Semiconductor Optoelectronics
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Lecture - 26
Semiconductor Optical Amplifier (SOA)

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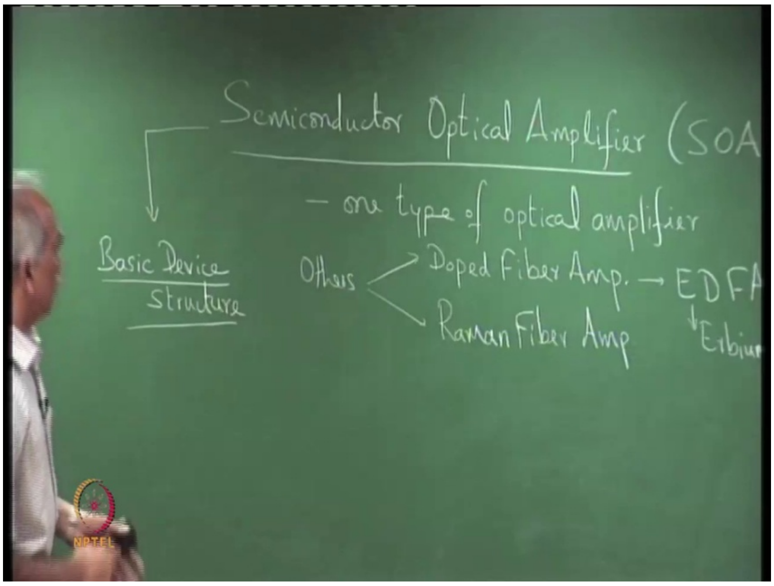

Welcome to this lecture on semiconductor optical amplifier. So, today in this class, we will see at another device, which is the semiconductor optical amplifier, or widely used abbreviation as SOA, semiconductor optical amplifier. This is one type of amplifier, one type one of the types of optical amplifier, so a type of optical amplifier. Other commonly employed optical amplifiers include doped fiber amplifiers; so, doped fiber amplifiers and Raman fiber amplifiers. Raman fiber amplifier makes use of the Raman effect, which is a non-linear optical effect, and widely used doped fiber amplifier in optical communication is the EDFA; that is erbium doped fiber amplifier; Erbium doped fiber amplifier, is a widely used amplifier, in optical communication. Let us first start with the basic structure of this device. So, the basic device structure, the basic device structure of this amplifier, is almost similar to the last device that we have discussed; that is the wave guide configuration of electro absorption modulate. The electro absorption modulated in the wave guide configuration, is similar to this in structure, but of course, the operations are different. So, let me show the device structure.

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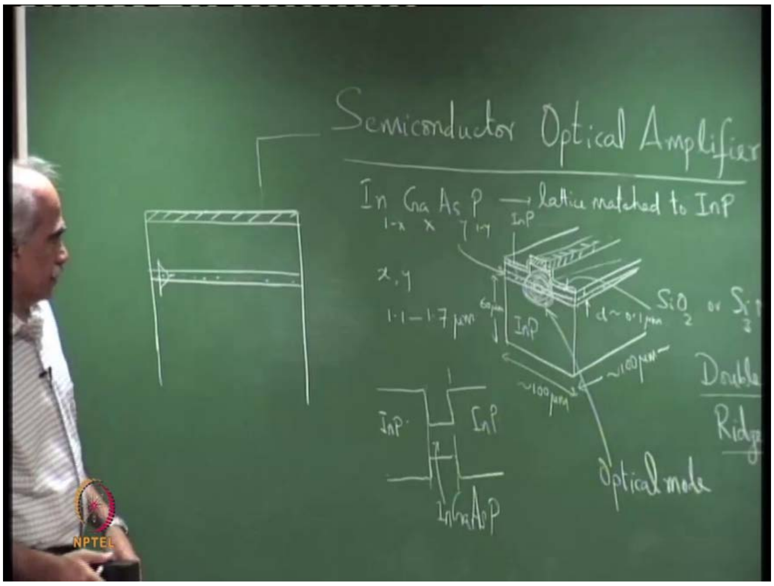

This is the substrate, the active layer, which has the cladding layer, this is a ridge wave guide structure as before, and then we have an insulating layer, and then the metal for contact. So, this region is the metal for contact, and this is the active region, and this is the substrate indium phosphide, widely used material in optical communication window, is the indium one minus x gallium x, that quaternary compound arsenide phosphide p 1 minus y. So, this is because depending on the composition of x and y. One can cover the entire range approximately from 1.1 to 1.7 micrometer, for amplification as well as for laser action. So this the quaternary compound, which is lattice match to indium phosphide, so this is lattice matched to indium phosphide over certain range of x and y values. So, this is the cross section, so the device in three d view will look like this. This layer is also an indium phosphide. So, indium phosphide, indium phosphide, metal for contact on top, this is the metal contact, and this is the layer of dielectric insulating layer, gaping layer. So, usually this insulating layer is SIO 2, or some time silicon nitrite.

