Introduction to Photonics
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lasers Part 4

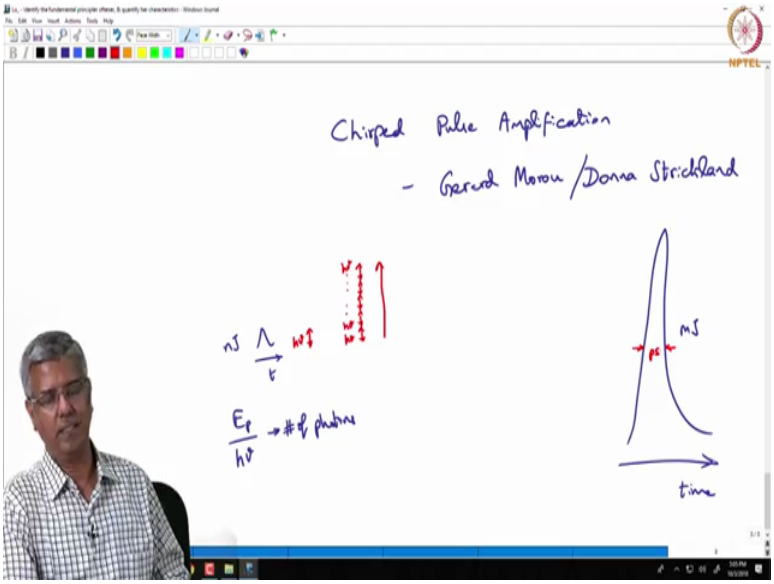
Okay, welcome to intro to photonics, so it has been cause for much celebration lately and you guys should feel proud to be part of this celebration because the Nobel Prize for Physics was announced yesterday and it is once again optics that is ruling the world so to say, I just pulled out the statistic you know just going back and looking at all the Nobel Prizes that have been awarded recently, since 2000, 20 Nobel Prizes have been awarded to optics related work and so we are continuing that trend, of course you say 18 years 20 Nobel Prize, how does that work?

It is not always in physics right physics of course has got most number of those prizes but there is also been contributions in chemistry I think three or four times chemistry and also biomedical imaging related work there was some Nobel Prize given for state microscopy to get a really you know less than hundred nanometer set of resolution in your imaging there was Nobel Prize given for that.

So overall you know it gives you a little more motivation probably to read about this because as you can see this is all leading up to something really good and I am sure more and more work in optics is going to get recognized as we go on because it is certainly changing the world around us right it is enabling us to do things which we had not dare to dream of before.

So I just thought I will take a few minutes to first of all talk about this particular work that got recognition Nobel Prize there are actually two aspects to it one was about cell manipulation and then the other part was about chirped pulse amplification, cell manipulation I do not want to talk about right now because it is off from what we had been discussing lately but chirped pulse amplification is certainly something that it is very much related to what we have been talking about.

(Refer Slide Time: 2:56)



Chirped Pulse Amplification

- Gerard Morou /Donna Strickland

So let us talk about chirped pulse amplification, chirped pulse amplification as the noble correctly recognized is something that was initially demonstrated by Gerard Mourou and Donna Strickland, right Gerard Mourou was actually the faculty or the director of the centre for ultra-fast lasers at University of Michigan at Ann Arbor so he is the professor and Donna Strickland was his PhD student and Donna was actually looking at how to increase the peak pulse energy of light. So essentially what she is looking at this I have a small pulse like this right let us say it is a picosecond pulse or maybe even a femtosecond pulse, how can I get a large pulse like this? So this is as a function of time right how can I get much larger pulse like this?

So I can essentially say the level at this is nano joules and the level at this is milli joules, okay so how do I achieve this sort of amplification of pulse? Now if you want to visualize this what is a pulse consists of? A huge number of photons right so you would basically say the pulse energy divided by h nu that actually gives the number of photons that are packed within this pulse right.

So even when you look at energy so let us say it is about 1 micron actually the experiments they did was around 1 micron, so corresponds to about 1.24 eV right, so 1.24 multiplied by 1.6 into 10 power minus 19 will give you the corresponding joules right. So you say 1 nano Joule 1 nano Joule is already packing something like you know billion photons okay so you have a billion photons to start with already within this pulse within a picosecond of duration and you can imagine when we are talking about amplifier what does the lifetime that we were talking about lifetime of these energy levels? Milliseconds right so picoseconds is a very very small fraction of that okay.

So we are talking about we are starting with a billion photons within a picosecond and now you want to go a billion times more or in this case a million times extra 10 power 6 extra photons all needs to be packed within that pico second so what is the advantage of that? Of course when you say you have so many photons going together and let us say it is interacting with a material okay normally your energy level corresponding to this in terms of energy would be something like this, right so one photon as an energy h nu right.

But if you have billions of photons all focused on to a same spot in a material okay it can interact with the material such that many of these photons add up they all come to the they all get they all come to the material at the same time so h nu, h nu, h nu can add up and you can get effectively the energy corresponding to a very high energy photon, so what am I talking about?

