Semiconductor Optoelectronics

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Lecture - 32
Laser Basics

In the next couple of lectures, we will discuss about semiconductor laser. So today, I will discuss basics of laser or laser fundamentals. Some of you would have done a course on lasers, but some of you would not have done. So this is basically reviewing laser physics and recalling the fundamentals of lasers. Let me start with the basic question, what is laser?

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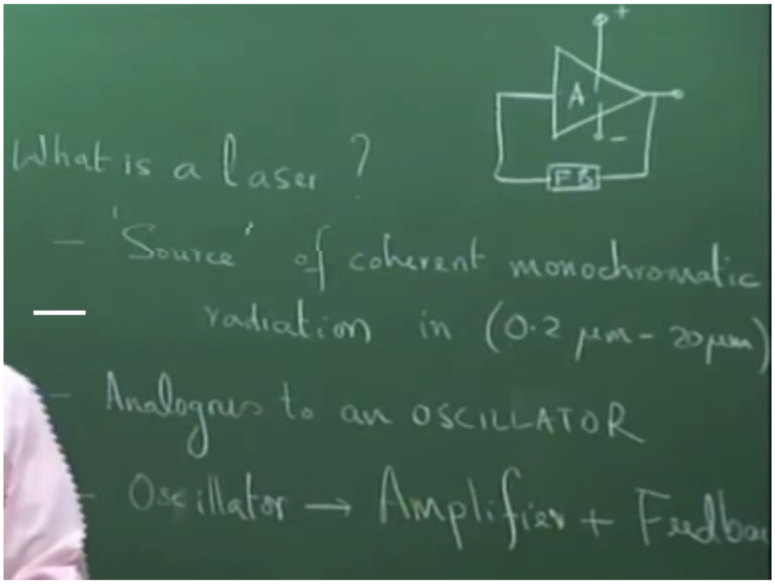

What is a laser ?
– 'Source' of coherent monochromatic radiation in (0.2 μm - 20 μm)
– Analogous to an OSCILLATOR
– Oscillator → Amplifier + Feedba

And we all know what is a laser. Laser is a source of coherent monochromatic radiation in the optical region of the electromagnetic spectrum. So laser is a source, the important point here is, it is a source, it is a source of coherent monochromatic radiation in the optical region. Typically, optical region means approximately 0.2 micrometers to 20 micrometers approximately in this region.

It is a source of coherent monochromatic radiation and it works on the principle of laser that is light amplification by stimulated emission or radiation. When it is a source, it is analogous to an electronic oscillator. Electronic oscillator is a source of RS and we know that an oscillator comprises of an oscillator is basically the amplifier and a feedback, amplifier + feedback. An amplifier followed by a feedback circuit gives you an oscillator.

So typically you could fill an oscillator like an amplifier, where here it has an output and there is a feedback circuit, feedback to the amplifier. A general oscillator has an amplifier. It is an active device and a feedback circuit. The active device is able to provide amplification when you power it for example, you have the supply +/-, so this forms a general oscillator. The feedback circuit may have RC, may have inductor, may have capacitor and so on.

Therefore, laser is a source of radiation in the optical region of wavelength and is analogous to an oscillator, therefore it has an amplifier and a feedback circuit. Amplifier in general consists of an active medium or an active device, which is pumped or which is powered by a power supply and therefore in general, the three important components of laser.

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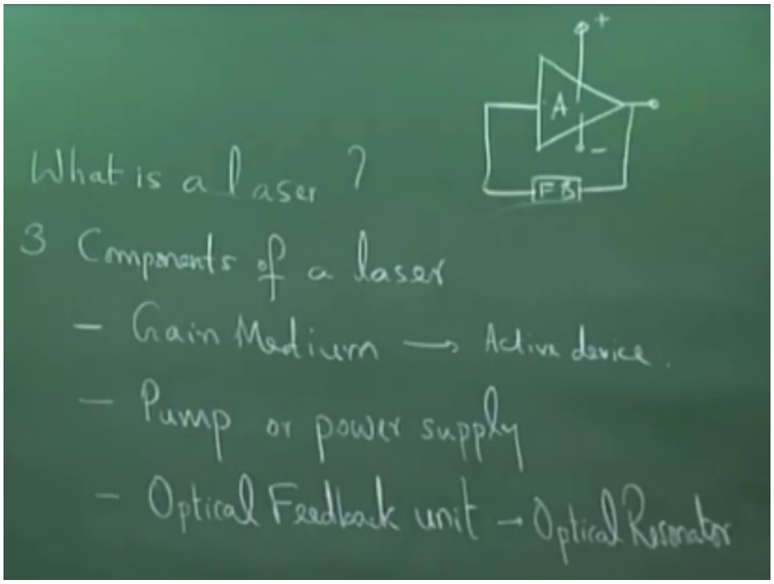

What is a laser ?

3 Components of a laser

- Gain Medium → Active device.
- Pump or power supply
- Optical Feedback unit → Optical Resonator

The three components of laser in general, this is not necessarily semiconductor laser, any laser have three components, first the gain medium or the active medium, which provides gain when pumped and therefore you need a pump or power supply and optical feedback. These are the three components. This could be an active device, which provides amplification when powered properly or when pumped properly and an optical feedback unit.

This is the optical resonator. Optical feedback unit is nothing but the optical resonator. These are the three components of a laser. So when the active medium is found, it provides gain and the resonator has a certain loss associated with it and whenever gain exceeds loss, you have net amplification and the laser can start oscillating. Let me show a general schematic of the laser, both for bulk and semiconductor.

