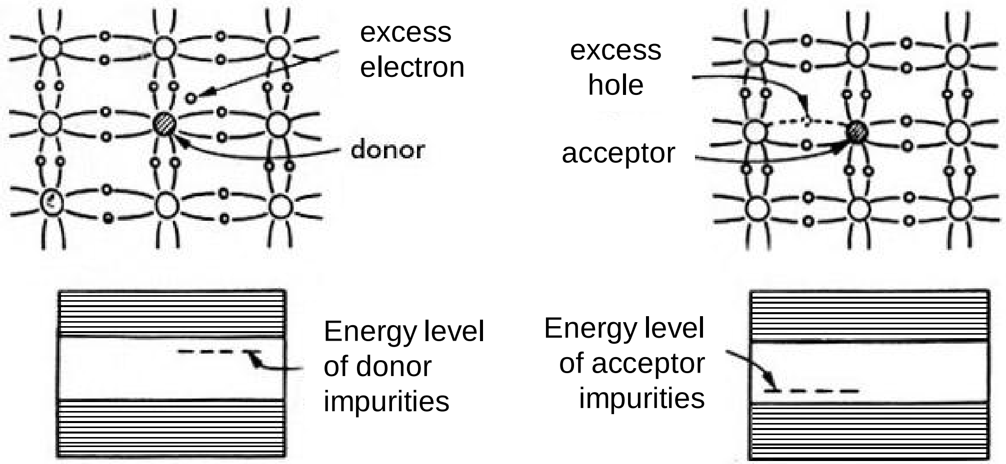
$\leftarrow$ **gain condition**.

Semiconductor lasers

<u>Pumping</u> – <u>*p* - *n* junction in forward bias</u>

First semiconductor laser (1962) was a homojunction GaAs laser, operated at T = 77 K. Homojunction – same basic material with two different dopings (*p* and *n*)





Donor and acceptor concentration ~10^{18} atoms/cm^3

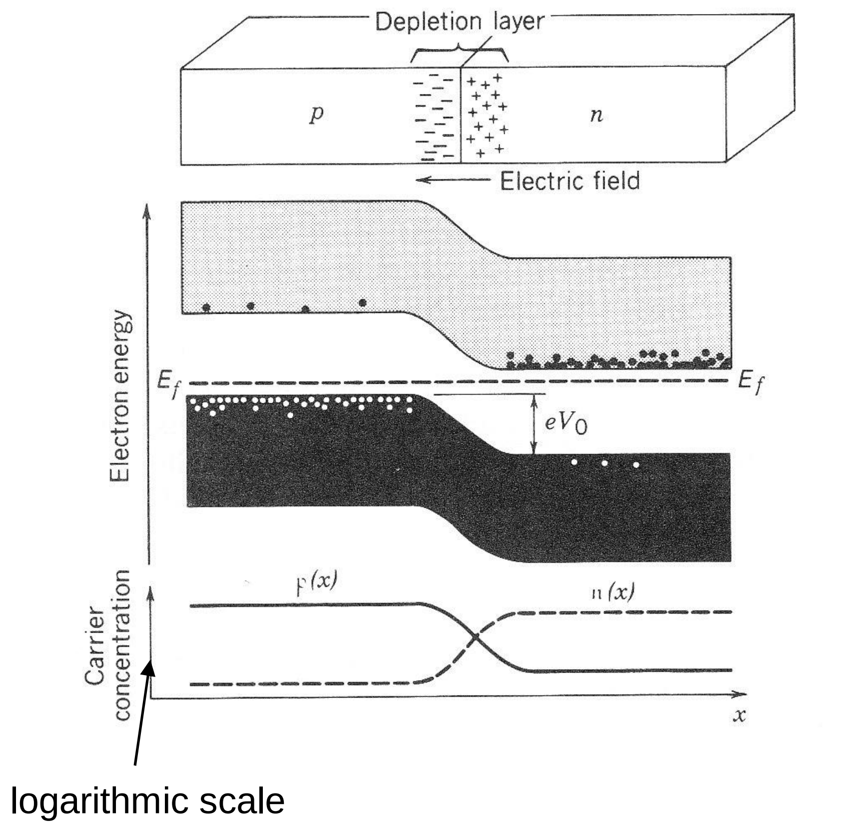
Semiconductor lasers

p - n junction in contact without bias

In thermal equilibrium at $T > 0$ K

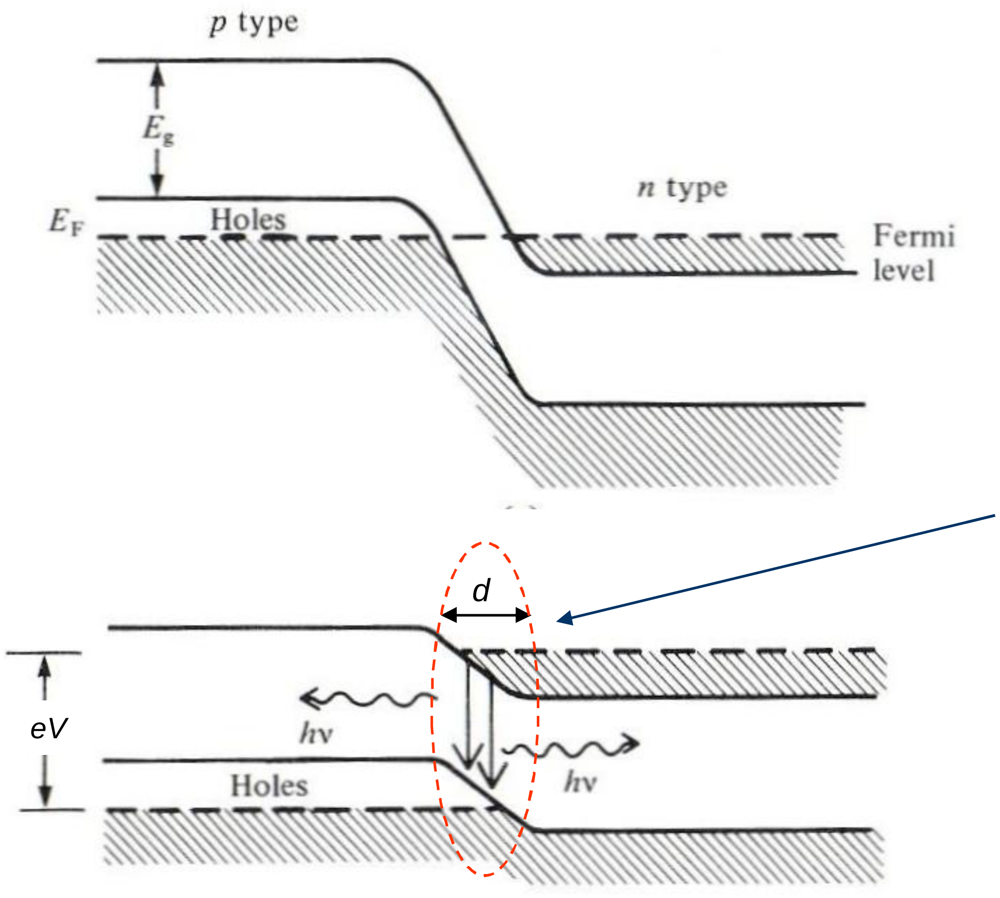
Electrons and holes diffuse from high to low concentration areas, resp. Electrons diffuse away from the *n*-region into the *p*-region leaving behind positively charged ionized donor atoms, in the p-region they recombine. Holes vice versa. → Depleted region of ~ 0.1 µm thick containing fixed charges and a built-in potential difference V_0 that obstruct the diffusion.

Single Fermi function for the entire structure, no net current flows across the junction.



Semiconductor lasers

Forward biased *p* – *n* junction (homojunction)



thickness of the junction region *d* >> depleted region

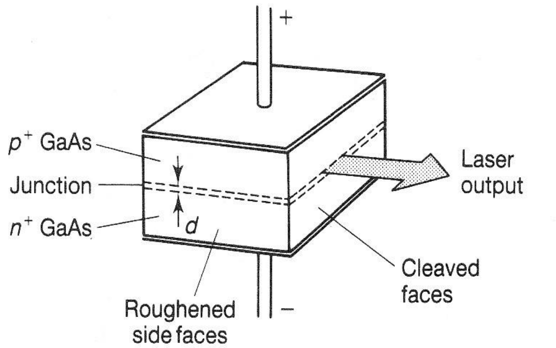
The + voltage applied to the *p*-region compensates the field charges and begins the flow of electrons (holes) toward the depleted region. The Fermi levels separate under bias voltage of *V* ($eV \sim E_g$) and population inversion evolves. For appropriate value of the current density the gain condition can be achieved.

Problem: diffusion of electrons (and holes) to the *p* (and *n*) region!

Semiconductor lasers

Forward biased $p - n$ junction (homojunction, cont.)

The thickness of the junction region *(d)* can be determined by the diffusion theory: $d = \sqrt{D\tau}$
D is the diffusion coefficient, τ is the electron lifetime (electron-hole recombination time). In GaAs D = 10 cm^2/s and $\tau \approx$ 3 ns, d ~ 1 – 2 µm, much larger than the width of the depleted layer (~ 0.1 µm).



Cheap laser diode: the resonator mirrors are the cleaved end faces of the semiconductor crystal:

n_{GaAs}= 3.6

$$R_{\perp} = \left(\frac{n-1}{n+1}\right)^2 = \left(\frac{2.6}{4.6}\right)^2 = 0.32$$

Limitations:

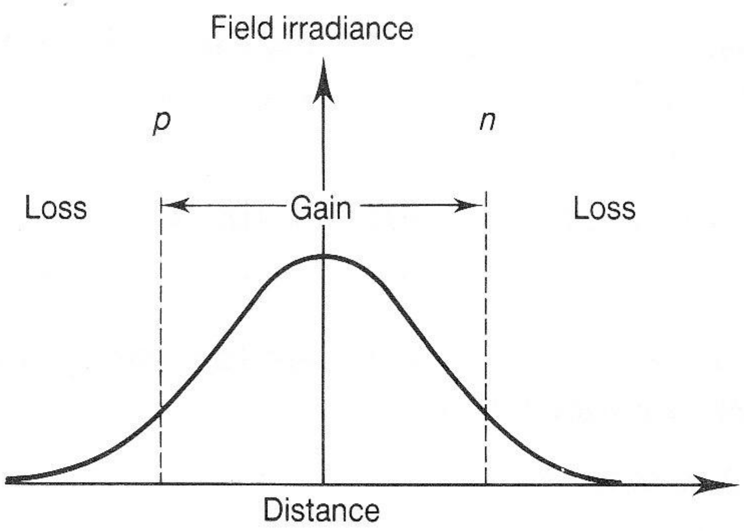
1. Because of the large active volume, high operation current is needed, the threshold current density J_{th} ~ 10^5 A/cm^2 (T_{room}), therefore cw operation at cryogenic temperature (T = 77 K, liquid N_2).

Semiconductor lasers

Forward biased *p – n* junction (homojunction, cont.)

Limitations (cont.):

2. Because of the diffraction the beam width is much larger than *d* (~ 5 µm) → significant absorption loss in the *p* and *n* regions (only small confinement of the beam: the refraction index of the junction region is larger with 0.1 – 1% because of the excess electrons)

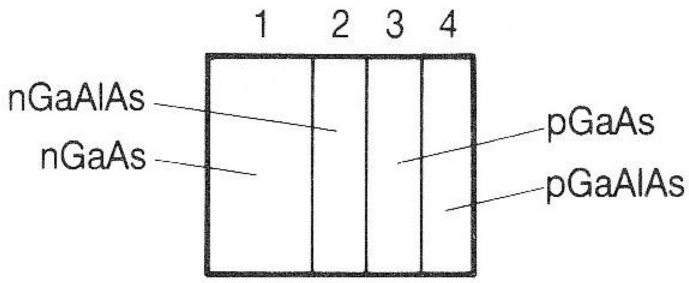


Semiconductor lasers

Heterojunction lasers (from 1970)

Goal: to decrease the losses due to diffusion of the carriers and due to the light absorption. Carrier and light confinement with multiple layers of different band gap and refractive index.

