2.8 LASERS

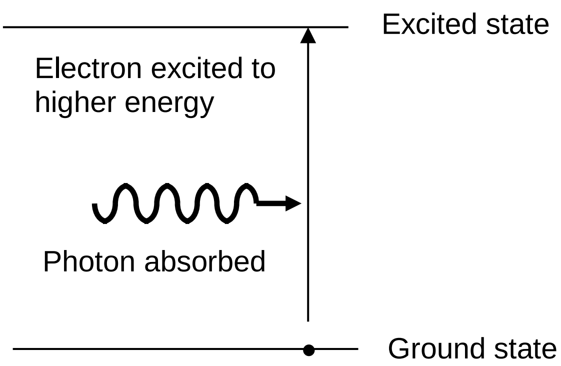
LASER is an acronym and stands for Light Amplification by Stimulated Emission of Radiation. Which leads us nicely onto what is stimulated emission?

The Three Important Atomic Processes

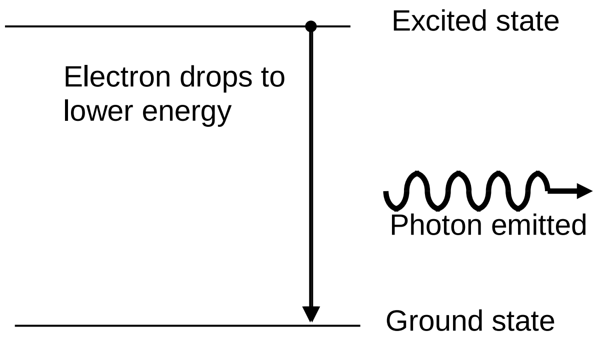
These three processes are:

1. Absorption of light
2. Spontaneous emission of light
3. Stimulated emission of light

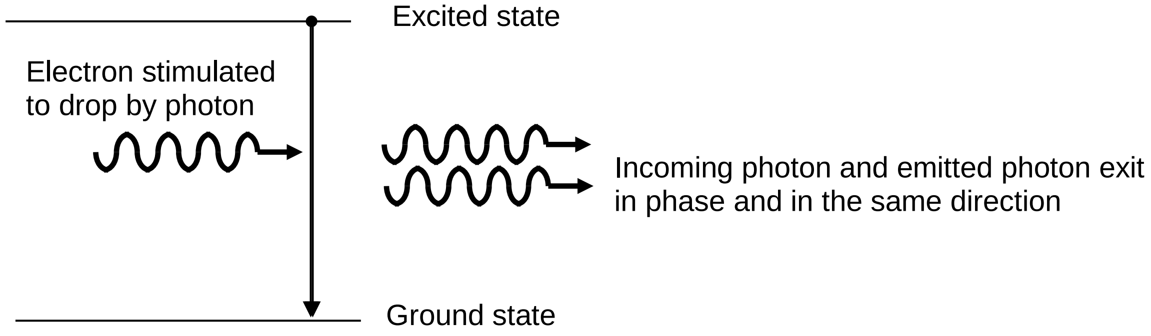
Absorption of light by an atom is shown in the diagram below – a **photon of the correct energy** is absorbed by the atom and an electron gains enough energy to move from the ground state to the excited state (Note: for the moment we are only considering the ground state and the first excited state only).



Spontaneous emission is the reverse process – an electron drops spontaneously (and randomly) from the excited state to the ground state and emits a photon of the **same** energy. These photons have random phase and random direction.



However, there is also a third process [which was originally proposed by Einstein in 1917]. This process is known as stimulated emission – an electron is 'stimulated' to drop from its excited state by an incoming photon.



The reason that the electron is stimulated to drop is that the incoming photon is an electromagnetic wave and its e-m field will exert an oscillating force on the excited electron. If the incoming photon is of the correct frequency, this oscillating force will cause the excited electron to drop and both photons will exit with the same frequency, phase and direction. Note: again, the incoming photon needs to be of the **correct** energy.

Inverting The Population

In order to get as much light out of a system as is possible we need to get as many atoms excited as is possible. Obviously, the more electrons we have in an excited state the more will drop and emit photons (either spontaneously or through stimulation). However, there is one serious problem that arises when we produce a lot of light – the very photons that we produce are the actual photons that can be absorbed (they have the correct energy to produce both effects). If we have photons being absorbed all the time then our laser beam isn't getting any stronger.