Typical dimension would be of the order of 100 to 200 micrometer here, length is again may be several hundred micrometer, the length, and height is so also approximately, so this could be 300 to 1000 micrometer, and this height is approximately 60 micrometer. And this thickness here of the active layer, the thickness of the active layer here, this thickness d is of the order of 0.1 micrometer. So, it is a double hetero structure, so it is a double hetero structure d h, double hetero structure ridge wave, so ridge wave guide configuration, as in the case of electro absorption modulated. So, we can see that indium phosphide has a larger band gap. So, if you have to plot the band gap of the hetero structured, so this is indium phosphide on both the sides, indium phosphide, and this intermediate layer is the active region, which is indium gallium arsenide phosphide. So, the basic structure is double hetero structure ridge wave guide configuration. The ridge is used for lateral confinement, the refractive index here, so if you see longitudinal cross section of this device, then it would look like this.

If you see the longitudinal cross section, then this the metal contact, and this is the active layer, and of course, this is the substrate. And the optical mode travels here, because refractive index of this region which has a lower band gap, is higher compared to the refractive index of indium phosphide. And therefore, this acts like an optical wave guide, but of we did not have the ridge, there would have been no confinement, no transverse confinement, and light would have been confined of course, in the vertical direction to this plane, but there was no confinement in the transverse direction, and therefore, we use this ridge which confines the optical field to this region, so the optical field. So, what I have schematically illustrated, is the optical mode, the optical mode is confined, otherwise that would have been no confinement, that is why we used the ridge wave guide structure.

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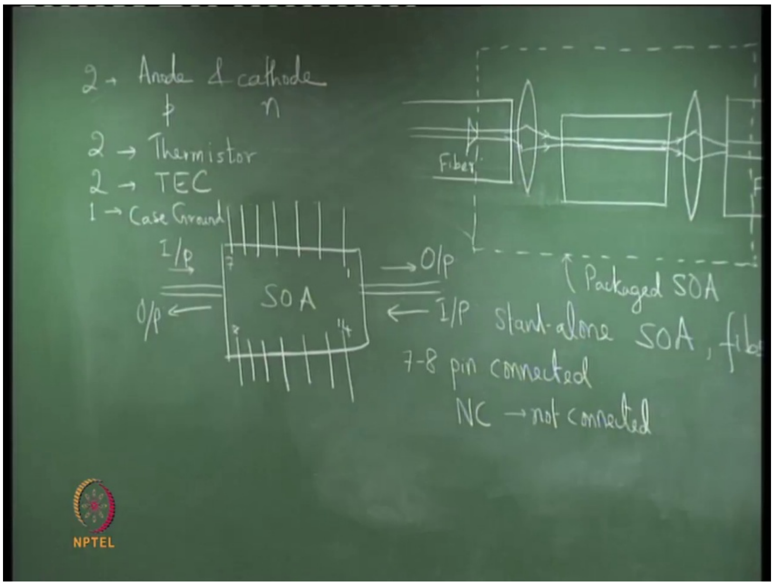

So, the complete device, package would be something like this, so we have wave guide here, the SOA amplifier, again a schematic, and there is a lens, and we use optical fiber buck couple to this. An optical fiber, which is sometimes it can be buck couple directly, there is no need of this less. So, the optical fiber pig tailing, and pig tailed optical fiber which focus the light beam into the active region. And the package device will look like this, optical fiber, optical fiber, and this whole device. So, let me erase these structure here, the basic structure, and the whole arrangement is encapsulated, it is permatically sealed, so that the device. So, this is the package SOA, which is fiber pig tailed SOA. So, this is a typical arrangement of a standalone SOA optical fiber amplifier, which is fiber pig tailed.

Let me show you the device, a practical device, a fiber pig tailed stand alone SOA, which will contain, the consist for the device, the semiconductor or device, and an arrangement to couple, buck couple or to couple from optical fibers, so that the device can be used as standalone amplifier. So, let me show you the device. So, the typical device would look like this, here is the chip, the SOA chip with fiber pig tailing on both sides, because the amplifier we need. The amplifier is a device which has an input and output, so here is a block diagram of an amplifier. So, you have an amplifier which has an input and an output. So, this is the block diagram of an amplifier here. So, exactly like that, the input is though an optical fiber, which is pig tailed to the chip, the semiconductor chip, and these are micro lenses, micro lenses which help in focusing that is minimizing the insertion loss of the device.

So, there are two fiber at the other end, and the entire thing is packaged in this, so it would a typical amplifier would look like this. So, here is the chip, and this is fiber pig tailing. The whole thing is mounted on a driver here. If there is a, the device is a fourteen pin butterfly device. So, as we can see it is a fourteen pin butterfly device, which means we have. So, this dotted line is this block here, and it is a fourteen pin butterfly device. So, we have 3 4 5 6 and 7, 8 14, and this is the fiber pig tail, so input and output, so this is the SOA chip. Usually there is a marking which shows the terminal number one, and then it is counted in this direction, so this is 1 2 3 4 5 6 7, and terminal number 8 is here 9 10 up to 14. So, this the pin configuration it is a fourteen pin device as you can clearly see.

