Introduction to Photonics
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Lasers Part 3

Okay, welcome to another session of Introduction to Photonics, so we had been talking about fundamental principles associated with a laser and we are trying to quantify its characteristics both in terms of the output power how it you know varies or how it increases as you increase the pump power but we also would also like to quantify the spectral characteristics ok.

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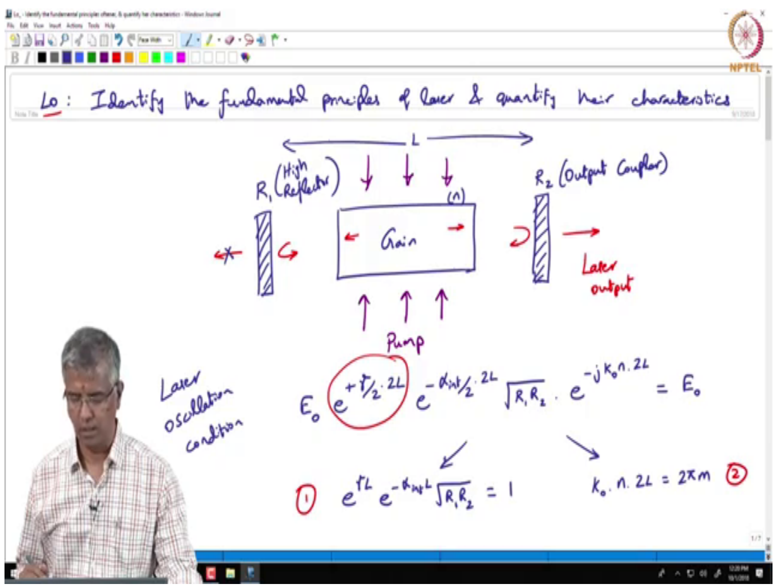

So that is what we were at so we were actually staring from the basic conditions that you need to satisfy so that you have laser built and that essentially meant that on one side you are offsetting the loss in the cavity with the gain and on the other side you are also saying that only specific frequencies can exists within the cavity specific frequencies that corresponds to the constructive interference criteria of this fabry perot cavity.

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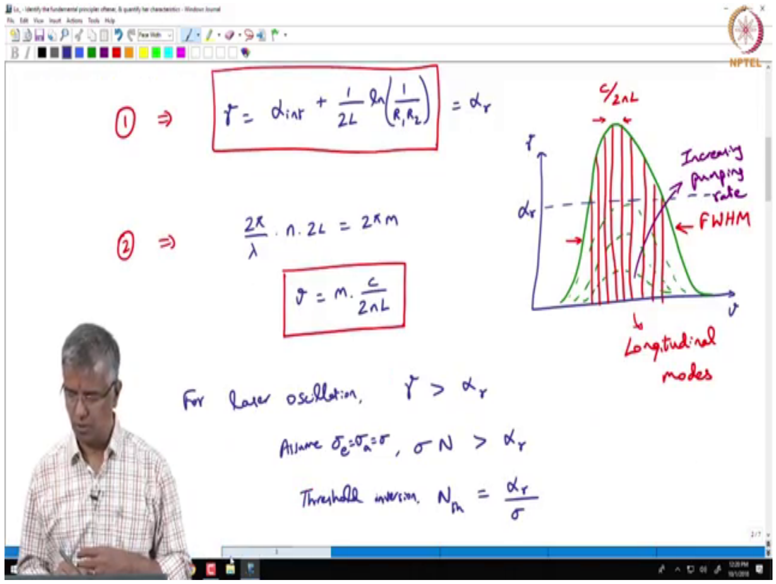

Those are the ones that will survive so we talked about case where you will have all this longitudinal modes corresponding to the case where the gain is greater than the loss those are the ones that will survive in the cavity.