Double-heterostructure (DH) laser: layers (a), energy bands (b)

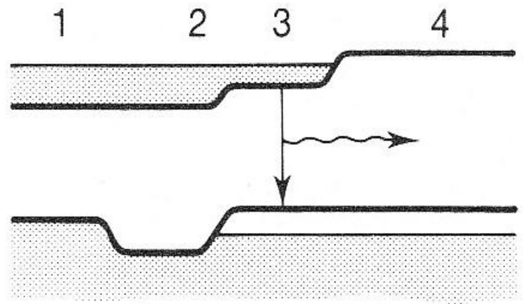


(a)

E.g.: 2. cladding layer n-$Al_{0.3}Ga_{0.7}As$
4. cladding layer p-$Al_{0.3}Ga_{0.7}As$

$n_3 = 3.6$; $n_2 = n_4 = 3.4$

$\Delta n \sim 6\%$



Energy bands with high forward bias

(b)

$E_{g3} \sim 1.5$ eV, $E_{g2} = E_{g4} \sim 1.8$ eV

Potential barrier around layer 3!

Semiconductor lasers

Double-heterostructure (DH) laser (cont.)

Advantages of DH laser:

1. width of the active layer is determined by the layer structure and not by the diffusion $\rightarrow$ 0.1 – 0.2 μm is feasible
2. the absorption loss decreases because of the waveguiding effect and the different band energies of the surrounding layers

Result: threshold current decreases $\rightarrow$ cw at T_{room} is feasible

Preparation of DH layers - requirement:

the lattice period of the active layer must equal (within ~ 0.1%) that of the cladding layer. Otherwise dislocations form $\rightarrow$ nonradiative recombination that causes loss and increases the threshold current density!!!
(atomic radii of Ga and Al are almost the same)

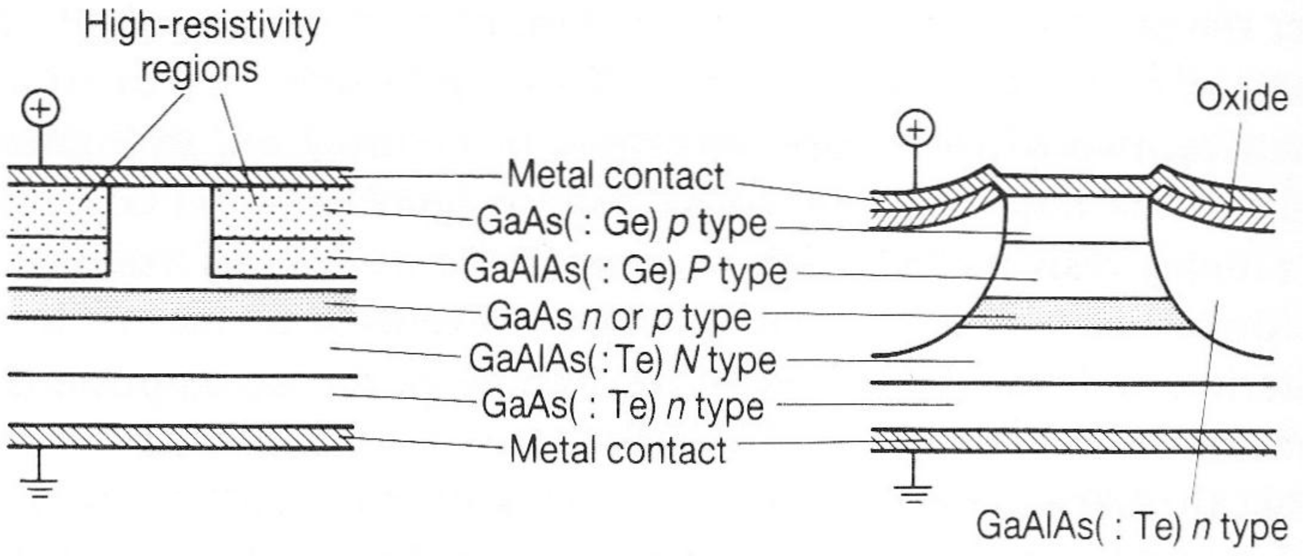
Semiconductor lasers

<u>Gain guided and index guided lasers</u>

The threshold current decreases when the active region is surrounded from four directions with different type layers – buried heterostructure laser. Lateral confinement of both the current and photon flux. New layer type is the insulator. Typical width is 1 – 2 µm.

Two types:

1. gain guided – carrier concentration with different band gap and insulator layers

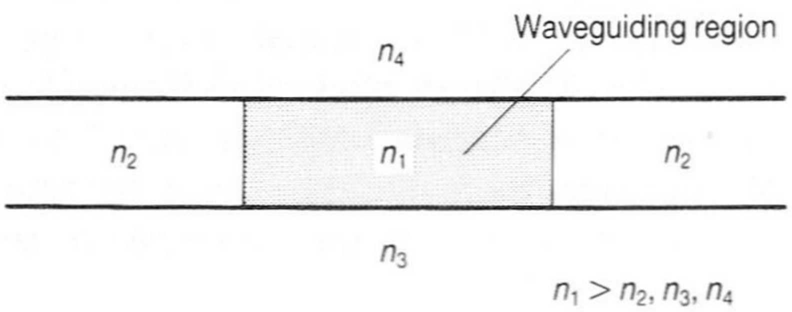


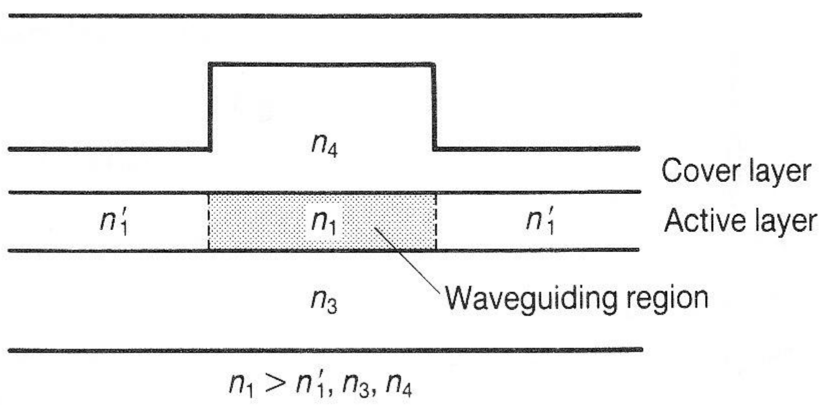
Semiconductor lasers

Gain guided and index guided lasers (cont.)

Two types (cont.):

2. index guided – optical waveguide is created with the buried high refractive index active layer, light concentration