Not all the pins are useful, usually many of several pins are not connected, and SOA typically has about 7 to 8 pins connected, and the rest of pins are not connected NC; the typical abbreviation use NC not connected. The pins which are usually connected, or the connection that are repaired or for the anode and cathode; that is connected to p and n side of the device, so two terminal for this two terminals would be there for thermister, because the device is semiconductor chip, is temperature sensitive, so one has to maintain temperature. So, the temperature change is sensed using thermister, and two terminal are used for TEC cooler; that this thermo electric cooler. So, two terminal, and one terminal is generally used for case ground. Most of the terminal are rest of terminal, are usually not connected.

So, this is a device as you can see clearly, the fiber, the input, the fiber is ended with a connector, this is a typical FCPC connector, here FCPC connecter, and there are two connectors at the two ends. Either this could be input or that could be input, the SOA is an amplifier as you can see, we could input the weak signal from here, and get an amplified signal from here, or we could also input from this side, it is possible, it's an amplifier, that you could also use this as the input and this side as the output. So, the amplifier is a device, where you can put input and output, and this is a typical amplifier device. A cable normally goes from the mount, which is connected to a driver. A separate driver unit is normally provided where you can set the temperature, the current limits and, so on. So, let us now see little bit about the amplifier characteristics, and what are the characteristics that are of interest to us.

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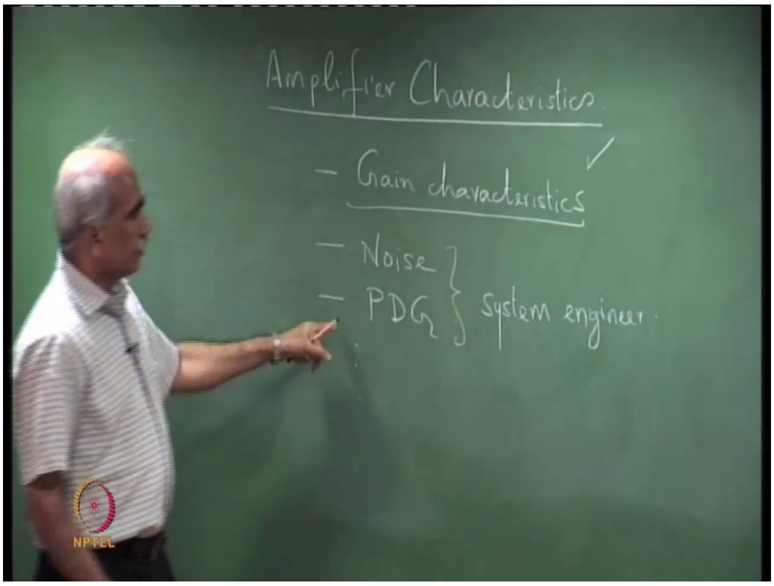

So, let see the amplifier characteristics, primarily these are gain characteristics, and noise. Also there are other parameters which are used; for example, polarization dependent gain PDG and so on. There are several characteristics, which one can study with respect to this amplifier. We are primarily with focusing on the gain characteristics, noise and PDG are more important for system engineers, or a design engineer, but let us first look at the gain characteristics, and this will be discussed in at another course; the noise and PDG characteristics, and therefore, our focus will primarily on gain characteristics.

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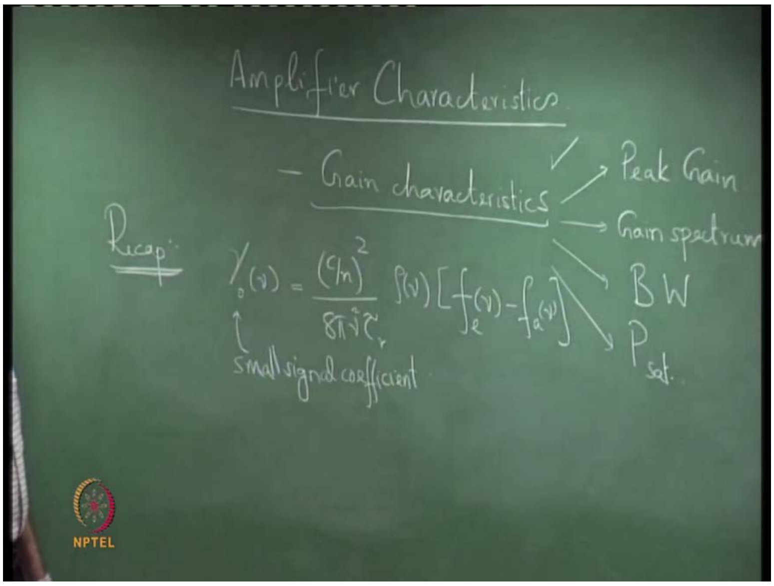

So, the gain characteristics include peak gain, gain spectrum, there is the range of wavelength or frequency, over which gain is present, the bandwidth, gain bandwidth. And an important parameter, which is p saturated; that is saturated output power, saturated output power, optical power output. So, let us see one by one these characteristics; recall recap that we have in an earlier class, we have obtained an expression for the gain coefficient gamma 0 of mu, the small signal gain coefficient, as c by n square divided by 8 pie mew square by tau r into rho mu, the optical joint density of states, tau r is the relaxation time, c is the velocity of light, n is the refractive index of the medium into f e of mu, probability of emission minus of a of mu. The small signal gain coefficient with, call this as the small signal gain coefficient, because we had assumed that this is independent of the intensity of radiation, signal coefficient, which is not really true at higher power, small signal gain coefficient.