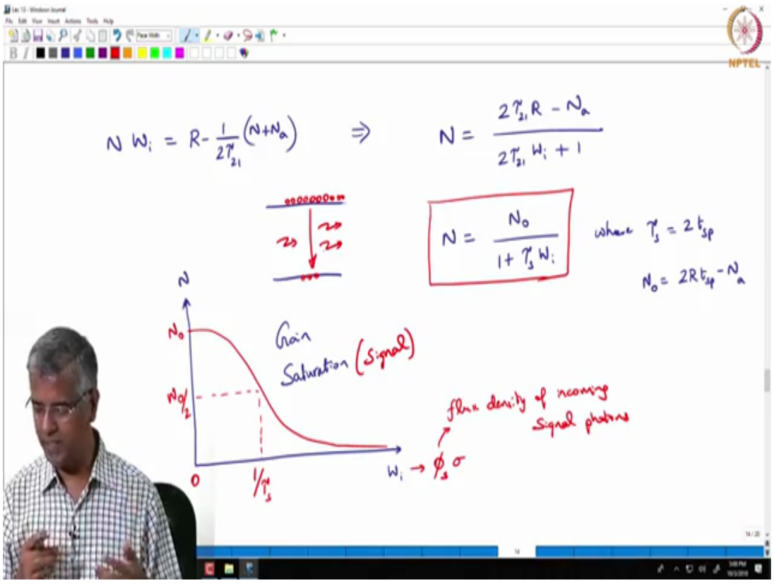
If I am saying one micron wavelength that corresponds to 1.24 eV of energy, but if I have five of those photons come together at the same time right instantaneously then I have 6 eV energy corresponding to 6 eV energy corresponding to 6 eV in this case would be 0.2 micron wavelength okay it is corresponding to the energy of a ultraviolet photon or you can even go beyond that and you can actually get the energy corresponding to x-rays by having multiple photons come together at the same point at the same time okay.

So when you go to very high levels of energy within a very short duration you can actually have you know this high energy physics now this whole dream of high energy physics becomes within your reach right so you can actually look at interactions, you can break bonds very high strength bonds you talk about diamond right it is one of the hardest materials that known to us right the bond energy is why is it hard? Because the bond energy is very hard right so you need to have a bond energy corresponding to that or higher than that to break that bond, if you break that bond then you can chisel away diamond, you can shape your diamond, you can cut your diamond, you can polish your diamond right.

So that is talking about the hardest material that is known to us, now every other material is child's play relatively. So you can talk about material processing at a much different scale, you can talk about depositing energy that can essentially allow formation of bonds also, you can break bonds and you can reform bonds, you can do chemical reactions that have never been thought about before, so lot of those things are enabled by having a way of reaching this this sort of energy levels within a very short thing, so how short? We are talking about pico second or even lower than that.

So question is lasik treatment in the eye would it be similar? Yeah, you can say that essentially to do a lasik treatment you need to chisel away your cornea, you need to shape your cornea, you need to ablate that. Now you do not necessarily need milli joules for that, even micro joule level is probably good enough, but that is still a challenge you know to get micro joules and within a very short pulse you know they use 100 femtosecond pulses in those cases and that is still a challenge.

(Refer Slide Time: 11:33)



$$N W_i = R - \frac{1}{2\tau_{21}}(N+N_a) \Rightarrow N = \frac{2\tau_{21}R - N_a}{2\tau_{21}W_i + 1}$$

$$\boxed{N = \frac{N_0}{1+\tau_s W_i}}$$

where $\tau_s = 2t_{sp}$

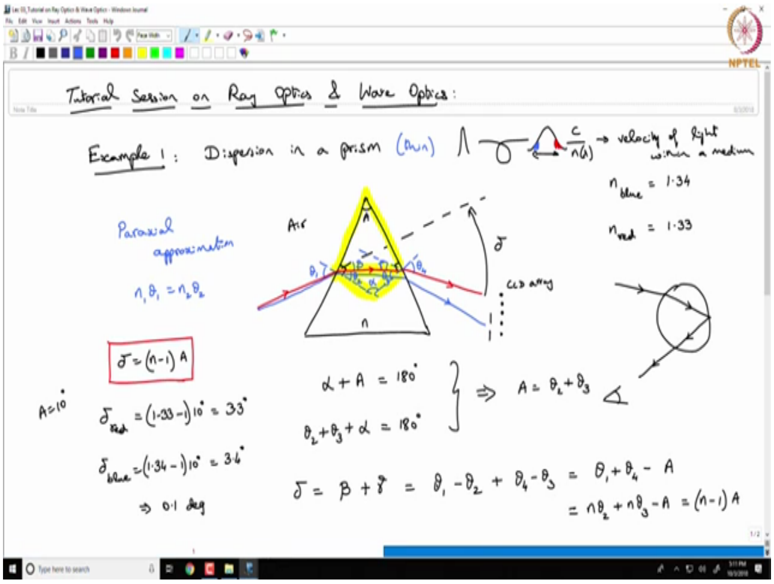
$N_0 = 2Rt_{sp} - N_a$

So to do this what exactly is the limiting factor, well we go back and look at this picture right that we studied upon, gain saturation. So you say you are trying to get an inversion, so you are trying to get an inversion between two energy levels, so you want such that you want the lot of ions sitting there compared to here okay and you are targeting these transitions to so you are coming in and stimulating with a photon and you are trying to get a gain from this material, so that gain will be proportional to the inversion that is what we have been studying over here.

But we also realize that as you go to more and more number of photons the first few photons that enter the system will see a huge gain but then it depletes the gain instantaneously depletes the inversion instantaneously and it is going to take some time for it to go back to that for to refill that excited state and within that time all the other subsequent photons coming in are seeing lesser and lesser inversion. So you essentially see saturation the gain saturation happening within that amplifier which limits the amplification that you can get.

So if you take a picosecond pulse with nano joule energy, you send it through amplifiers if so happens you cannot get all that amplification in one go, you can actually have multiple amplifiers and from nano joule you can go to 10 nano joules, 10 nano joules to 100 nano joules and 100 nano joules to a micro joule when you are trying to get to that you are starting to face some serious inversion issues this gain saturation issues because now you are trying to amplify several hundred billions of photons together right and now you do not have so much inversion that you can provide the same gain for all those photons, so your gain essentially gets limited you are not going to be amplify beyond a micro joule.