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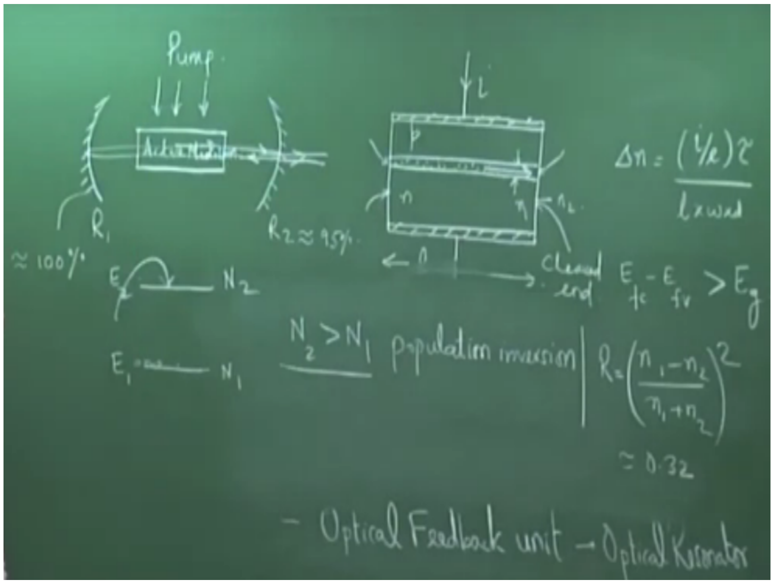

Let me then have a comparison. In general, if you take bulk laser, say an EI laser. There is an active medium, which is found externally, maybe by flash lamp, may be by another diode laser externally formed and the amplifying medium is placed inside an optical resonator between 2 mirrors, let us say of reflectivity R1 and R2 and this forms the basic schematic of a bulk laser. The semiconductor laser also has almost similar structure.

We have the schematic, the active medium here. I am not drawing all the layers. These are the electrodes. This is the longitudinal cross section of the laser and this is our active medium and a current flows through this forward biased PN junction. There is a current I, this is P, this is N and here is the electrode. You know that if it is pumped properly when the injection current is sufficiently large, we can have the separation between the Fermi levels.

Please recall that delta n = i/e*tou/l*w*d where d is the thickness of the active region, w is the width from the front side if you see and l is the length.

So depending on the current through device, a delta n can be large and if delta n is large, the separation between the Fermi levels can be large enough, so that we can have a situation where efc-efv is greater than ev or greater than hu. So in this situation you can have gain in the medium. So the gain medium here, the active pumps a gain medium when you pump a sufficiently strongly to reach such a situation.

In this case, this is an atomic system, so gain is probably simple terms. Those of you who are familiar with laser, if you have n1 and n2 as the number of atoms per unit volume in the energy level e1 and e2. If you pump sufficiently hard that raise atoms from the ground state to the higher state through some mechanism in a 2 level, you do not have steady state oscillations, but to some mechanism, if you pump and create a situation where n2 is greater than n1.

It is called population inversion, we have gained. This medium becomes a gain medium, that is why you are pumping externally, the pump here just taking the same role as the current and the pumping leads to population inversion. It is possible to have population inversion, which means this becomes a gain medium, this becomes the gain medium, here the gain medium is placed inside a resonator, so that there is light which is traveling in this direction, gets feedback.

Light which goes in this direction could come back, which acts as an optical feedback because the same light is spread into the gain medium. The same thing happens here. If you cleave the 2 ends, so this is the cleaved end. Both the ends are cleaved. Cleaving is initiating a break along a crystallographic plane, so that that results in mirror like finish. It is not cutting, it is cleaving, so you have to scribe and initiate cleavage and when a crystal is cleaved along the crystallographic plane, you have perfectly reflecting mirror like processor.

So if you have this medium has refractive index n1 and this medium has refractive index which is n2, which is outside air, then the reflectivity here at this end, that is the light which is generated, which reaches this end has a reflectivity, which is = n1-n2/n1+n2 the whole square and if you put the numbers, as we have already discussed, if you put 3.6 here, 1 here outside, you get this approximately = 0.32 that is 32% reflectivity due to the cleaved end.

Normal lasers do not have any mirrors at the ends. The feedback is obtained by the 32% reflection at the 2 ends of the cavity. So in this case, the cavity is here. so light goes back and forth, the optical resonator, the mirror, the active medium space inside the mirror here forms the optical cavity or the resonator whereas in this case, the active medium with the 2 cleaved ends here, so this ends here and this ends here, cleaved ends form the optical resonator.

It acts like the mirror. The reflectivities are just about 32%, but in a bulk laser normally you have one of the mirror almost 100% reflectivity, very high reflectivity and the other 1 partial reflectivity of approximately 90% or 95%, because so that a part of the light goes out. In every reflection, part of energy goes out, which forms the useful light for you. So you can redraw the same diagram again.

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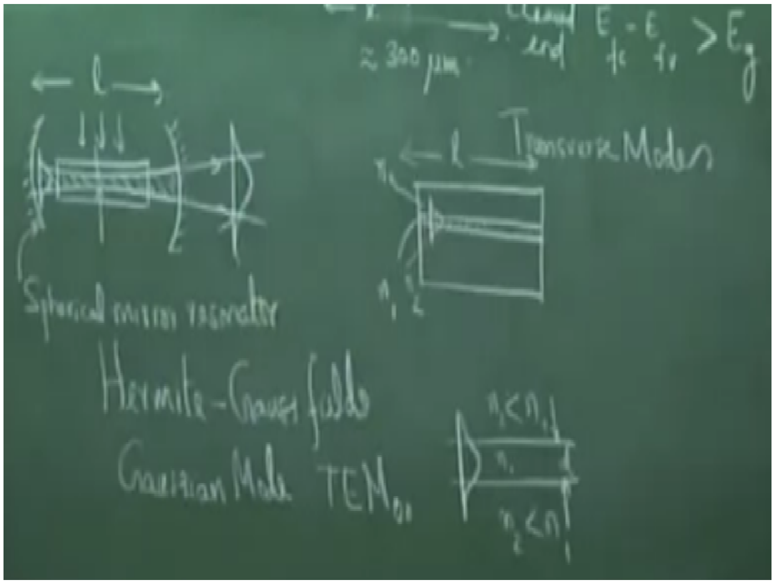

Therefore, the laser would look like this. So you have the active medium. I am just again drawing rather than showing there. So you have the laser beam, which is going back and forth and a part of that coming out. So these are the two mirrors and this is the beam, which has formed inside here the rays which are going back and forth, if you have spherical mirror, you can show that in a spherical mirror resonator.

You can show that most of the resonator are Hermite-Gauss fields or Laguerre-Gauss fields. The fundamental mode of this family, Hermite-Gauss fields represents the whole family of modes. The fundamental mode of this is the Gaussian mode, which is the TEM00 mode. Those of you who are familiar, this is the transverse electromagnetic mode. The fundamental mode is TEM00 and this has a field profile, which is like this.

