Semiconductor Optoelectronics
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Lecture - 36
Semiconductor Laser – III
Single Frequency Lasers

We continue our discussion about various laser structures, and today we will discuss about Single Frequency Lasers. Single Frequency Lasers referred to semiconductor lasers, which oscillate in a single longitudinal mode and a single transverse mode.

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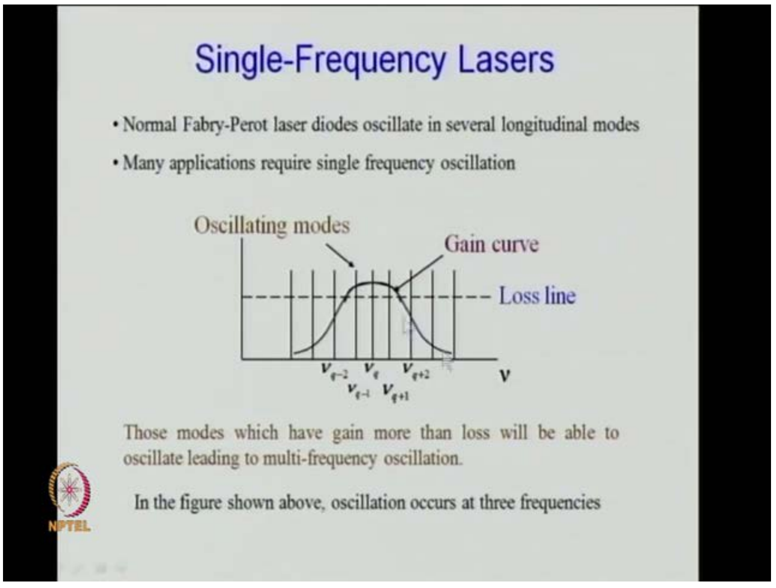

The basic idea of single frequency lasers is illustrated here; we have discussed this, but let me recall it. That normally Fabry-Perot laser diodes oscillate in several longitudinal modes, because you can see here that this is the gain curve here, and this is the loss line. And those frequencies the vertical lines represent the resonance frequencies allowed by the resonator, but only those frequencies here 1, 2, 3, these 3 frequencies have gain at those frequencies gain is more than loss.

Loss line is here, horizontal line, gain is more than loss and therefore, only these 3 frequencies, these 3 resonance frequencies or these 3 longitudinal modes can oscillate in a laser. So, normally all longitudinal modes or all resonance frequencies allowed by the resonator, for which gain is more than loss will oscillate which means generally we have few modes oscillating in a semiconductor laser.

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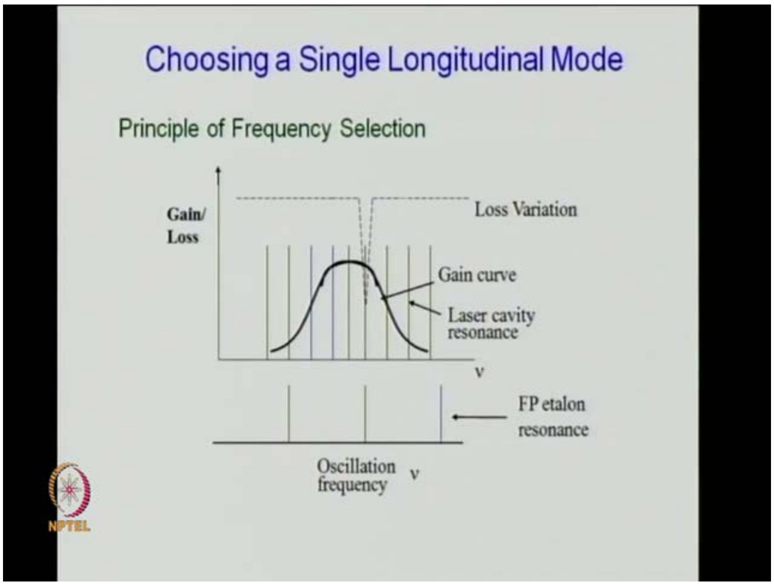

If you can some how increase the loss for all modes, but one mode which want to which you want to lays, then it is possible to choose only one longitudinal mode. So, the idea is here again, the gain curve is the same, the resonance frequencies are the same, but if you can have a loss profile where, loss is more for all frequencies, but for one here, then it is possible that only one of these longitudinal modes will oscillate. For example, we will see the mechanism of a choosing single frequency lasers, but if you have a Fabry Perot etalon we will see let me show the next diagram and then come back.

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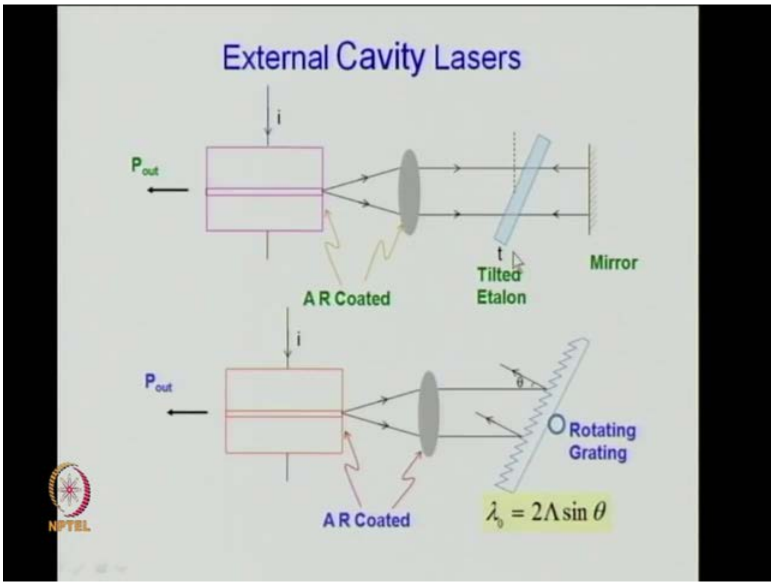

So, this is the laser here, it is A R coated anti reflection coated here, and the light output from this end passes through this. So, this is the semiconductor laser the basic device, current passes through the device and gain is provided by this medium and there is a Fabry Perot etalon Tilted Etalon, we have discussed how the tilted etalon chooses a particular required frequency. So, this is a tilted etalon in the cavity.

So, the cavity comprises of this mirror and the mirror at this end, the cleaved end at this end which is not antibodies-reflection coated, and this mirror which is usually 100 percent reflecting that is the one which cavity. So, this is the cavity from here, right of. So, this is the way light is going back and forth, but there is an etalon in between etalon permits only certain resonance frequencies to pass through.

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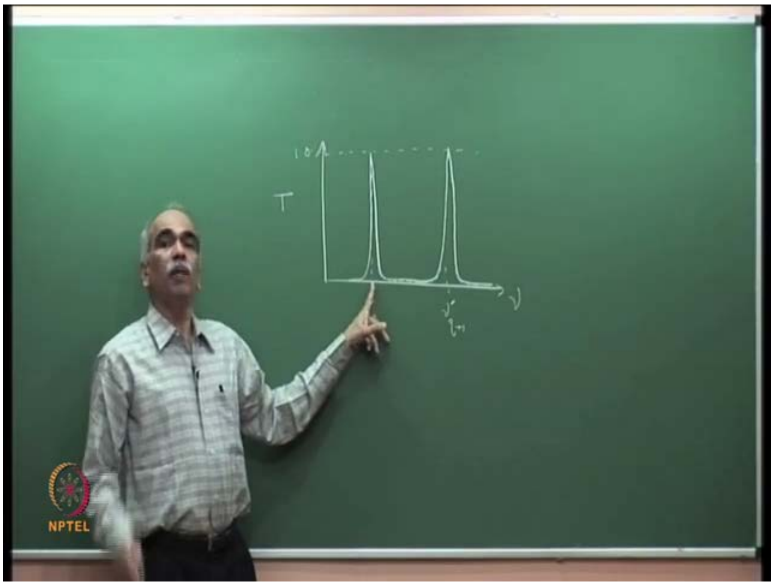

The transmission of this etalon if I may use the board if you see the transmission of the etalon, so this is frequency nu then the transmission shows peaks like this, the narrow. So, what I have plotted is the transmission of the etalon. So, this is transmission and this is one. So, 1 point transmitting v t or transmission verses frequency. So, there are frequencies here nu q and nu q plus 1 this is of the resonator. So, let me put them as dot these are the etalon not of the resonator. So, there are transmission peaks here, which means a frequency which is here, will pass through the etalon as if the etalon there.