(Refer Slide Time: 14:19)



Tutorial Session on Ray Optics & Wave Optics:

Example 1: Dispersion in a prism (Sun)

$\frac{c}{n(\lambda)}$ → velocity of light within a medium

$n_{blue} = 1.34$

$n_{red} = 1.33$

Paraxial approximation

$n_1\theta_1 = n_2\theta_2$

$\boxed{\delta = (n-1)A}$

$A = 10^\circ$

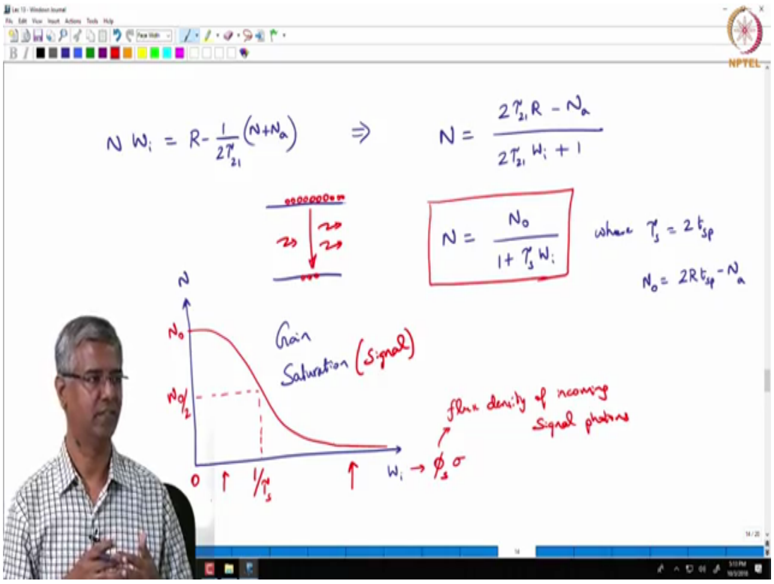
$\delta_{red} = (1.33-1)10^\circ = 3.3^\circ$

$\delta_{blue} = (1.34-1)10^\circ = 3.4^\circ$

⇒ 0.1 deg

$$\left.\begin{aligned}\alpha + A &= 180^\circ\\ \theta_2+\theta_3+\alpha &= 180^\circ\end{aligned}\right\} \Rightarrow A = \theta_2+\theta_3$$

$$\delta = \beta + \gamma = \theta_1 - \theta_2 + \theta_4 - \theta_3 = \theta_1 + \theta_4 - A$$
$$= n\theta_2 + n\theta_3 - A = (n-1)A$$



$$N W_i = R - \frac{1}{2\tau_{21}}(N+N_a) \Rightarrow N = \frac{2\tau_{21}R - N_a}{2\tau_{21}W_i + 1}$$

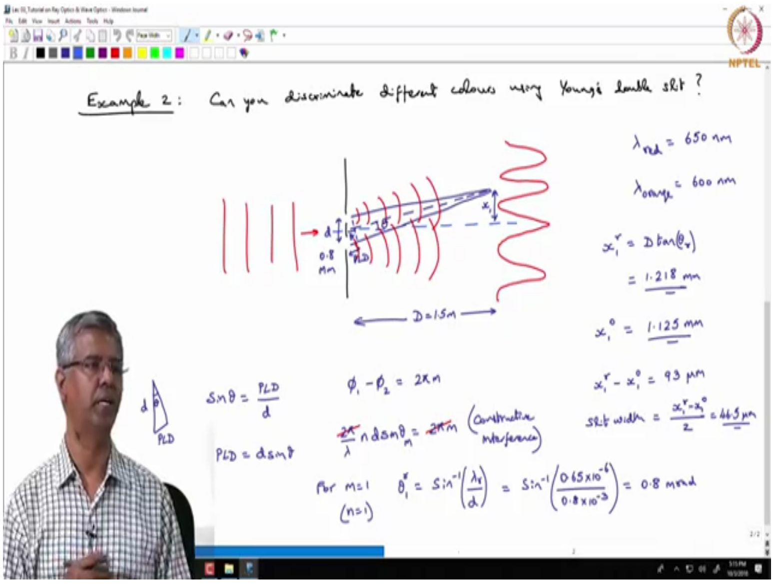
$$\boxed{N = \frac{N_0}{1+\tau_s W_i}}$$

where $\tau_s = 2t_{sp}$

$N_0 = 2Rt_{sp} - N_a$

Gain Saturation (Signal)

flux density of incoming signal photons



Example 2: Can you discriminate different colours using Young's double slit?

$\lambda_{red} = 650\ nm$

$\lambda_{orange} = 600\ nm$

$x_1^r = D\tan(\theta_r)$

$= 1.218\ mm$

$x_1^o = 1.125\ mm$

$x_1^r - x_1^o = 93\ \mu m$

slit width $= \frac{x_1^r - x_1^o}{2} = 46.5\ \mu m$

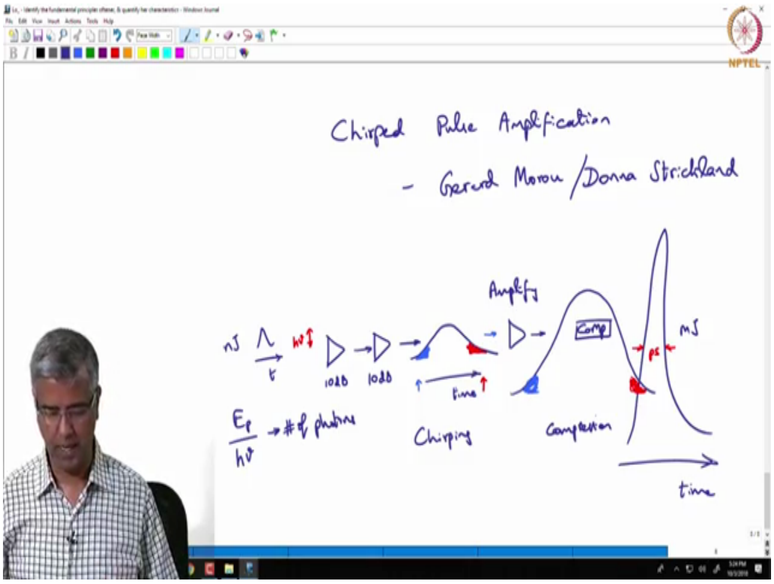
$\sin\theta = \frac{PLD}{d}$

$PLD = d\sin\theta$

$\phi_1 - \phi_2 = 2\pi m$

$\frac{\cancel{2\pi}}{\lambda} n\, d\sin\theta_m = \cancel{2\pi} m$ (Constructive interference)