So what I am drawing here is the amplitude distribution and the same mode is coming out here. So a bulk laser has taken a spherical mirror resonator, typical Nd:Yag lasers are of this form. You have the mirror radius of curvature could be about 80 cm, 100 cm, is the radius of curvature. It is almost flat and the Gaussian beam forms the resonator mode and this is the active medium, which is placed, which is pumped.

If you see the semiconductor laser, let me draw again. Here also there is an optical mode, which is formed. The mode here is determined by the optical wave guide, recall that this active region here has a higher refractive index than n1 and the cladding regions have refractive index n2, which is less than n1. So it is like an optical wave guide, a simple flat wave guide. So this is n1, this is n2, n2<n1.

The modes of this structure are actually cosine and exponential, but they also look like this approximately. The field inside is cosine and outside, it is exponentially decaying, you can follow the Maxwell's equation for this with the boundary conditions and you will see that they are cosine inside and exponentially decaying field outside. So the combined mode fields will also look like a Gaussian. This is not a Gaussian, but almost looking like a Gaussian.

So in this case, the modes, I am referring to modes as transverse modes. So the transverse modes. We will have one more mode, which is for the longitudinal mode or the transverse mode, are determined by the refractive index n1, n2 and the thickness t. Here is Gaussian with a raised width here, which is again determined by the radius of curvature of the mirror here and the separation l, so this is l. In this case, this is l, I have shown you here.

Although I have shown almost of the same size, a typical Nd:Yag laser l is of the order of 1 meter, big Nd:Yag lasers, there are compact lasers also. Diode formed solid state lasers now are quite compact, but still may be 10 cm, this l here is approximately 300 microns. This is from very small and very compact and this is big size, but I have shown these together just to bring out a comparison and those of you have studied laser physics, you can immediately relate the 2.

So this is regarding the structure. The basic structure has an active medium, which is pumped and there is a resonator. The resonator determines the modes of the structure, the modes of the laser. We will discuss the resonator a little bit more, but let me first discuss about the gain. With the gain medium placed in an optical resonator, let me first discuss a little bit more about this and then we come to the modes.

The interest basically the theory is very simple. The basic laser theory is quite simple, laser dynamics.

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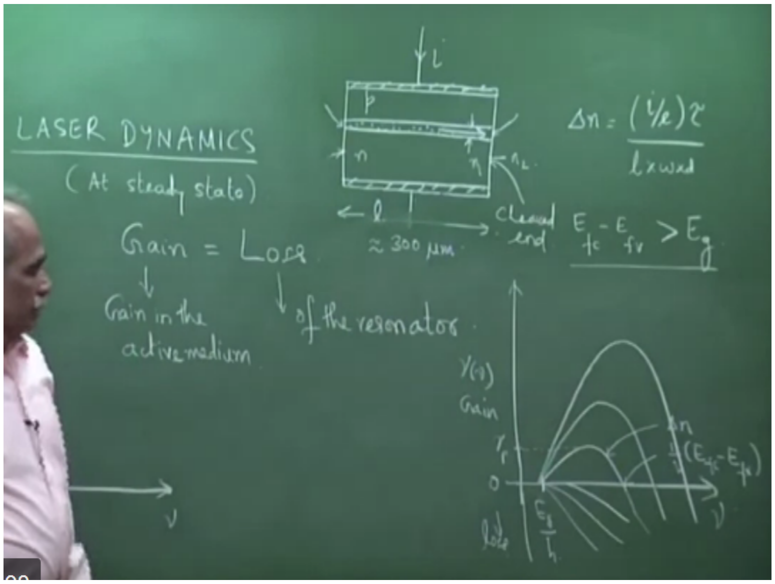

Laser theory at steady state, because there are transient analysis, which is involved. At steady state, the laser theory is just this study of gain = loss. This is all, the laser theory is very simple. Gain = loss. Gain here refers to gain of the active medium or laser medium, loss here refers to loss of the resonator or in the resonator. First let us discuss about gain. We have seen for a semiconductor laser and just for comparison let me also draw for the bulk laser.

This is mu versus gain coefficient gamma of mu. We have expressions for gamma of nu. So semiconductor laser, if you pump the laser so that this condition is satisfied, then we had worked out in detail that you have gain profile, which goes like this, then it becomes loss, starts approximately around eg. So this is for particular current or a particular delta x, some value of delta x. If you had not pumped, then the medium was absorbing.

Recall that the medium was absorbing and therefore it had some curve like this or maybe it was going like this and as I pump, it started going like this. What I am showing is, here it is 0, therefore this side it is loss, loss coefficient and that side it is gain, this side it is gain means when gamma is greater than 0 is gain and gamma is less than 0, it is loss. You have not pumped, then the medium was absorbing, we have discussed this in detail.

And the absorption coefficient is varying like this starting from eg and increasing energy. If you start pumping and you are able to maintain this, then the gain will become positive, so this value here corresponds to, if I plot this mu, then this is eg/h and what was this value, here energy corresponds to efc-efv, therefore 1/h*efc-efv. So the bandwidth was this region. This region we call amplification bandwidth, amplifying the frequency range over which we can get amplification and this is the p gain coefficient. This is gamma p.

We pump harder, that means if you inject more forward current, then this will go up and this will also go up because the separation is increasing. I plot for another value, so what I have plotted here is gamma as a function of delta n, different values of delta n and recall the expression here. So if you know what is the current that you are sending, 50 milliampere, 100 milliampere, then you can immediately calculate delta n, because e is known, this is the combination time.

These are the dimensions. So d is this thickness, l is this 1 and w is the width from the front side.