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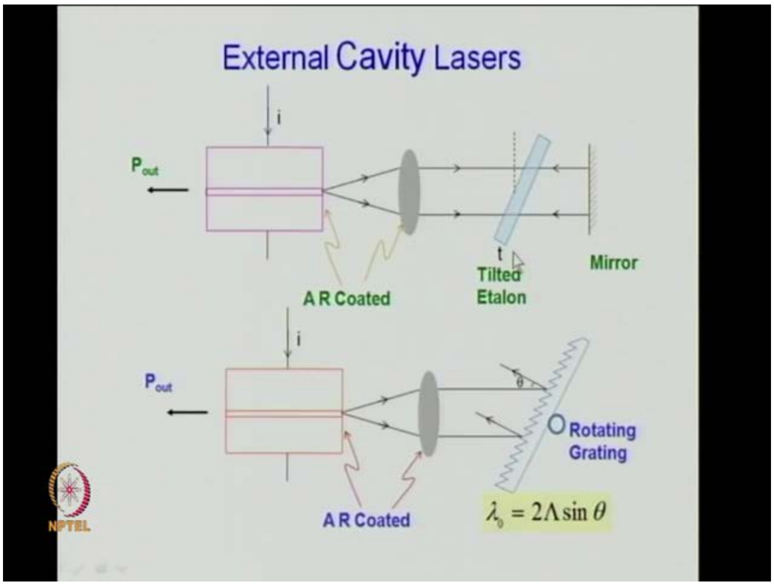

So, this etalon here, that frequency will pass through if the etalon is not there, which means for that frequency for these resonance frequencies this cavity is a low loss cavity. Whereas, for any other frequency the etalon transmission is very small, which means the does not act as a good cavity and this is the idea by which you choose, so let me go back to the figure again.

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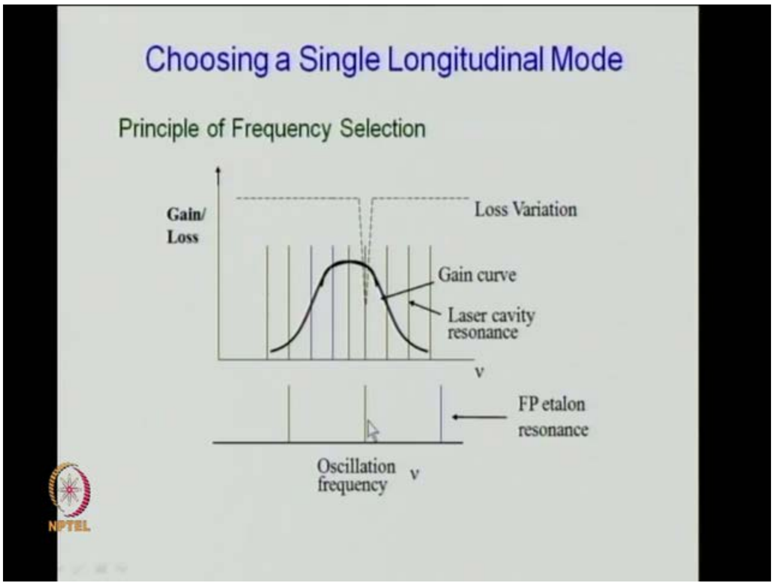

Here, you see the etalon resonance frequency are these, these are the etalon resonance frequencies separated by a free spectral range within large.

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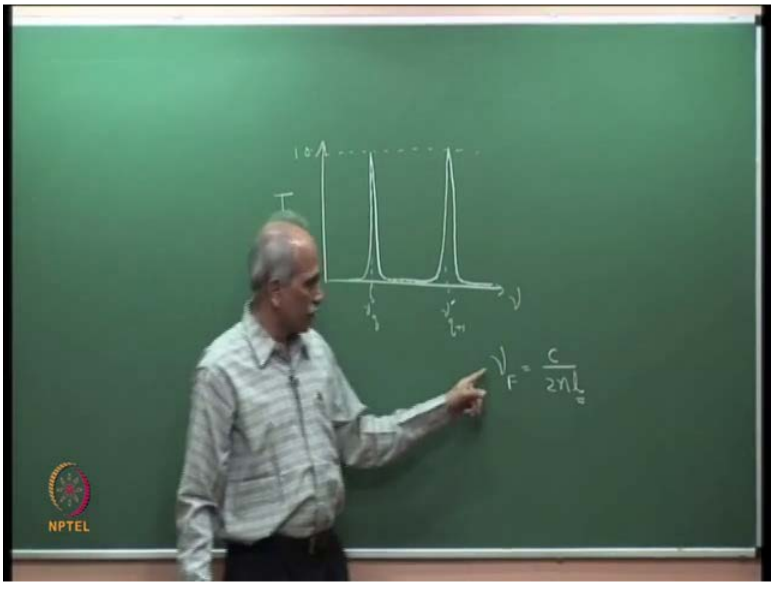

Because, the free spectral range nu, f if you be recall is given, by c divided by 2 n into l where l is the length of the cavity. For the etalon l is very small and therefore, the free spectral range or separation where in the resonance frequencies is large.

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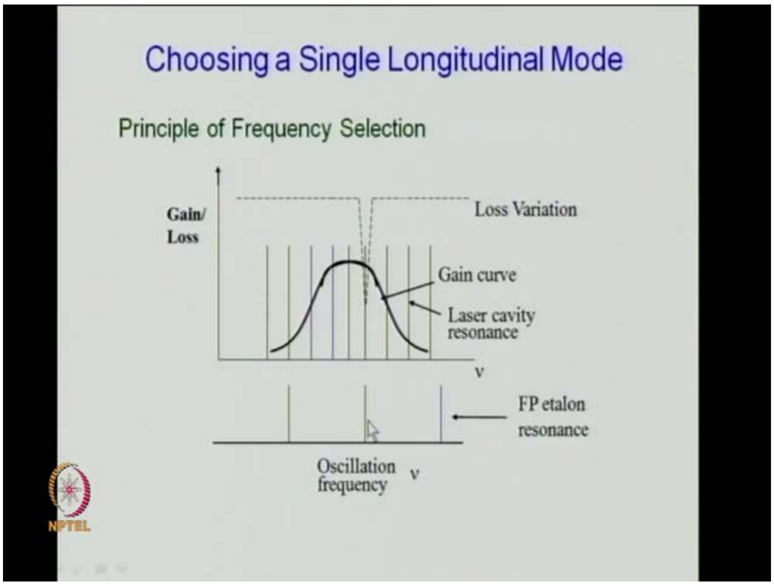

But, for the laser cavity, the laser cavity comprises of this whole cavity. Let me show again here.

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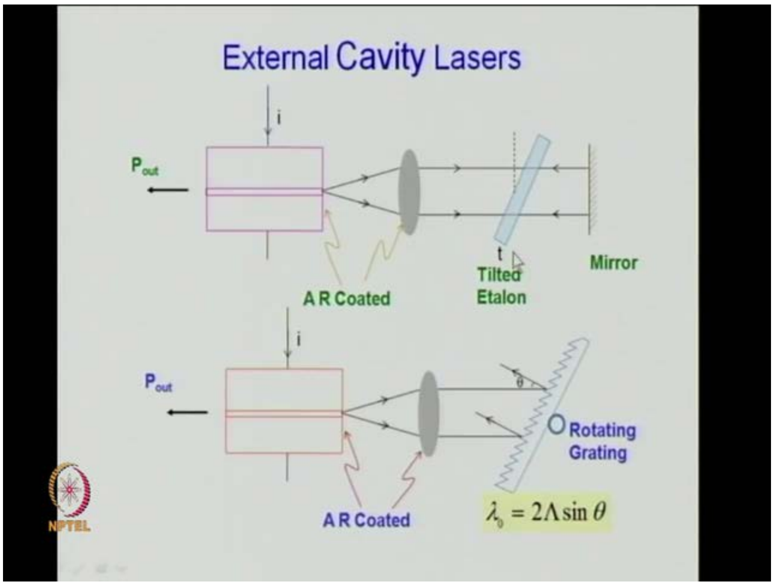

So, this is the laser cavity, from here to here this l is very large, and therefore the resonance frequencies permitted by this cavity are much closely placed or the free spectral range for this whole laser cavity is much smaller.