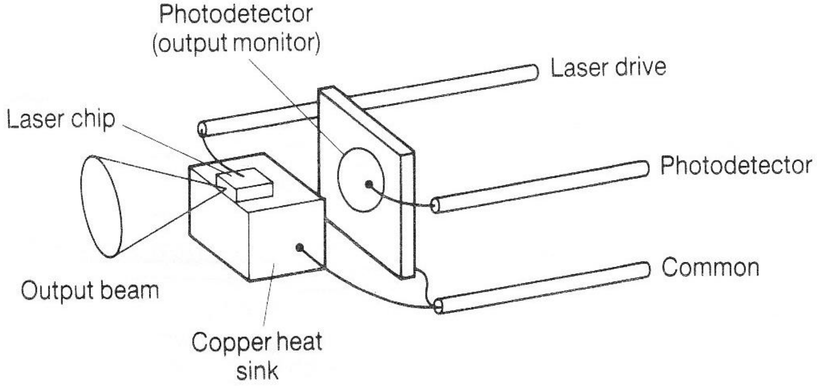


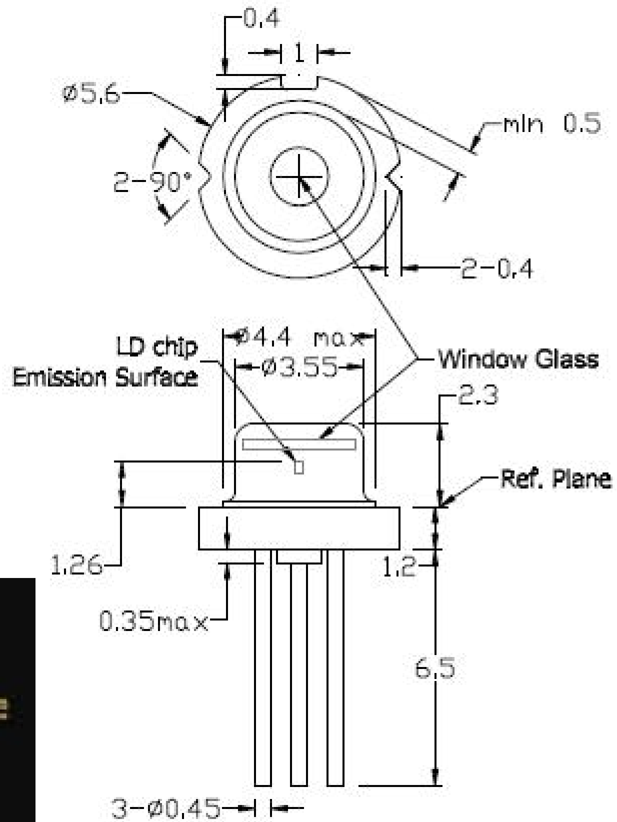


Semiconductor lasers

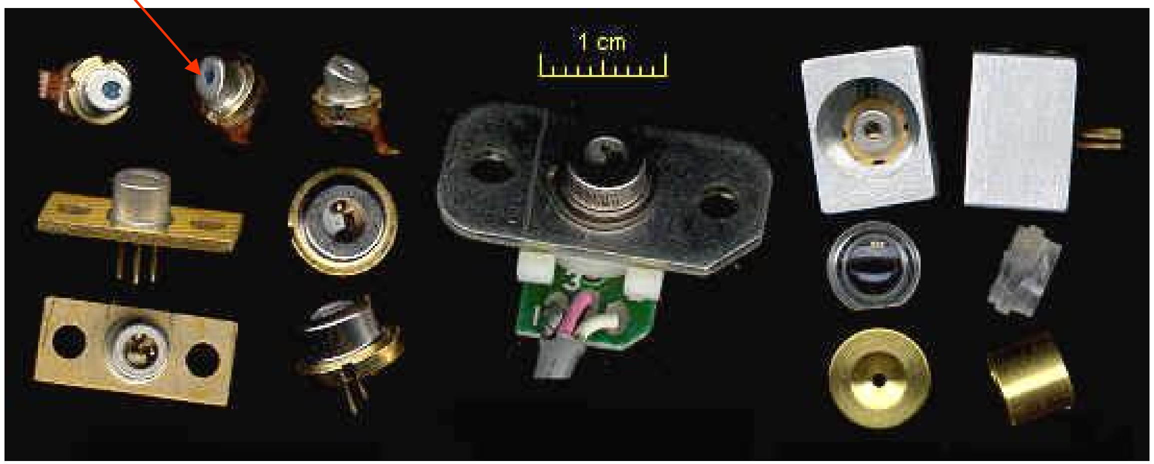
Laser diode packaging

built-in photodiode



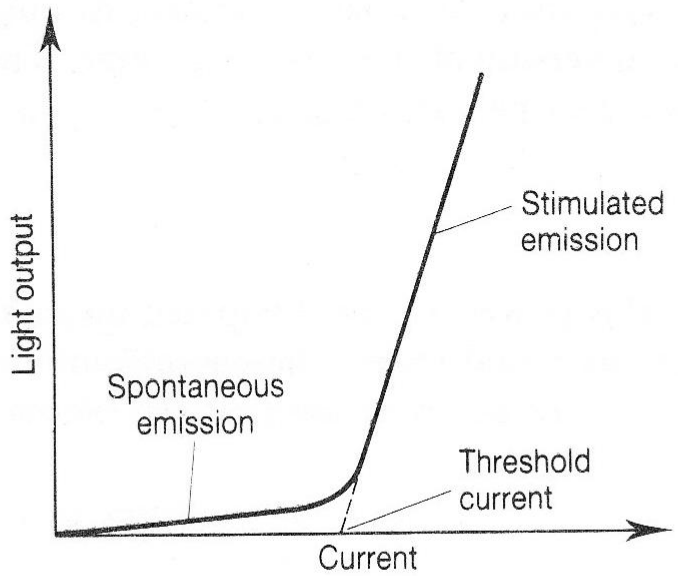


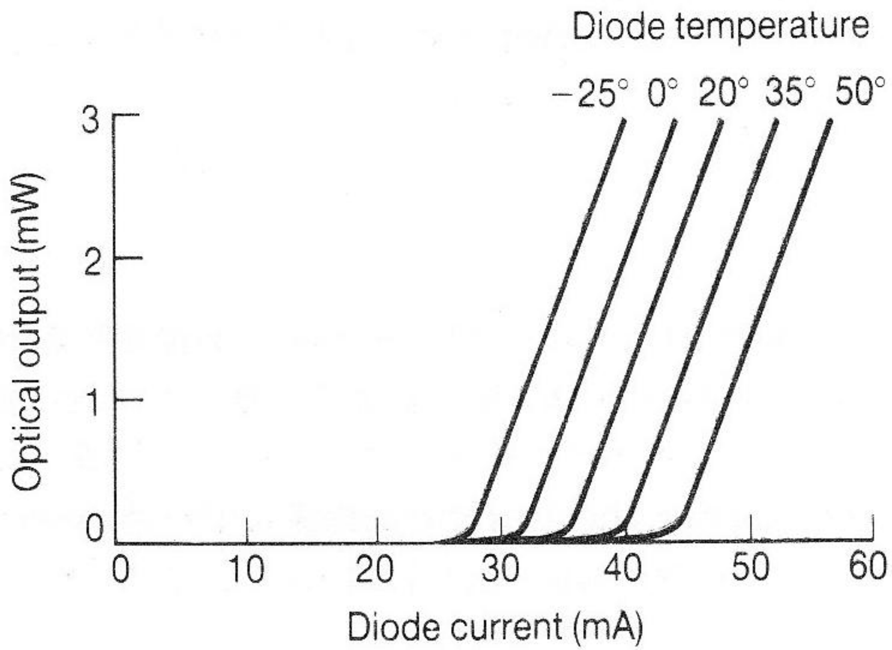
Brewster- window



Semiconductor lasers

Properties of laser diodes: **light output – current characteristics**

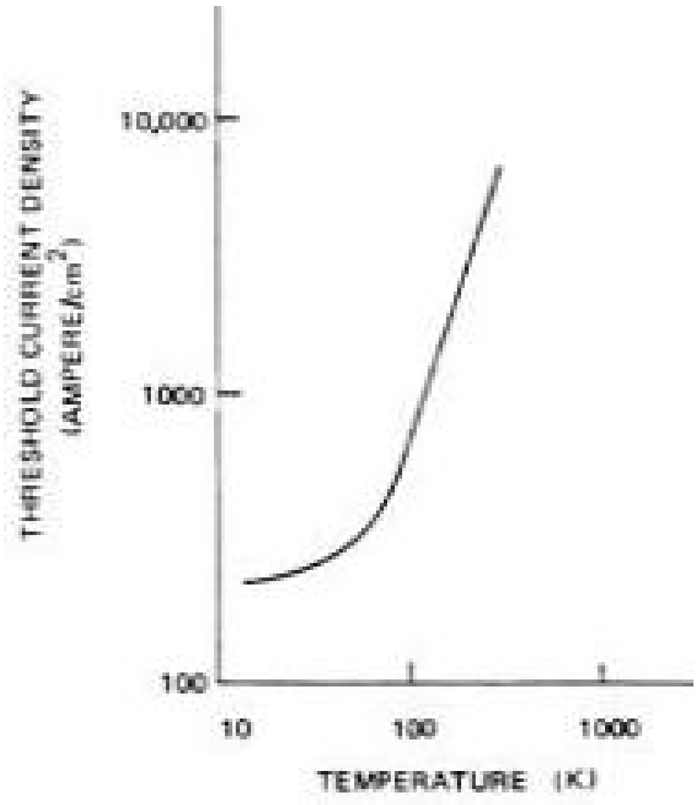


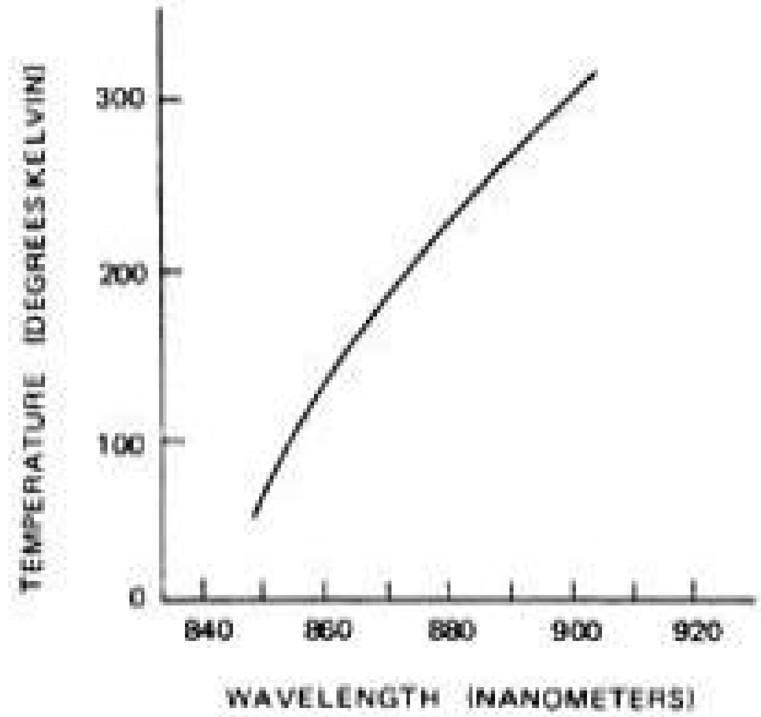


Temperature dependent characteristics of a GaAlAs laser diode

Semiconductor lasers

Properties of laser diodes: **temperature dependent threshold current density and wavelength**





Semiconductor lasers

Properties of laser diodes: **spectral output**

Wavelength difference between consecutive longitudinal modes: $\Delta\lambda_m$, if L is the length of the resonator, $n(\lambda)$ is the refractive index of the material:

$$L = q\frac{\lambda_q}{2n(\lambda_q)} \quad \rightarrow \quad q\cdot\lambda_q = 2n(\lambda_q)L \qquad q = 1, 2, 3, \dots \text{ integer}$$

Since q is very large we may regard it as a continuous variable, a change in q (Δq) is related to the change in λ ($\Delta\lambda$):

$$\frac{\Delta q}{\Delta\lambda} \cong \frac{d}{d\lambda}\left(\frac{2n(\lambda)L}{\lambda}\right) = 2L\left[\frac{1}{\lambda}\frac{d\,n(\lambda)}{d\lambda} - \frac{n(\lambda)}{\lambda^2}\right] = -\frac{2L}{\lambda^2}\left(n(\lambda) - \lambda\frac{d\,n(\lambda)}{d\lambda}\right)$$

$$\Delta\lambda = -\frac{\Delta q}{2L}\frac{\lambda^2}{n(\lambda) - \lambda(d\,n(\lambda)/d\lambda)}$$

$\Delta\lambda_m$ ($|\Delta\lambda|$ when $\Delta q = 1$):

$$\Delta\lambda_m = \frac{\lambda^2}{2L}\frac{1}{n(\lambda) - \lambda(d\,n(\lambda)/d\lambda)} = \frac{\lambda^2}{2n_{eff}L}, \quad n_{eff} = n(\lambda) - \lambda\frac{d\,n(\lambda)}{d\lambda}$$

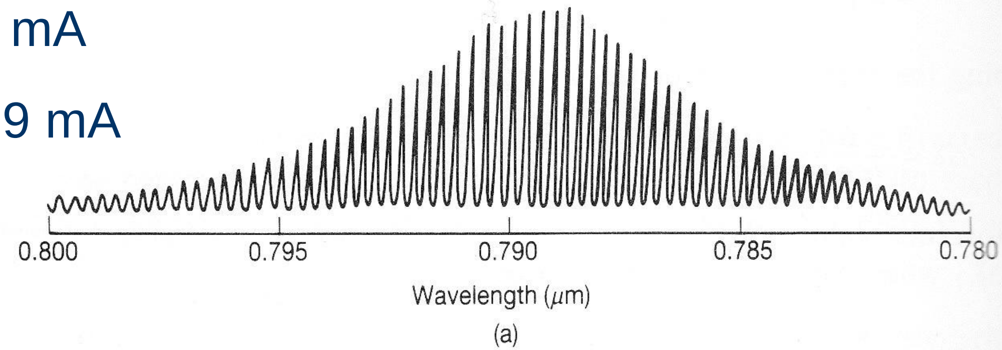
n_{eff} is much larger than n in the semiconductors!

Semiconductor lasers

<u>Properties of laser diodes</u>: **spectral output** (cont.)

(a) below threshold (LED, I=35 mA

(b) above threshold (laser), I=39 mA

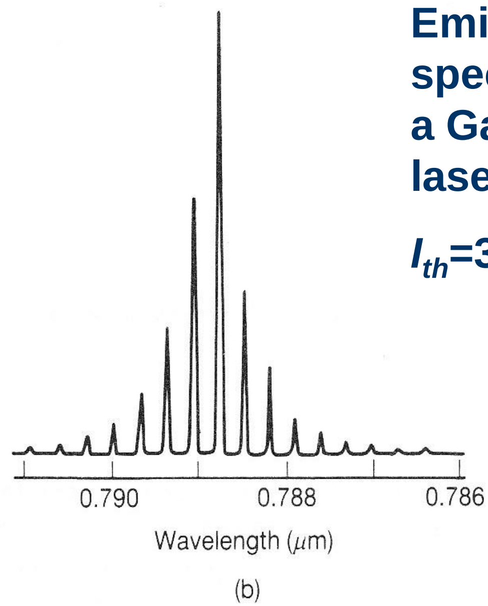


Typical spectral width of a GaAs LED is 30 nm, therefore below threshold ~ 100 longitudinal modes oscillate.

Above threshold much less modes in $\Delta\lambda_m$ distance.