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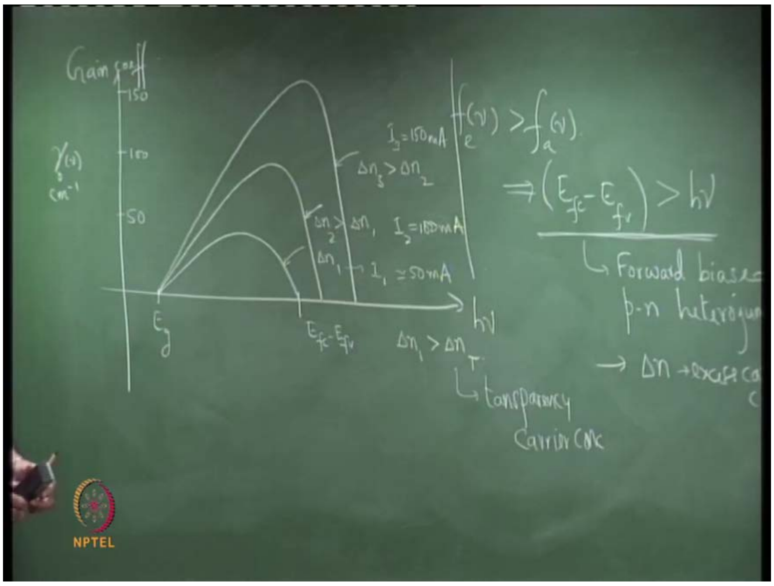

All the parameter in this are positive, all are positive, only this is the parameter which can be negative or positive, depending on whether the probability of emission is greater than the probability of absorption or not. So, to have f e of mu greater than of a of mu, we have seen that the necessary condition is E f c minus E f v, the separation between the quasi Fermi levels should be greater than h mu. And the one of the methods used in achieving this, is by the use of a forward biased p n junction, forward biased p n hetero junction. We have discussed this already forward biased p n hetero junction. And the separation between them, is a function of forward bias current, because the current the forward bias, induces a delta n excess carrier concentration, which results in separation, increasing the separation between E f c and E f v. And at certain values of delta n, one can have gain coefficient positive; that is f e of mu greater than f a of mu. So, if we plot this gain characteristics which we have seen, so h mu hear, for a certain value of delta n, then this is let's say some value of delta n 1, which is greater than the transparency carrier concentration.

So, delta n 1 is greater than delta n t, this is the transparency carrier concentration. Then we gave gain, this is gain co-efficient, gain coefficient gamma, gamma 0 of mu in centimeter inverse. Let me also give some typical numbers. So, this point is e g, so this is energy axis h mu, and this point is E f c minus E f v. For this injection current an injection current, which give carrier concentration delta n 1. If we increase the carrier concentration, then this curve would move like this, and E f c minus E f v gets pushed forward. The separation between then increases, and therefore, the gain coefficient increase, at even a larger value. So, this is for delta n 2, which is greater than delta n 1, and this is delta n 3, which is greater than delta n 2, may correspond to three different currents, so I 1. So, delta n one corresponds to a forward bias, forward current I 1; say 50 milliamphere. I am just taking some typical numbers, and this is for I 2 is equal to 100 milliamphere, and I 3 is equal to 150 milliamphere. These are the typical currents used in SOA to achieve gain, gain in and SOA.

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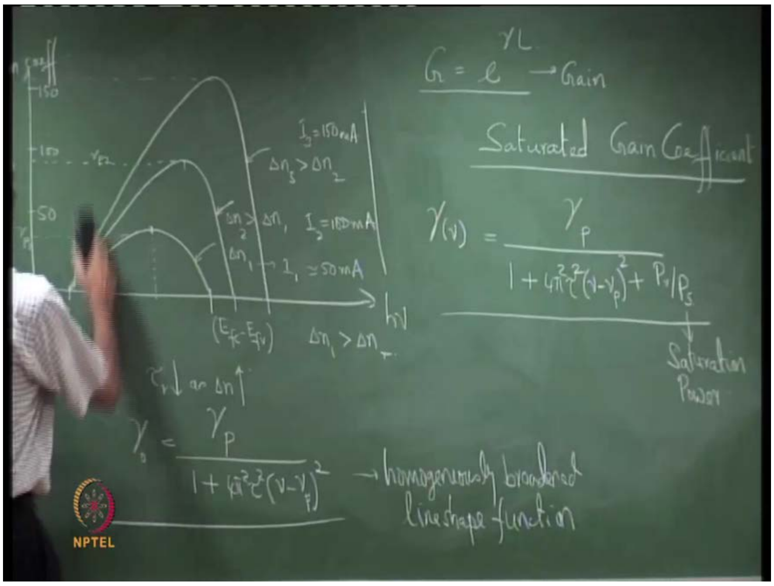