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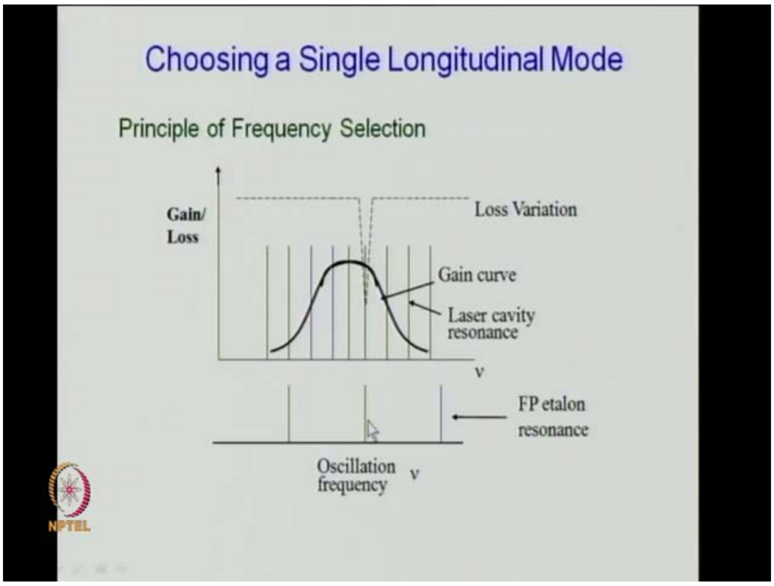

And therefore, let me go back again to the other figure here. So, these vertical lines correspond to the laser cavity and these vertical lines, correspond to the resonance frequencies of the etalon. Whenever, the etalon resonance frequency co inside with the laser cavity resonance frequency, that particular frequency will pass free real's at the cavity.

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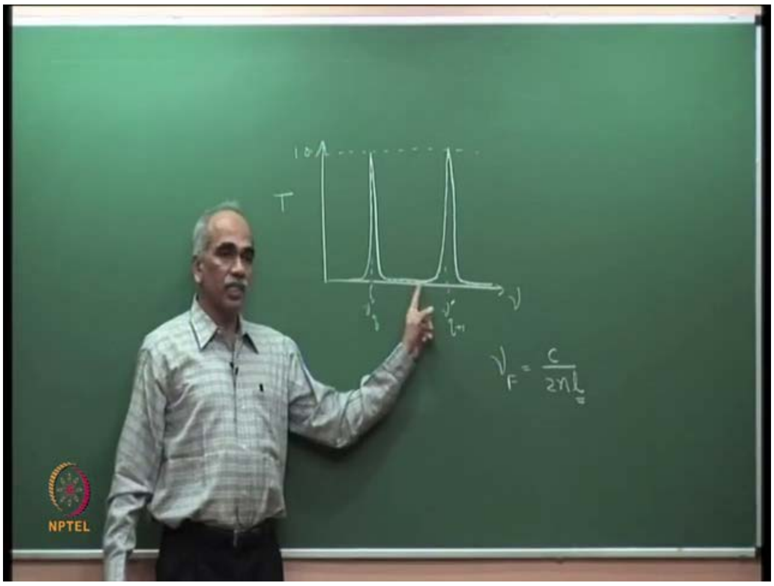

That is if this happens to be co-in siding with the allowed resonance frequency of the laser cavity, then this frequency transmission is one, which means it does not see the etalon at all it is low loss etalon is a low loss device for this frequency. Inside the cavity there is an etalon which is a high loss device for any frequency which is here, because it is not allowing those frequencies to pass through.

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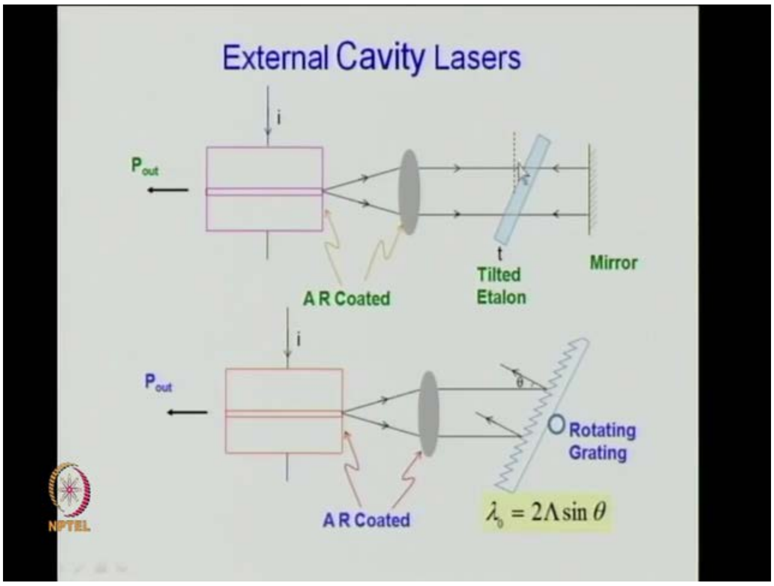

So, what happens to those frequencies? Those frequencies which are incident here, will get reflected in this direction it is a tilted etalon the tilted etalon the tilt has two reasons, why do we need a tilted etalon one, the frequencies which are not transmitting will get reflected. And when it get reflected when it gets reflected it will go like this, at an angle. So, does not go back the second reason why you do the tilted etalon is by changing this angle theta, you can change the separation nu f.

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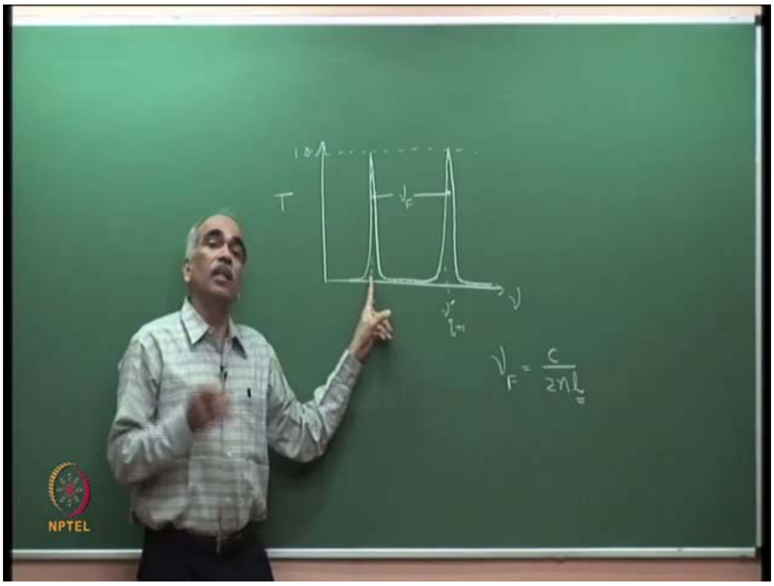

So, nu f is the frequency separation nu f. So, this frequency separation can be tuned. So, that at least one resonance frequency co-insides with the resonance frequency of the laser cavity.

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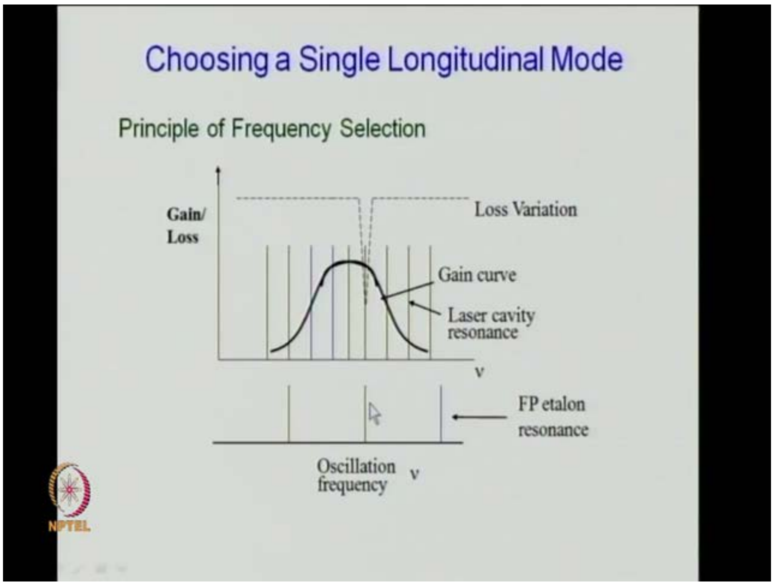

So, at least one resonance frequency this one or this one, co-insides with the laser resonance here. So, that particular frequency loss is very low, for all other frequencies here the loss is very high. So, this frequency here c is low loss because that is the transmission resonance of the etalon. So, this is the principle by, which it is the same laser structure, but the cavity is now, lousy for all frequencies, but for one.