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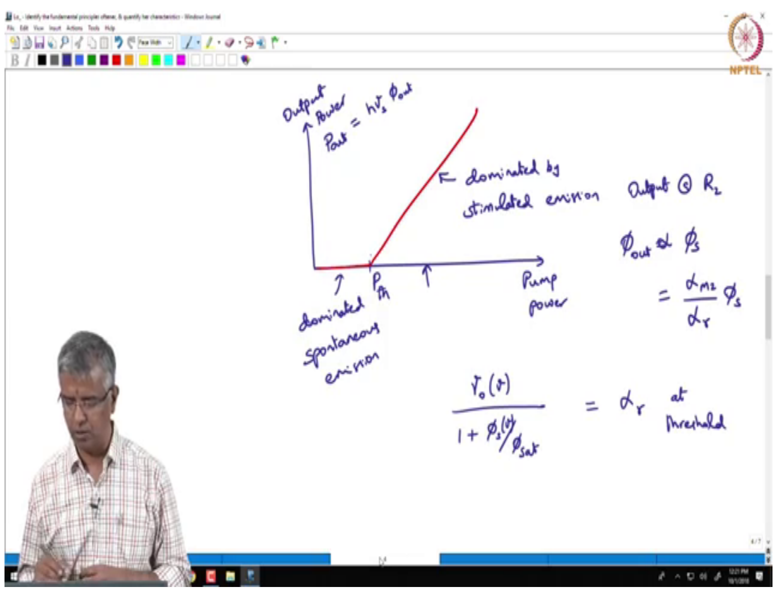

And specifically we went on to look at the issue which includes saturation of the gain so we said as we build up these photons inside the cavity through stimulated emission you start reducing the gain also.

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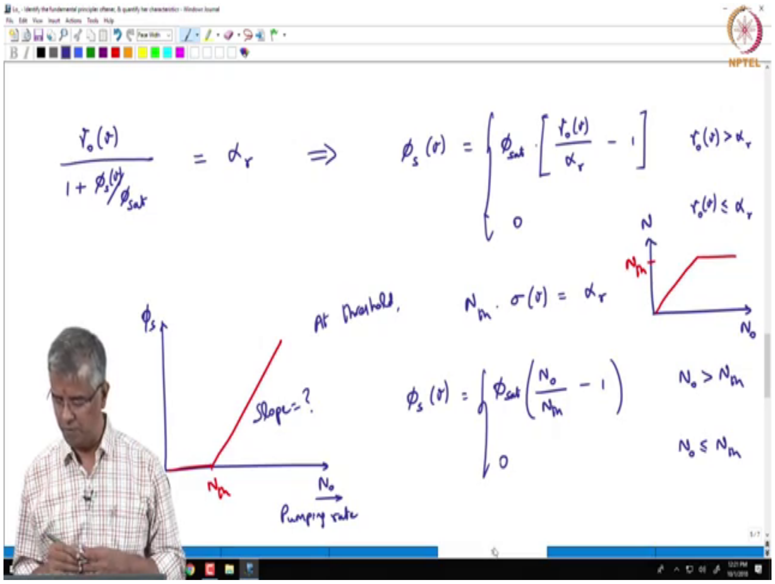

To the point at when we were looking at what happens when you turn on a laser.

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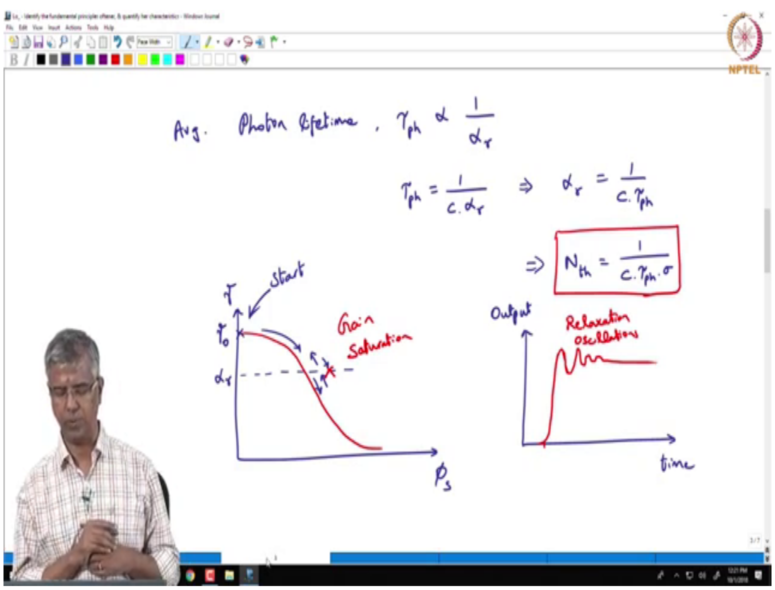

I think we were talking about this particular picture, what happens when we turn on the laser is. We have initially very few photons at the signal wavelength and so you have a fairly high gain that is what we call as a small signal gain but as you build up more and more of this photons at the signal wavelength the gain starts saturating it may go to a point where we gain is actually saturated below the loss in the cavity and at which point the gain recovers ok and then it will go through some oscillations before it is stops at steady state and the key point that we noted was at steady state gain equals the loss.

