Fiber – Optic Communication Systems and Techniques

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Lecture - 40
Semiconductor optical amplifier

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In this module we will look at Semiconductor optical amplifiers, which is one of the optical amplifier that is used in fiber optic communications and fiber optics signal processing fields.

Now, the reason I am discussing semiconductor optical amplifiers is because you can convert a laser semiconductor laser into a semiconductor optical amplifier by removing the optical feedback or by requiring the optical feedback be very low, ok. Of course, that is what differentiates between any optical amplifier or in general any amplifier with a laser being the oscillator. So, when there is a feedback, then this feedback will be sufficient for the device to generate self sustained oscillations in the steady state. Whereas, when you remove the feedback or you adjust a feedback such that the feedback is not important then you will not be able to you know build on the you know oscillations and what you will actually have end up with having is a optical amplifier.

Much of the working that we look from a semiconductor optical amplifier the principles of working is the same as that of the semiconductor laser, you will have an inversion layer where there will be stimulated emission. But this stimulated emission will be brought about by the externally applied signals the cavities will still be there in some form of the other, but the cavity reflectivities are usually kept very low. So, as to obtain a broadband lasing I mean broadband amplification rather than lasing. And all the other principles of you know laser also remains. So, you have to have a hetero structure laser or you know have a hetero structure material and then you have to have an injection pumping, injection by way of applying an appropriate current forward bias in the junction. For example, all that thing that we discussed will still be there, ok. So, then what is the different features of semiconductor optical amplifiers is what we want to look at, ok.

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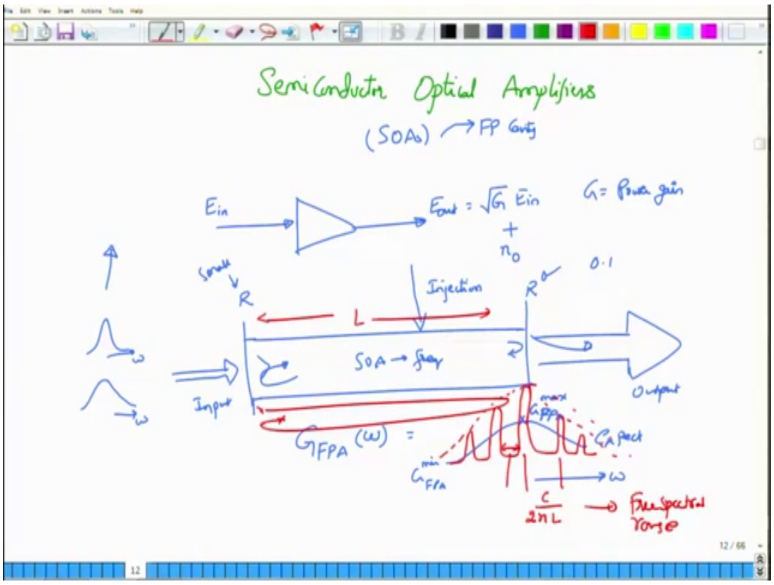

Now, any amplifier the function of that any amplifier would be very simple. So, you send in certain light here which has an electric field E in then the output would be ideally square root G times E in. And using square root G because G or gain is usually referred to the power quantity and not a electric field, ok. So, G is usually what is called as the power gain and not to the electric field. So, for electric field we simply square up the power gain and therefore, you will be obtaining what is the field gain, ok.

Of course, if it was an ideal amplifier this is what it would have done but most physical amplifiers also add a certain amount of noise to the output, ok. This is kind of a amplifier spontaneous emission noise that is added from the semiconductor material itself. And the amount of noise that goes into the band depends on the bandwidth of the input signal itself. Usually the gain is broadband and when you send in light at a particular frequency or with a certain bandwidth around a particular carrier frequency the in band noise is determined by what is the bandwidth of the input signal. So, this is what one would expect from an ideal amplifier and what one would expect from a non ideal amplifier, ok.