When n_{eff} (GaAs, λ=0.85 µm) ~ 4

$$\Delta\lambda_m = \frac{\lambda^2}{2 n_{eff} L} = \frac{(0.85\cdot 10^{-6})^2}{2\cdot 4\cdot 300\cdot 10^{-6}} = 0.3\,nm$$



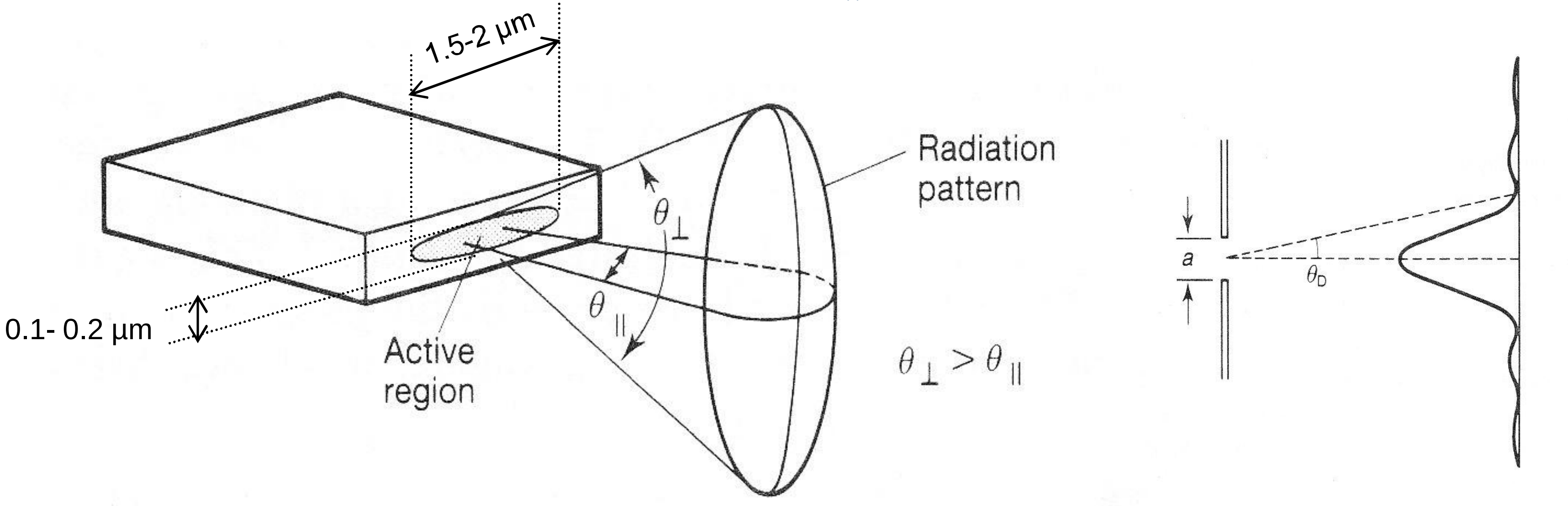
Emission spectrum of a GaAlAs laser

$\boldsymbol{I_{th}}$**=37 mA**

Semiconductor lasers

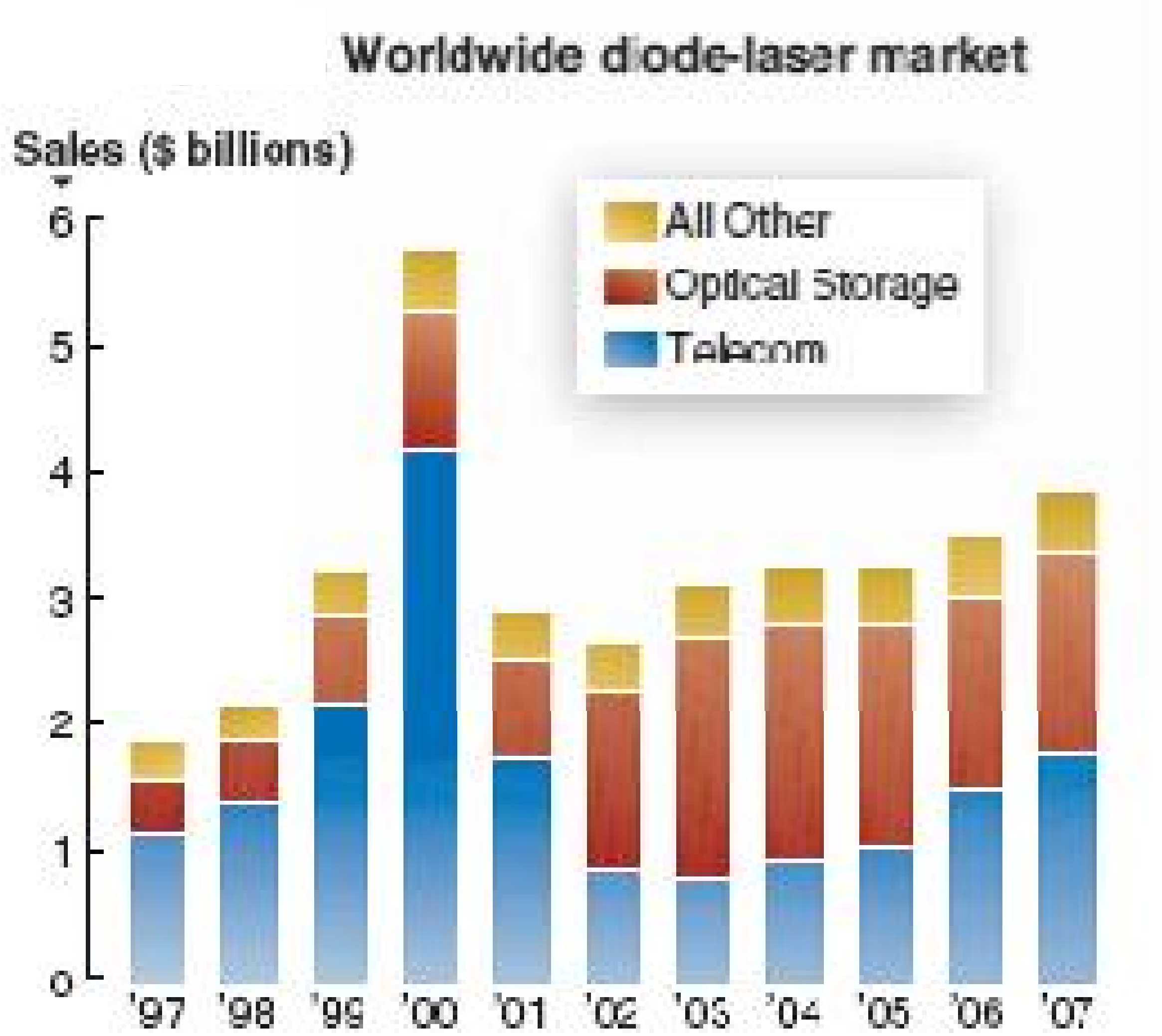
Properties of laser diodes: **divergence**

The output beam diverges largely because of the small asymmetric emitting area (comparable in size with the wavelength), the divergence angles differ in the direction parallel ($\theta_{//}$) and perpendicular ($\theta_{\perp}$) to the junction plane - elliptical Gaussian beam. $\theta_{\perp}$ ~ 20 - 30°, $\theta_{//}$ ~ 5 - 10° for cheap lasers.



The beams in these two orthogonal directions originate from different point on the axis of the laser, property known as astigmatism. The astigmatism of index-guided lasers is much lower.

Semiconductor lasers - applications



Source: Laser Focus World February 2008

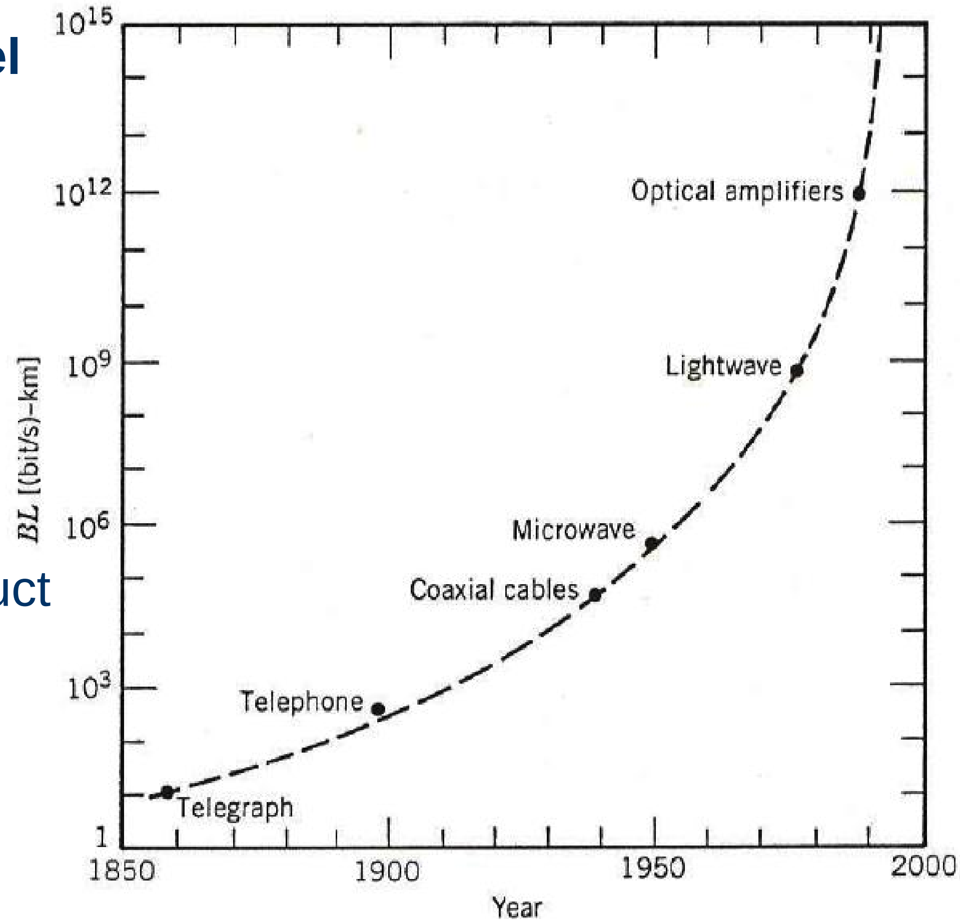
Semiconductor lasers – applications

1. Optical communication

Need for Fiber Optical Communication

Idea: Charles K. Kao in 1965, Nobel Prize in 2009!

A figure of merit of communication systems is the bit rate – distance product, *BL*, where *B* is the bit rate and *L* is the repeater spacing.



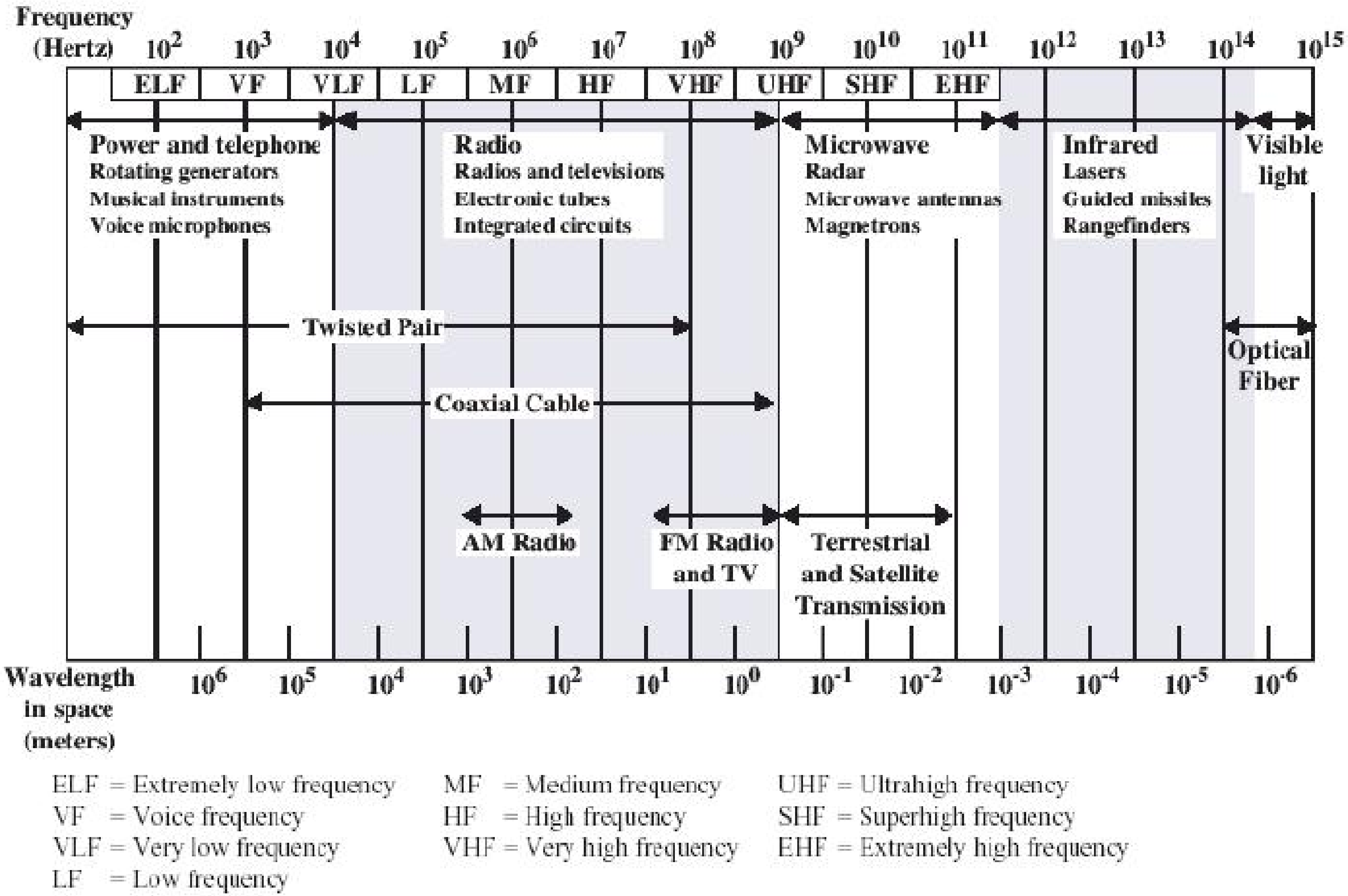
Increase of the bit rate distance product *BL* for different communication technologies over time.