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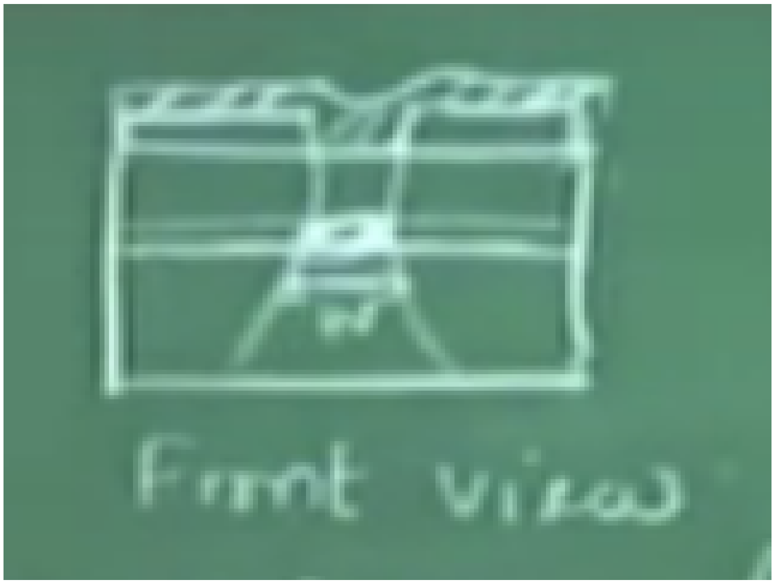

So recall that let me show briefly here the front side, then you have. If I place the electrode width blocking layer here silica, then this is how the carriers will flow and therefore this is the region where you will have gain, in the front view. This is longitudinal cross section. The light is coming like this. In this case, light is coming through the sides. The light is coming here. So I have this field distribution, which is coming up. So this width here is w, typically 5-10 microns.

So you can substitute the values and find out the values and find out what delta n. If you take for materials, then this delta n is of the order of 10 to the power of 17/cc, actual numbers. You can put some numbers for laser amplifiers and that is of that order delta n corresponds to 10 to the power of 17/cc. So as you pump the gain available increases, gain bandwidth increases.

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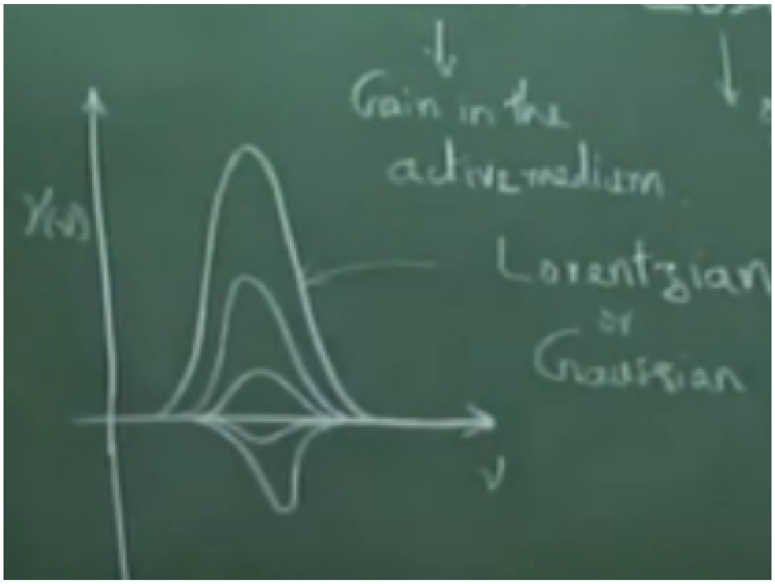

Those of you who have done laser physics course, you would know that in this case also when you have not pump at the medium, you have a loss, which is characterized by this and you start pumping then this increase becomes smaller and then beyond a certain pumping region, you will have the gain curve showing this. Usually symmetric in the case of atomic system, the same thing, gamma of mu as a function of mu.

These state normally correspond to either Larentzian, which corresponds to homogenously broadened medium and are Gaussian. So homogenously or inhomogenously broadened medium you will suspend of. So they are showing because they are identical. What are these curves, these are gain curves for different pumping power, different pump power. Here it is gain curve for different injection current and therefore different delta.

They are identical. If you have studied one laser system, that is why I showed that comparison. There is also mirror, here also you have mirrors, no separate bulk mirror, but the mirror is formed by the cleaved ends of the semiconductor layers. So gain = loss, we know what is the gain. What is the loss, loss of the resonate. What kind of losses we have.

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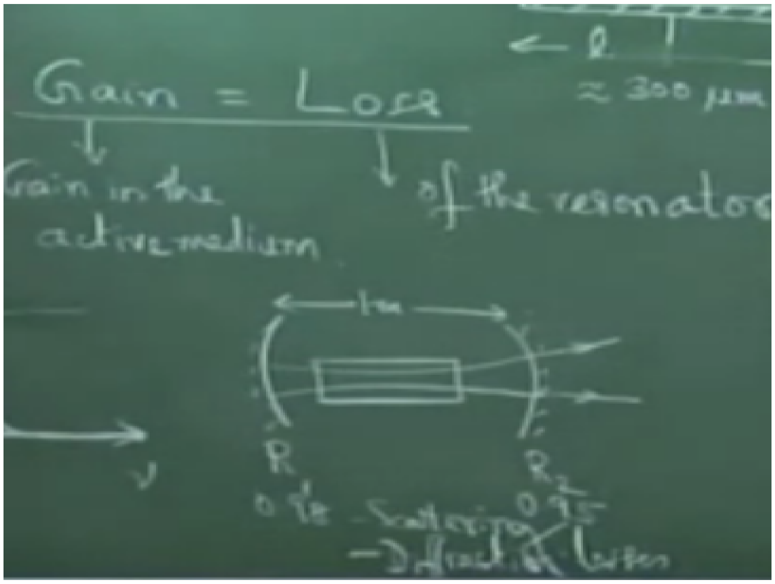

If I take bulk resonator here, loss in the resonator, the beam is going back and forth, the mirror have a finite reflectivity of r1 and r2, may be almost 1 or may be 0.98, 98% reflecting and this is 95% state. I have put numbers just as an example, r1 and r2. This is the separation, maybe 1 meter and it is the medium, the beam is going back and forth in the medium. When it goes back and forth in the medium, there are 2 types of losses, which you encounter.

1 is catering losses in the medium. The medium, there can be scattering because of inhomogeniety, there can be scattering loss in the medium and the second loss is because it is a finite beam, usually there is a defraction loss, so you have scattering losses and defraction loss and losses due to finite reflectivity of the mirror, it is 95% reflecting, means 5% is going out, this 5% is your useful output power.

