PH 201

OPTICS & LASERS

Lecture_Lasers_10

Laser Pumping Requirements & Techniques

Population inversion is a necessary condition.

Sufficient condition for laser action is realized by having enough gain in amplifier to reach saturation intensity within laser cavity.

Sufficient gain involves optimizing product, $\sigma_{ul} \Delta N_{ul} L$

Length

Cross-section, constant for most lasers

Population density difference

For several reasons (cost, compactness, availability of amplifier material), it is aimed that *L* should be decreased.

Burden of obtaining sufficient gain falls mostly upon producing sufficient ΔN_{ul}, which requires generation of adequate population density N_u in level *u*. It involves optimization of excitation or pumping mechanisms to populate laser levels.

Pumping or Excitation

Optical pumping (with flashlamps or lasers)

Particle pumping (particles within a gaseous or plasma discharge or particle beams interacting with a potential gain medium)

Excitation or Pumping Threshold Requirements

Applied excitation flux = Density of pumping state *N* × Rate of excitation *Γ*

= *NΓ*

Any amount of population that is pumped into level *u* will decay within lifetime associated with that level.

Steady-state solution for N_u, $$N_u = \frac{N_j \Gamma_{ju}}{\chi_u} = N_j \Gamma_{ju} \tau_u$$

N_j = Density in state j of species from which energy is to be transferred.

Minimum pumping flux Γ_{ju}

$$\sigma_{ul} N_u L = \sigma_{ul} N_j \Gamma_{ju} \tau_u L \approx 12 \pm 5$$ with no mirrors

$$\sigma_{ul} N_u L = \sigma_{ul} N_j \Gamma_{ju} \tau_u L = \frac{1}{2} \ln\left(\frac{1}{R_1 R_2} \right)$$ with two mirrors

These Eqs. determine threshold value of amplifier gain necessary to make a laser in terms of factors associated with providing enough population in level *u*.

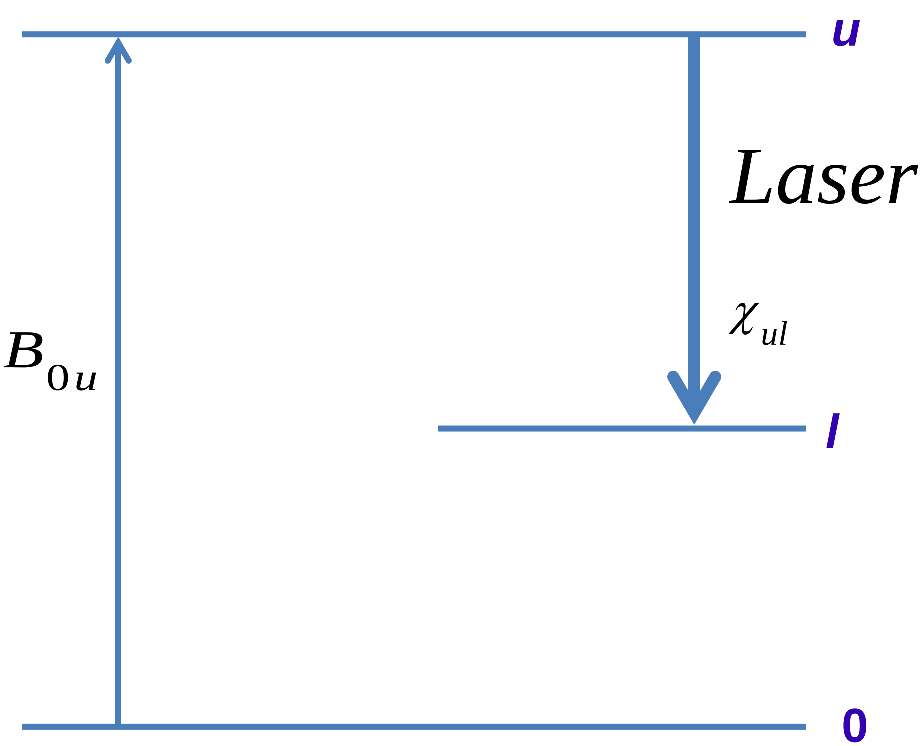
If level *l* has significant population, then one or more of pumping factors would have to be increased in order to make up for absorption.