So, the point here is or we can see is as you increase the forward current, through the SOA. Please recall that it is a device, which is a p n device, it is p n junction device, as you increase the gain coefficient as you increase the current through the device, the gain coefficient moves up, and E f c, separation between E f c and E f v moves forward, which means the bandwidth, the frequency range over which the amplification can takes place increases. So, this is what we see; that the frequency range increases, and the peak gain also increases. The frequency range increases, because the separation between E f c minus E f v get increases, and the peak gain increases primarily, because tau r, which is in the denominator of that expression, decreases as delta n increases. The access carrier recombination time decreases as delta n increases, and therefore gain coefficient increases. The peak gain coefficient refers to peak value, so this is the peak gain coefficient. Here this is gamma p 1 gamma p 2 gamma p 2 and gamma p 3. So, this is the peak gain coefficient. So, now we know, what we refer to as peak as gain coefficient please recall that the gain coefficient or a given device, gain is e to the power gamma into l, and the peak gain correspond to the e to the power gamma p into l.

So, this gain, and gamma is a gain coefficient; this is gain. So, both the gain and the bandwidth increases with increasing forward current. So, the second thing which we have to discuss, is saturated gain coefficient. The gain coefficient obtained in the earlier expression, as the earlier expression was independent of the intensity, intensity of light inside the laser cavity; that is inside the active region, but an actual analysis will give that the gain coefficient gamma of mu, depends as gamma p divided by 1 plus. The small signal gain coefficient gamma p, the small signal gain coefficient gamma 0, can be expressed as gamma p divided by the peak gain coefficient divided by 1 plus 1 plus 4 pie square tau square, into mu minus mu p the whole square. If we assume that the medium is characterized by a homogenously broadened line shape function. We will not be going into the detail of this, because this is the part of a laser course, homogeneously broadened line shaped function.

There we can show that, the gain coefficient depends in the form a Lorenzian, the gain coefficient is given in terms of a Lorenzian, approximated. This is not exactly a Lorenzian, but this can be, if we assume that the gain is, the medium is characterized by a homogenously broadened line shape function, than one can represent the gain coefficient as gamma 0 equal to gamma p divided by 1 plus 4 pie square tau square into mu minus mu p, where mu p is the frequency corresponding to the peak gain coefficient, toe is the relaxation time or carrier recombination time, and gamma p is the peak gain coefficient. However, as the intensity of or power inside the semiconductor increases, then the expression changes to the form 1 plus 4 pie square tau square into mu minus mu p whole square plus p at mew divided by p s, where p s is called a saturated power, saturation power. So, this is the expression, if we consider that the gain coefficient also depends on the intensity of radiation. Let me just discuss this a little bit more, why this saturation came into effect. We will not be able to go into derivation in this course, but conceptually we can see why this saturation occurs.

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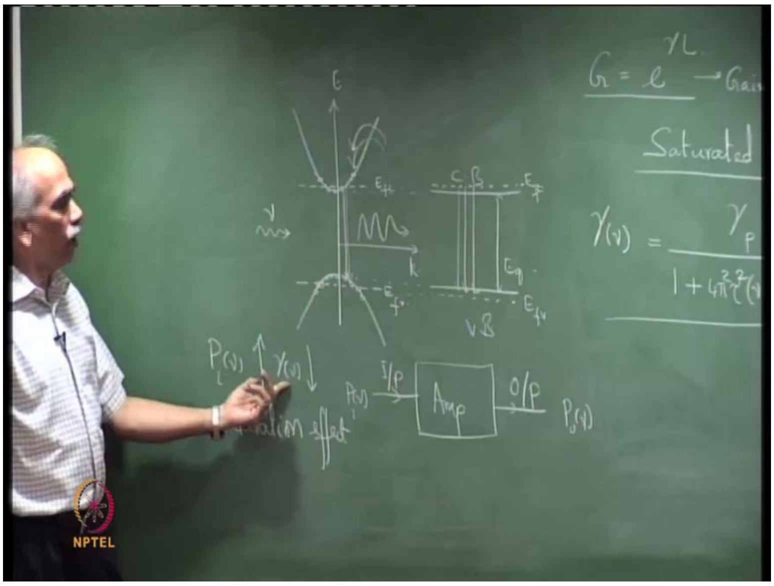

If we recall the e k diagram, if we have a pumping mechanism, through which we pump large number of electrons to the conduction band. So, here is the equivalent conduction band. This is the c b conduction band, and this is valence band, this is the e k diagram picture, and we have large number of holes here, this represent the active region, where you have simultaneously large number of electron, and large number of holes, and the Fermi levels. So, this is E f c and E f v; the quasi Fermi levels, E f v, this is e g; the quasi Fermi levels E f c and E f v. A radiation which is passing through the medium, will induce stimulated emission, and stimulated emission will dominate when E f c minus E f v is greater than h mu and you get amplified radiation coming out.

as the density of radiation, as the input here, the density of input radiation increases, it will bring down more and more electron downwards in the process of amplification, and therefore the carrier concentration in these bands drop down, as the intensity here or the input power increases, as the input power to the device, so this is the amplifier, and here is the input and output. As the input power, so this is p mu, which is the input p i of mu and p out p o of mu. As the input power signal power increases, it will bring down more and more electrons, it will lead to higher levels of recombination’s here, in the process of amplification, and in the process the carrier concentration drops down. When the carrier concentration drops down, E f c will start coming down, E f v will start coming down, in other words the gain coefficient drops. So, as the input power p i increases the gain coefficient at that value drops down, and this effect is called saturation effect, for low power signal.