Forget, for the moment about spontaneous emission (we are allowed to but we'll explain why later). When a photon arrives at an atom one of three things can happen:

1. It can pass by and do nothing.
2. It can be absorbed (if the atom is in the ground state).
3. It can cause stimulated emission (if the atom is in the excited state).

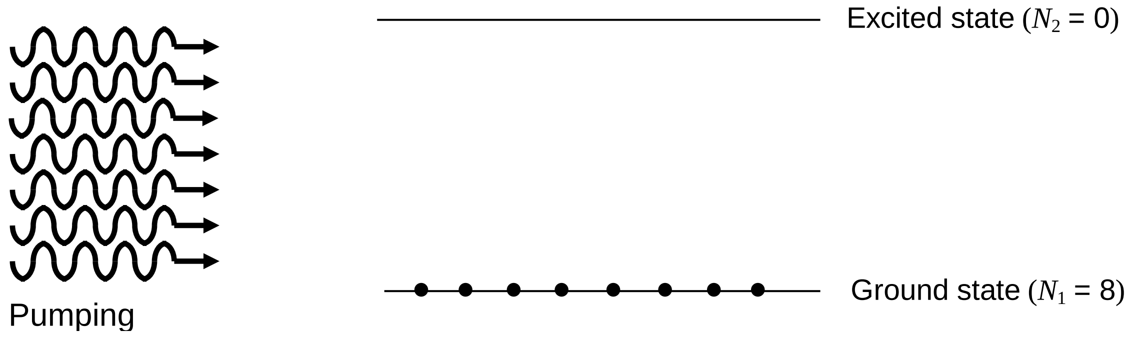
When it comes to producing a laser beam with a high intensity the three options above will have the following effect on the beam.

1. No change in the beam.
2. Net loss of one photon from the beam.
3. Net gain of one photon in the beam.

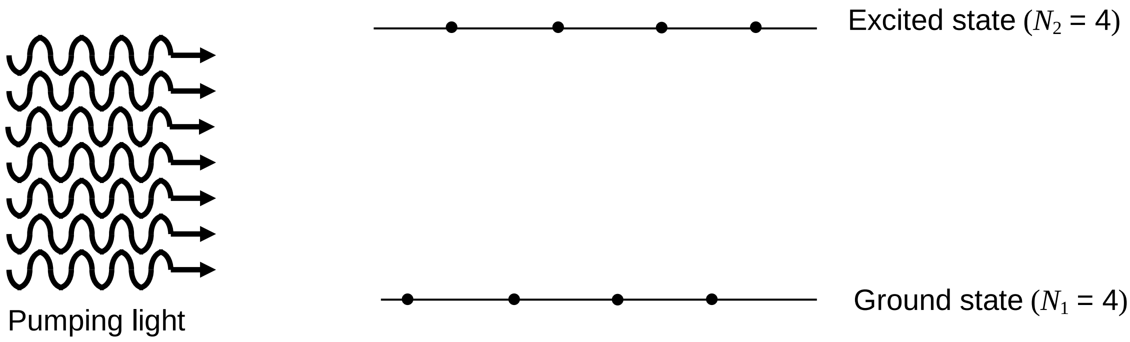
We need to arrive at a situation where **stimulated emission** is more likely than **absorption** so that the laser beam increases in intensity. Since stimulated emission occurs if the electrons are in the upper level and absorption when electrons are in the lower level we need to get more electrons into the upper, excited level. This is called **population inversion** (or $N_2 > N_1$ as stated in the syllabus, where N_2 and N_1 are the number of electrons in the excited state and the ground state respectively).

Unfortunately, this goes against what happens in nature – lower energy levels are always more heavily populated than higher energy levels when we have thermal equilibrium (*as we go up 1 eV to higher energy levels the probability of occupation of the level drops by a factor of 10^{17}*). There's only one thing for it – get rid of this thermal equilibrium. How do we do this? We continue to **pump** energy into exciting electrons to higher energy levels to maintain a population inversion and to break the conditions of thermal equilibrium.