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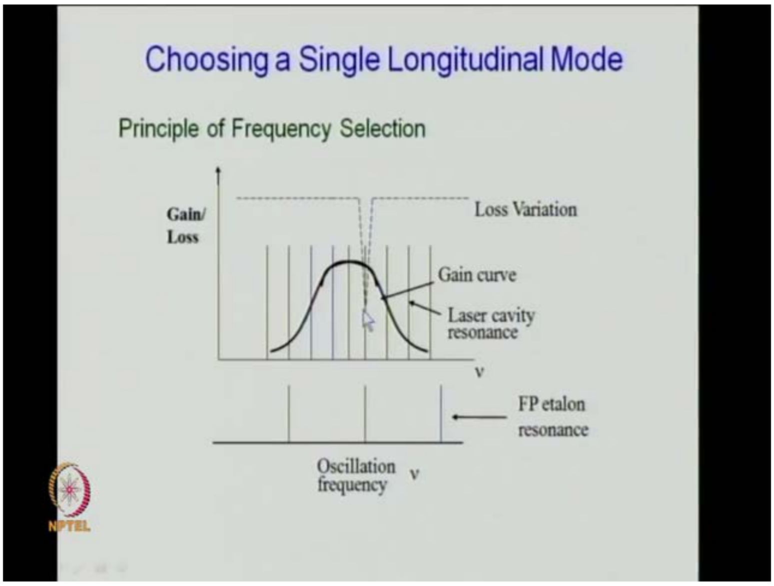

Therefore only the loss curve here, for one particular frequency. And which means here for this frequency (( )). So, gain is higher than the loss and therefore, this is the frequency which will oscillate in this place by, this means we have chosen one single longitudinal mode thus laser structure here.

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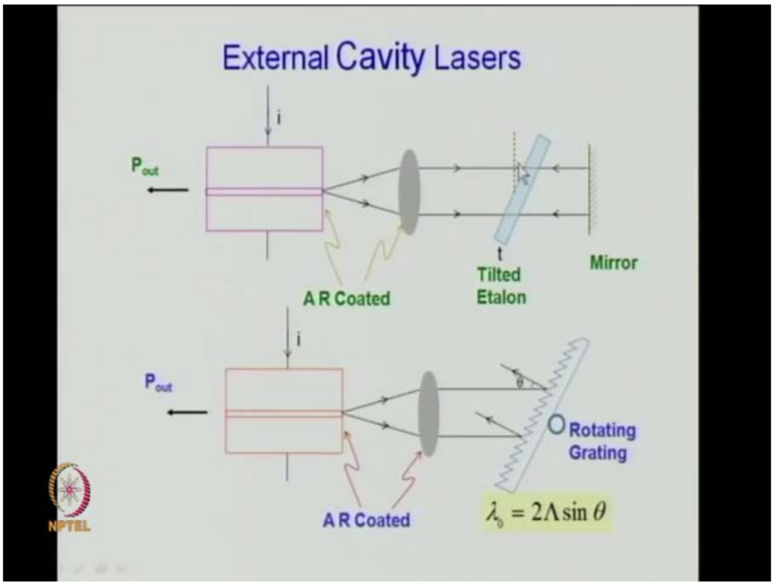

This is an external cavity laser. So, external cavity laser, which means this is the cavity, which is coupled to the laser, and therefore by using this etalon you can force the laser to oscillate only in one frequency, corresponding to the resonance of the etalon. This one of the widely used a technique called external cavity laser external cavity laser.

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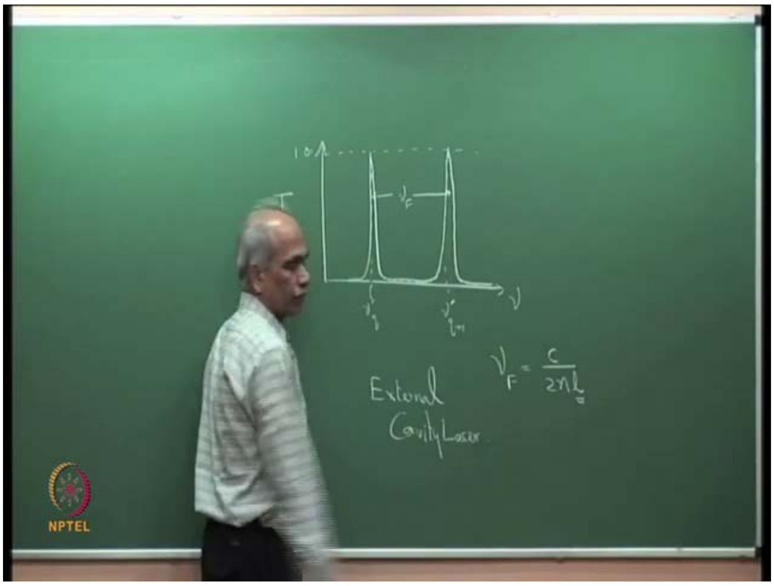

E C L External Cavity Laser, no it is written already External Cavity Laser, there are other means by which you can single frequency.

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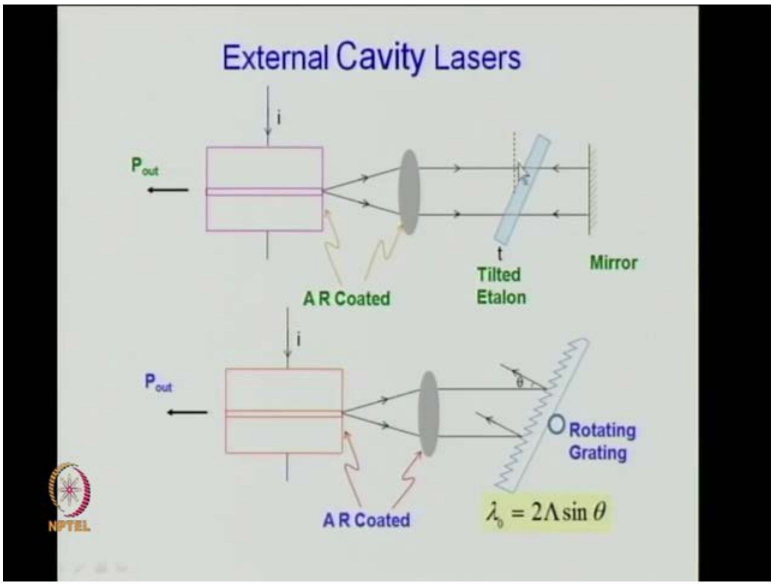

The second one which is shown here, which is shown here is a grating. So, there is no cavity here. So, this is anti-reflection coated here, if this end is the cleaved end which as 32 percent reflectivity. So, light which is going back and forth this is a rotating grating, by rotating the grating you can make only one wave length, which is reflected back this is the grating.

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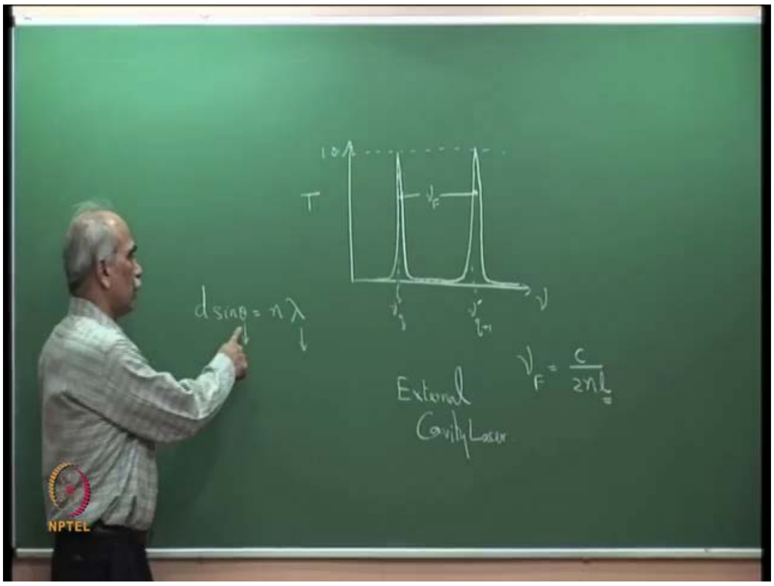

So, if you have a spectrum as you know for the grating you have d sign theta equal to n lambda. So, different lambdas will have different theta, is a reflection grating there are transmission type of gratings and reflection type of gratings. So, this is a reflection grating, in a reflection grating.