But how exactly is this created? Well, if you look at the structure of a semiconductor optical amplifiers most structure fall into two types, one is called as the FP cavity type structure, wherein the lasing material is actually kept or the active medium is actually kept in between two mirrors, ok. These mirrors can be physical mirrors or depending may be in the form of a grating whatever way that you make them. But they essentially are the properties instead of a mirror and then they have reflection coefficients R, ok. If R is close to unity then what would happen? As the mode start to propagate it would move and then it would get fed back here almost all of the optical mode would be fed back which would then pass through the SOA material in between or the gain material in between and induce more stimulated emission, and then when it comes back to the first medium it will again be reflected if R is very close to 1.

And this process continues to happen thereby you will essentially have a nice laser. But that is not what you want what you want is not a layer what you want is an amplifier therefore, you keep this R values to be quite small, ok. So, most R values are just about point one and one asked one tries to make this R value even less than that, but most materials unless they are specifically made then they will have reflectivity of about 0.1 1 or flight are less than 0.1, ok.

So, that most of the light is not getting reflected most of the light is actually coming out of their cavity in the sense that when you launch a probe light at a certain wavelength then what you would get at the output is an amplified version with some amount of noise but almost faithful replication as that of the input, ok. So, this is what you would have.

Of course, how do you inject here? What is the pumping mechanism? This is the injection current that you need to supply and this is a PN junction therefore, you take this SOA and then forward bias this junction and then essentially send in some input and you obtain the output. But because this SOA material is kept in the cavity there are differences in the way the gain actually comes out, ok. So, what we are now going to do is not to go back to the semiconductor basics, we are already looked at that theory enough. Whatever we have said about lasers most of that also applies to the semiconductor optical amplifiers also. But what I am interested is to look at the amplifier gain as a function of frequency omega.

You first of all agree that this will be frequency dependent when it will be frequency dependent because you have to agree it because the SOA material itself is a frequency dependent material. Remember all lasers have a certain line shape, this line shape will be either in the form of a Lorentzian or in the form of a Gaussian line shape. This is of course, a function of frequency omega. You do not have any lasers which generate or any gain medium which has a delta like spectrum. So, most of them actually have a certain variation and you would expect that the gain of this FPA also to be something like this with respect to omega with a maximum gain which we will call as this is FPA max and a minimum gain that would occur at that tail which we would call as G min FPA this is what you would expect. So, this is what I would actually expect from this one.

But what in reality you get is a different thing. So, you would actually get something like this. So, you notice that you have an overall Gaussian type function, I did not write the other difference currently but essentially this is a Gaussian type functions, ok. But there are these regions where the gain is at a minimum level. So, there are these blanks in between and there are these peaks, multiple peaks within the gain spectrum of the amplifier material this is a characteristic of the cavity.

So, if you assume that the cavity has a certain length L then the spacing between these two peaks is about c by nL or maybe c by 2 nL, ok. We can fit a half length or something. And the idea is essentially the same. So, you have a cavity it would serve to have standing modes rather than the traveling modes they are actually the standing modes and only certain standing modes that satisfy by the boundary conditions will be sustained by the cavity. And because you have now have some sort of a periodicity, right periodicity in the form of wave going here coming back and then moving again in the same direction.

So, one round trip propagation can be considered to be a spatial thing, and because periodicity is there in one domain there actually discreetness in the other domain and this is preferably the discreteness that you are actually seeing. And this spacing between the gain medium is called as free spectral range, ok, to increase the free spectral range, to increase the spacing between the peaks you want to make n to be as large as possible. Of course, there are practical limitations as to how long you can make these devices. Therefore, you have to live with the fact that the gain spectrum is discrete and actually shows up multiple peaks, ok. Of course, within these peaks the peak themselves are reasonably broad so that most of the wavelengths can be fit into it. But not every wavelength in the operating fiber optic communication system can be fit into one of those two peaks.