Population inversion is not usually possible if we only have two energy levels (if pumping is carried out by light). As we start to pump our system we have the following situation:

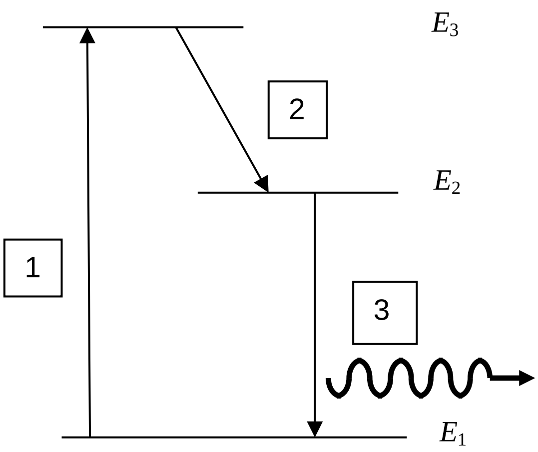


Many electrons will be promoted to the higher energy and all seems fine. Unfortunately, if we succeed in exciting half the electrons we are now in the following situation:



In this situation the incoming flood of photons is just as likely to cause an electron to drop (stimulated emission) as it is to cause an electron to rise (absorption). The best we can achieve here is $N_2 = N_1$ which is not quite good enough.

The 3 Energy Level Laser System

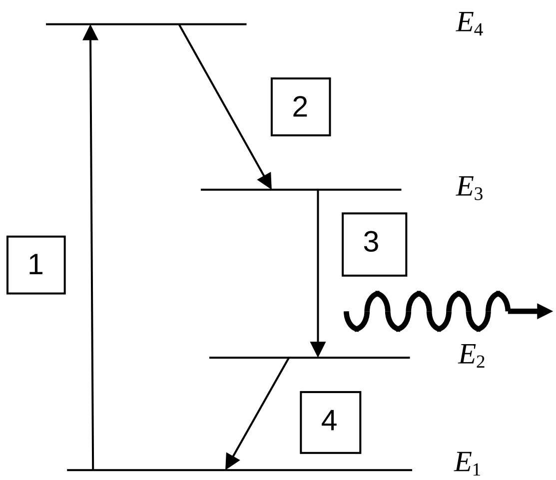


1 Pumping. Electrons are promoted from the ground state (E_1) to E_3 usually by using an external light source *or by electron collisions*.
2 Electrons drop quickly (because E_3 is chosen to have a short lifetime *of the order of nanoseconds*) to the **metastable** (E_2). Calling E_2 metastable means that it has a long lifetime and electrons stay there for a long time (*not that long really around a millisecond but that's a very long time for an electron*).
3 This is the transition that produces the laser photons so we must have $N_2 > N_1$. Note that, although stimulated emission still reduces our population inversion, the pumping is at a different wavelength. We have to make sure that the pumping [1] exceeds the stimulated emission [3] to maintain a population inversion.

Other things to note:

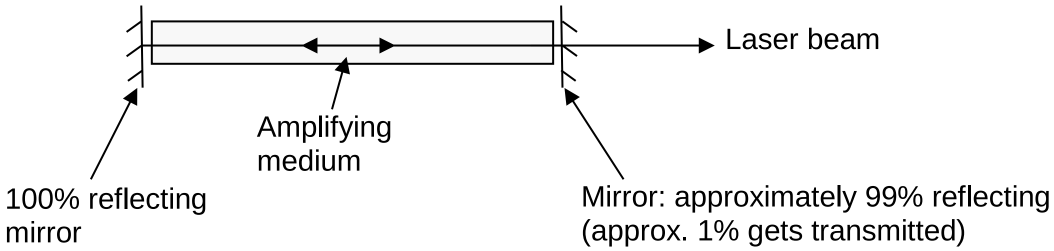
- E_3 (to E_2) has to have a short lifetime because E_3 cannot start to fill up – pumping won't then be possible. *Also, we don't want the electrons to stay in E_3 and have them stimulated to drop back to E_1 by the pumping light – that's back to the 2-level system again which wasn't quite good enough*.
- More than half the electrons from E_1 must be pumped to E_2 (via E_3) in order to obtain a population inversion – that's a lot of electrons!

The 4 Energy Level Laser System



1 Pumping again.
2 Quick drop to the metastable state E_3.
3 This is the laser light producing transition so this time $N_3 > N_2$. However, because E_1 is the ground state, E_2 is practically **empty initially** so obtaining population inversion is far, far easier (definitely no need to pump half the electrons!).
4 Another quick transition so E_2 has a short lifetime. This is because we want E_2 to be empty so that we have a population inversion (if N_2 is small it's easier for N_3 to be larger than N_2).