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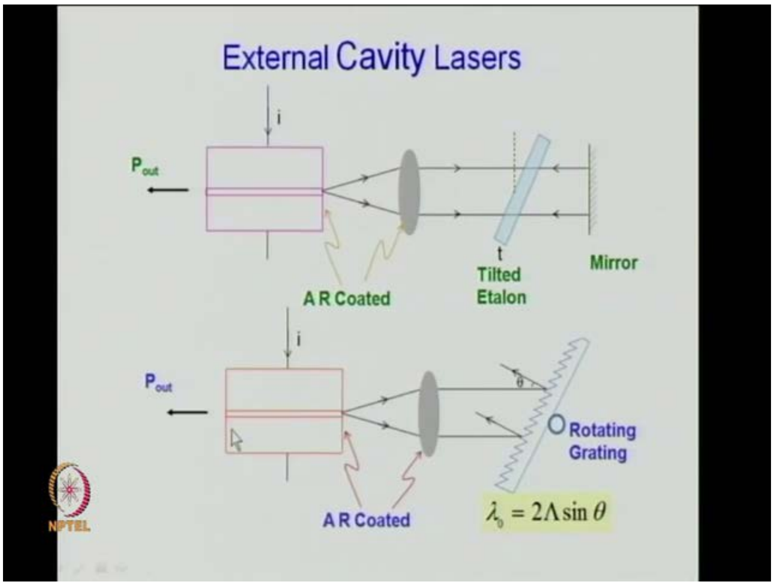

So, different wavelength correspond to different theta in general a theta would get reflected like this, which means it will not go back to this, but only one particular incident angle we will go back into this and therefore, only one wave length will satisfy this condition of going back.

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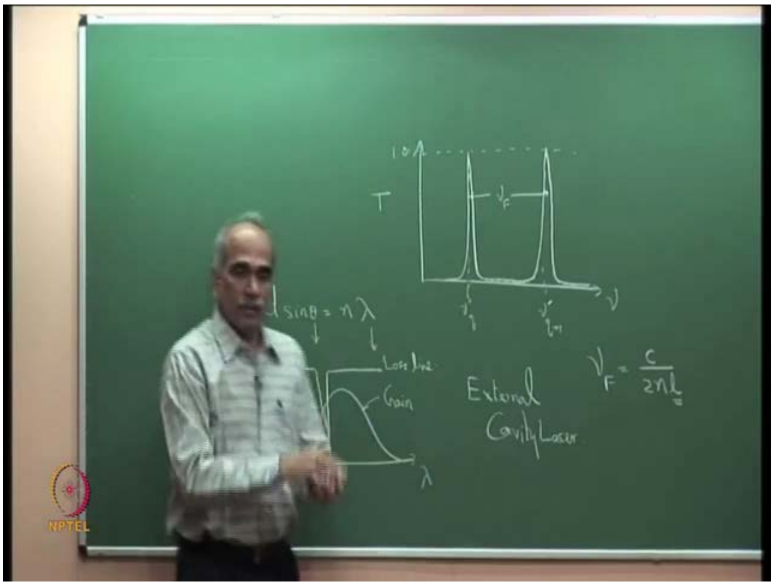

So, by rotating the grating you can choose different wave lengths to lays in this cavity or at a given angle there is only one wave length please see, if you see the gain curve. So, this is lambda or frequency whatever, the gain curve is like this, if you choose the grating. So, that at one lambda, theta is such that light goes back. So, it could be here for example. So, for that loss will be very low, principle is the same for all other wavelengths loss will be very high. So, this is loss line, this is the gain curve, one wave length lambda here, which satisfies this condition where the wave length is reflected back into the cavity will have very low loss.

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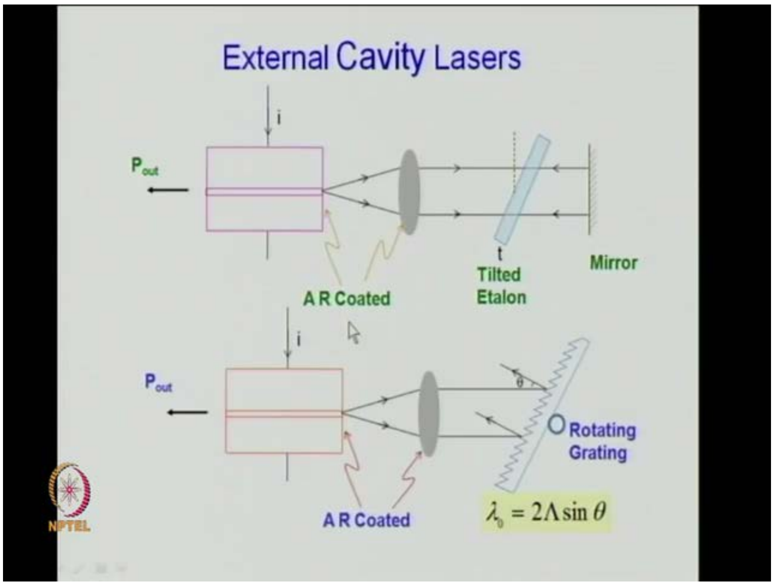

For all other wave length the light which is reflected here, those wave length which are reflected are at an angle. So, they do not go back exactly, here they may heat here, they may heat here or they may just go out. So, there is no feedback it is highly, lousy cavity for other wavelength.

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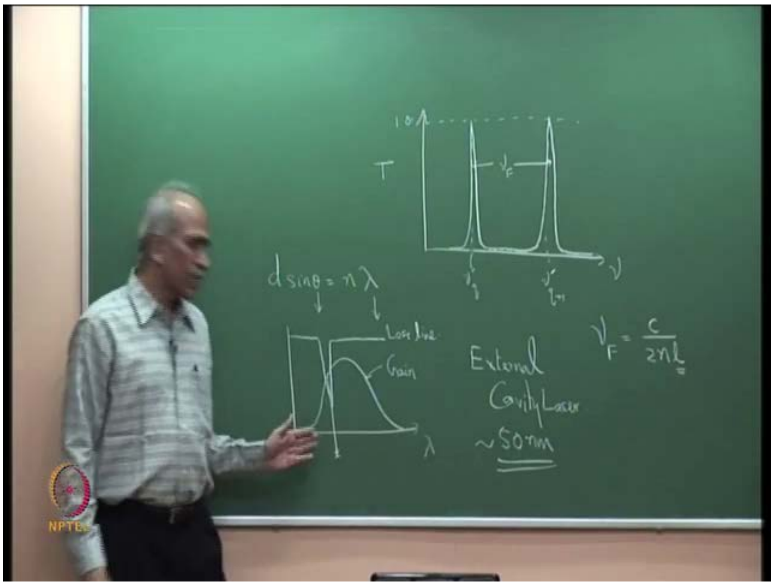

So, this is the way, that you can choose any particular wave length, and force the laser to oscillate in a single longitudinal mode. This is also the principle for tunable lasers, external cavity lasers, there are tunable lasers which are based on a external cavity structure you can tune as you can tune 50 nanometers the lasing wave lengths can be tune of the order of 50 nanometers, by using external cavity lasers.

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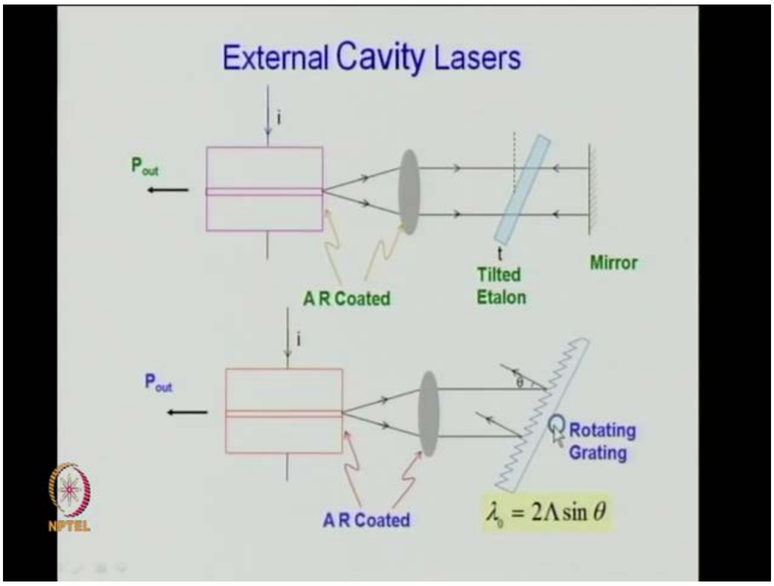

Where you will use a rotating grating here, the grating is the rotated by peso controls, by current it is not the manually rotated, it is the with the high decision you can control the feedback and therefore, the wave length which you want to choose one can use the stepper motors here to rotate this and you can choose the wave lengths in steps or you can continuously, choose the wave lengths which you want to which you want to less.