But as far as the resonator is concerned, resonator is losing 5% from this side, 2% from this side. So the mirrors are also losing and therefore you can show that the loss coefficient, I will not go into the details of the derivation, but the resonator loss coefficient comprises of alpha s + alpha m, this is primarily due to scattering and defraction and this is due to mirror. So this is = alpha s + 1/2ln 1/r1r2. You can solve this; I leave this as an exercise.

This is a simple derivation, should show that the mirror loss is 2l*n. You can see that if the reflectivities were 1, that is 100% affecting, r1=1, r2=1, ln1 is 0, so there is no loss due to mirror, but reflectivities cannot be 1 and we do not want it also 1 because we need useful output coming. So this means the resonator loss. We have already derived loss coefficient for expression for the gain coefficient. So if equate gain = loss, that is it, you get the expression for gain coefficient.

Gain = loss gives you the laser dynamics. What is this gain = loss? Let me erase and explain again, very quickly just recalling the basic laser physics. I am sure most of you have done. For those of you who have done, it is just a revision and those who have not done, please refer appropriate books. So if I plot now.

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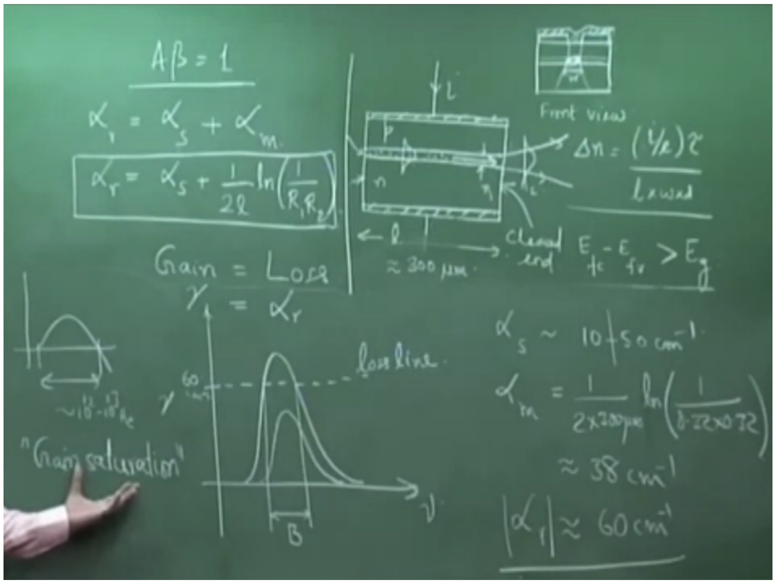

For example, let me give you some numbers in case of semiconductors. In the case of semiconductors alpha s is of the order of 10-50 cm, the scattering and defraction losses is of the order of this. Actually, there are no defraction loss because this is guide wave structure. In the case of bulk resonator, there is no guiding, because the beam is just going in free space inside the resonator, but here it is guided, the wave guide does not have an defraction.

So there is no defraction losses, but there are losses due to the wave guide scattering and imperfections at the boundaries and so on. So that is typically in this range and if I substitute this alpha m=1/2*300 micrometer in here* ln and substitute this 1/0.32*0.32 and you will see that this is approximately 38 cm inverse. You calculate and see that it is about 38 cm inverse. Almost similar order and therefore the total resonator loss, alpha r is approximately 38 and 22.

Let me take somewhere in between, just to make it a round figure is approximately 60 cm inverse. It would just get feel for the number, so what type of number that we are talking about, alpha r is and we want gain=loss, means what. Gamma mu must be = alpha r, which means to have gain=loss, you require a gain of about 60 cm inverse, if you want gain=loss to be satisfied. Now what is happening, if I plot this mode of alpha r.

This is actually gamma and alpha r is actually negative, -gamma, but if I plot mode of gamma here, then 60 is here, let us say this is 60 cm inverse. So this is shown, we are plotting this as a function of frequencies, the quantities here are generally independent of mu over the range of interest. The reflectivity had both alpha n and alpha s are almost independent of mu over the region of interest, what do I mean by region of interest?

Recall that the amplification bandwidth that we have calculated from numbers and I had said that this we had calculated approximately 10 to the power of 12 to 10 to the power of 13 hertz, the bandwidth for semiconductor laser. So we have also seen that this is very small compared to the light sequence itself, which is 10 to the power of 14 to 10 to the power of 15 and therefore over this small range of frequencies, this does not change.

You normally see in books that they show a dotted line like this and call this as loss line. So what is loss line, loss line is this value of loss in the resonator. If you start pumping the laser, the gain is here, gain is less than loss, so the laser cannot leave. If you pump harder, then you could. For another pump power, you may have the gain curve exceeding the loss curve, which means for these frequencies here over a bandwidth b, you have gained more than the loss.

This is the condition for starting of the oscillations. You call the electronic oscillators which has the Barkhof criteria, abeta = 1, when oscillating or -1, a is the amplification factor, beta is the feedback ratio. So abeta = 1, but at the time of starting oscillations, abeta should be greater than 1 and then due to saturation, non-linear saturation, this will come out to be 1 at steady state. This is how the electronic oscillators work.

Exactly like this, that as you pump harder, this gain will exceed the loss line, but due to gain saturations, this is the dynamics. Actually gain saturation is the dynamics. I would urge you to understand this very clearly, but I do not wish to digress too much to explain to you what is gain saturation, but gain saturation simply means whenever the gain is larger, which will be pulled down by the dynamics of the system, this will be pulled down.

What do I mean by dynamics? I do not want to get into, but alright let me very briefly explain.