So anymore pump photons coming into the cavity is getting converted into signal photons right anymore pump photons that are coming into the cavity beyond the point where you reach threshold beyond the point where the gain equals a loss right all those other photons will escape the cavity and so we have a conversion of the signal photons or the pump photons into signal photons.

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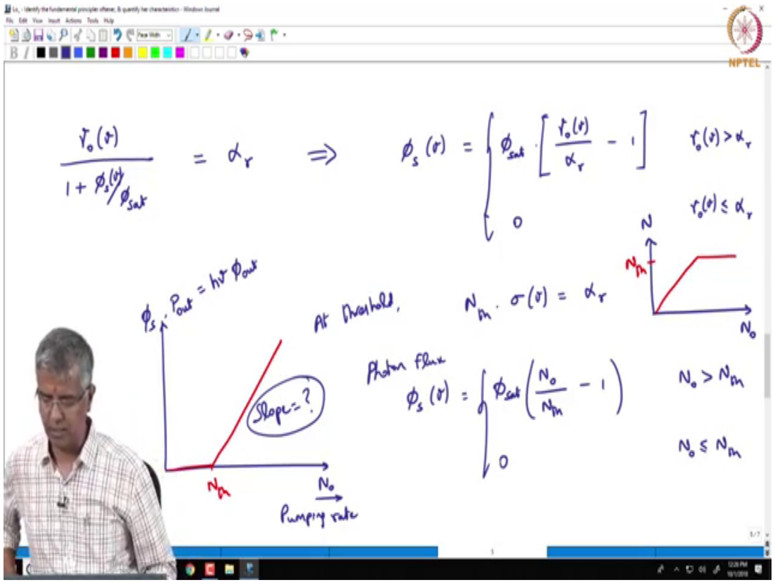

So in our last discussion we looked at photon flux right so this is the photon flux from the cavity and within the cavity and that photon flux we essentially came over the expression where we said it is phi sat multiplied by n knot over n threshold minus 1 where n knot corresponds to the small signal inversion and n threshold corresponds to the inversion required for achieving the lasing condition. So anymore inversion beyond the threshold inversion is going to result in the generation of this extra signal photons which will essentially escape the cavity.

So that is what we are projecting over here and we stopped at the point of saying you know this conversion happens at a with a particular efficiency and we wanted to quantify that efficiency right so that is where we stopped. So we said this would be look at phi s or you could also looked at it in terms of the output power, the output power as a function of the input pump power and this output power which will be given by h mu multiplied by the output signal flux ok that output signal flux is actually a fraction of the phi s corresponds to the signal photons that are generated in the cavity ok.

So what determines that fraction? What determines that fraction that escape the cavity? The mirrors basically the mirror reflectivity or the transmission over the mirror. So what we will find is first of all we will get an expression for that for phi out and what we will find is that there is an optimum reflectivity ok for extracting this output power from the cavity so we will actually look at what is the optimum reflectivity, what is the expression for the optimum reflectivity ok. So let us continue over here.