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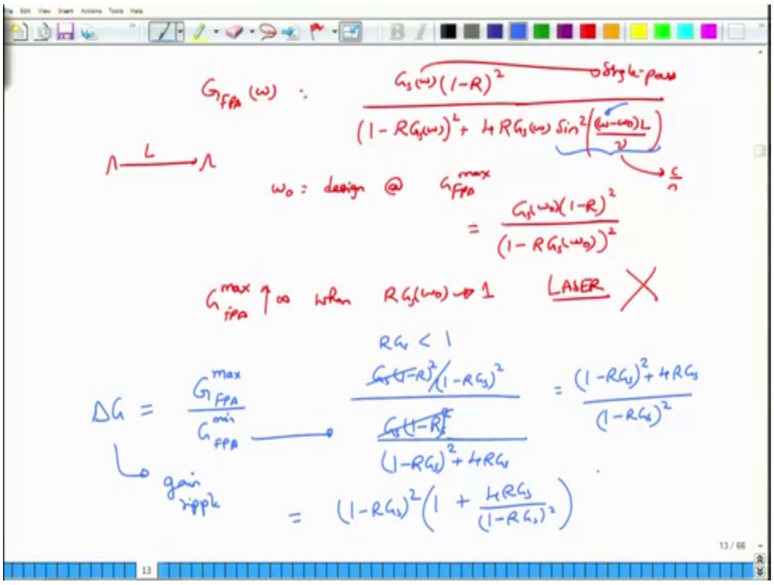

$$G_{FPA}(\omega) : \frac{\overset{\text{single-pass}}{G_s(\omega)}(1-R)^2}{(1-RG_s(\omega))^2 + 4RG_s(\omega)\sin^2\left(\frac{(\omega-\omega_0)L}{v}\right)} \qquad v \rightarrow \frac{c}{n}$$

$$\wedge \xrightarrow{L} \wedge$$

$$\omega_0 : \text{design} \ @ \ G_{FPA}^{max} = \frac{G_s(\omega_0)(1-R)^2}{(1-RG_s(\omega_0))^2}$$

$$G_{FPA}^{max} \uparrow \infty \ \text{when} \ RG_s(\omega_0) \to 1 \qquad \underline{\text{LASER}} \ \times$$

$$RG_s < 1$$

$$\Delta G = \frac{G_{FPA}^{max}}{G_{FPA}^{min}} \longrightarrow \frac{\cancel{G_s(1-R)^2}/(1-RG_s)^2}{\cancel{G_s(1-R)^2}/(1-RG_s)^2+4RG_s} = \frac{(1-RG_s)^2+4RG_s}{(1-RG_s)^2}$$

$$\hookrightarrow \text{gain ripple} \qquad = (1-RG_s)^2\left(1+\frac{4RG_s}{(1-RG_s)^2}\right)$$

If you are interested in the expression for what would be that gain as a function of frequency. You may actually see that this will be given by G s of omega, where G s of omega is the line shape function of the basic lasing material whatever the active gain material that you have used times 1 minus R G s cos omega square plus 4 R G s of omega sin squared omega minus omega 0 into f by v, ok, where v of course, is given by c by n is the phase velocity, ok. Because sin square is an oscillatory function the overall gain will be an oscillatory function. Omega 0 is called as the design frequency it is the frequency at which the gain will be maximum, ok.

So, if you are making a fabricate in a semiconductor optical amplifier and you want to maximize the gain at a particular wavelength you choose that wavelength to be omega 0 or corresponding to the frequency omega 0 and you get a maximum gain. What is the maximum gain? When omega is equal to omega naught you have G s omega naught 1 minus R whole square divided by 1 minus R G s omega naught squared because you will get a maximum gain when the sin square term goes to 0 of their sin does not. This term could have gone to negative but because it is a sin square term it will not go to negative, and G s of course, is always a positive quantity because this is a gain of the basic material or sometimes also called as single pass gain, ok. That is the gain that the optical medium will undergo when it passes through the semiconductor optical amplifier of length L, ok. So, this is what you would get.

And if you now look at different values of R, you can then change the different I mean you will get different values of gain, ok. That is something that you can easily observe from this equation which I do not bother you too much but notice that the gain can actually go all the way to infinity, right. So, it I can go to infinity when R G f omega naught at that particular frequency approaches 1, right. So, when the denominator goes off to 0 when the gain goes to infinity and essentially you would have obtained instead of an amplifier, you would have obtained a laser therefore, this condition is not suitable for us and R G s would always be kept less than one inside it should be kept much less than 1, that is the first observation.