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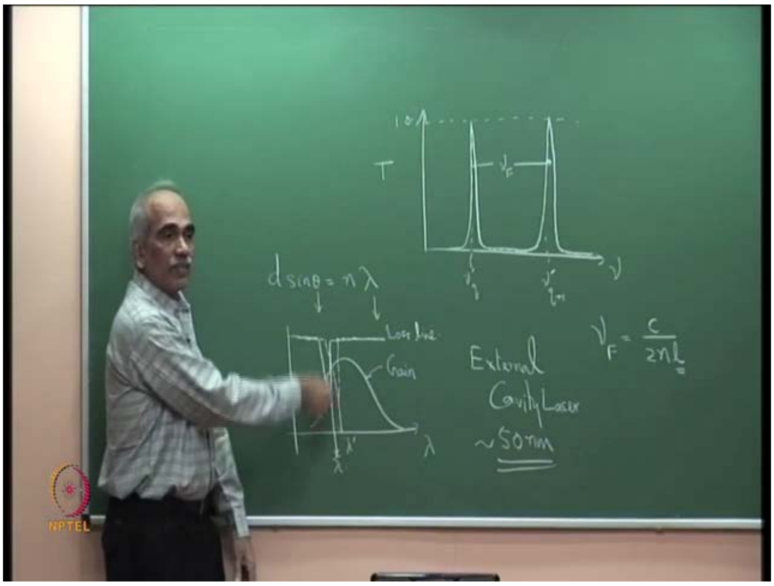

In other words what you are doing by rotating the grating is now, this is the curve for a particular angle and later angle. So, let me draw this with dotted line, the curve could be like this which means at a later position, at a different position this is the lambda for (()) So, this is the lambda dash this is lambda for which initially, there was low loss, but by rotating I have shifted the curve, the wave length for which we have low loss is this one. And therefore, only this wave length will less, this is the principle of external cavity tunable laser's based on external cavity, external cavity rotating grating.

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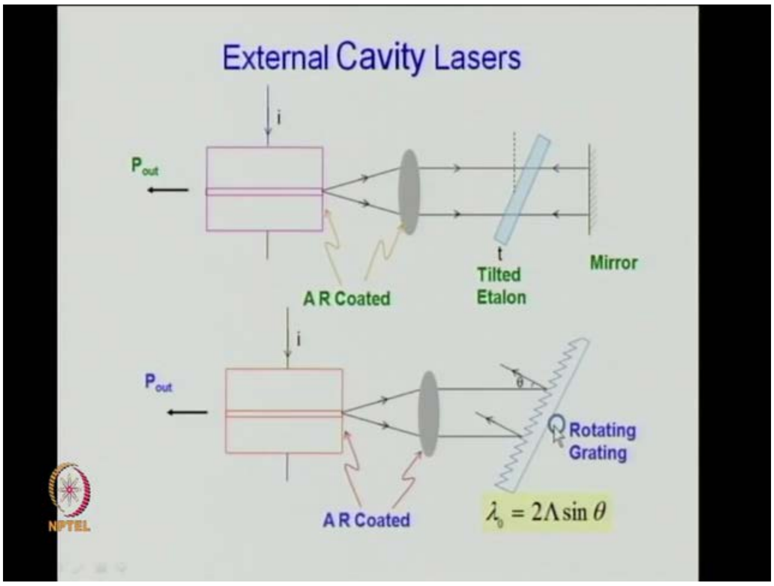

The wave grating condition is given here.

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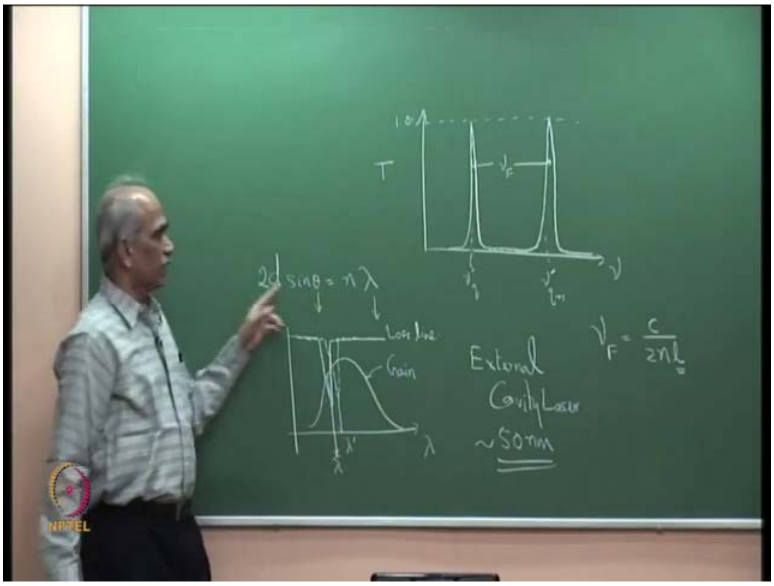

This is actually 2 d sin theta equal to n lambda I am sorry this is 2 d sin theta equal to n lambda.

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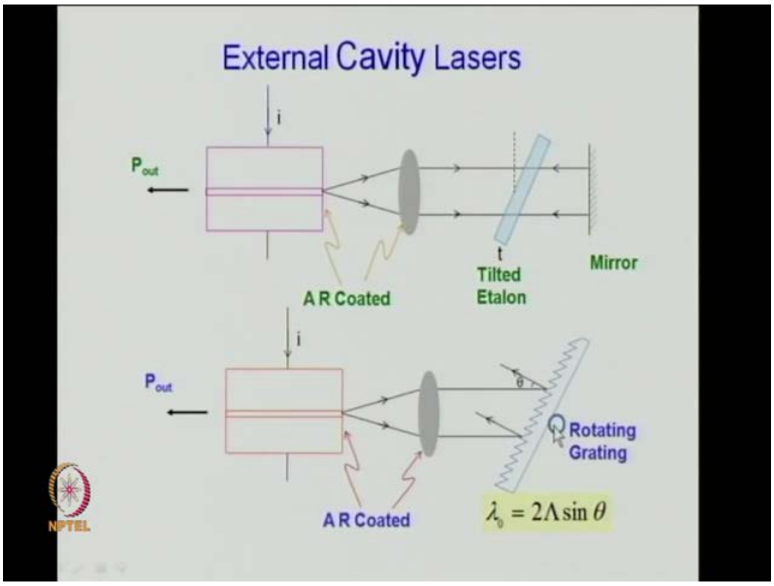

So, d is replaced by the period here, grating period 2 d 2 d sin theta equal to n lambda n is order one.

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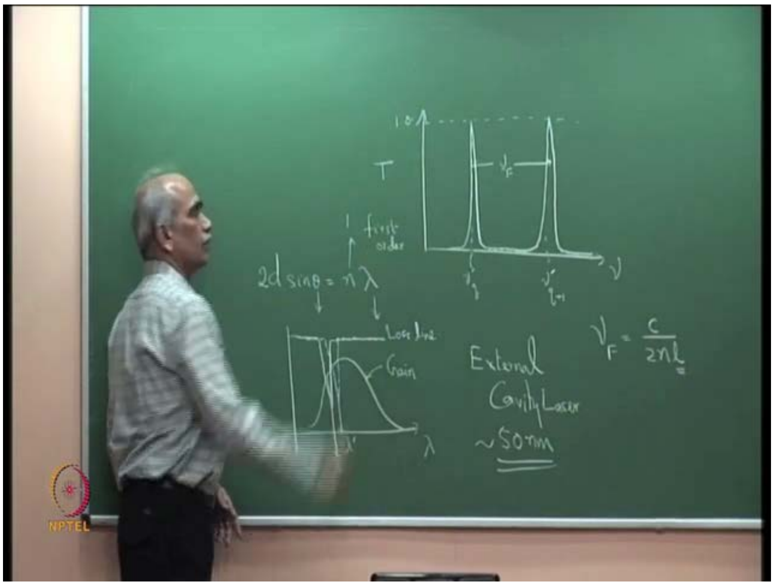

Therefore, n is not written for the first order it is n equal to 1 first order 1 can use higher order also. So, let me go to the extension of this external rotating grating, what the grating was doing is one particular wave length had high reflection going back into the cavity.