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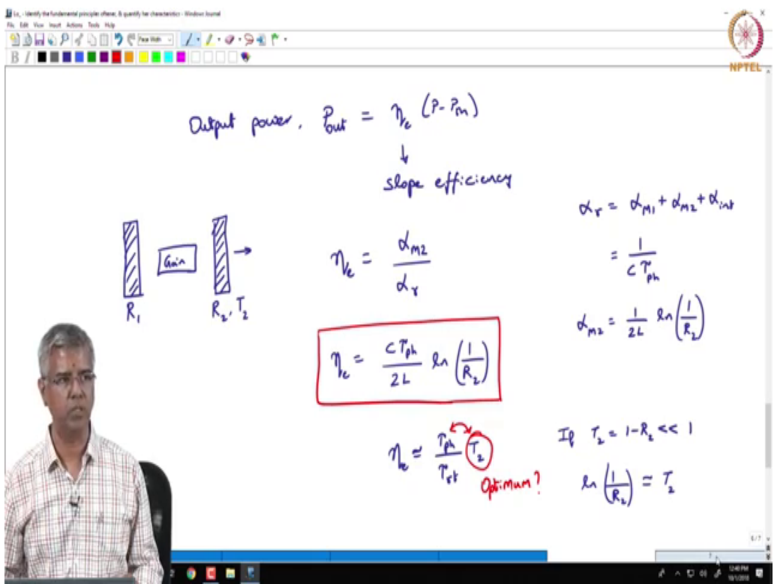

So what we are saying is this output power P out can be written as some efficiency let us call that the slope efficiency multiplied by the power that is available beyond threshold power. So the we cavity is going to consume a certain amount of pump power just to reach threshold anymore power beyond that is getting converted to signal photons that are escaping the cavity right so that is the output power that we are looking at. So what we want to see is what is this quantity which we call as the slope efficiency right and that slope efficiency is just the slope of this output power versus input pump power right. Now we can actually say that the slope efficiency eta e so this slope efficiency can be expressed as so if we have a cavity let me just draw the cavity again so we have one mirror here another mirror here so this is let us say reflectivity R1 this is reflectivity

R2 and ofcourse we have the gain medium here and we are tracking the output power in this direction.

So as far as the slope efficiency is concern with respect to the power that we are monitoring coming out of reflector with the second reflector we can say that corresponds to the fraction fractional loss given by mirror 2 with respect to the overall loss right. So the overall loss is alpha r, where alpha r we said corresponds to alpha m1 plus alpha m2 plus the internal losses in the medium right inside the cavity. So you can write the slope efficiency as is corresponding to the fractional loss for mirror 2 and divided by the overall loss. Now overall loss we said is inversely proportional to what? We talked about the average photon lifetime inside the cavity we said it is inversely proportional to the average photon lifetime and we said alpha r is given by C, where is c is the speed of light in vacuum multiplied by the photon the average photon lifetime.

Ok and then what is alpha m2? Alpha m2 corresponds to the mirror loss which is given by 1 over 2L (())(11:17) of 1 over R2 right, where did we get that 1 over 2L? That is just the 2L corresponds to the round trip propagation but we are normalizing the mirror loss with respect to 2L so that all of this is overall resonator loss can be you know represented as a per meter basis right alpha int is distributed across the medium whereas the mirror losses are just lumped elements at the ends but when we are looking at alpha r it is a per meter quantity so just so that we have everything equivalent we are basically taking a lumped quantity and making it like as if it is distributed across the cavity but (you know) physically you know that the mirror losses are just lumped quantity it is not a distributed (quantity) ok right.

So I can put all of this together and get an expression for the slope efficiency which is going to be C over C multiplied by tau photon, it is a photon lifetime divided by 2L (())(12:59) of 1 over R2 ok so does this make sense? What are we saying here maybe it will make sense if I represented slightly differently 2L over C what do they correspond to? That corresponds to some time right so what is that? That corresponds to a round trip time round trip time for a photon inside the cavity right. So I can write this as tau photon over tau R t where tau R t corresponds to the round trip time inside the cavity right and (())(14:13) of 1 over R2 if R2 is my reflectivity let me say that T or may be T2, T2 corresponds to the transmission of this mirror so I can basically say that R2 plus T2 has to be equal to 1 for energy conservation and so R2 can be represented as 1 minus T2 right and if P2 which corresponds to 1 minus R2 is far-far less than 1 if it is very low transmission then I can basically say that (())(15:09) of 1 over R2 is approximately equal to T2 right.

So (())(15:20) of 1 over a very small number can e approximated as that number itself right and so I can write this as T2 ok this I should say is approximately this is valid only when we have a very low transmission right. S what does that tell you I am just writing it so that we can get a little bit of insight into this so we want if we want high slope efficiency if we want high conversion efficiency for the pump to signal photons beyond the threshold right so you loose certain energy to overcome the losses right that is your threshold pump power so forget about that but beyond that threshold if we want to covert the pump photon to signal photon with higher efficiency I need to have a long photon lifetime.