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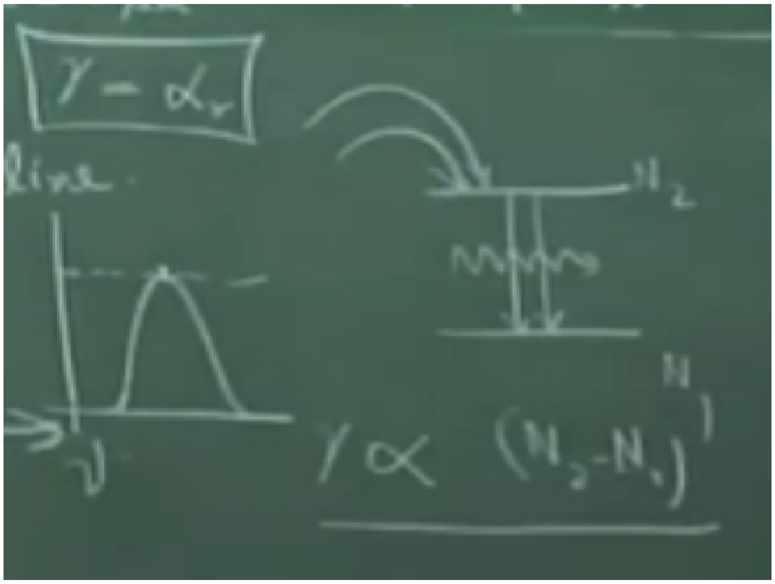

We cannot go so much into. We pump harder, which means we create a larger population inversion. It is easy to understand here, that is why I am showing you. Therefore, n2-n1 becomes larger, which means gain becomes larger. When gain becomes larger, more laser radiation intensity increases. When laser radiation intensity increases here, it will bring down more n2 downwards and therefore n2-n1 decreases. We see the gain coefficient gamma is proportional to n2-n1.

If the laser intensity in the cavity increases, it will bring down more of atoms downward, more stimulated emission. When more stimulated emission occur, n2 decreases and therefore n2-n1 decreases and therefore the gain is pulled down. In other words, at steady state, what I have drawn here is, if I independently show you the loss line, and independently show you the gain curve, this is it, but when a laser is oscillating in steady state, the graph is this.

This is the loss line and this is the gain curve, that is when a laser is oscillating in steady state gamma = alpha r, always, irrespective of the power output of the laser when a laser is oscillating in steady state, the gain coefficient is = loss coefficient. That is why I have written gain=loss. You have to understand it more how this is. This is called gain clamping and gain is always clamped at the edge.

Depending on homogenously broadened or inhomogenously broadened there are what are called hole burning in the gain profile and so on. Let me not go into this.

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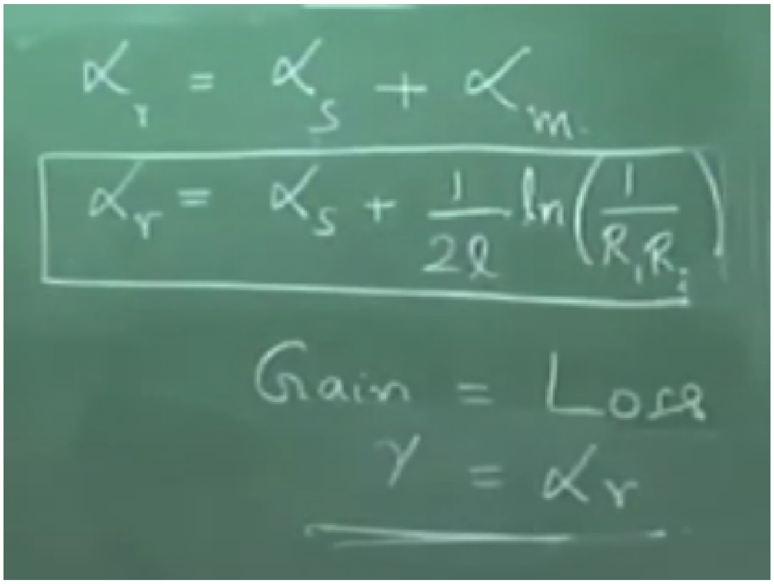

$$\alpha_r = \alpha_s + \alpha_m$$

$$\boxed{\alpha_r = \alpha_s + \frac{1}{2l}\ln\left(\frac{1}{R_1R_2}\right)}$$

Gain = Loss

$$\gamma = \alpha_r$$

So the main point is this, when a laser is oscillating, gain=loss or gain coefficient=loss coefficient. This is as far as the amplifying medium is concerned. So the amplifying medium is the active medium, which when pumped appropriately gives you gain. Now the second component is the optical resonator.

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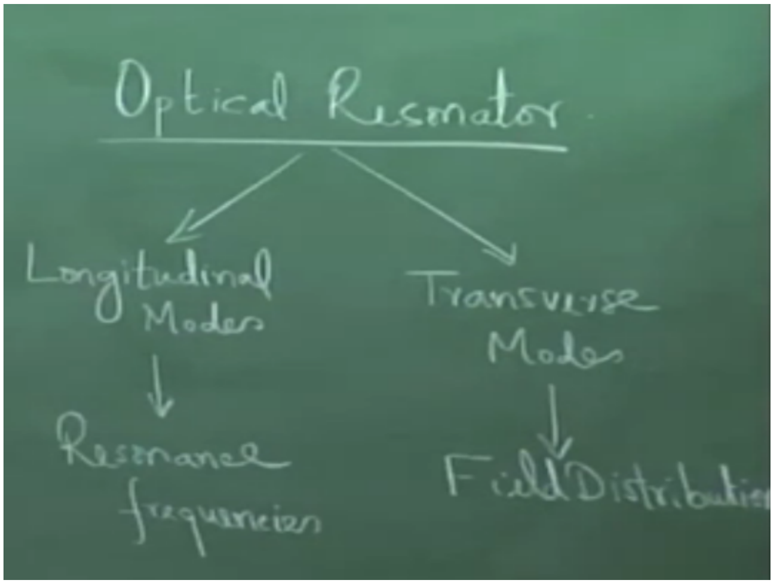

Optical Resonator

Longitudinal Modes

Resonance frequencies

Transverse Modes

Field Distributi

The optical resonator determines to the, that is the longitudinal modes and the transverse modes. Longitudinal modes refer to resonant frequency. I will explain in a minute. Transverse modes refer to field distribution or the modes. First let me talk about the longitudinal modes or the resonant frequencies.