For $m=1$ $(n=1)$ $\theta_1^r = \sin^{-1}\left(\frac{\lambda_r}{d}\right) = \sin^{-1}\left(\frac{0.65\times10^{-6}}{0.8\times10^{-3}}\right) = 0.8\ mrad$



Chirped Pulse Amplification

- Gerard Morou / Donna Strickland

$\frac{E_p}{h\nu} \rightarrow$ # of photons

So what did these people come up with? So yes we just erase this for a minute, so we are talking about having you sending it through one amplifier, you get let us say 10 dB amplification there and then you send it through another amplifier another 10 dB amplification and then you go beyond that you hit a stop because of gain saturation you are not going to be able to amplify beyond that.

So what did they do? They actually came up with a way of chirping the pulse, so what is chirping the pulse mean? Instead of a (small) narrow pulse like this you actually have a broader pulse okay so broader in terms of time okay and you made it such that you know the red color is over here, the blue color is over here and all the other colors are in between okay. So you essentially you broaden the pulse but you broaden the pulse such that you can you are essentially dispersing the pulse. Remember we talked about dispersion several weeks ago.

I want to go back and see if we can pull up that that particular discussion we had lecture three maybe (yeah bingo) we are talking about dispersion in a prism. So what is the basis for dispersion? Different frequencies travel at different velocities because the response of the medium is different, the refractive index post by the medium for different colors is different right. So you can you can essentially use something like this something like the dispersion to spread out the pulse okay and spread out the pulse in time.

So what's the advantage of that? Now what I can do is essentially at this point I have the red wavelength and that is relatively smaller amplitude pulse and then I go to the orange wavelength, then I go to the you know yellow and so on and then I come to the blue wavelength and it is a relatively smaller pulse, one large pulse like that I have basically flattened out I chirped it so it is actually smaller each of those colors have smaller magnitude and not only that they are all spread out in time okay.

So now first the red goes in gets amplified and before the orange goes in you have given some time for it to recover the gain the inversion to recover and then the orange gets amplified and before the next color comes in you are once again giving time for the gain for the system to recover and so on.

So I am actually making it look like it is discrete but in reality this is all continuous and these are not as broad as red, (L) orange and all that, these are just different shades of a color in reality but you are chirping the spectrum such that and you are spreading them in time such that these different colors essentially get amplified at slightly delayed time and that delay is enough for the gain to recover the atomic system to recover so that you can provide gain, you are essentially what you are doing is, in this picture you know we are we are at actually at this level with an individual pulse you are at this level right with a very narrow pulse you are at this level, but now when I have taken the same energy and I stretched it out okay each of those constituent colors are somewhere at this level, you have removed it from saturation and so now we are able to give achieve more gain okay.

So with that I am able to go through and I go through another amplifier and what I will do is I will I will actually go through amplification like this right I will get a larger pulse, but once again in this pulse also the red is somewhere over here, the color sequence I am maintaining and finally I go through in fact there is a paper in 1985 optics communications, so Donna is the first author Gerard is the second author. So it talks about compression of chirped pulses okay and that essentially is talking about once it gets amplified like this, it talks about going into a compressor, which is actually like a dispersion compensating element like a grating.

Remember that is what we talked about when we were discussing here that same dispersing element we can turn it around and we can actually compensate for that dispersion and we said this is one way of doing dispersion compensation, we said this multiple slits are grating is another way of doing a dispersion compensation and a grating type dispersion compensator is preferred over here because when you are compressing it back you are actually having so much energy.

Remember I talked about with so much energy you can ablate material, so if you propagate this pulse or you try to compress this pulse in some optical fiber let us say you will end up burning the optical fiber because you have so much energy that is going to ablate that material and so the entire you know material will be destroyed, whereas if you actually have a grating reflective type grating, yes of course there is still this possibility that the pulse can hit the reflection coating and it can end up ablating the coating also.

So what you have to do is take that beam and actually expand the beam, so the power density that is hitting on that grating is lesser, instead of a narrow beam going in you expand it to this size of beam. So the number of photons per unit area is lesser, so you do not have the possibility of ablation in that case. But you essentially have to go through that, go through a grating which essentially delays the red with respect to the blue and recompress the pulse to the original form. So you are taking all this photons that are scattered in frequency and scattered in time and you are compressing them back to achieve this original pulse shape itself.

So I know there are a couple of questions, so one is this process which we calling us chirping and this process is amplification and this process is compression. So this is chirp pulse amplification they left out compression but compression is a essential part in it to put everything back and get that large pulse, I know there are a couple of questions you raised your hand first.

So chirping is actually separating out the frequencies, so you are separating out the frequencies in time. So it is basically you can look at it as negative dispersion, if you thought dispersion is spreading in time but spreading in time meant that blue was traveling faster than red this is the negative dispersion red is traveling faster than blue you know it is that that sort of a thing but both of them end up spreading in time.

So one is negative slope like this and other is positive slope like this, so it compensates the two, yes? No, no it cannot create new (freq) well if you have a nonlinear material coming into the picture it can create new frequencies also but you can do that also, but in in this case normally you are just trying to stretch the pulse, you try to keep the frequency content and (huh)? Yes, exactly so what we are talking about is a picosecond pulse which is already a few nano meters wide so it has got the wide range of frequencies and that you are yes stretching out further.