For low powers signals this is not an issue, because if the pumping is strong enough, then for low powers the amount of carriers which are recombining, will always be immediately made up of by the pumping. However, when the input power increases, than the carrier concentration in the bands decreases, leading to a lowering of E f c and E f v here, resulting in a smaller separation, and hence a smaller value of gamma. This is expressed in this expression here, saturated gain coefficient. We are not going in to the derivation of the expression, but as you can clearly see, that if this is nothing, but the small signal gain coefficient. So, I can write this as gamma 0 divided by 1 plus p mu divided by p s into. So, I take this, this term outside, this whole tern outside, then p s into one plus 4 pie tau square into mu minus mu 0 the whole square. The quantity p s into this, if I call this as p s dash, then I can write the saturated gain coefficient.

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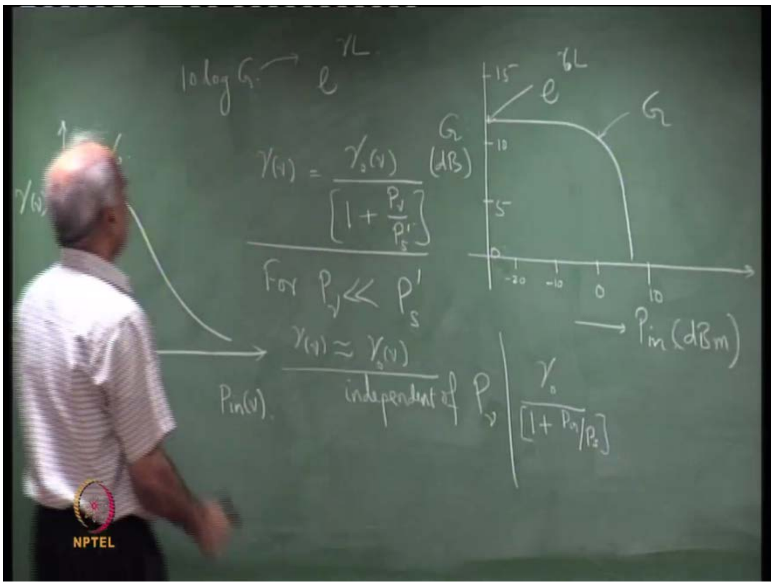

I can express the saturated gain coefficient as gamma of mu, is equal to gamma 0 of mu, which is the small signal gain coefficient, which is encircled here, gamma 0 of mu divided by 1 plus p mu divided by p s dash. So, we can represent this in the same expression, I am representing it in this form. So, what it indicate is, for small values of p n p mu; that is for p mu much less than p s dash p s dash, gamma of new is equal to gamma 0, which is independent, this is independent of the input signal power p s. For p mu much less than independent of the signal power, input power p mu, and this is the small signal gain coefficient. However, when p mu is sufficiently large, or when it is comparable then this term cannot be neglected, and as you can see that p mu is equal to p s dash, the gain gamma 0 will drop down to half of its value.

At p new is equal to p s dash this is 1, so 1 plus 1 2. Therefore, the gain coefficient drops down to half of its value. This means that if I plot a curve, if I plot a variation of p input as a function of gamma here. This is gamma of new, than it will for small values of p mu, this is p input at a frequency mu, at a particular frequency mu. For small powers p mu, when p mu is much less than p s dash, the gain coefficient when p mu is much less than p s dash, the gain coefficient gamma of mu is constant, is equal to gamma 0 of mu. We can see here that this part does not depend on signal power, only this is the signal power, p mu is the input signal power at the frequency mu input signal power.

So, for small power input signal powers the gain remains constant, the gain coefficient here remains constant, but as the signal increases this will start dropping down. So, this if I can show, that this will drop as 1 by x, so it will drop in this way. So, as this increases this drops is, this value here is gamma 0, gamma 0 of mu, and this starts dropping down as the signal power increases. Normally we show this in terms of gain g, gain in dB, if we take a typical data sheet, or if you make a measurement, then it would be in this form. So, gain g here in dB; that is 10 log g, and g is simply e to the power of gamma into l. So, this is in dB, and typical numbers would be 5 10 15 versus pin, a typical SOA characteristics, the gain remains constant for small values of signal power, but then it drops down to, this is 0. Gain equal to 0 means, this going down to 0 dB; that means there is no gain.