High speed coaxial systems need repeater spacing of ~1km.

Ref.: G. P. Agrawal, Fiber-Optic Communication systems

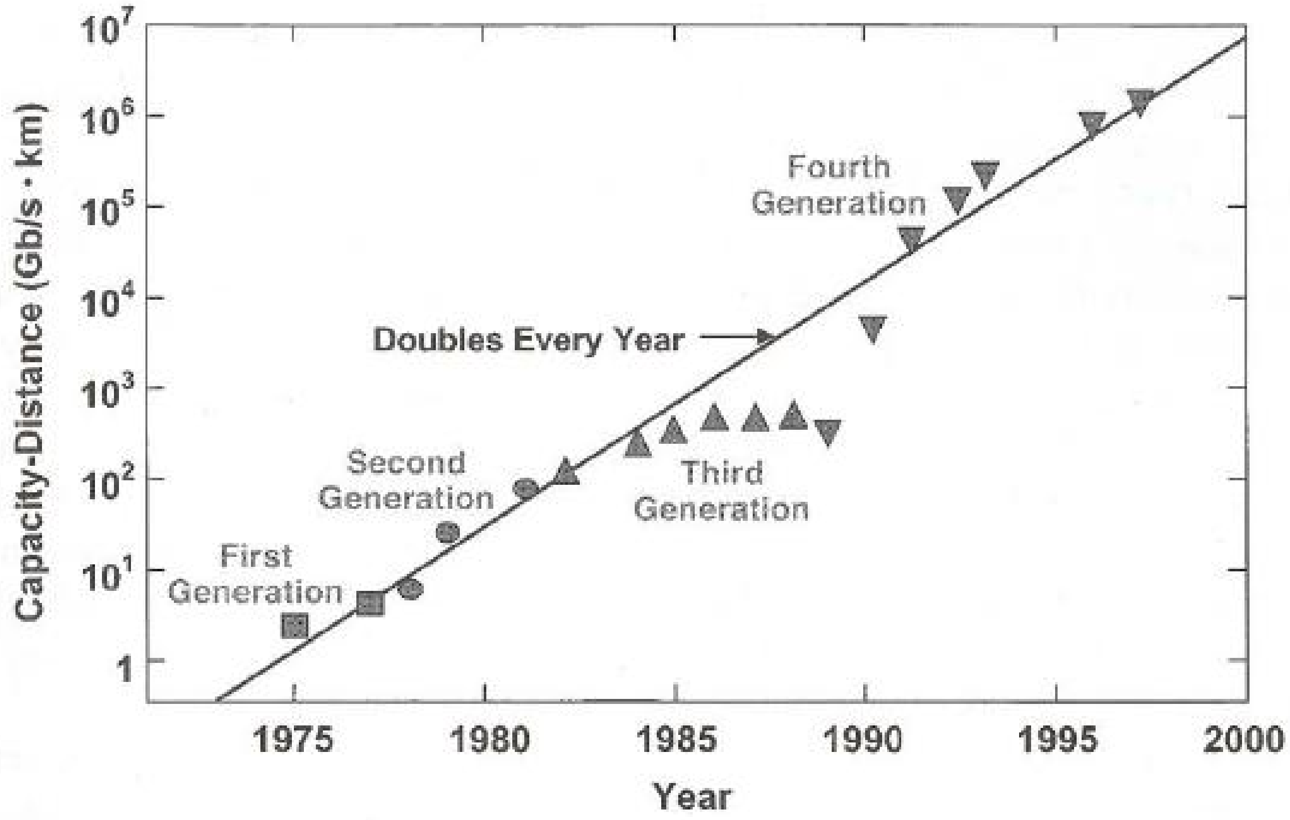
Semiconductor lasers – applications

1. Optical communication



Semiconductor lasers – applications

1. Optical communication



Bit-rate distance product (BL) for different generations of optical communication systems.

1. Generation:
λ **= 0.8 µm**

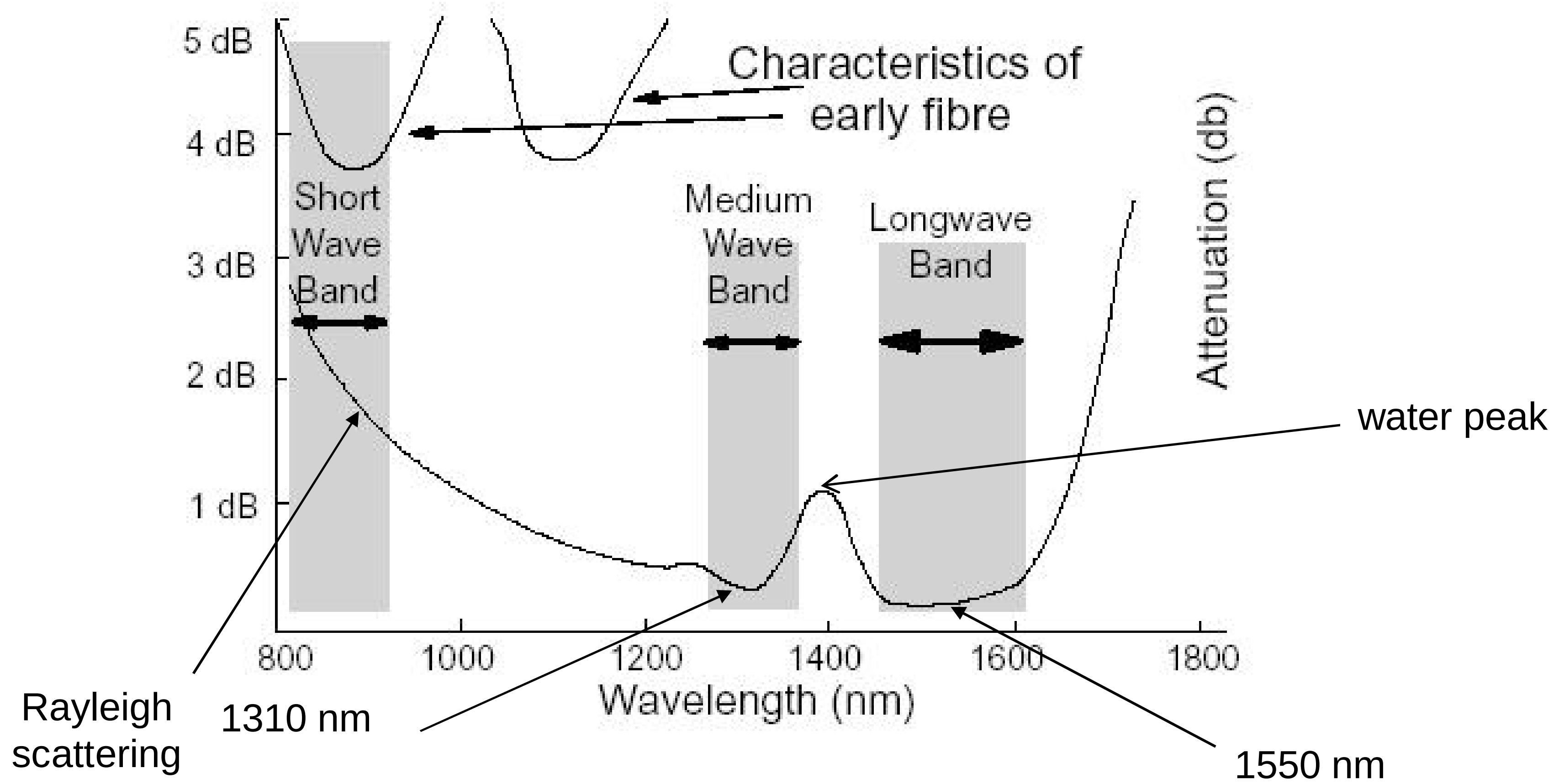
2. Generation:
λ **= 1.3 µm**
single mode fiber