The second observation is if you look at the ratio of the maximum gain to the minimum gain, right. I leave you to find out what is the minimum value of the gain or at least show that this minimum value of the gain is given by G s 1 minus R square divided by 1 minus R G s whole square plus 4 R G s and it will happen at those frequencies where this sin square term goes of to 1, ok. So, when the sin square term goes to 1, you can find out what frequencies that that condition hold and for those conditions you will actually have a minimum value of G or the gain.

The maximum value anyway we have written it is G s 1 minus R square in the numerator divided by 1 minus R G s in the denominator. So, what you can see that you can cancel off these two and you get 1 minus R G s whole square plus 4 R G s divided by 1 minus R G s whole square, ok. You can of course, take this 1 minus R G s whole square as a common thing and then call this one as delta G, delta G stands for the gain rippled, ok. Gain ripple means certain frequencies or certain bands will have a larger gain and certain bands will have a minimum gain.

So, what is the difference between the max and the min gain? In terms of usually in terms of the ratio would be about 1 minus R G s whole square 1 plus 4 R G s divided by on1e minus R G s whole square, ok. So, you can if you wish to simplify this further and you can calculate certain numbers which are actually going to be interesting.

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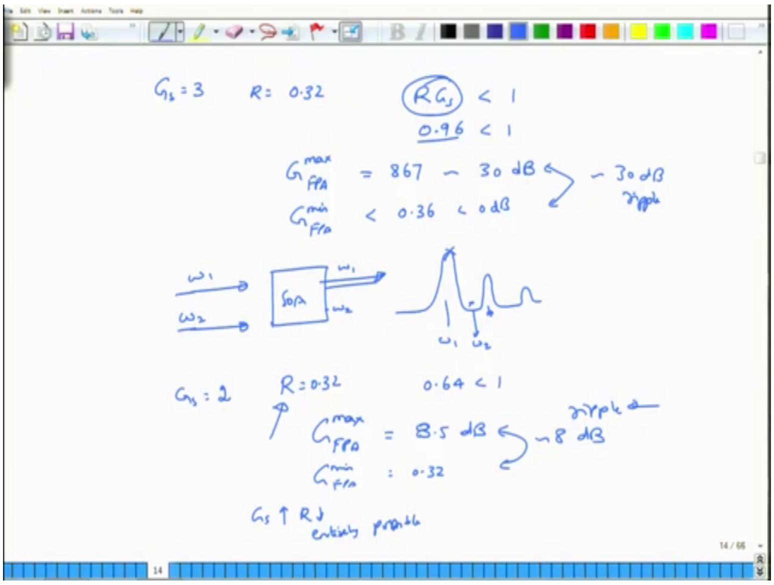
$G_s = 3$ $R = 0.32$ $\boxed{RG_s} < 1$

$\underline{0.96} < 1$

$G_{FPA}^{max} = 867 \sim 30\ dB$ } ~ 30 dB ripple

$G_{FPA}^{min} < 0.36 < 0\ dB$

$G_s = 2$ $R = 0.32$ $0.64 < 1$

$G_{FPA}^{max} = 8.5\ dB$ } ~ 8 dB ripple

$G_{FPA}^{min} : 0.32$

$G_s \uparrow R \downarrow$ entirely possible

Suppose I take G s equal to 3, and I take R equals 0.32, ok. So, what would be the product R G s? This would definitely be less than one because the product is actually about point. So, this is 3 times, right. So, 3 2 is a 6, if it is the 9, so you are very close but if you are not exactly close.

But if you look at what is a gain in you know the maximum gain for this particular case the maximum gain will actually be about 867 in the linear scale or about 30 dB approximately in the degree scale, this is a huge value. Whereas, the minimum gain for the same condition would actually be even less than 1, in fact it would be a loss if you choose this particular value and, in fact it would be less than about 0.36, right.

If you look at the difference between these two which would of course, be less than 0 dB the gain ripple is about 30 dB. So, if you have signals of two different wavelengths. So, or two different frequencies omega 1 and omega 2, if omega 1 and omega 2 happen to fall into this unfortunate situation that this is your omega 1 and this one is or rather this one is omega 2, ok. So, this is omega 2 then you can see that omega 1 channel will experience an extremely large gain omega 2 channel will experience almost no gain or, in fact if you experience for loss and when you had initially same power but after passing through the SOA now you have a large power here and almost no power in omega 2.