So this is what they got part of the Nobel Prize for, which is by itself a huge achievement and since then for those of you that are interested there is actually a femtosecond laser lab in our campus, so Mano here is actually working in that lab, so he uses that laser on a daily basis and that laser uses this technique chirped pulse amplification technique it is a commercial laser it is sold for several hundred thousand dollars but it is capable of putting out six milli joules, six milli joules with a hundred femtosecond pulses, the what at least the vendor when they sold it to us told us that this is the highest energy laser in India as one system, I think people at RRCAT, RR what does it stand for Raja Ramanna Centre for Advanced Technology, RR in Indore they deal with a lot of these high power lasers and they do chirped pulse amplification also, so they might actually contest whether but what they meant was that this is the highest energy commercial system that is available in India okay.

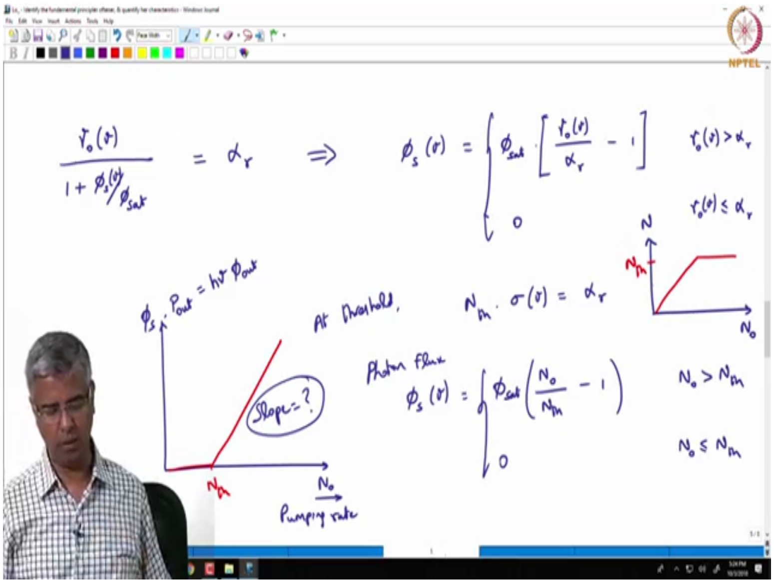
But you can go and see that it is of course not see it but what you see how the laser is working right so and we do try to ablate diamond artificial diamond do not think we are storing diamonds there, artificial diamond we try to ablate using those lasers and thanks to thanks to these guys for enabling that technology.

So yeah so we are before chirping you are at about micro joule level and you can go through several stages of amplification and you can get to the milli joule level, two or three stages of amplification you typically need to do. So the minimum pulse width, well you cannot say it is a minimum pulse width it is like if you take a nanosecond pulse you can go up to milli joules okay without chirped pulse amplification.

If we take a picosecond pulse you can go up to you know micro joules before you need chirped pulse amplification, if you take a femtosecond pulse one femtosecond pulse you are limited to nano joules, it is basically the total energy that you can get out of the amplifier system for a unit pulse width that is limited. So you are essentially overcoming gain saturation issues involved with ultra-short pulses through this chirped pulse amplification technique.

Make sense? You would have thought this is easy straightforward to do right why did they are getting why they are getting a Nobel Prize for this? Yeah, now that they have done it now it looks very simple but yeah those days they were stuck with those nano joule energy pulses so that was the deal.

(Refer Slide Time: 30:20)

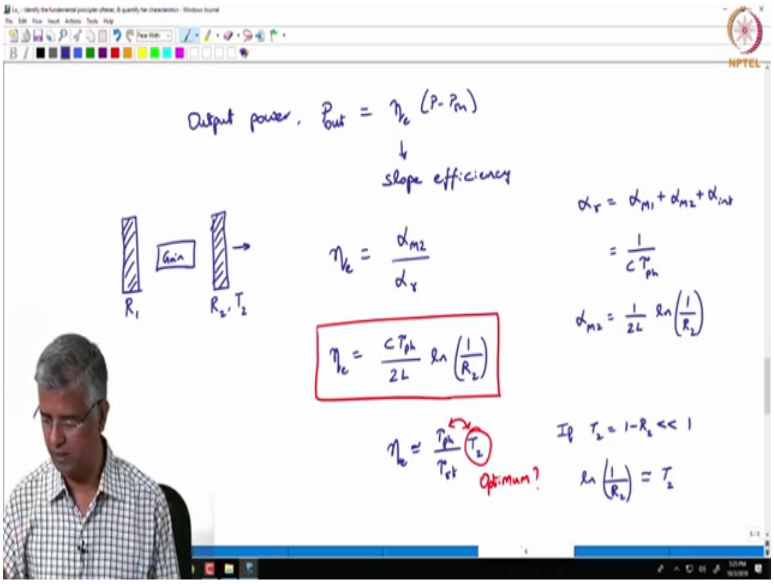


$$\frac{\gamma_0(\nu)}{1+\phi_s(\nu)/\phi_{sat}} = \alpha_r \Rightarrow \phi_s(\nu) = \begin{cases} \phi_{sat}\left[\frac{\gamma_0(\nu)}{\alpha_r} - 1\right] & \gamma_0(\nu) > \alpha_r \\ 0 & \gamma_0(\nu) \le \alpha_r \end{cases}$$

At threshold, $N_{th} \cdot \sigma(\nu) = \alpha_r$

Photon flux

$$\phi_s(\nu) = \begin{cases} \phi_{sat}\left(\frac{N_0}{N_{th}} - 1\right) & N_0 > N_{th} \\ 0 & N_0 \le N_{th} \end{cases}$$