Two types of excitation pathways can be used to produce pumping of upper laser level: <u>Direct pumping</u> & <u>Pump and transfer</u>.

Excitation by Direct Pumping

In direct pumping, excitation flux is sent directly to upper laser level from a source or target state *j* in which source state is highly populated ground state 0 of laser species.

$$\Gamma_{0u} = \frac{1}{c\Delta\upsilon} B_{0u}$$



Optical pumping rate associated with direct pumping

Optical Pumping

- **used mostly for solid-state & organic dye lasers.**
- **excitation involves absorption of pumping light within gain medium,**

$$\Gamma_{0u} = \frac{I(\upsilon)}{c} B_{0u} = \frac{I}{c.\Delta\upsilon} B_{0u}$$

Optical pumping intensity is the intensity *I* that is within absorption linewidth of absorbing species. This can be converted to an energy density within medium by replacing *I/c* by energy density.

Particle Pumping

- **used for gas lasers & semiconductor lasers.**
- **for gas lasers,** $$\Gamma_{0u} = N_p k_{0u}$$

***N_p* is pumping particle density (equivalent to intensity factor for optical pumping) &**
***k_{0u}* is reaction probability for causing a transition from level 0 to level *u* when a particle p collides with laser species in level 0.**
***k_{0u}* has dimension of volume per time.**

Reaction probability *k_{0u}* depends on two factors, cross-section or probability for transfer of energy from level 0 to *u*, & average relative velocity between colliding species & target species.

$$k_{0u} = \tilde{\upsilon}_{p0}\sigma_{0u}$$

Population flux rate into level u from level 0,

$$\Gamma_{0u} N_0 = N_p \tilde{\upsilon}_{p0}\sigma_{0u} N_0$$

In case of gaseous discharge, particles labeled p are electrons,

$$\Gamma_{0u} = n_e \tilde{\upsilon}_e \sigma_{0u}^e$$

Electron density (no. per volume)

Average electron velocity

Velocity averaged electron excitation cross-section from level 0 to level *u*.

Disadvantages of Direct Pumping

Several effects prevent direct pumping from being an effective excitation process for many lasers.

- There may be no efficient direct route from ground state 0 to laser state *u*. For optical pumping that would mean – B_{0u} associated with pump absorption is too small to produce enough gain: for particle pumping it would mean that electron collisional excitation cross-section σ_{0u} is too small.

Disadvantages of Direct Pumping

- There may be a good direct route from ground state 0 to *u*, but there may also be a better route from 0 to *l* by same process. In this case, ratio Γ_{0l}/Γ_{0u} may be too large, to allow inversion.

- Even though there may be a good probability for excitation – via absorption either of pump light associated with B_{0u} for optical pumping or of σ_{0u}^{e} for electron excitation – there may not be a good source of pumping flux available.

  There may be insufficient intensity *I* for optical pumping, or insufficient density N_p (or electron density ne) for particle pumping, at specific energies necessary for pumping population from level 0 to level *u*.

Excitation by Indirect Pumping (Pump & Transfer)

Indirect pumping provide alternate route to obtaining sufficient population inversion ΔN_{ul} for laser action.

It involves an intermediate level *q* & can be considered in three categories: transfer from below, transfer across, & transfer from above.