So, therefore, this is not a very good mechanism or this is not very good value to choose because you are then essentially creating unequal gain distribution in the multi channel system which is not at all good, because you expect all the channels to be amplified with the same level not with different levels. How do I you know ensure that that is happening? So, the way to ensure that one would be to further reduce R G s consider taking the single path gain to be G s equal to 2 while keeping R to be the same 0.32. In this case the product is about 0.64 which is less than 1, ok.

The difference is not too much you would think you have 0.96 in one case, of 0.64 in the other case but it turns out that the maximum gain again you have to verify that these numbers are correct, ok. Please do that one the maximum gain is about 8.5 dB, ok. So, this is 8.5 dB the minimum gain is still quite less than 1. So, the minimum gain is just about 0.32, but now you see that the gain ripple is down to just about 8 dB. So, this is the ripple that you actually get which is much smaller than this one. So, this is actually very important.

But if you can reduce R further which is what normally we do you can keep the single pulse gain high but reduce R further which is entirely possible by the technology that we have today, ok. So, what you would essentially convert or what you would essentially do is to minimize this gain ripple, ok. So, but still the gain ripple would be present if you were to use an FP cavity type filters, ok.

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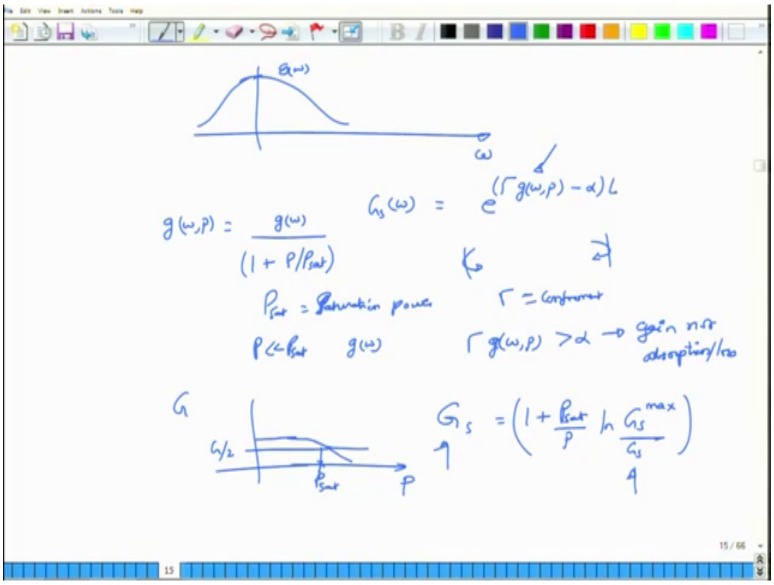

$G_s(\omega) = e^{(\Gamma g(\omega,P) - \alpha)L}$

$g(\omega,P) = \dfrac{g(\omega)}{(1 + P/P_{sat})}$

P_{sat} = Saturation power

Γ = Confinement

$P << P_{sat}$ $g(\omega)$

$\Gamma g(\omega,P) > \alpha \rightarrow$ gain not absorption/loss

$G_s = \left(1 + \dfrac{P_{sat}}{P} \ln \dfrac{G_s^{max}}{G_s}\right)$

We are also interested in the bandwidth of these devices. So, if you actually look at the bandwidth you would you can actually find out what would be the bandwidth of this one.

But the bandwidth actually depends on how the wave shape or the line shape itself goes or the single pass gain itself goes, and the single pass gain itself is given by E to the power or exponential of gamma, g of omega comma P minus alpha times L. Where, alpha corresponds to the resonators or the reflection losses that would happen in the cavity. Gamma corresponds to confinement which is kind of an overlap between the optical mode and the cavity design itself and most importantly this is the gain medium frequency dependence. So, this is where you are actually getting all of your gain differences.