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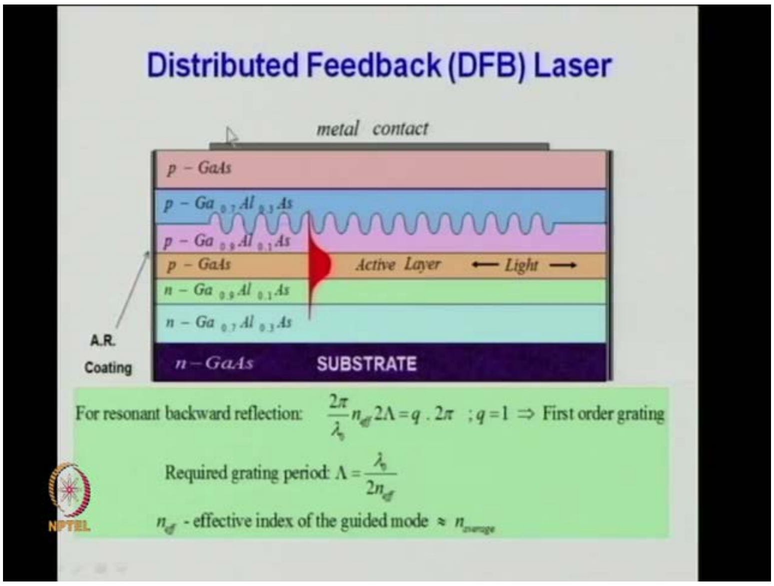

So, here is the structure which is call the distributed feedback laser, first up all it is the feedback is distributed all along the length, that is by the name distributed feedback laser. Please see the laser structure. The 2 ends are antireflection coated A R coated, the 2 ends are antireflection coated which means there is no cavity as such; however, this structure supports a more here, like all other double etalon structure lasers, it supports a guided mode.

In the case of distributed feedback structure there is a grating, which is a corrugated grating a periodic structure in the cladding. The mode which is propagating in this direction, continuously see reflections at this corrugation by, this periodic structure. The mode which is going in this direction gets reflected continuously and therefore, the feedback is distributed all along the length, hence the name distributed feedback laser. Let me explain this a little bit more on the board distributed feedback laser.

These are of coursed fixed frequency laser not like external rotating rating a lasers you can tune them, you can rotate the grating and make different angle's correspond to different wave lengths, which get highly reflected, but in the case of distributed feedback lasers they are fixed wave length laser fixed wavelength lasers with a little bit of tenability possible.

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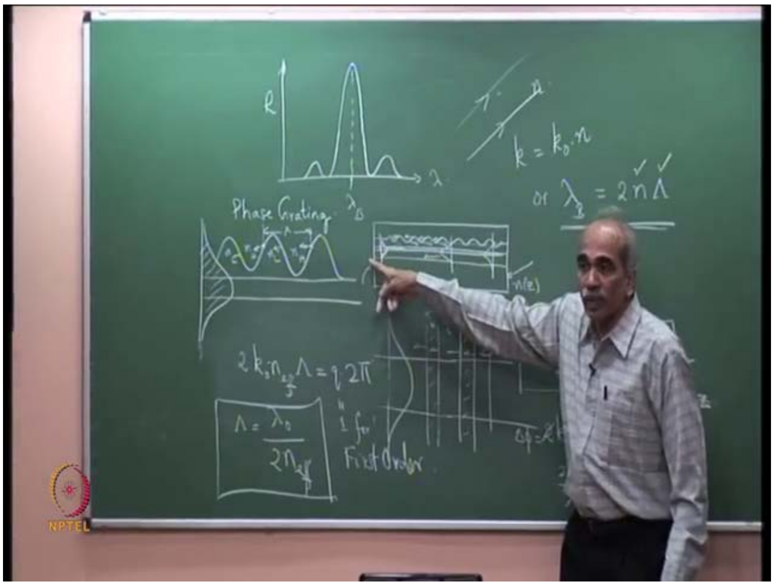

So, let me draw it on the board here. So, I have drawn only. So, these are the let me show the cladding layer. So, this is the active layer and there is mode which is traveling because this is the wave guide recall that this is high band gap region, high band gap region which means low index, low index and high index. So, this forms and optical wave guide.

So, they it supports they more which goes back and forth. If you palter this mode, this mode is let me show it, like this many of your study fiber back gratings where there is a grating which is in the core of the fiber, in the core of the fiber. So, if you have a periodic structure, let us see there is a periodic refractive index variation in this direction. So, this is a periodic refractive index variation, there is a guided mode which is propagating, but in encounters a periodic refractive index variations.

So, n high, n low a modulated n high, n low it is get it is having a periodic reflection. So, the mode is undergoing periodic reflection at the interfaces like this, the mode is continuously undergoing periodic reflection, as it travels in this direction which means it is getting reflected at interfaces continuously for simplicity I will show this as a step variation. So, let me show the refractive index variation like this, step variation.

And here is the light mode, mode or plane wave you can look at plane wave also, going like this it is a this is the same principle as intervenes filters. High reflecting coatings, multi (( )) multi-layer coatings, this is the same principle So, if the wave is propagating like this. So, this is n high this is n low, n high n low, but I have plotted is reflective index n verses x, if x is the propagation direction z select me put z n of z. So, high index, low index, high index, low index and so on.

So, if you see plane waves ray to look at the ray picture for simplicity, a ray is reflected from here at this interface this propagates here, and this also gets reflected here. The reflected wave comes back and both of them joined here. Now, the ray will get resonantly reflected, the wave will get resonantly reflected, if let me call this as lambda wave length lambda. And this is half the wave length lambda by 2.

So, the this ray or this wave which gets reflected and comes back, if it adds then face with the wave which is reflected here, then there will be coherent addition and you get reflection, high reflection for those wave lengths, which means the wave k 0 into n refractive index, into the thickness lambda by 2, round trip therefore, 2 times lambda by 2 please see, this is the path length and face, face different of the wave between this and the one which has been reflected from here this one.

So, this delta phi, but you remember that if this is high index, this low index that is an additional face change of pi here, but there is no face change of pi, here and therefore, if this difference happens to be and integral multiple of pi that is odd integral or if I take the first order then if this is equal to pi. Then I will have a resonant reflection, please see the wave which is coming back from here, will add in face with the wave which is reflected here if this condition is satisfied. Two times round trip face that is why two times, face constant into refractive index of the medium, into the distance equal to pi that is del phi.

So, what does the give you this gives you that this goes off and we have 2 pi here 1 pi goes there and therefore, this is 2 pi by let me write 2 pi by lambda lambda b into n into lambda equal to pi or lambda b lambda b is that wavelength. So, lambda b is equal to 2 times n into not. If you take a period lambda and the refractive index of the medium n then this wave length will get resonantly reflected, no other wavelength will get added in face So, they will get transmitted.

So, if you see the reflection spectrum of such a structure, you will see that there are side lops because of Fourier components of the of the step like variation. So, this will be the wavelength lambda b. So, what I have plotted here is reflection r versus wave length lambda, this is the basic idea behind operation of a brag grating, is the same which you see in fiber brag gratings also where the grating is written write into the core.

In the case of a semi-conductor lasers you could have written grating in the core, but you do not try to write a grating in the core because any fabrication step which is which introduces some variation here, will also introduce defects in the active region. And the active region or generation of light is highly sensitive to defects, we always wanted defect density to be as minimum as possible, otherwise non-radiative recombination's will take place, and the light generation will go down.

And therefore, instead of writing across the whole wave guide, they make corrugations or periodic refractive index variation in the cladding, that is why you see that structure which you saw on the P P T there, that you have periodic refractive index variation here because the materials are different please see this materials different, this material is different here and therefore, the refractive index here is different refractive index here is different.

And the mode here please see this is the mode, guided mode the tail of the mode sees this periodic structure. If any part of the mode is perturb mode is one distribution if you perturb it anywhere, the whole field distribution will get perturb it is not that if you even if the tails is this periodic structure, the entire field will see the periodic structure. And therefore, the periodic reflection which takes place from here, is seen by the entire mode.

In other words as the mode propagates, there is continuous reflection which is coming like this backward reflection, as the mode is propagating because what I have shown here is the material structure, but if you see the refractive index variation that will also be the same the refractive index here is different n high this is n low, n low, n high. This is what you see and what is this. the tail of the mode. So, this is the mode I assumed the same structure a little bit more like this.

And you see the periodic the tail of the mode or the evanescent field here see is this periodic structure as it propagates and it continuously suffers reflection, why it is suffering reflection because it sees interfaces. The condition in this case is that the reflected the face difference between identical face points here this is one wave length this is a face grating, a grating is a structure where there is either refractive index variation or transmission variation.

The normal gratings that we see are called amplitude grating, we are familiar with the gratings where you a make corrugation by the diamond as blade and then you have a grating structure. So, what do you get, you get a structure where there is opaque there is transmitting, opaque transmitting. So, this is opaque where we have crimed it this is transmitting, this is opaque, this is transmitting, this is opaque, this is the normal diffraction getting that we are familiar in light experiments.