Output power, $P_{out} = \eta_e (P - P_{th})$

↓

slope efficiency

$$\eta_e = \frac{\alpha_{m2}}{\alpha_r}$$

$$\alpha_r = \alpha_{m1} + \alpha_{m2} + \alpha_{int} = \frac{1}{c\tau_{ph}}$$

$$\alpha_{m2} = \frac{1}{2L}\ln\left(\frac{1}{R_2}\right)$$

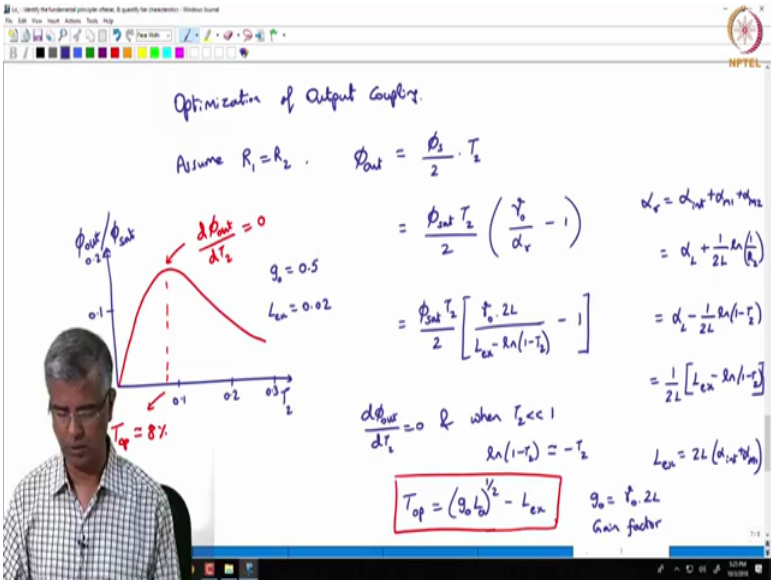
$$\boxed{\eta_e = \frac{c\tau_{ph}}{2L}\ln\left(\frac{1}{R_2}\right)}$$

$$\eta_e \simeq \frac{\tau_{ph}}{\tau_{rt}} T_2$$

Optimum?

If $T_2 = 1 - R_2 \ll 1$

$$\ln\left(\frac{1}{R_2}\right) \simeq T_2$$



Optimization of Output Coupling.

Assume $R_1 = R_2$. $\phi_{out} = \frac{\phi_s}{2} \cdot T_2$

$= \frac{\phi_{sat} T_2}{2}\left(\frac{\gamma_0}{\alpha_r} - 1\right)$

$= \frac{\phi_{sat} T_2}{2}\left[\frac{\gamma_0 \cdot 2L}{L_{ex} - \ln(1-T_2)} - 1\right]$

$\alpha_r = \alpha_{int} + \alpha_{m1} + \alpha_{m2}$

$= \alpha_L + \frac{1}{2L}\ln\left(\frac{1}{R_2}\right)$

$= \alpha_L - \frac{1}{2L}\ln(1-T_2)$

$= \frac{1}{2L}\left[L_{ex} - \ln(1-T_2)\right]$

$\frac{d\phi_{out}}{dT_2} = 0$ & when $T_2 \ll 1$

$\ln(1-T_2) \simeq -T_2$

$L_{ex} = 2L(\alpha_{int} + \alpha_{m1})$

$\boxed{T_{op} = (g_0 L_{ex})^{1/2} - L_{ex}}$

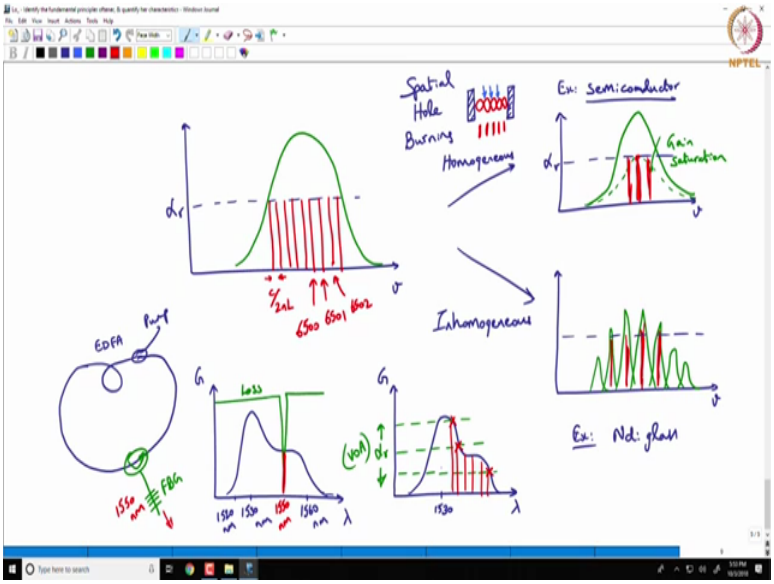
$g_0 = \gamma_0 \cdot 2L$

Gain factor

Okay, now I want to go back to what we were discussing previously and what we were discussing previously was characteristics of the laser we said okay the one part of it is the you know output power characteristics and we said output power when you plot as a function of pump power you have a certain amount of pump power that goes into creating gain in the medium gain in the cavity to overcome the losses in the cavity and so that is what we call as the threshold pump power.

And you can also say that below threshold it is primarily spontaneous emission that is dominant, but above threshold you have lot of these pump photons getting converted to signal photons. And so we were trying to figure out what is the slope efficiency for that and then we went around and derive some expression for the slope efficiency and then within that expression we said we needed to optimize the partial reflection of your or the transmission of your output coupler so that you can extract the optimum amount of energy. So we went through some math to figure that out what has got to be that optimum transmission.