3. Generation:
λ **= 1.55 µm**

Semiconductor lasers – applications

1. Optical communication

Attenuation of a single mode fiber per kilometer

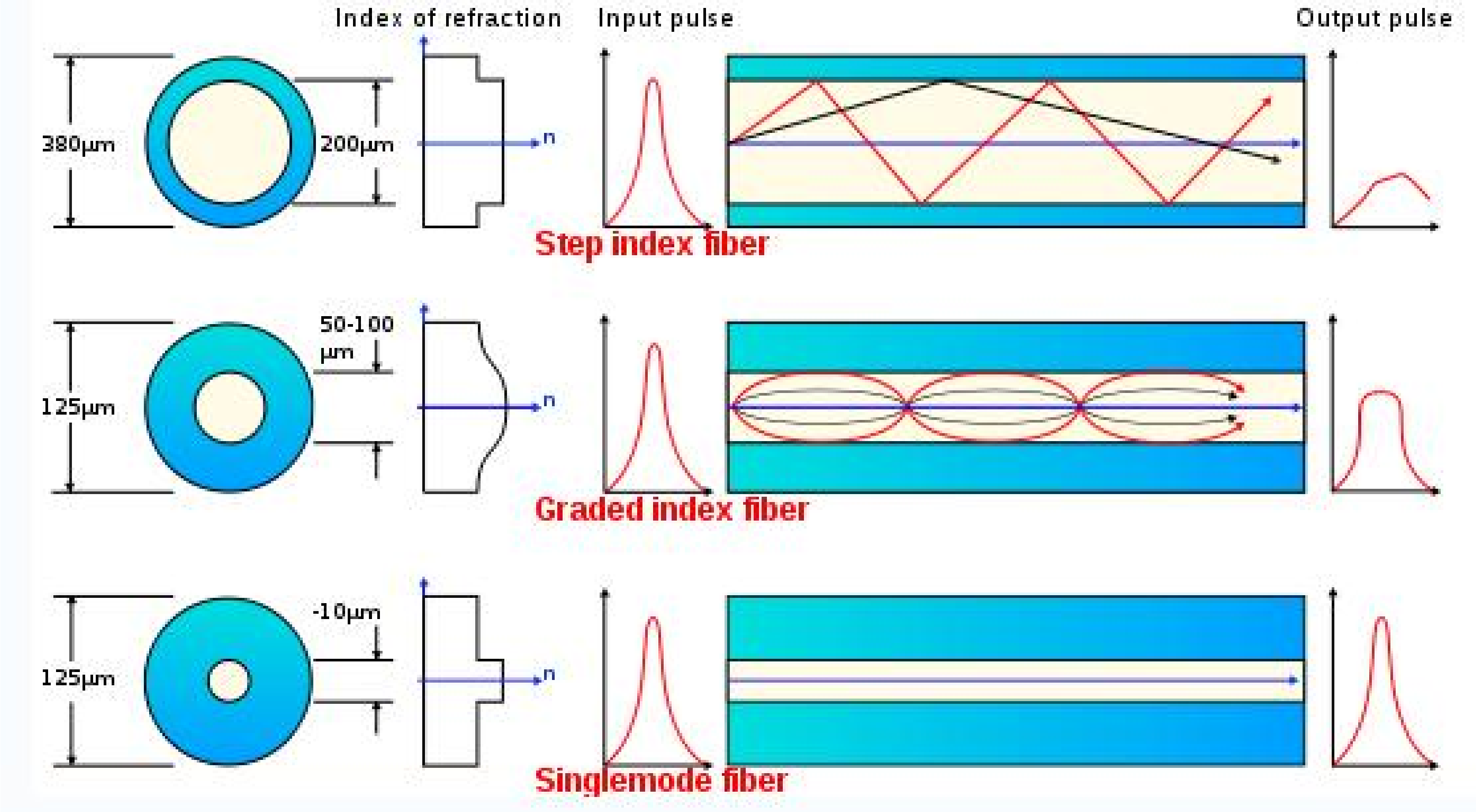


Low loss „windows” of glass fibers

Semiconductor lasers – applications

1. Optical communication

Fiber types



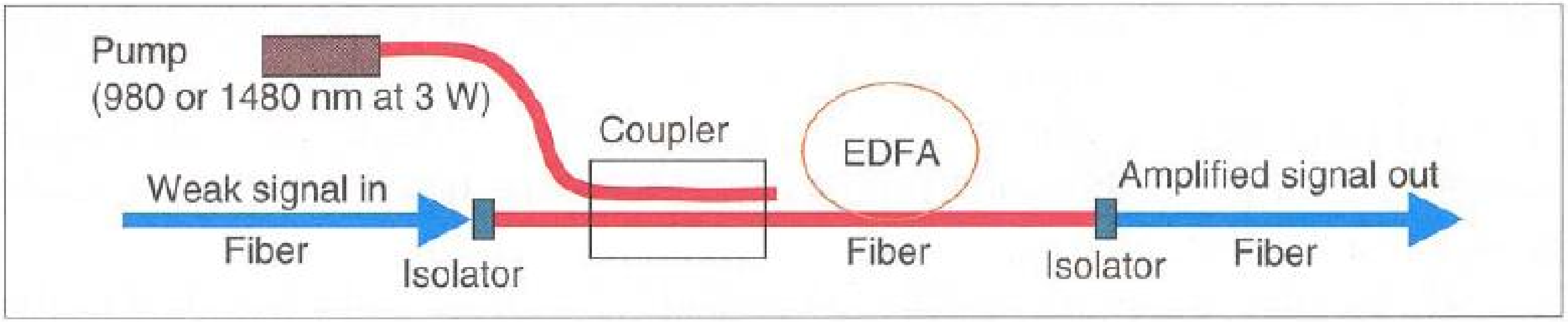
Semiconductor lasers – applications

1. Optical communication

3. Generation:

Main disadvantage: the optical signal is transferred to an electrical signal, the signal is regenerated and amplified before the signal is again transferred to an optical signal.

4. Generation: development of the optical amplifier



Schematic sketch of an erbium-doped fiber amplifier (EDFA).

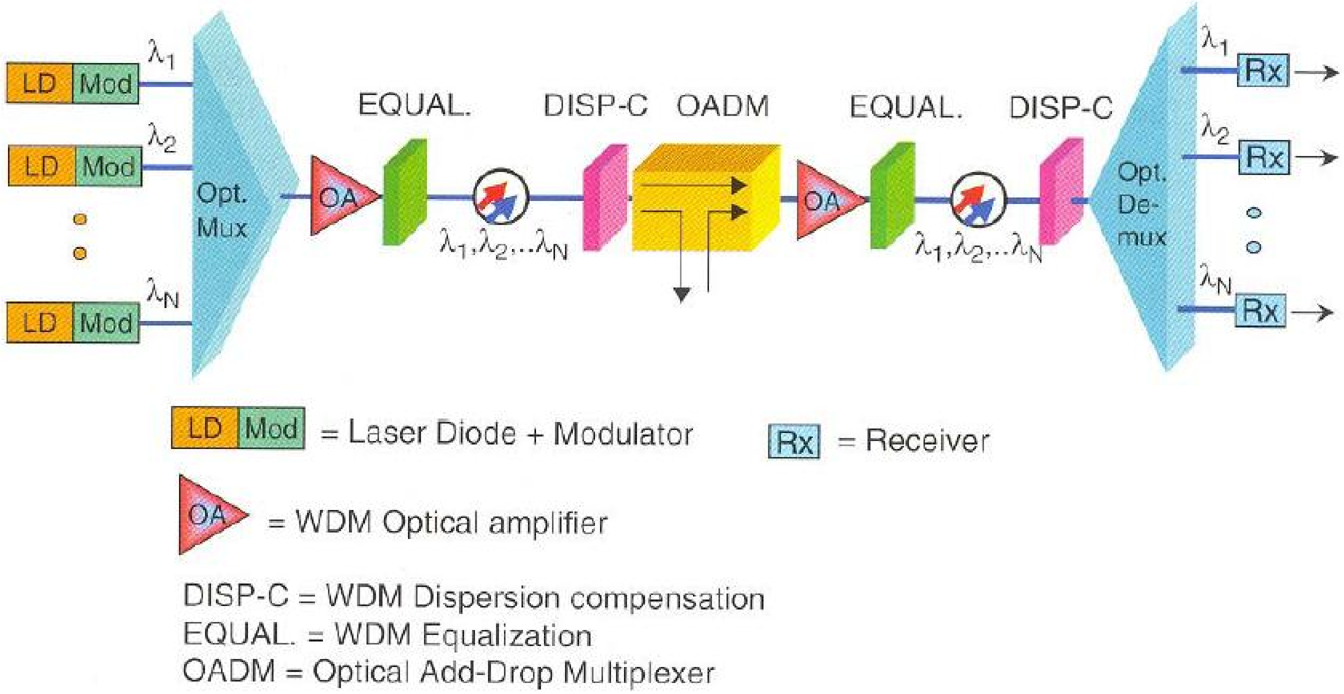
Semiconductor lasers – applications

1. Optical communication

4. Generation: State of the Art optical communication system

Dense Wavelength Division Multiplex (DWDM) in combination of optical amplifiers. The capacity doubles every 6 months.

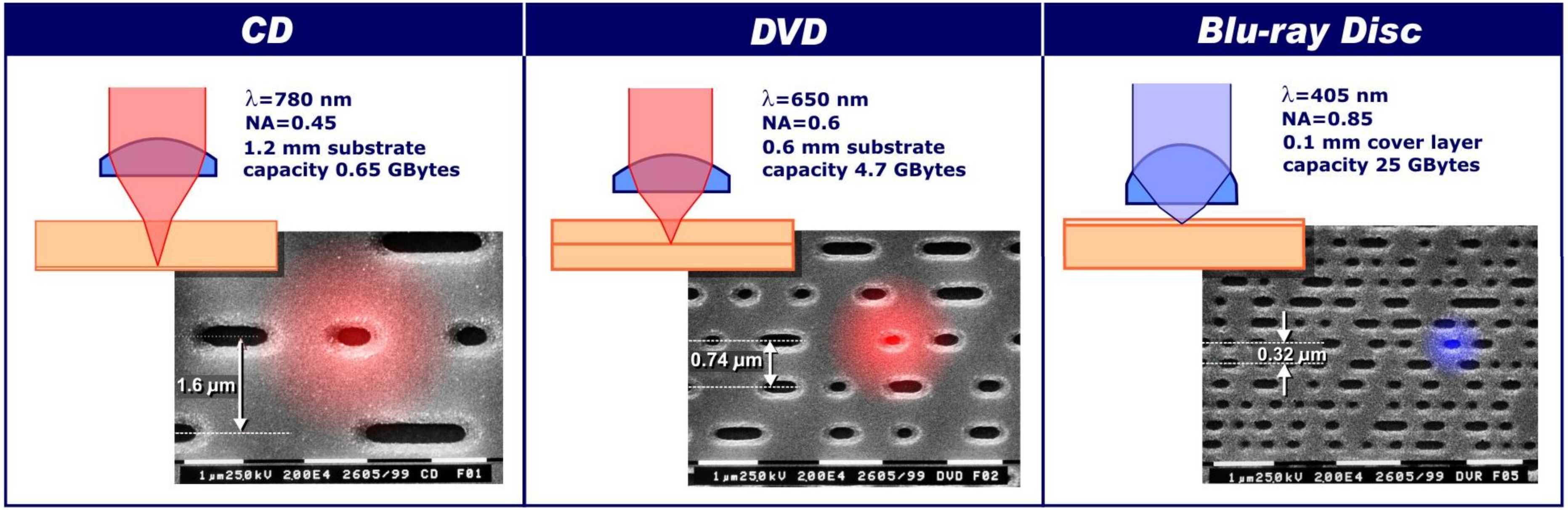
The current laboratory fiber optic data rate record is multiplexing 155 channels, each carrying 100 Gb/s over a 7000 km fiber (Bell Labs in Villarceaux, France).



Semiconductor lasers – applications

2. Optical data storage

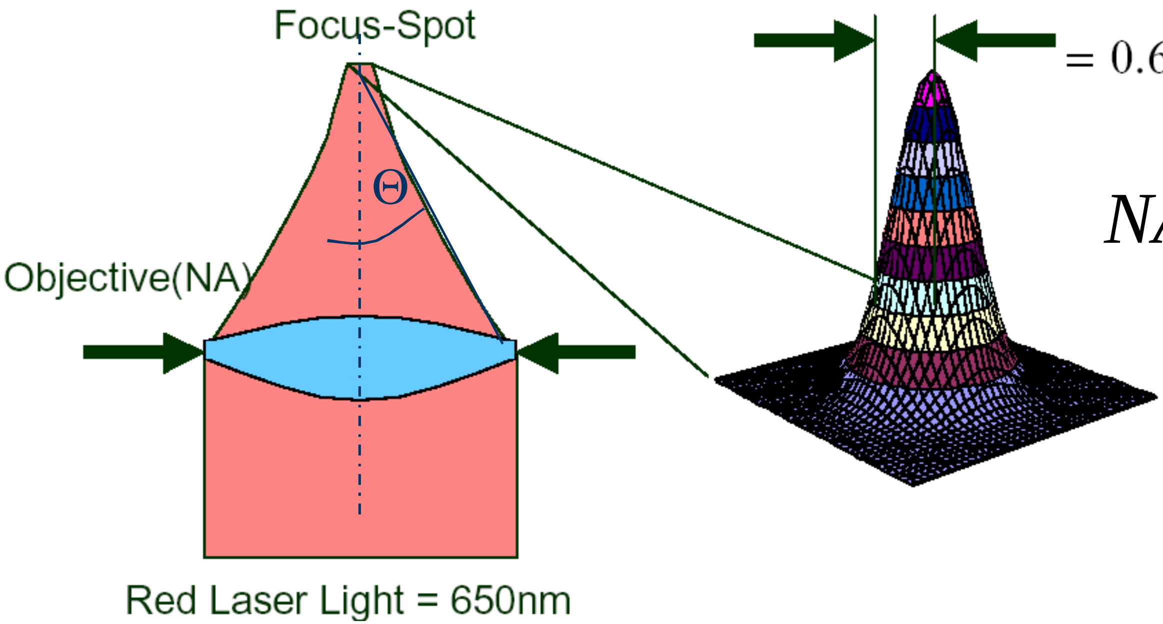
Capacity enhancement in different optical data storage devices