Of course, for this to actually be positive gamma g of omega comma P at every frequency and for every power must be greater than alpha so that is overall we will have gain and not absorption or loss, ok. So, these conditions are to be satisfied for any type of op-amplify for a gain. But this is what you would actually have.

And further this g of omega comma P itself is given by a frequency independent gain function, and divided by this term in the denominator. And this term in the denominator where we have written P sat we called the saturation power. At the saturation power what will happen? For P much less than P sat the denominator can be approximated to 1 and the gain would be essentially independent of the power, ok. So, and it would have some sort of a variation that is dependent on the gain shape function G of omega itself.

But if you were to plot the gain as a function overall gain let us say as a function of the input power or the probe power or the input channel power then for P is less than saturation landed a gain is almost 1, but at this point actually starts to drop and then eventually drops off for that. So, the value of the gain at the saturation value then P equals P sat is just about G by 2, ok. So that would essentially correspond to the bandwidth in terms of the saturation power. It is kind of quite difficult to obtain you know proper equation or an understanding between gain and P because it is a complicated process that takes place.

But approximate equations have been derived, so approximately G s depends on the input power in this particular manner. It is a transcendental equation, so you will have to solve this equation, numerically most of the times otherwise you will not be able to find because there is G s on the, right hand side G s on the left hand side as well, ok.

Again please note that there are many competing processes that are happening in the semiconductor optical amplifier, the actual gain depends on cavity designed, reflectivity if you know the tray light that the enters into it, the packaging all those things have to be optimized if you want to create a good amplifier. And of course, you have to also do some sort of a optimization if you want to create good lasers, ok. So, this was about semiconductor optical amplifiers.

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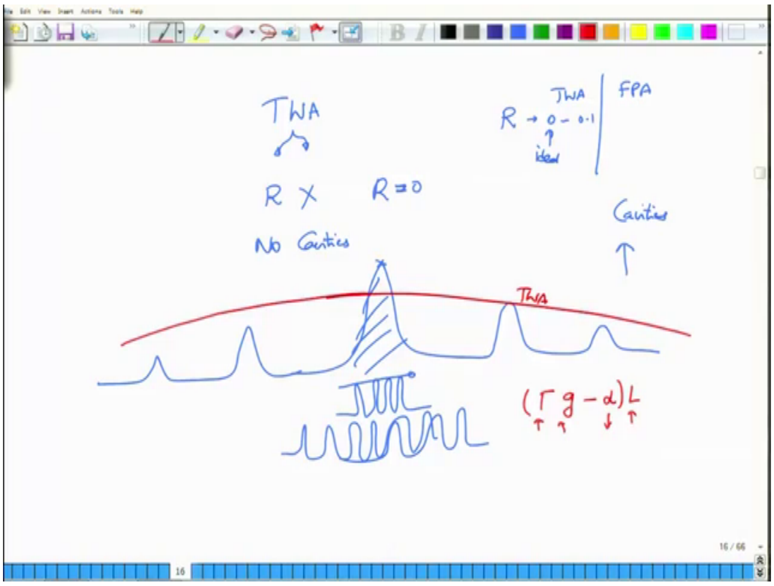

The last type of semiconductor optical amplifier that I am going to look at is what is called as traveling wave amplifier, ok. The principles of traveling wave amplifier are slightly difficult and different and we do not want to go into that, but the basic idea is that you do away with the reflections you know R will not be there R, in fact will be approximately 0.

In fact, you cannot get R approximately 0, so what you would actually have is a you know a range of values of R say from ideal 0 value to about 0.1 let us say wherein you would treat the commitment or optical amplifier as traveling wave amplifier and beyond that we would treat them as Fabry-Perot amplifier, ok. So, beyond the value of R of say 0.1, 0.12, 0.15 you would build them as a Fabry-Perot amplifier.

The gain of the traveling wave amplifier is actually much smaller compared to the Fabry-Perot design because there are no cavities here. Cavities serve to have standing modes and therefore, the gain can actually shoot up. So, you are trading off a large gain, in your

Fabry-Perot cavity, so you will have a larger gain here at the appropriate frequencies, and if this is the only frequency of interest that you are working with then there is no problem. You can easily have multiple channels here between that band and then you almost all of them will have equal amplification and you are all very good and very nice, ok.