(Refer Slide Time: 31:54)



Now that is on one side, the other side is we want to look at what are the spectral characteristics of your laser? And to look at the spectral characteristics now we are looking at it as function of laser frequency, we say okay the loss is at this level right and if your gain line shape is like this then you basically say that you have all these longitudinal modes that are spaced what C over 2 times nL, where L is the length of the cavity and n is the refractive index of the medium inside the cavity, so you have all these longitudinal modes in this laser.

But of course this picture is slightly flawed okay this is not typically what you see from your laser okay. So what happens is of course your gain gets saturated as you have all these photons that are oscillating in the cavity and then it can create some issues, to track that we have to consider two different types of material one is called homogeneous broaden material and another is called inhomogeneous broaden material okay.

So example for homogeneous broaden material is probably semiconductor material so gain in a semiconductors are like this, where when you look at the gain as a function of frequency we said it has got a certain line shape right it has got a certain line shape and when you saturate the gain medium when you have large number of signal photons inside the cavity what happens is that line shape remains but the overall gain actually saturates.

So this is basically the effect of gain saturation in a homogeneously broaden medium because when the gain saturates it is uniformly saturates across that entire medium if it is a semiconductor we are talking about something in the order of 100 microns that is the typical size of the semiconductor and the saturation is such that the photon density you can say is sort of uniform uniformly spread around that region and the saturation is uniform. So the entire gain you know spectrum comes down sort of in a uniform manner okay.

So if you have let us say the case where your this is corresponding to alpha R if your losses inside the cavity is at this line, then this is actually suggesting that of course in steady state what can you say about the laser in steady state? What can you say about the gain of the laser in steady state? Gain should be equal to the loss. So if you say the whole line shape remains and the gain gets clamped at the lost line what does it say? It basically says that only a single longitudinal mode can survive in the cavity okay, so that is what you expect as far as a homogenously broaden theoretically a homogeneously broaden medium should have only one longitudinal mode.

But in of course when you talk about practical situations the practical situation so if you have let us say one mode one longitudinal mode existing within the cavity let us say my cavity is like this, so if I say there is only one longitudinal mode happening within the cavity, basically it says that something like this only one particular mode is there so the reflected component will be like this. So the that will be like a there will be one standing wave pattern okay.

But if you have one standing wave pattern there are regions of high intensity and low intensity, if it is a standing wave pattern it corresponds to regions of high intensity and low intensity, at low intensity your gain is not saturated, at high intensity the gain is saturated. So it cannot remain as one mode because your gain is unsaturated in these regions at these null regions and it is saturated in the other regions.

So then it the gain actually grows in a non-linear fashion, the you gain available to you is more in this other region. So it tends to actually find some other mode, where you can you know you can have that constructive interference criteria. So it does not remain in this mode, it starts oscillating in some other mode, some other neighbouring mode and some other neighbouring mode and so on. So it actually jumps between all these modes do you understand?

So your gain saturation typically should happen such that the line shape is maintained, so under that condition the gain clamps at the lost line and you have only one longitudinal mode oscillating. But one longitudinal mode corresponds to a standing wave pattern and a standing wave pattern has got high and low intensity regions, high intensity regions are heavily saturated gain, so you do not get as much multiplication, whereas at low intensity regions you have more gain so you multiply more and that means it is not low intensity anymore it is going to high intensity.

So that means it is actually looking for some other mode which satisfies which can fit within the cavity. So it will be one of the other longitudinal modes that can fit into the cavity. So it actually oscillates between different longitudinal modes in the cavity, line shape overall remains the same so now you basically the overall line shape would have to change accordingly.

So if it is the steady state condition is that whatever mode that is oscillating has got to have gain equal to loss, but which mode satisfies that condition? It is actually changing as a function of time. So if you are looking at a time average picture it will feel as if all those modes are oscillating because they are fluctuating at a fairly small a timescale in a microsecond time scale. So you would it would seem like in a steady state if you are doing a measurement over a millisecond, it seems like all those modes are oscillating simultaneously.

But theoretically the point is without (you) if we do not consider gain saturation, only one mode should oscillate in a homogeneously broadened system that is a question back there. So it takes away gain enough to overcome the loss, it gets clamped there but for this picture, but for this gain saturation picture where you know this is actually an effect called spatial hole burning, so spatially it is burning a hole meaning its saturating some specific points along that gain medium.

Yeah, what is the question? So in this case you have well if you are talking about one longitudinal mode that longitudinal mode corresponds to a standing wave pattern and standing wave pattern essentially means you have you know clearly defined high and low intensity regions. So the saturation level in these regions are different so that means it has to it is always trying to go to some other you know modes where it can actually you know that can supported by the cavity, so it oscillates between different modes.

If it is one mode it corresponds to one specific intensity pattern, so what we are saying is it corresponds to this is high low, high low, high low, high low. So in these regions where it is high the gain is lower and the other regions where it is low intensity the gain is higher. So it is actually trying to amplify those photons in in those low intensity regions, then that then that does not satisfy this particular mode condition because what defines this mode is specific standing wave pattern that standing wave pattern essentially gets distorted by this gain saturation phenomena, so that the specifically at the lower intensity regions the gain is higher.

So it tries to find some other mode where it you know it can satisfy it will be a slightly shifted mode (())(44:45) that the path length is fixed its path length is fixed. So what this all these longitudinal modes mean is that each one of those correspond to a standing wave pattern, but they are slightly different period. So let us look at it like this if I am looking at some mode like this you know when I look at that condition or the mode that satisfies a particular cavity this mode number can be 6500, this mode number 6501, this mode number 6502, what does that mean? It has got 6500 fringes within that cavity.

Now if there is anything distorting that pattern it will go into the neighbouring pattern which allows 6001 fringe or 6499 fringes. So it will it will distort and it will go to some neighbouring modes it will get into that. So that is what we are talking about it is when you consider that it is that many it corresponds to a wavelength, I randomly throughout a number 6500, but let us say your cavity length is 100 microns, if you have 1 micron wavelength, so 100 wavelengths would have to fit into that.