For all three cases, flux transfer rate from a level *q* to upper laser level *u* is given as,

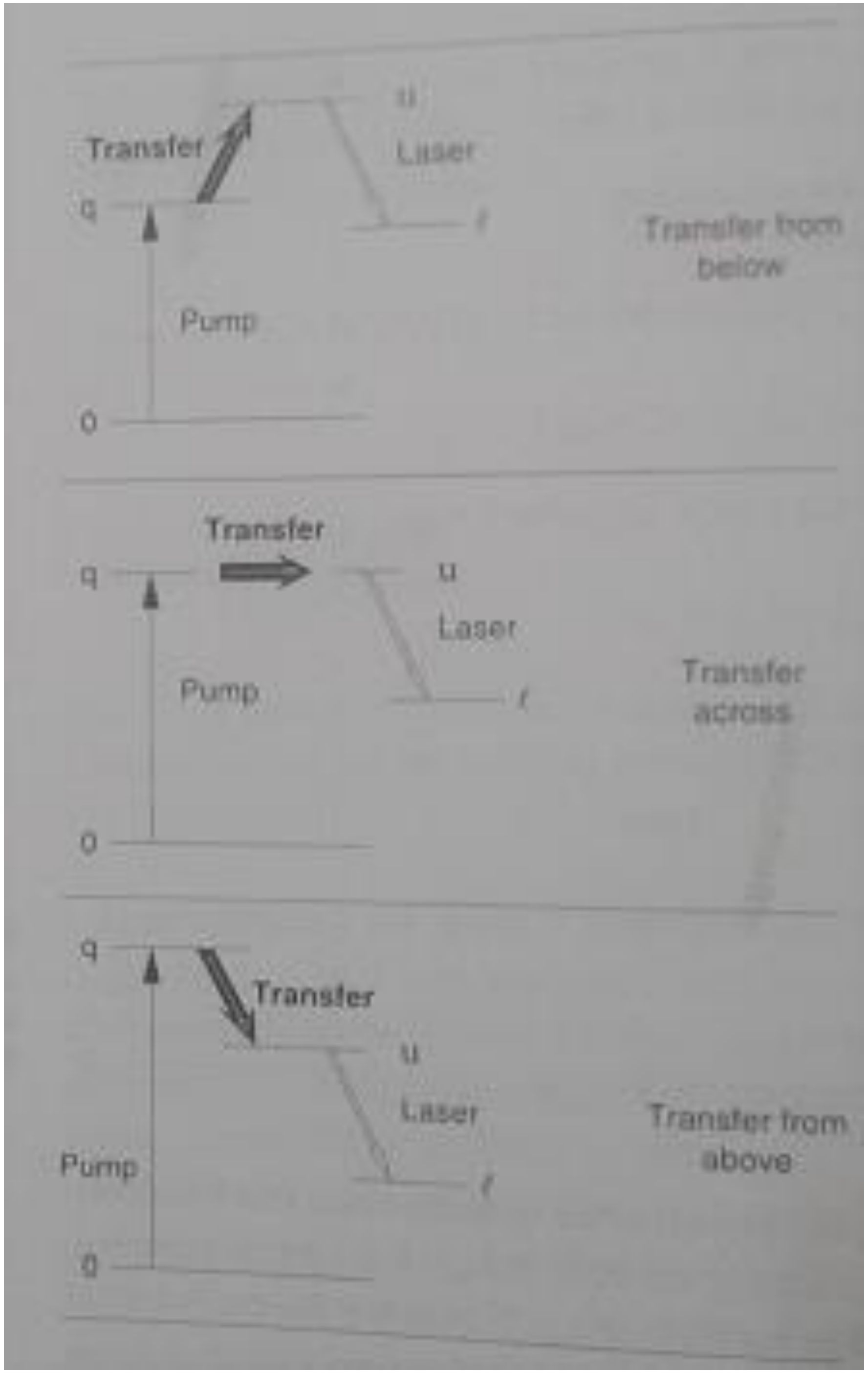
$$N_p \tilde{\upsilon}_p \sigma_{qu} N_q$$

for particle transfer, such as electrons or heavy particles,

$$\frac{1}{c.\Delta\upsilon} B_{qu} N_q$$

for transfer by photons.

Three types of indirect pumping



Advantages of Indirect Pumping

Indirect pumping involves an intermediate level *q* that receives pumping flux before it arrives at upper laser level.