But if your number of channels actually go around this region then you are in trouble, because some of the channels will see lesser gain. The traveling wave amplifier overcomes this problem it gives you almost kind of equal gain frequency dependence. So, this is the traveling wave amplifier, but the gain peak value is actually quite small, ok. So, you have to of course, improve the single pass gain because that is exactly equal to the gain of a traveling wave amplifier by continuously changing g increasing lamb gamma increasing g and then reducing this alpha and increasing L. So, this has to be increasing, this has to be increasing, loss has to be reducing and L has to be increasing all with certain constraints and approximations, ok.

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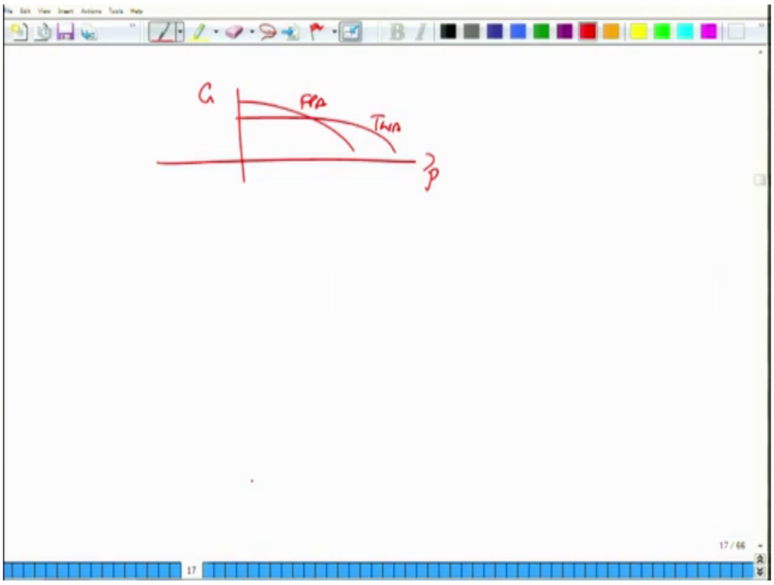

Even the bandwidth of a traveling wave amplifier if you were to look at it will actually be much wider compared to that of the Fabry-Perot cavity, ok. So, this is the traveling wave amplifier and this is the overall gain that we talk about to the saturation value for the traveling wave amplifier is usually much larger than that of the Fabry-Perot cavity.

The big advantage of course is that traveling wave amplifier will never lays because there is very little feedback that the amplifier is sustaining. On the other hand Fabry-Perot amplifiers can be made to lays you know even externally by actually putting the entire SOA in the middle of a certain cavity and a bigger cavity and then increasing the feedback of that external cavity. So, SOAs are also used for lasers not a very good way but it is also used for lasers. And most importantly SOAs offer high non-linearity much higher than the non-linear fiber non-linearity and therefore, they are actually excellent for many non-linear optical signal processing.

For example, you can send in two different frequencies into the SOA and under, right conditions you actually end up having 4 different frequencies, ok. So, you can actually create multiple frequencies by employing the non-linearity. You can also clean up your input signal by what is called as a phase conjugation, you can improve the data rate by actually putting in a SOA based which conjugating the middle of the fiber optic communication link in the form of what is called as a phase conjugation. So, all these advantages that you would get are from the semiconductor optical amplifier.

The down side of semiconductor optical amplifier is that there is a large gain fluctuation, because the lifetime of electrons in the conduction band is about 1 nanosecond any bandwidth which is greater than about 1 or any bandwidth which is less than 1 Giga Hertz will experience severe losses, right. Because if you have lesser than 1 nanosecond then you will or if you have a larger this one then the smaller lifetime will actually cause the gain pulsations to occur.

So, compared to an erbium doped fiber amplifier the gain pulsations or the gain is very noisy from a semiconductor optical amplifier. And therefore, for this reason it is not used in optical amplification but it is widely used in other non-linear signal processing applications that I just mentioned, ok. There are other differences between semiconductor optical amplifier and erbium doped fiber amplifier. We will not get into these differences at this point and we close this by saying.

Thank you.