Laser Construction



In order to ensure that the laser produces light of a high enough intensity, the above set up is used. The amplifying medium is the region where the population inversion exists. This means that the conditions are right in the amplifying medium for stimulated emission. Under these conditions one photon has the potential to produce two photons and these can produce 4 photons, then 8 photons etc. Like a chain reaction, this process will lead to an exponential increase in output energy. Laser physicists aren't happy with this, they go even further – they use mirrors to ensure that this exponential increase happens many times. Because only 1% of the light exits each time it reflects back and forth between the mirrors, on average, the beam will pass through the amplifying medium a hundred times before it exits. Now, considering that each time the beam passes through the amplifying medium it is increasing exponentially, this factor of 100 makes an enormous difference. [Try calculating $e^{0.1}$ and then e^{10} on your calculator and see the difference!]

This all leads to very high light intensities inside the amplifying medium and this is why (as was said earlier) we can forget about spontaneous emission. Imagine that you're an excited electron sitting happily in your higher energy level. Normally, you'll just drop down spontaneously when your time is up. But, inside a laser, there's so much light that you never drop spontaneously because before your time's up you've been disturbed by another photon, stimulated to join in with all the other light and join in coherently as well!

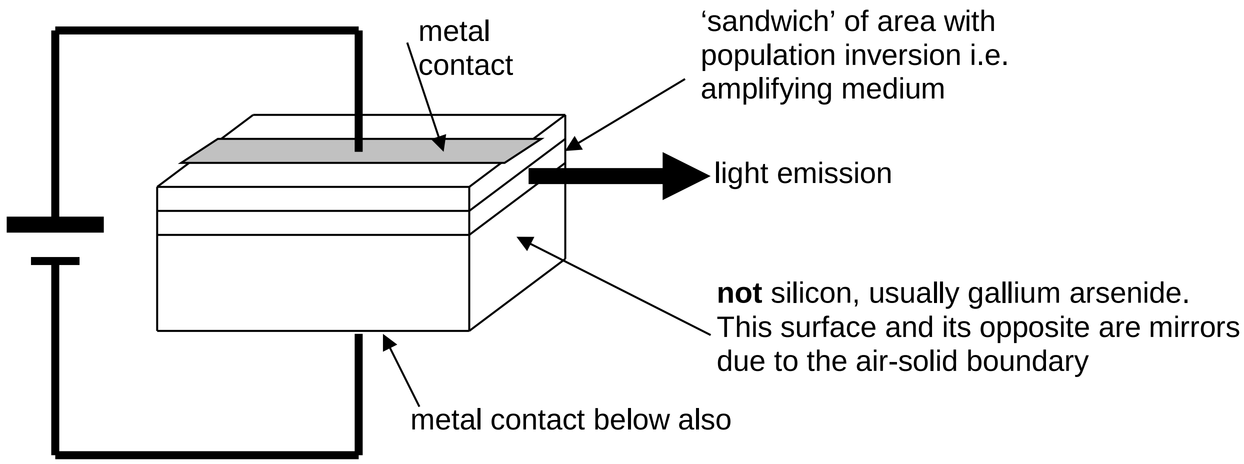
Efficiency

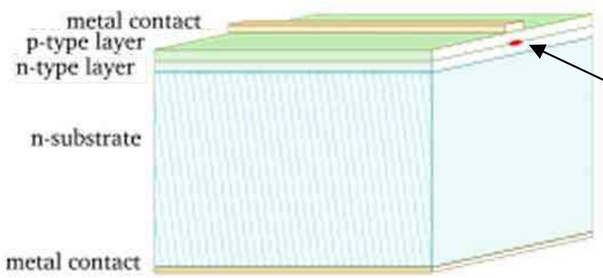
Usually, lasers are very inefficient beasts. Because of the large energies required to maintain a population inversion, their efficiencies are generally far below 1%. Some reasons for this.

- The pumping energy (see [1] in the 3 and 4 level systems) is considerably larger than the output photon energy.
- High intensity pumping combined with the high intensity of the laser beam means that the amplifying medium will get very hot. So, there will be large heat losses. To make this matter worse, we need to cool the amplifying medium usually so that it, or its container, doesn't melt. By cooling the system we just transfer more heat and increase our losses but better this than destroy a £50 000 laser!

Semiconductor Lasers

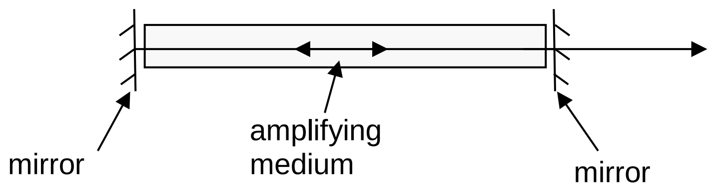
The basic structure of a standard ‘edge emitting’ semiconductor laser is shown below. The whole block shown below is a semiconductor chip with dimensions approximately 0.5 mm × 0.5 mm × 1 mm.