Level *q* is much more closely located in energy to upper laser level *u* than is initial level 0. Therefore transfer of energy from level *q* to upper level *u* is much easier than pumping directly from level 0 to level *u*.

- **In some cases, intermediate level *q* has a lifetime that is much longer than lifetime of level *u*.**

$$\tau_q >> \tau_u$$

Level *q* might accumulate more population than level *u*.

$$N_q = \Gamma_{0q} N_0 \tau_q$$

For the case in which pumping rate to levels q & u are equal ($\Gamma_{0q} = \Gamma_{0u}$), N_q will still be much larger than N_u.

Hence level *q* can serve as a reservoir of population that is energetically near level u, with the possibility of transfer from *q* to *u* being simpler than direct transfer (due to much smaller energy separation).

- **In some cases, pumping probability (cross-section) for pumping from level 0 to *q* is much greater than that from 0 directly to *u*. This can significantly lower pumping requirements.**

- **Transfer from q to u can be quite selective in many cases, which implies that it occurs much more favorably to upper level than to lower level.**

- **Level *q* can belong to different species of material than that associated with level *u*. This could allow use of a material that can be efficiently excited to a storage level *q*.**

- **Level *q* can have a broad width & thus accept pumping flux of intensity over a broad range of energies, in contrast with upper level *u*, which might be quite narrow in order to provide a high stimulated emission cross-section.**

Electrical Pumping of Semiconductors

Semiconductor lasers are pumped by flowing an electrical current across junction region where *p*-type & *n*-type materials are joined together.

This current is produced by applying a voltage across junction, thereby producing an electric field within junction that forces electrons from *n*-type into *p*-type region & holes into *n*-type region because of their opposite charges.

In that region, those electrons & holes are attracted to each other & thus recombine at a rate that is of order of 10^9 s^{-1}.

Current required to produce an inversion,

$$j = n_c e v_D$$

j = current density flowing across junction region (A/m^2)
n_c = density of electrons in conduction band
v_D = diffusion velocity of electrons into junction

$$v_D = \frac{d}{\tau_R}$$

d = diffusion length or distance over gain can occur
τ_R = recombination time (reciprocal of recombination rate)

Diffusion length can be estimated from

$$d \cong (D_c \tau_R)^{1/2}$$

D_c = diffusion coefficient of electrons in conduction band of *n*-type material (m^2/s)

Let us consider a GaAs semiconductor with an electron concentration *n_c* of 10^{24}/m^3, a recombination time of 10^{-9} s, and a diffusion coefficient of 1.5 × 10^{-3} m^2/s. Investigate the current requirements for a regular homojunction laser, a double heterojunction laser, and a quantum well laser.