So we are talking about if it is 99 wavelengths fitting into that that corresponds to a slightly higher wavelength than 1 micron maybe 1.01 micron or something like that. So all these longitudinal modes are corresponding to that, multiple modes are possible in a laser cavity it is not like all of them are present that is what we are trying to say here, huh? It cannot be because as technically standing waves essentially says that you have a high and low. So then we are talking about different levels of saturation, different levels of gain for different points in that cavity.

So the lower gain or I mean lower intensity or higher gain they will multiply faster than the other guys. So then that is distorting the standing wave pattern. So it will tend to go to a neighbouring pattern that fits that to momentarily because the saturation once again happens and all that. So that is that is what we are talking about. Well things are much simpler luckily when we are considering inhomogeneous broadening. Inhomogeneous broaden systems are such that I do not have the same property everywhere, so some location has got this sort of gain spectrum, some other location has got this sort of, some other location as this sort of gain spectrum and so on.

So it is like multiple independent oscillators are present in this system and in this oscillation at one does not prohibit oscillation at because the saturation levels are different. So I can have multiple modes that could be present within my you know cavity, multiple independent modes that could be present within the cavity as long as they independently satisfy the gain and loss criteria.

So this is allowed, the other case if you say it is homogeneously broadened it means homogeneously saturating and if it is homogeneously saturating, theoretically only one mode can be oscillating, but then practically we see all these because of the special hole burning issues we have all these other things happening. But here you could have independent oscillation, independent saturation of the medium.

So example for this is (())(50:33) glass okay that is one good example but even when we talk about erbium doped fibers, terbium doped fibers, they exhibit inhomogeneous broadening. Erbium for example you were experiencing this in your last experiment that you did when you look at the gain as a function of frequency or wavelength in an erbium, the gain spectrum would have looked something like this and it has got a long tail here or some somewhere over here.

So the peak is at 1530 and it comes down rapidly beyond 1560 does not have much gain below 1520 nano meters, so with erbium system you have a certain portion around 1530 let us say that is actually that portion is homogeneously broadened meaning all the oscillations around there they saturate uniformly. But when you consider the entire spectrum especially at the peripheries of the spectrum, they correspond to inhomogeneous broadening meaning their saturation is independent.

So this is the experiment you did in one case in your ring cavity. So you had basically a erbium doped fiber amplifier, which is pumped counter pumped with some with pump at 980 nano meters. But what you did was you took that and you looped it back so there is no external signal fed in, it is all within I mean whatever was the output of the erbium doped fiber you fed it back as the input that is how you made a ring laser.

And what you did was you put an element over here, you put you send it through a circulator which led to a element called a fiber bragg grating, you put a fiber bragg grating into this so that light actually goes through the fiber bragg grating and comes back and the fiber Bragg grating what it did was, it was reflecting only at one wavelength okay all the other wavelengths it was providing very high loss.

So my loss line now it looked like this, this is my loss of the cavity which incorporates the fiber bragg grating and this made sure that only at one wavelength you have gain overcoming the loss and only at that wavelength you are having oscillation. So if the grating was highly reflecting at 1550 nano meters that is where it is highly reflecting 1550 nano meters is the oscillation wavelength you saw because all other wavelengths are just escaping through this fiber bragg grating they are not recirculating in the cavity, FBG is a filter it is a reflection type filter, it reflects only one particular wavelength all other wavelengths it is very high loss. So you don't have enough gain to overcome the loss okay.

And because of that you are able to get oscillation only at one wavelength, you locked your output to only one wavelength that is the laser you built. Now we have built one more laser, you remember what you did, what was that laser about? I still had the same erbium gain spectrum at the peak at 1530 nano meters, but in this what did I do? Instead of a FBG instead of a circulator and FBG, I introduced a variable optical attenuator.

So what was I doing in that case? By changing the attenuation in the cavity I was actually changing your alpha r through the VOA variable optical attenuator. So now in this case what happens? You have essentially when you consider the highest or the lowest loss case, the lowest loss case it can oscillate anywhere but if we oscillate around 1530 it is getting severely saturated and on top of that at 1530 you also have absorption happening, your absorption cross section at 1530 is higher than what it is at longer wavelengths. So lot of those wavelengths were getting reabsorbed inside that.

So with the result that at this level you are having you are seeing some oscillation over here and then as you increased your loss in the cavity you are moving to this point as you increase the loss further your loss and gain point was meeting at some other wavelength at a shorter wavelength and when you increase the loss further you got to this point even shorter wavelength because with very high loss only the peak of the gain can overcome the loss the peak of that gain spectrum can overcome the loss and because of that your oscillation was actually happening at a much lower at a shorter wavelength.

So you saw as a function of if you were to plot the output wavelength as a function of attenuation as I increase my attenuation the output wavelength became shorter, did you observe that? As you increase your attenuation in the cavity your output wavelength became shorter. So these are the considerations when you think about the spectrum of the output spectrum of your laser.

So the output spectrum typically is determined by where the gain meets the loss that is right yeah it has got to be a longitudinal mode, there is no way to get around that so it has got to be a longitudinal mode around that particular frequency. Yes, it has to line up with one of the possible longitudinal modes in the cavity, only those will satisfy the phase matching condition okay.

So what we will do in the next lecture is actually jump little bit I think we have talked about enough (())(59:11) systems this dilute gas type of systems let us actually jump into semiconductors and let us start understanding how these holes and you know electrons how they interact with how they recombine to generate photons? How photons can be absorbed in the material to generate electron hole pairs? You know so one is the source and others is a detector. So how does all those physics work out and what are the corresponding photonics issues related to that we will discuss that starting tomorrow okay, thank you.