[Although the chip itself has dimensions approximately 0.5 mm × 0.5 mm × 1 mm, the beam has an approximate cross sectional area of 30 μm × 5 μm and passes along the ~1 mm length of the chip.]

The above laser fits the basic shape of a normal laser (shown below).

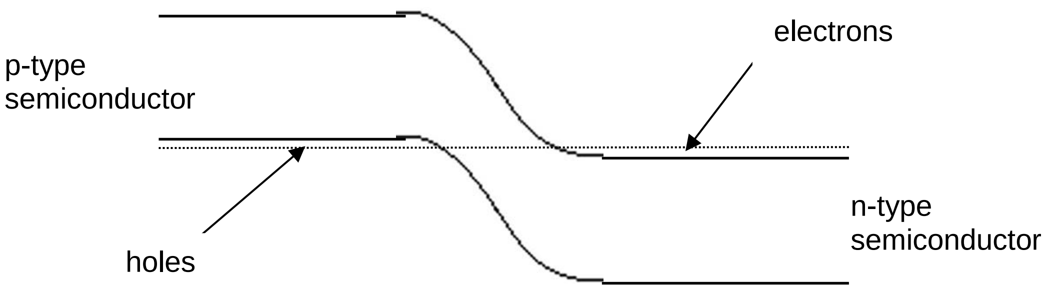


The mirrors, however, are far from the 100% and 99% reflecting ideals discussed earlier. The mirrors are simply due to the semiconductor-air boundary at the edges of the chip. [This in fact gives 40% reflection only (at both sides).] This would be disastrous for highly inefficient gas lasers but not for our semiconductor laser. The reason why:

- The population inversion inside the semiconductor sandwich area is millions of times higher than in gas lasers [$\sim 10^{25}$ electrons/m^3].
- The exponential increase in light intensity (i.e. 1 photon becoming two, becoming four etc.) occurs far more quickly because of the higher population inversion.
- So the fact that we lose 60% of the light at each reflection is compensated for by having huge gains between the mirrors.

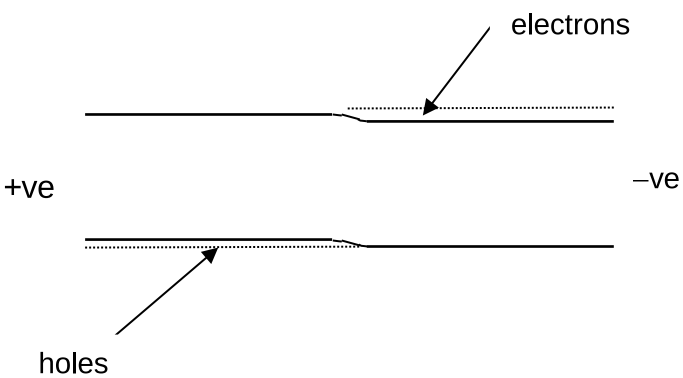
How can a population inversion be set up just by applying ~3 V d.c. voltage?
[You don't need to know this but you might find it interesting]

Here a couple of band diagrams of a p-n junction in a very highly doped semiconductor.

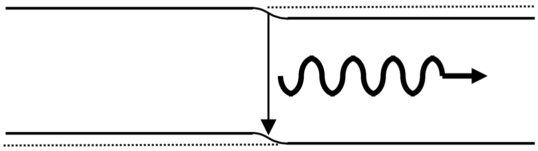


Note: This is a diagram for a horizontal p-n junction but the junction in the laser diode diagram is vertical.

After a small (~3 V) p.d. has been applied, we get:



Can you see the area of population inversion? If you look carefully, there's a small region in the middle between the p-type and the n-type where we have a high concentration of electrons above holes. These are the electrons that can be stimulated to drop and provide laser light.



Advantages and Uses of Laser Diodes

These are straightforward and can be summarised as follows:

Advantages:	Some Uses:
• Cheaper • Smaller • More efficient • Easy to mass produce	• Inside DVD and CD players • Barcode readers • Telecommunications (via optical fibres) • Image scanning • Laser surgery

The usefulness of laser diodes is 'reflected' in the number of them produced annually – around 1 billion (10^9) laser diodes are produced worldwide per year!