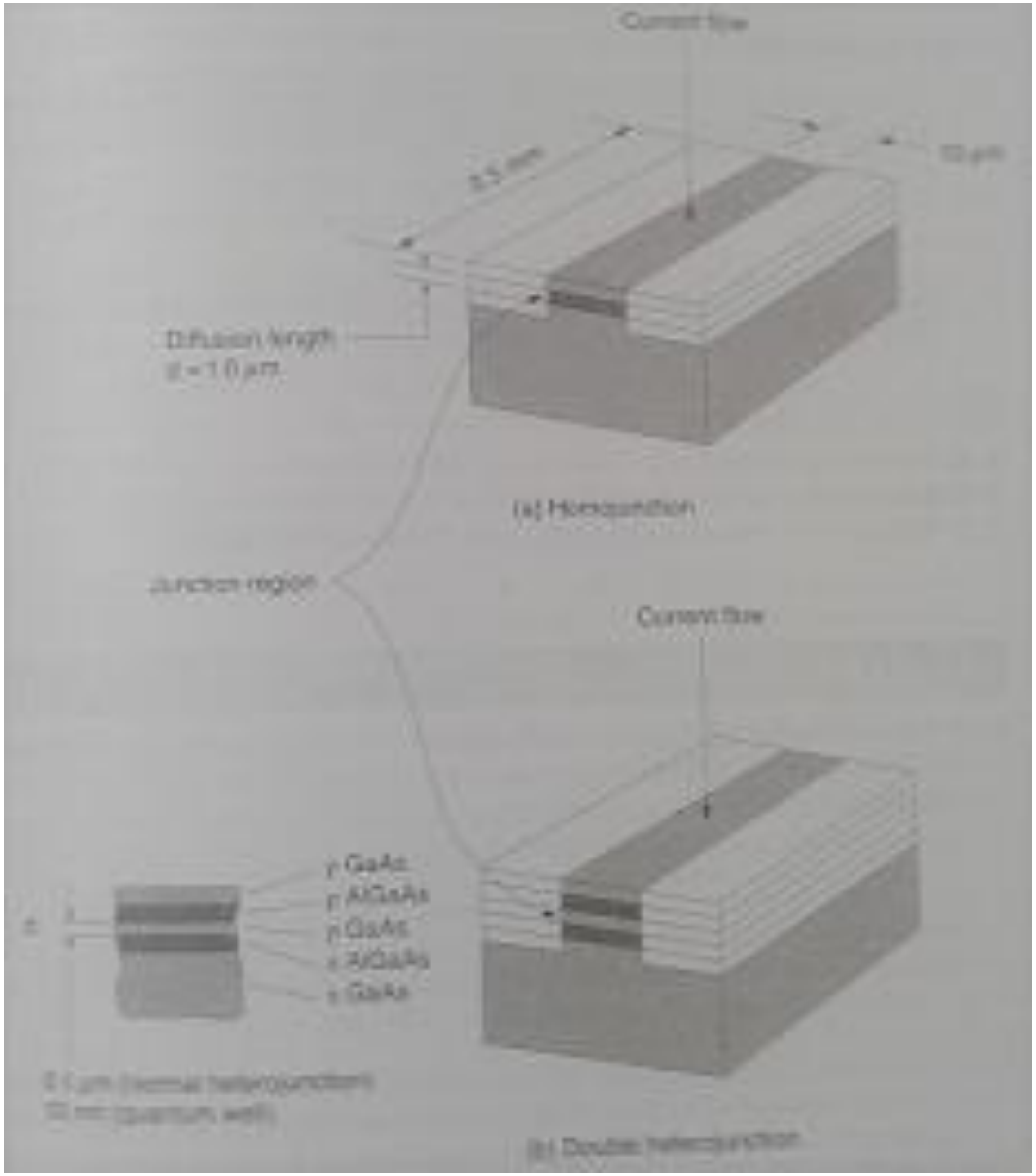
$$d = (D_c \tau_R)^{1/2}$$

$$= [(1.5\times10^{-3} m^2 s)(1\times10^{-9} s)]^{1/2} = 1.22\times10^{-6} m$$

$$v_D = \frac{d}{\tau_R} = \frac{1.22\times10^{-6} m}{1\times10^{-9} s} = 1.22\times10^{3} m/s$$

$$j = n_c e v_D = (1\times10^{24}/m^3)(1.6\times10^{-19} C)(1.22\times10^{3} m/s)$$

$$= 1.95\times10^{8} A/m^2$$



Current flow through (a) homojunction GaAs laser & (b) a conventional double heterojunction laser or a quantum well laser

A junction length of 0.5 mm & a junction stripe width of 10 μm would provide a cross-sectional area of 5 × 10^{-9} m^2. Multiplying this by current density gives a total current of approx. ONE Amp. Such as current is too high to maintain cw operation, owing to the amount of heat that would be dissipated within junction region. Hence, there is a need to narrow the junction with either heterojunctions or with quantum wells.

A 0.1 μm double heterojunction would reduce current to 100 mA.

A quantum well will significantly reduce current density by reducing d from the order of 1 μm to a thickness of 10 nm – a factor of 100! Threshold current density would be approx. 200 A/cm^2. The current would be of the order of 10 mA.