Long photon lifetime will allow me to you know keep multiplying the signal photons within the cavity right but that by itself does not help ok you also need to extract this power from the cavity so you need to have transmission you need to have sufficiently high transmission so that you can extract power from the cavity right. So this are contradicting requirements to have long photon lifetime what do you do? You make a very low loss cavity which means that you need very high reflecting mirrors but it does not help that you have so high reflecting mirrors that all the power remains within the cavity you need to extract some power from the cavity right.

So you need to leak out a little bit but then the question is how much do you leak out? Is there an optimum value for T2 right where you leak out without comprising the buildup of power within the cavity right. So you need enough signal photons to keep the stimulated emission going you cannot comprise that if you go for very high extraction very high value of transmission for this mirror 2 then you are very high loss if you have very high loss not only is your threshold going to be higher but the buildup is also not very good right so do you understand the contradiction? On one hand you can actually get to very low thresholds right or in this case you can also say you can give very high slope efficiency by making highly reflecting mirrors for both R1 and R2 basically high value.

But in that case we are not extracting much power from the cavity and but on the other hand if you try to extract a lot of power from the cavity and by making one of the mirrors low reflecting which corresponds to high transmission right in that case you may not have enough photons to sustain the laser or solution so sustain stimulated emission. So we need to there is an optimum value for T2 which you need to figure out right so let us try to figure that out, any questions after this point?

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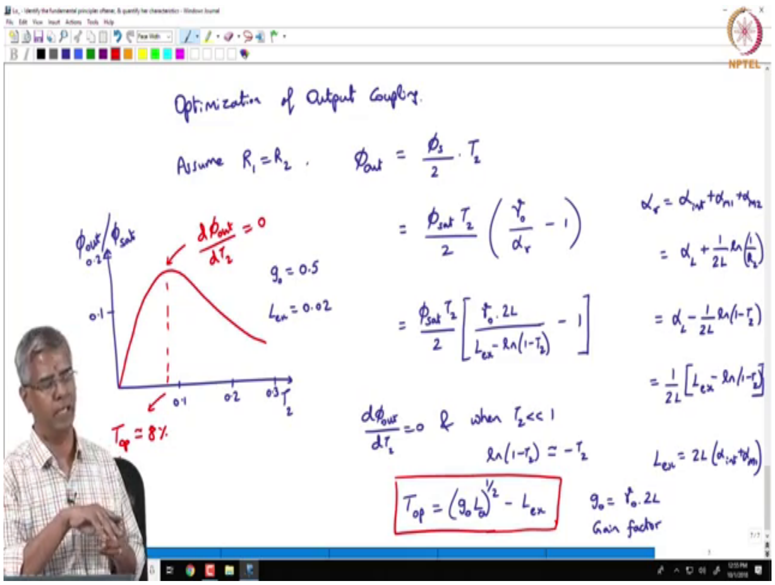

So let us say optimization of output coupling right so let us assume R1 equal to R2 ofcourse you can change that assumption also I will just come back to that in a minute. But if you assume R1 equal to R2 then what you are getting the photon flux that you are getting out is corresponding to the flux that you have built in the cavity divide by 2 multiplied by T let us say T2 (in this case) right if we are extracting if we are looking at a light out of mirror 2 I said divided by 2 because there is a similar extraction happening from mirror 1 also right. Infact I do not want that, what is the point of having a laser like this and the light going this way, light going this way, right.

You are going to utilize the laser to do something in one particular directions so you do not want like going from here. So what do you do you make R1 as close to one is possible ok so that everything escapes out of R2 and if you have that condition then actor of 2 will go away because you are extracting everything out of one end ok, you understand that. So I am just being consistent with what is giving in (())(22:13) textbook. Now phi S I have an expression for phi S is it here? Will be here so phi s I have expressed in terms of phi sat and then the small signal gain and the total losses ok so I can use that expression over here so I can write this as phi sat multiplied by T2 divided by 2 gamma knot which is the small signal gain divided by alpha R minus 1 right.