This is dropping down with signal power, typical signal power showing here. So, this is minus 20 minus 10 minus p in dB m minus 10 0 plus 10, so typical, this is the gain curve g. So, this represent gain saturation, as you increase the signal power the gain coefficient drops down as gamma 0. So, this value here is actually e to the power gamma 0 into l, small signal gain coefficient gamma 0 into l, where l is the length of the semiconductor chip. So, gamma 0 divided by 1 plus p input at the frequency mu divided by some saturated power p s. So, this is a gain characteristics; but usually one tends to plot gain coefficient versus the output power, because it gives an indication, of what is the maximum output power that is possible.

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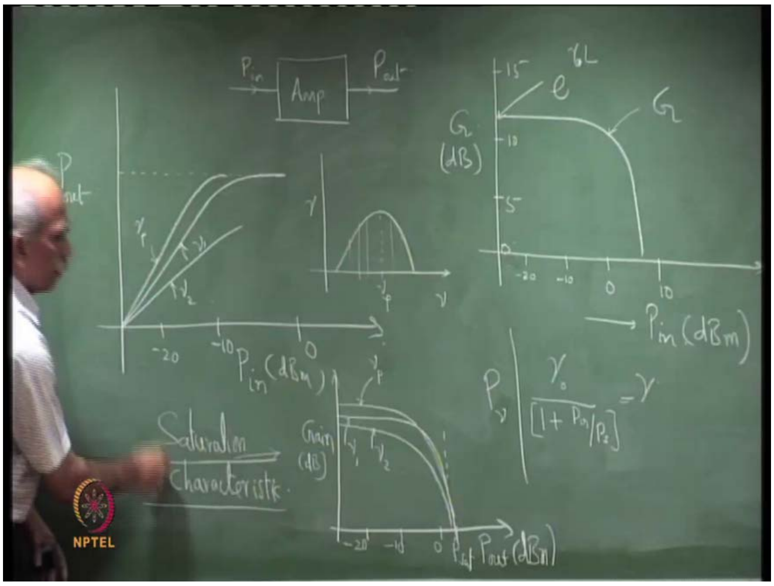

Now to understand this, we can plot input verses output. How would input verses output look like. So, this is p input, let me put the same number minus 20 minus 10 dB m and 0 dB m minus 20 minus 10 input power, input power to the amplifier. So, we are looking at the amplifier here. So, amplifier, this is the p in and p out, so p out. Initially the gain is constant as we can see here, that the gain is constant, which means the input verses output will be a linear straight line here. So, as the signal power increases, the output power increases. However, when the signal power increases, saturation take place; that is the gain coefficient starts dropping down. As the input power increases the gain coefficient gamma drops down, and therefore, e to the power gamma l drops down, so the output power, which starts here. The output starts saturating, because as this come down to 0, 0 means the ratio is 1 p out to pin is 1; that means, it will finally lead to saturation here. So, this is the saturated output power. So, whichever be the frequency you take, so, this is for particular frequency.

The gain is a function of frequency, if you recall here in the box. So, new versus gain, h mu or mu versus gain, then we know that the gain is the function of frequency, corresponding to this frequency here mu p we have maximum gain. At another frequency which is on the side, we may have a different gain coefficient, which means in this graph if I were to show, that it could. This is another frequency if I call this as mu 1, at another frequency this may be mu 2, and for gamma p of course, the slope will be maximum, so this is gamma p; that is the centre corresponding to the centre, but all of these lead to a saturated output power. So, it is customary to plot the gain characteristics, saturated saturation characteristics as this p out in dB m, here verses gain. So, you will have the same characteristics as with p in, but all of them saturating to the. So, any frequency you may take, you may have this gain, but all of them will saturate to the same value. So, this is for some frequency mu.

So, what I have plotted is gain in dB m in dB versus output power. So, this power where all of them is called the p saturated. So, typical numbers could be again, so minus 20 or minus 20 minus 10 0. This is little smaller value, but generally the saturated power could be about 10 to 15 dB m. So, this is at new p, corresponding to the peak, this is another frequency of mu 1 within the gain bandwidth of course mu 2 and so on. So, this is called the saturation characteristics of an amplifier of an SOA. So, we have discussed about the gain spectrum, the bandwidth, and gain saturation, the saturation characteristics of an amplifier. Let me briefly touch upon, so I have already discussed about the gain, peak gain, the saturated gain power, and gain bandwidth, and their dependence on the pump power, and the input signal power. Let me briefly touch upon noise.

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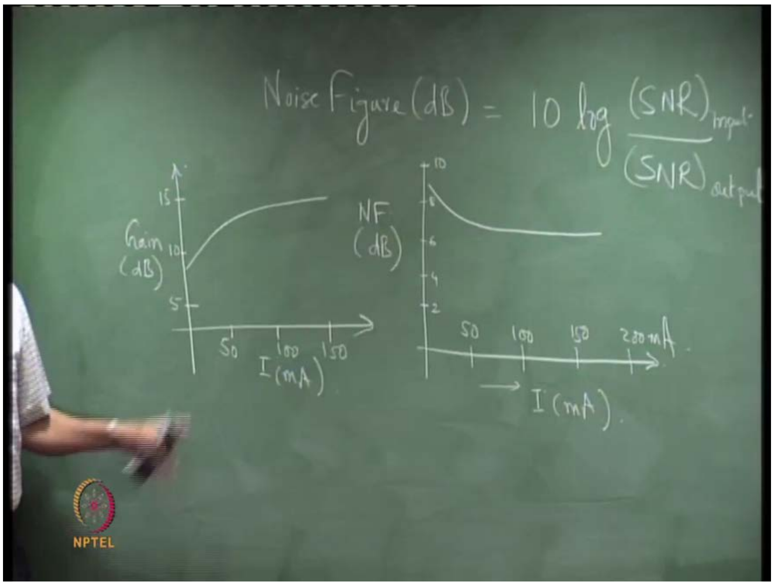