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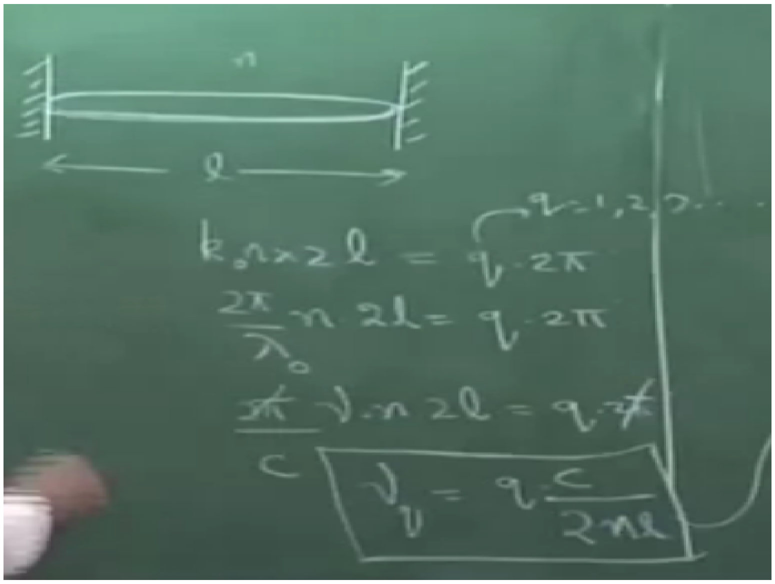

$$k_0 n \times 2l = q \cdot 2\pi \qquad q = 1, 2, 3 \ldots$$

$$\frac{2\pi}{\lambda_0} n \cdot 2l = q \cdot 2\pi$$

$$\frac{\cancel{2\pi}}{c} \nu \cdot n\, 2l = q \cdot \cancel{2\pi}$$

$$\boxed{\nu_q = q \frac{c}{2nl}}$$

For simplicity, I will show you a plain mirror resonator. This l here when light goes back and forth inside the resonator is going back and forth, only those frequencies, which satisfy round trips = integral multiple of 2pi will build up because any light, which is coming back after 1 round trip, if it adds in phase with the light, which is there or which is generated, then it will start building up and therefore the condition is round trip phase is K not * 2l =, 2l because round trip, must be = integral multiple of q * 2pi.

If there is a medium of refractive index n, then you have to write K not * n, if there is a medium of refractiveness. So 2pi/lambda 0 *n*2l=q*2pi. This lambda 0 I can write c/mu, so this is 2pi*c*mu*n is the refractive index, q is an integer, q=1, 2, 3, ..., q*n*2l=q*2pi. So 2pi and 2pi goes, so what you have left with this mu q=q*c/2nl. These are the resonant frequencies. The resonance frequencies are allowed frequencies, which build up inside the resonator.

The resonator supports certain discrete frequencies, which build up inside the resonator and they are given by the resonance frequency. I have added a suffix q to say that it is of the q-th order. So if q = 1, it is mu1, so what is this, what we are showing is qr plotting on the mu axis, only certain frequencies are allowed to build up. These are called, this is mu1 or mu q, mu q+1, mu q+2, mu q+3, and so on.

The resonator determines which are frequencies which will build up inside the resonator because of the round trip phase matching condition, these are the resonant frequencies. Now let me complete the discussion of resonant frequencies.

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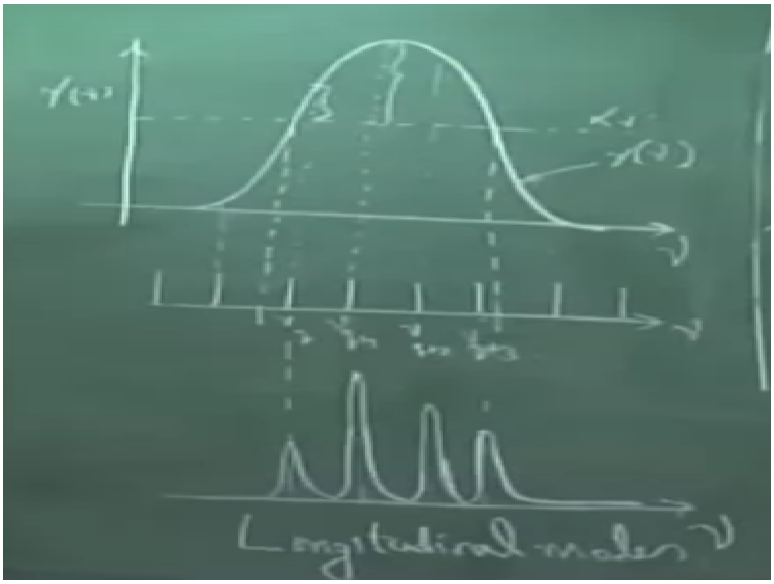

I just now told you that for this is the gain curve, gamma of mu, this is axis mu, and if the loss line is here, alpha r, then all the frequencies which are in this range, they have gained more than loss, however, this amplifying medium has been placed inside an optical resonator, the resonator allows only certain frequencies, so I just keep this here, which means resonator stays only these frequencies can build inside. This says all the frequencies in this range have net gain.

However, resonator phase, only these frequencies are the ones, which are build up inside the resonator, mu q+1, mu q+2 and so on and therefore only these frequencies will be there in the laser output. If you see the output of the laser, you will have under a high resolution optical spectrum analyzer, then you will see an output which looks like this. This is the output of an optical spectrum analyzer.

The laser output, if you feed it to an optical spectrum analyzer, which means it is resolving, and you will see output like this. The strength of a mode is proportional to the difference in gain. So you see if I take it here, it will intersect here, so this is the additional gain over loss. For this 1, all these details I will not be able to cover, here it is the part of the laser course, but it is proportional to the difference, gain – loss, the strength of these modes.

Because this is bigger than the other 1 and so on. Other frequencies, although the resonator allows other frequencies, please see this. Resonator allows all frequencies which are discrete; however, for these frequencies the gain is smaller than loss and therefore, they do not build up inside a laser. Only those resonant frequencies for which gain is greater than loss, build up inside the resonator and in the laser output, you will see this.

What you see are called the longitudinal modes of a laser, so these are the longitudinal modes. Normally if you take a laser there will be plenty of longitudinal modes. Why I am bringing this concept is, we are next going to see special laser structures and devices, which is choose only 1 of them to make it single longitudinal mode laser and that is why we have to know what is in longitudinal mode.

We quickly come to the field distribution and then we will stop. We have to make a small turn. The transverse mode, I have already mentioned about the transverse modes.