Semiconductor lasers – applications

2. Optical data storage (cont.)

Scale of data density:



$$\text{Spotsize} = 0.6\frac{\lambda}{\text{NA}} = 0.6\frac{650\text{nm}}{0.6} = 0.65\mu\text{m}$$

$$NA = n \cdot \sin(\Theta)$$

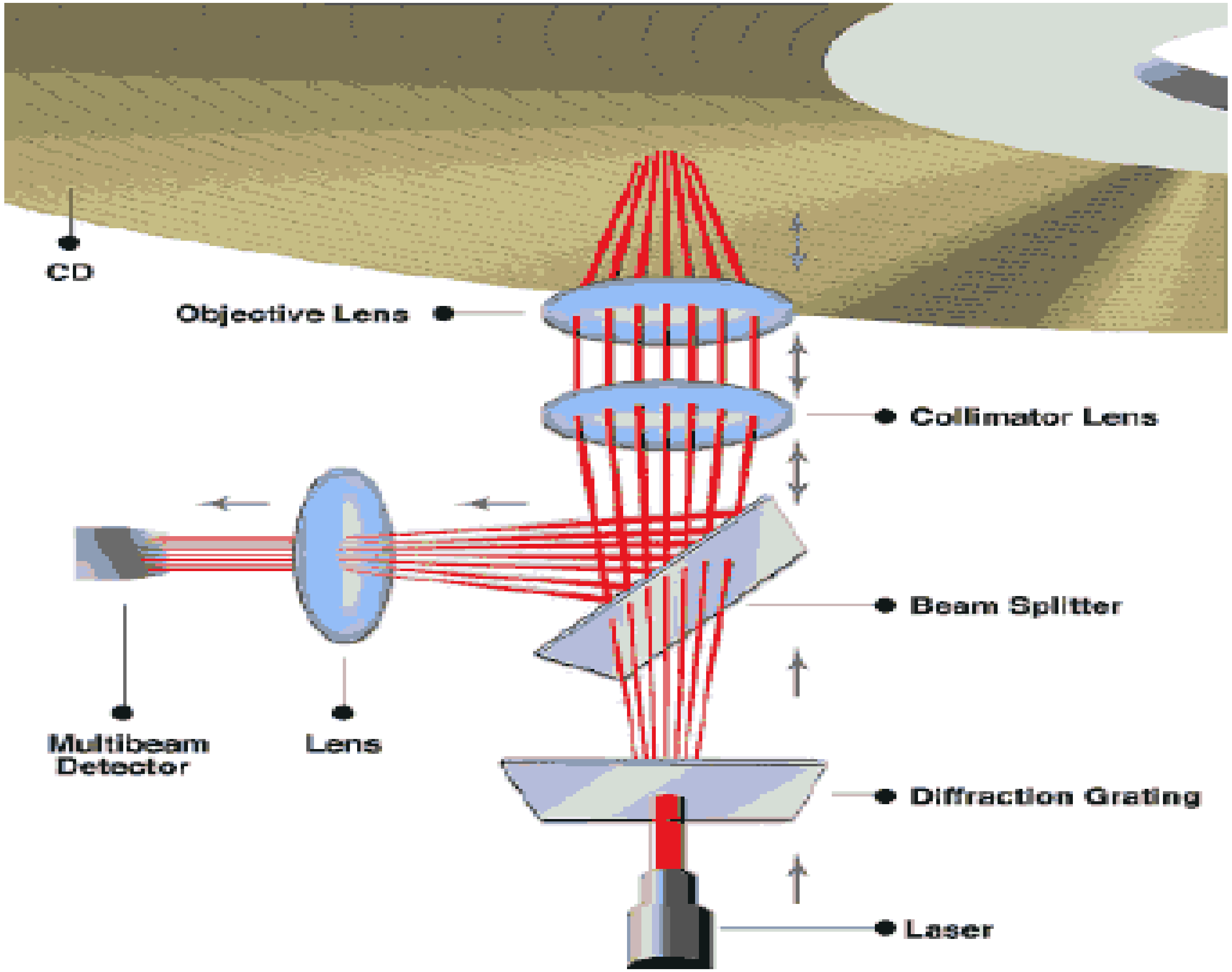
Data density: $$DD \cong \left[\frac{NA}{0.6 \cdot \lambda}\right]^2 = \left[\frac{n \cdot \sin(\Theta)}{0.6 \cdot \lambda}\right]^2$$

Semiconductor lasers – applications

2. Optical data storage (cont.)

Example: CD

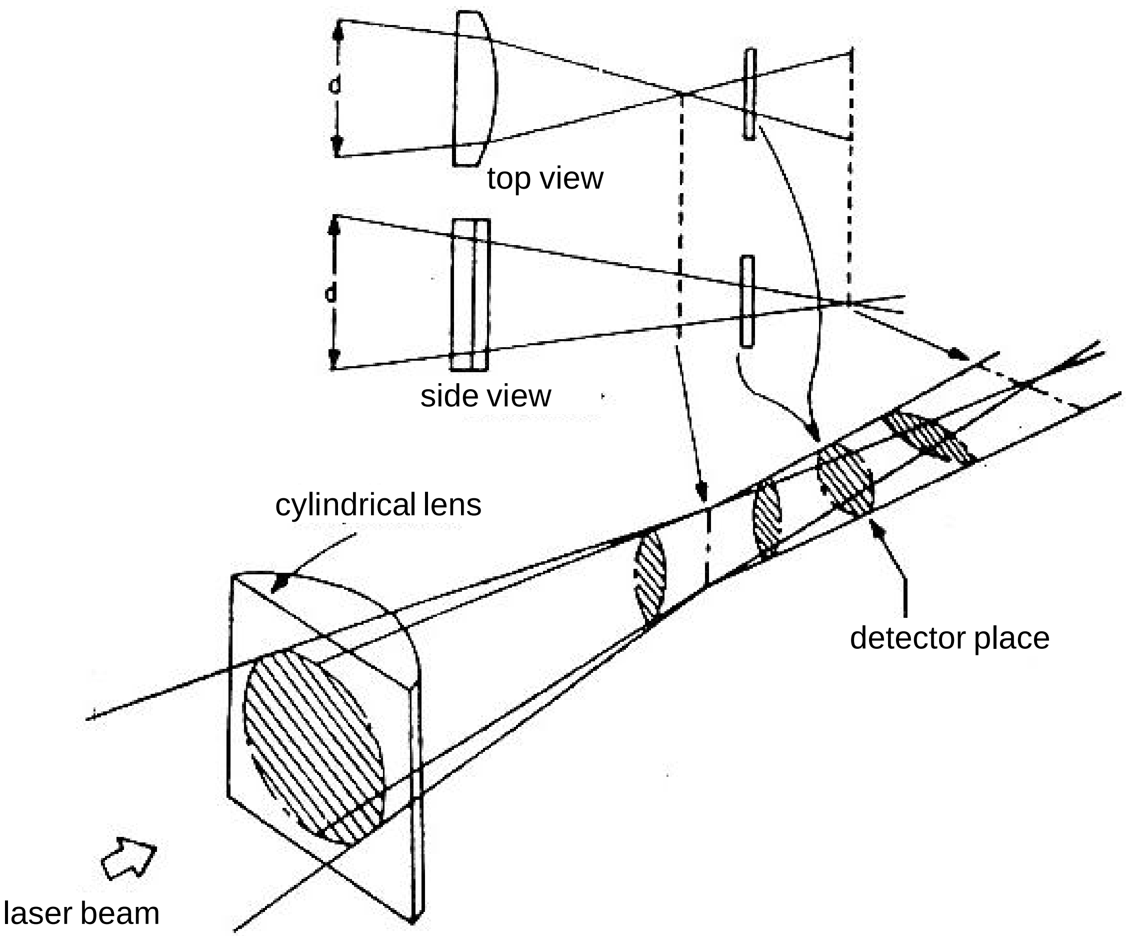
Typical CD-head

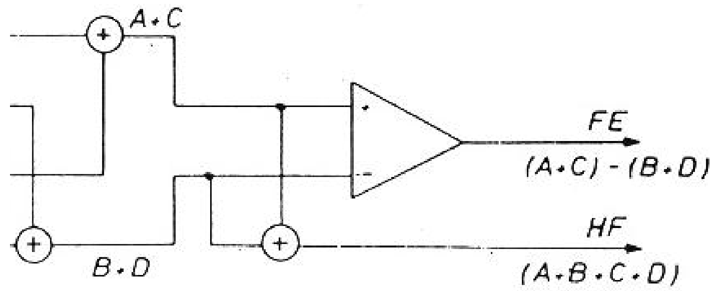


Semiconductor lasers – applications

2. Optical data storage (cont.) Example: CD (cont.)

Focusing





Focus error signal:

$$FE = (A+C) - (B+D)$$

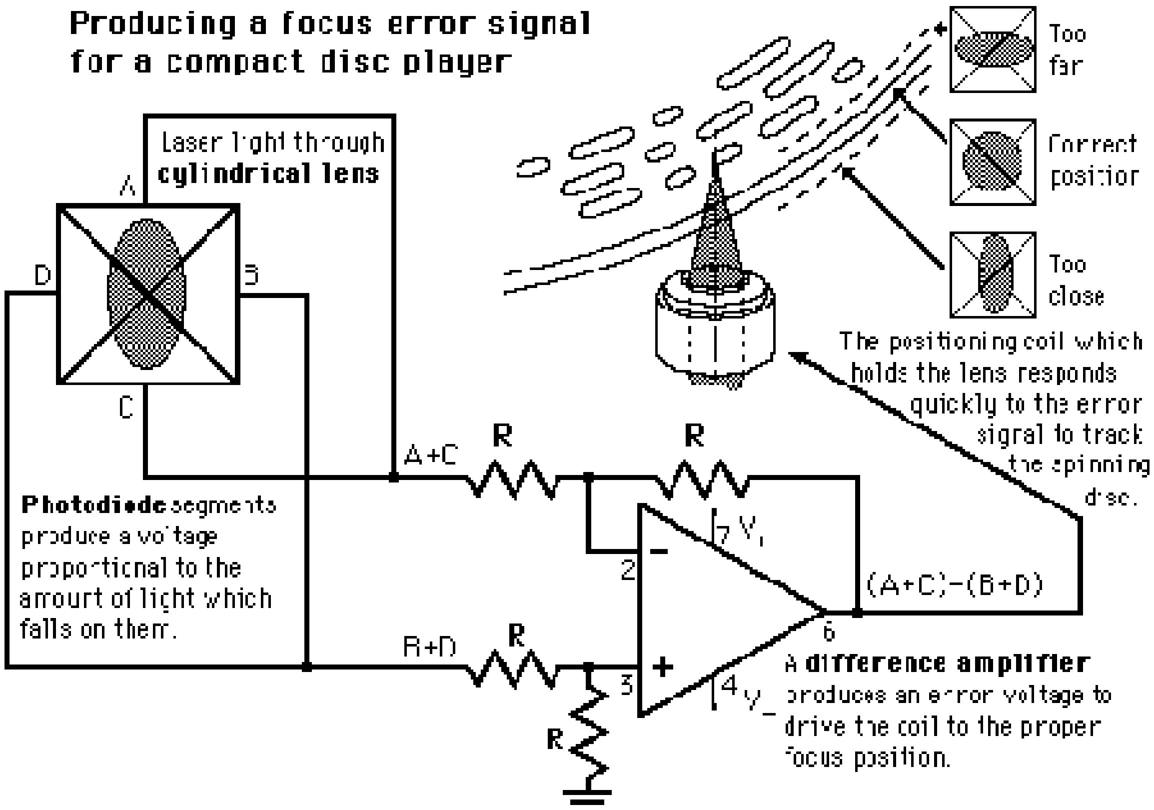
Sum signal:

$$HF = A+B+C+D$$

Semiconductor lasers – applications

2. Optical data storage (cont.)

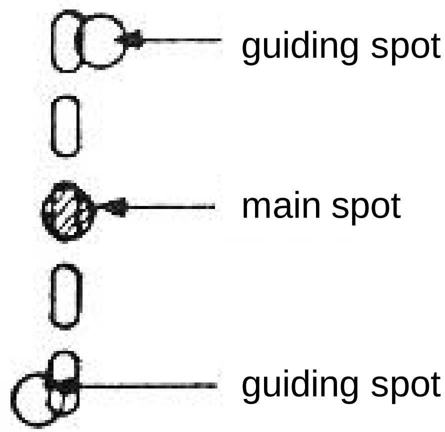
Focusing (cont.)