So, the noise figure will not go into many of the details, noise figure is defined in dB is defined as 10 log f, which is signal to noise ratio SNR, optical signal to noise ratio, at the input divided by optical signal to noise ratio o SNR at the output. And typical gain noise characteristics of an amplifier, so this is signal to noise ratio. We will not go into the details of noise figure in this course here, because this will be covered in communication course. And what we have is, as a function of the power, the pump power p out. The current, the pump current i, so this is the pump current i into m A, because depending on the pump current we have gain characteristics. The gain will be larger for larger current through the device, and noise figure here N F in dB typically varies.

So, typical numbers for an SOA 50 ma 100 milliamphere 150 milliamphere, may be 200 milliamphere, and the typical numbers here are; 2 4 6 8 10 noise figure in dB. As initially if you see the gain as the function of i. So, i here versus gain, then typically it looks like gain here, 5 gain dB ten 15 for current, and using the same consistency 50 100 150 milli ampere. So, the gain initially increases with current; that is why the noise figure drops down, because noise figure depends on the gain, and after some time gain is slowly saturating, and therefore the noise figure is also saturating. So, they are consistent gain and noise figure, typical characteristics for semiconductor optical amplifier. How does the performance of SOA compare with a fiber amplifier.

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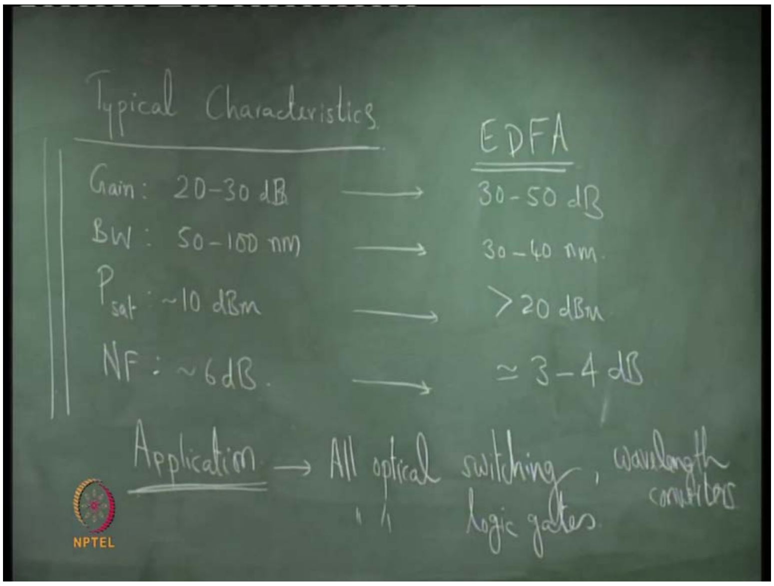

So, let me, if I give you typical characteristics, I have shown the characteristics typical curves, but typical numbers, all are there in the graph that I have shown. So, gain generally about 20 dB, or may be maximum 20 to 30 dB maximum gain. Bandwidth typically 50 to 100 nanometer gain, bandwidth, p saturated, saturated power, typically 10 dB m of the order of 10 dB m, approximately the order of 10 dB m, and noise figure.

There are several other characteristics, but we are not going in detail in to those characteristics, or primary emphasizes is on the device rather than the characteristics of the device, is of the order of 6 dB. How would this compare with a typical fiber amplifier EDFA. EDFA one can have gain anywhere from 30 to 50 dB, bandwidth of course little less 30 to 40 nanometer, saturation power is greater than, easily one can get greater than 20 dB m, and noise figure, almost 3 dB, almost to the limit, you can get noise figures, almost greater than or equal to, almost at that level 3 to 4 dB, let me write 3 to 3.5 dB.

So, what we see, with these characteristics is that EDFA scores, except for bandwidth, the EDFA scores in every way over an SOA. However, therefore, the application of SOA is not for long haul communication. It is not used for long distance communication, high speed communication, because the noise performance, gain performance, everything is much better in then the case of EDFA. However, the range, the domain of application of EDFA's, he has to do with all optical signal process, all optical switching; for example, all optical logic gates, and very widely used in wavelength converters and so on. So, the range of application of SOA is usually different from those of optical amplification for communication. So, we will not be in a position to go into the details of this, but I would recommend that you see some books; reference books on SOA, to look at the range of application. So, this is being developed for signal processing, and in metro networks, flexibility of wavelengths routing, and application are also being developed for all optical logic gates for signal processing. So, we will stop at this point here.