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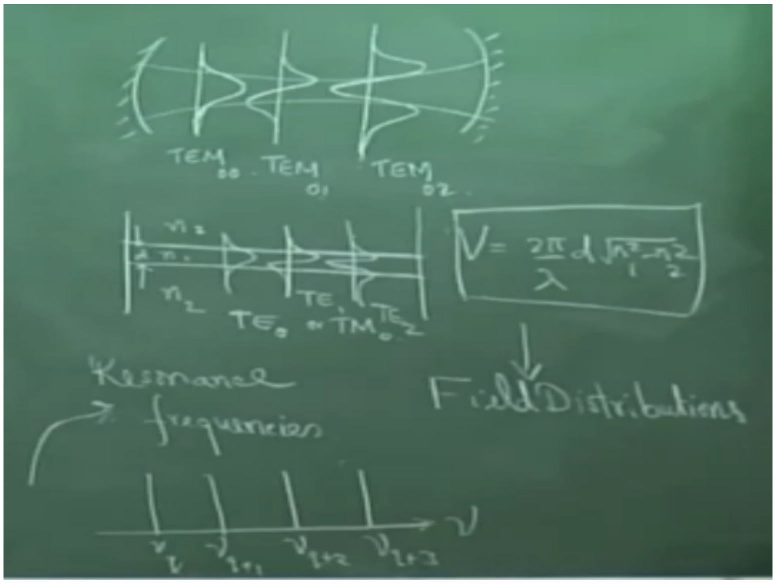

I have already talked about this that our field distribution, the transverse field profile. If you take a spherical mirror resonator, you can show that Hermite-Gauss field distributions, which meets the fundamental mode looks like this, the second mode looks like this and the third mode will have a field distribution approximately like this. So this TEM00, this is TEM 01. It depends on x direction or I have shown in 2D, so I can write 01.

This is TEM 02 because there are 2 0 crossing, there is 1 0 crossing, that is why 1, 2 0 crossing that is why 2, no 0 crossing. This is not 0, this is actually going to infinity. It is asymptotically showing down. There is no 0 crossing. This is for a bulk laser. In a semiconductor laser, it is a wave guide, which determines what are the most it can support. So this is n2 as before, this is n1, and this is n2. The fundamental mode here is this. So it is either TE or TM, there can be T.

These are TEM, this is TE or TM. So TE0 or TM0. I do not want to again go into this modal details, but you can find out TE0 or TM0. TE1 looks the same way. So this is TE1 or TM1, TE2 almost the same way and so on. The point is the mode field profile and how many modes will be there is determined by the optical wave guide. That is what is the difference between n1 and n2 and what is the thickness d here.

Those of you who have studied optical wave guide, you familiar that there is a v parameter. This is defined by 2pi/lambda *d * square root of n1 square –n2 square. It depends on the v value, for v , pi it supports only 1 mode, v between pi and 2pi it supports 2 modes, and so on. What is important to recognize these, transverse modes refer to field distributions by an appropriate choice of n1, n2, nd, it is possible to make this oscillating only on a single transverse mode.

It is possible to make it oscillate on a single longitudinal mode by appropriate measures. We will see what are these appropriate measures and it is possible to make it oscillate on 1 single transverse mode. A laser that operates on 1 single transverse mode and 1 longitudinal mode is called a single frequency laser.

So we will talk about single frequency laser. Single frequency laser does not mean it has only 1 frequency, there is no source, which is strictly monochromatic and 1 frequency, but single frequency laser means, it operates on a single transverse mode and a single longitudinal mode. Let me stop here and in the next class, we will directly start with semiconductor lasers. We have covered almost all the basics, everything on the board.

So next class, I will start the talk on PPT because we will now look at structures and designs and characteristics. There is no point in spending time on drawing the structure. So we will go over to PPT. We come to the quiz, very simple quiz, very quick. Ready all of you are ready?

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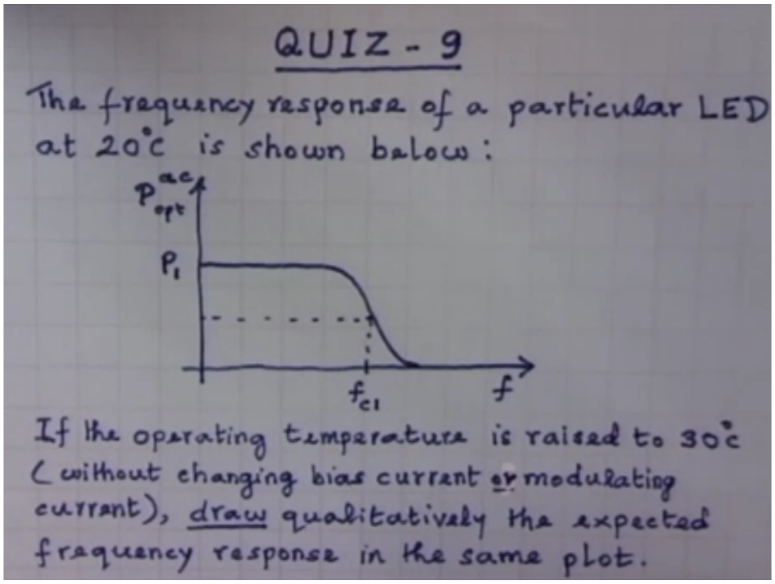

QUIZ - 9

The frequency response of a particular LED at 20°C is shown below:

If the operating temperature is raised to 30°C (without changing bias current or modulating current), draw qualitatively the expected frequency response in the same plot.

The frequency that forms of a particular LED at 20 degree centigrade is shown below. What is shown is PAC optical versus frequencies, that normal frequency response. If the operating temperature is raised to 30 degrees centigrade without any other change, I have written those brackets, you do not have to read. Without any other change, only temperature has been raised. Draw qualitatively the expected frequency response in the same plot.

Which means first please draw this plot, and then on the same plot, qualitatively draw the expected frequency response. At a higher temperature, which is 30 degree centigrade, what would be the state of the frequency response. Please draw the given curve and then on the same plot draw, the expected frequency that is on variation. That is AC optical power, we have discussed in the last class versus frequency.

As we know, the cut off is defined when PAC drops to half its value. So a typical FC1 is the cut off which is shown. So at a higher temperature, this plot qualitatively, what type of variation is expected. No explanations are required. Just plot.