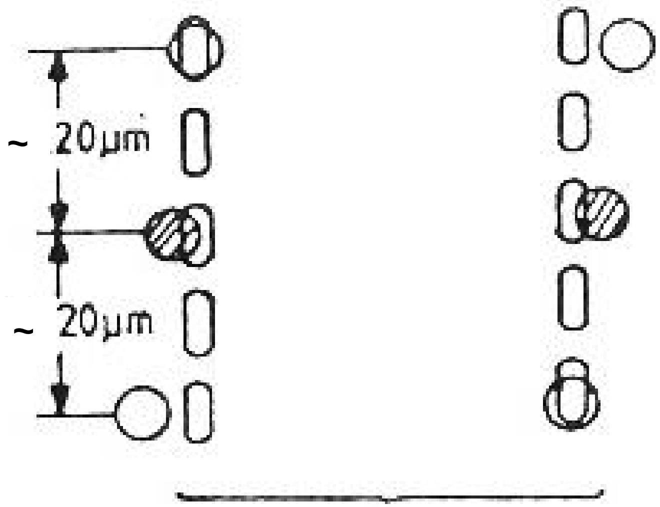
Semiconductor lasers – applications

2. Optical data storage (cont.) Example: CD (cont.)

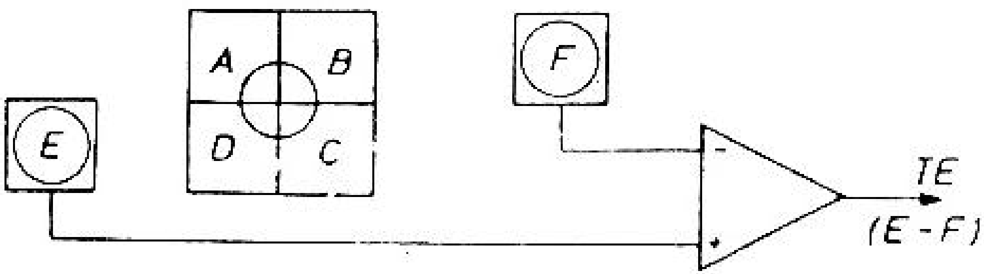
Tracking



optimal position



the spot is
left right
from the optimal position



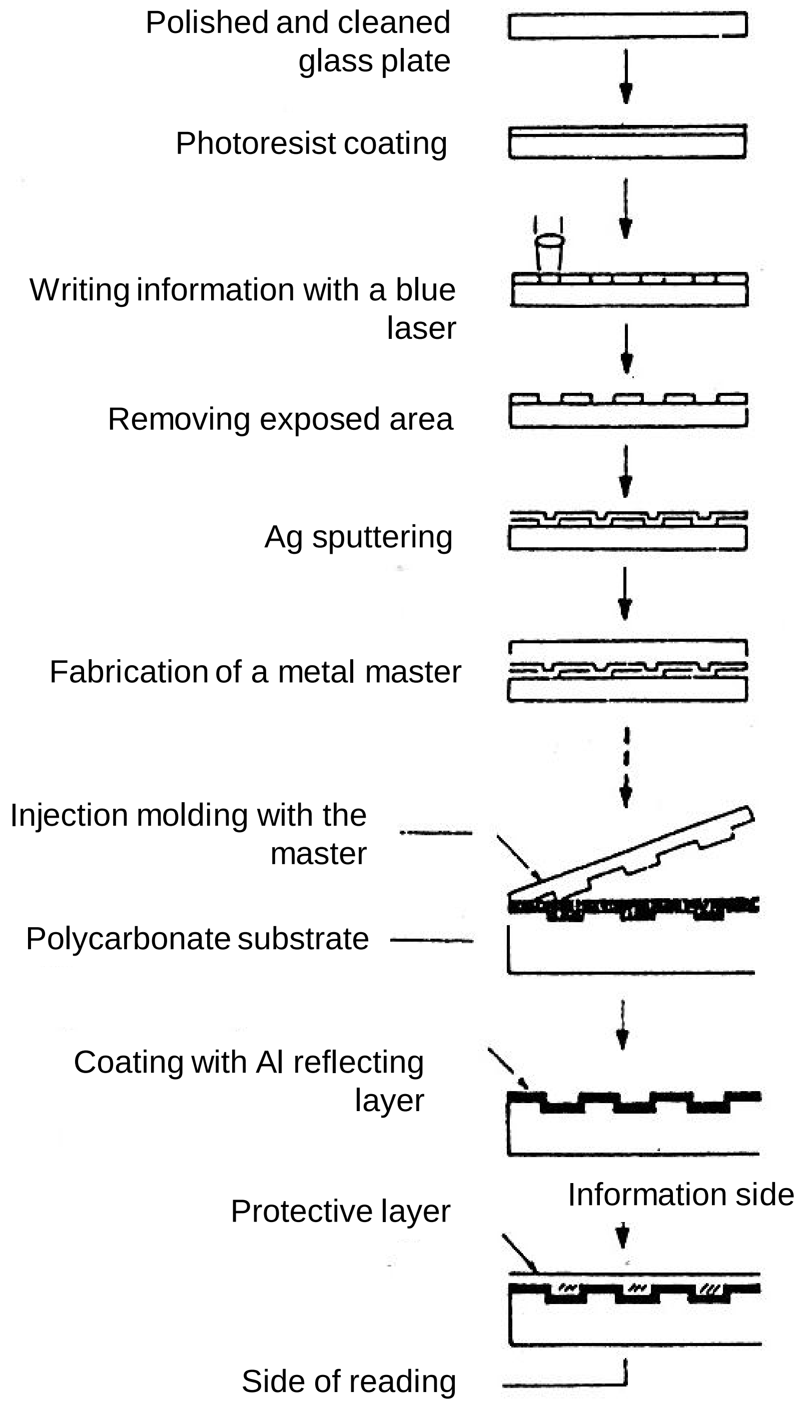
Tracking error signal:

$$TE = E - F$$

Semiconductor lasers – applications

2. Optical data storage (cont.)

Fabrication of CD disk



Semiconductor lasers

Table 1. Worldwide commercial diode-laser sales 2007–2008 (units)

DIODE UNITS		Materials processing	Medical therapeutics	Instrumentation	Basic research	Telecommunications	Optical storage	Entertainment	Image recording	Inspection, measurement, and control	Barcode scanning	Sensing	Other	Solid-state laser pumping	TOTALS
<700 nm	2007	0	0	0	0	0	355,000,000	25,000,000	21,500	15,090,000	6,950,000	0	0	10	**402,061,510**
	2008	0	50	0	0	0	369,000,000	20,000,000	21,500	15,100,000	6,990,000	0	0	50	**411,111,600**
750–980 nm <100 mW	2007	0	0	0	0	0	359,000,000	0	9,800,000	0	0	24,270,000	15,700,000	0	**408,770,000**
	2008	0	0	0	0	0	345,000,000	0	10,100,000	0	0	29,124,000	19,598,000	0	**403,822,000**
750–980 nm 100 mW–10 W	2007	0	195,000	0	0	207,000	0	0	102,500	0	0	0	1,700	538,000	**1,044,200**
	2008	0	185,350	0	0	207,000	0	0	100,750	0	0	0	1,800	807,000	**1,301,900**
750–980 nm >10 W	2007	7,150	147,400	0	1,000	0	0	0	5,000	0	0	10,000	31,100	29,000	**230,650**
	2008	7,475	162,900	0	1,000	0	0	0	5,000	0	0	10,000	31,100	30,050	**247,525**
908–1550 nm	2007	0	925	0	0	12,643,000	0	0	0	0	0	0	2,331,500	0	**14,975,425**
	2008	0	1,300	0	0	14,243,000	0	0	0	0	0	0	2,916,200	0	**17,160,500**
>1550 nm	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Stacks	2007	500	3,609	0	0	0	0	0	0	0	0	0	1,840	9,800	**15,749**
	2008	525	4,713	0	0	0	0	0	0	0	0	0	2,080	10,750	**18,068**
TOTAL UNITS	2007	7,650	346,934	0	1,000	12,850,000	714,000,000	25,000,000	9,929,000	15,090,000	6,950,000	24,280,000	18,066,140	576,810	827,097,534
	2008	8,000	354,313	0	1,000	14,450,000	714,000,000	20,000,000	10,227,250	15,100,000	6,990,000	29,134,000	22,549,180	847,850	833,661,593

Source: Laser Focus World February 2008

Semiconductor lasers

Table 2. Worldwide commercial diode-laser sales 2007–2008 ($ thousands)

DIODE DOLLARS		Materials processing	Medical therapeutics	Instrumentation	Basic research	Telecommunications	Optical storage	Entertainment	Image recording	Inspection, measurement, and control	Barcode scanning	Sensing	Other	Solid-state laser pumping	TOTALS
<700 nm	2007	0	0	0	0	0	1,234,800	9,000	5,450	11,910	13,600	0	0	30	**1,274,790**
	2008	0	150	0	0	0	1,377,647	6,400	5,450	12,070	8,600	0	0	105	**1,410,422**
750–980 nm <100 mW	2007	0	0	0	0	0	364,180	0	13,070	0	0	29,852	79,425	0	**486,527**
	2008	0	0	0	0	0	312,492	0	13,580	0	0	35,823	96,380	0	**458,275**
750–980 nm 100 mW–10 W	2007	0	7,000	0	0	119,030	0	0	11,650	0	0	0	1,600	72,560	**211,840**
	2008	0	6,500	0	0	113,850	0	0	11,300	0	0	0	1,680	101,436	**234,766**
750–980 nm >10 W	2007	10,850	45,800	0	2,000	0	0	0	11,000	0	0	2,000	9,000	49,500	**130,150**
	2008	11,100	47,650	0	2,000	0	0	0	11,200	0	0	2,000	9,000	50,125	**133,075**
908–1550 nm	2007	0	1,850	0	0	1,619,030	0	0	0	0	0	0	15,625	0	**1,636,505**
	2008	0	2,600	0	0	1,749,030	0	0	0	0	0	0	18,552	0	**1,770,182**
>1550 nm	2007	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	2008	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Stacks	2007	5,000	8,250	0	0	0	0	0	0	0	0	0	4,600	49,000	**66,850**
	2008	5,250	9,425	0	00	0	0	0	0	0	0	0	5,200	53,750	**73,625**
TOTAL DOLLARS	2007	**15,850**	**62,900**	**0**	**2,000**	**1,738,060**	**1,598,980**	**9,000**	**41,170**	**11,910**	**13,600**	**31,852**	**110,250**	**171,090**	**3,806,662**
	2008	**16,350**	**66,325**	**0**	**2,000**	**1,862,880**	**1,690,139**	**6,400**	**41,530**	**12,070**	**8,600**	**37,823**	**130,812**	**205,416**	**4,080,345**

Source: Laser Focus World February 2008