So I can just substitute instead of phi s I can substitute you know phi sat and this other part. Now what do we want to optimize? We want to optimize T2 but T2 if you look closely is not just sitting in the numerator it is sitting in the denominator also, where is it sitting in he denominator? As part of alpha R right so alpha R which I say is alpha int plus alpha m1 plus alpha m2 right I can I want to isolate alpha m2 right because that is what I want to optimize. So I can just basically say this is alpha int plus alpha m1 is alpha L and alpha m2 is 1 over 2 L (())(24:16) of 1 over R2 right and 1 over R2 I can write as you know R2 I can write as 1 minus T2 so I can just write this as this equals alpha L minus 1 over 2L (())(24:42) of 1 minus T2.

Why do I get a minus sign over here? Because it is 1 over 1 minus T2 I will just you know take a 1 of 1 minus T2 in which case there is a minus sign comes out ok and this I can further write I can take 1 over 2L outside ok as a common factor and then what I have is some total loss let me call that Lx right that is extra loss minus (())(25:30) of 1 minus T2 where Lx corresponds to 2L multiplied by alpha l, alpha l corresponds to alpha int plus alpha m1 ok, why I am doing all of that till the obvious in a minute so just bear with me so I am just going to substitute that expression for alpha R over here so I will have phi sat T2 over 2 and here I am going to have gamma knot multiplied by 2L divided by this loss factor Lx minus (())(26:40) of 1 minus T2 minus 1 ok.

So here lies the contradiction so you can say that when T2 is very small right then (())(27:11) of 1 minus T2 can be written as you know plus T2 so that will be Lx plus T2 sort of thing in the denominator and T2 is very small you know that is the assumption tat we started with T2 is very small than that factor essentially is very small with respect to the extra loss factor so T2 has very little effect in the denominator for small values of T2 it is dominated by what is in the numerator ok but for larger values of T2 you start having the denominator coming to the picture so then it will essentially you know start playing a role in terms of the power extraction.

So if I were to plot this function in general right let me just say the output flux normalize it with respect to the saturation flux because saturation flux we know is a constant for a given gain medium that is a, what is this saturation flux depend on? That is the excited state lifetime as well as the emission cross section ok. So that will be a constant for a given medium so I can just take that out of the equation that is not a variable that I am interested in, what I am interested in, in the X axis is T2 ok so if I plot this I will get some function like this right at small values of T2 the whatever is in the denominator is negligible right T2 does not have that part you can neglect and so it is proportional to T2 right the output flux is proportional to T2 and then it is you know then as you increase T2 you will have increase in the output flux and also the output power.

But as you increase T2 further you start having the denominator coming to the picture so then that will end up reducing phi out ok so we are looking at what is this optimum value, what can you say about this point, that is a point of inflection what happens at the point of inflection? The slope is zero so the derivative of phi out with respect to d T2 that is zero at that point right so what I can do is you know apply that I can take a derivative of this entire expression corresponding to phi out with respect to T2 and also under specific conditions so if I am looking at d phi out over D2 equal to 0 and when T2 is far-far less than 1 such that (())(31:26)of 1 minus T2 is approximately equal to minus T2 right if I have those two incorporated then I will come up with a final expression which says that the optimum transmission is going to be given by G knot into Lx to the power of R minus Lx.

Lx corresponds to the extra loss so this is what you get as the optimum transmission for this cavity. This cavity where I should also mention where G knot corresponds to gamma knot multiplied by 2L right that is the gain factor this is the gain factor for cavity and Lx corresponds to the extra loss factor inside the cavity ok. If you look at specific values you know this values are used by your book if we say G knot is 0.5 and Lx corresponds to 2% which is 0.02 then in that case what we find is this is about 0.1, 0.2, 0.3 and so on that is 10%, 20%, 30% transmission and this is 0.1 (0.2 is way up there) so on right.

So we find that for this values you find that the optimum transmission is roughly about 8% right. So and if you have higher, so what this tells you is if you have higher gain right if you have higher gain inside your cavity while you freeze all other losses then you can afford to push this optimum point to higher values then you can afford to get use higher transmission extract more power from the cavity ok. So that is the physical (())(34:35) so let me stop at this point.