It is opaque transmitting, opaque transmitting means what there is no transmission from here, but there is full transmission from here. This is the refraction grating, but this is the amplitude grating whereas, here this is called a face grating, there is no opaque or transmission, but the refractive indices are different and these are called phase gratings. So, a distributed feedback laser has a face grating in the gladding region, 2 points why in the cladding because the fabrication process should not introduce defects.

If there are defects in the active region here core it will be detrimental to the performance of the source therefore, it is corrugated in the cladding. Second the periodic structure gives continuous feedback all along the length, there is no refraction from these ends are anti-reflection coated. So, that there is no reflection coming from here, reflection is only by this, but this being a periodic structure the reflection is wave length selecting the reflection is wavelength selecting, which means only one particular wave length which satisfies the brag condition this is the brag condition.

We will get resonantly reflected as the mode goes in this direction similarly, when the more comes back in this you see it is continuously grating reflected means, it is generating the backward propagating mode, the backward propagating mode as it continuously propagate in this direction, this is the backward propagating mode it gets continuously reflected like this in this direction. So, when the mode is coming in this direction, it is continuously getting reflected to the other side where as when it is traveling from this side it is continuously getting reflected.

But, the reflection is not at the end, but distributed all along the length, hence the name distributed feedback. Reflection is a feedback in the case of lasers and reflection is distributed all along the length, hence the name distributed feedback pleasures. So, in a periodic structure the condition is returned like this. So, these are the 2 phase points identical phase points and this is lambda.

So, you can show that 2 times k naught into n effective now, n effective because effective index of the mode is k naught into n effective, it is not a plane wave. A plane wave is there is a refractive index n and a plane wave is traveling like this, then its k will be equal to k 0 free space wave number multiplied by refractive index. But, a mode is characterized by a propagation constant beta which is equal to k 0 into n effective, effective index of the mode which lies between the refractive index of this medium and this medium. So, this in two lambda will be equal to q times 2 pi. This is the resonance condition where q is the order, if you are taking first order grating then q is equal to 1 equal to one for first order grating. If you simplify, this how did I write this that the round trip face with in one period is an integral multiple of 2 pi general condition for resonance.

Round trip phase is an integral multiple of round trip phase is twice wave length into phase constant k 0 into n effect, this is k phase constant multiplied by the distance in one round trip 2 lambda must be equal to integral multiple of 2 pi these nothing to remembers is just the concepts are remembered and you get that lambda here is equal to lambda 0 divided by 2 n. So, this is the brag behavior only if you choose a period lambda for the corrugation here, only this wave length will suffer maximum reflection.

And therefore, the loss will be much less for that, all other wave lengths will simply get a transmitted out these ends are anti-reflection coated. So, there is no refraction coming that what other wave lengths will simply go out which means there is no feedback, feedback is for only this wave length, what kind of numbers that we have, what kind of period that you have. So, if you substitute some number let us saying optical communication you want to use at 1.55.

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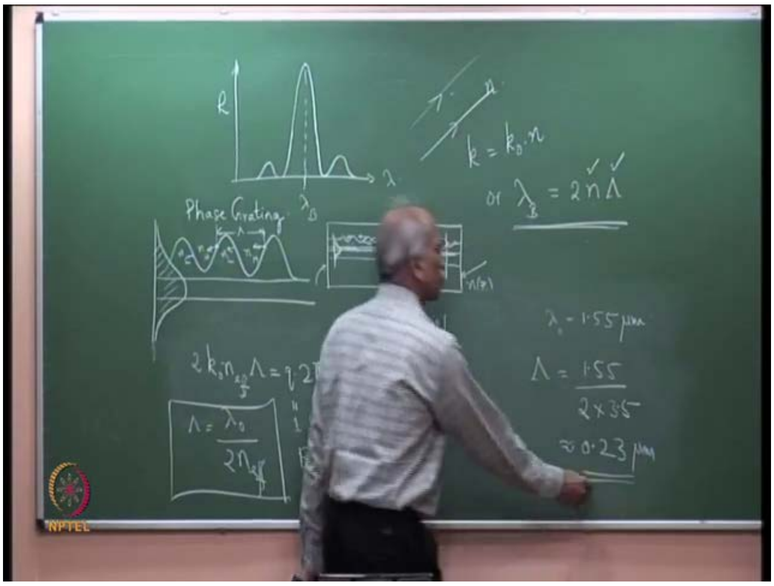

So, let say lambda 0 that you want laser to oscillated 1.55 you want to make a source distributed feedback per 1.55 micro meter, then you will have to use lambda is equal to 1.55 divided by 2 n effective, n effective is approximately 3.5 why 3.5 because the active media may be 3.6 outside media may be 3.4 these are typical number's for semiconductor's refractive index is 3.5 and therefore, n effective have you chosen as 3.5. So, this is how much will be approximately 0.23.

So, that is the period, that is required the corrugation that is required to be made in the (( )).

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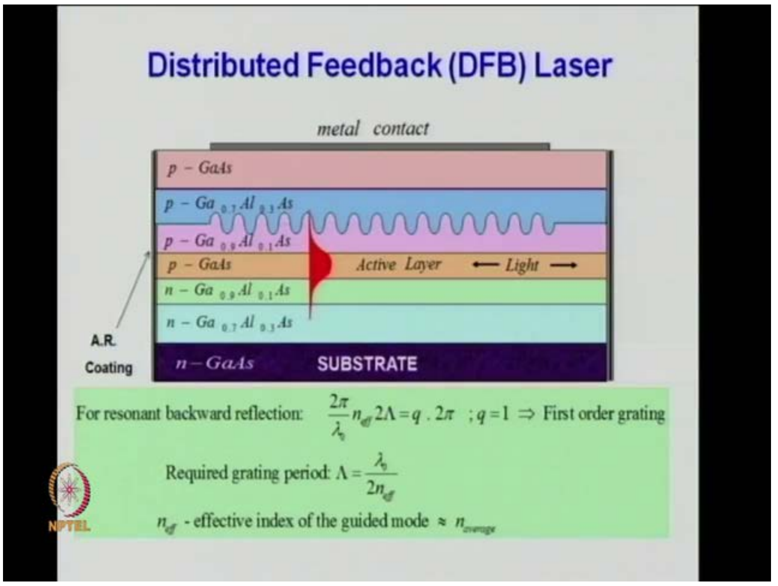

This is a distributed feedback laser, which is all this conditions are here, in the slide you can see k naught into n effective into 2 lambda is equal to q times 2 pi, q is equal to 1 for first order grating is are all given in the slide, n effective is the effective index of the more. So, all communication sources uses for optical communication are distributed feedback laser. Why we use distributed feedback lasers, because we want a narrow line width for the laser, as we discussed in the last class if we use a narrow line width source the dispersion will be much less.

And therefore, you need a narrow line width source or a single frequency laser. So, the distributed feedback laser is a single frequency laser. There are some intricacies here more details and related to distributed feedback laser I have talked about the basic principle actually, although this is the wave length that I have written, when you make a distributed feedback laser if it is perfectly symmetric. Then it will oscillate in two modes which are adjacent and there are techniques to suppress such modes.

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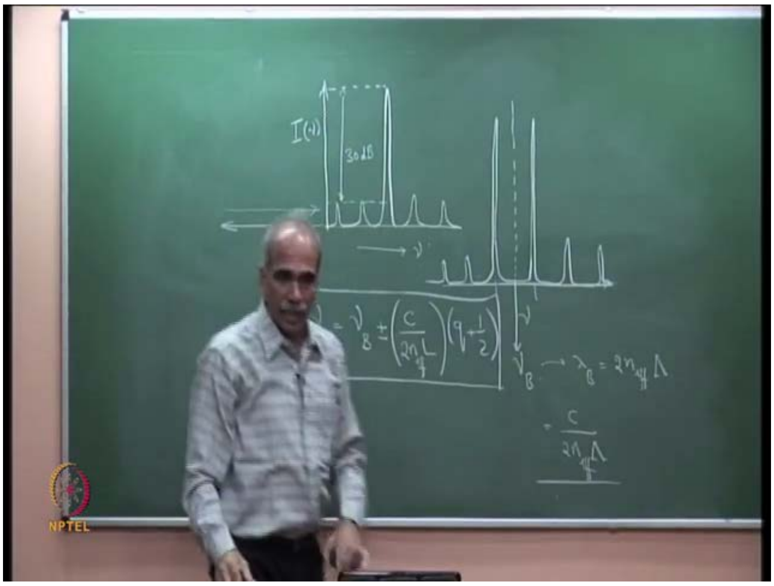

If you see the actual spectrum of a distributed feedback laser, if you see this is nu verses distributed then if this was nu b, this nu b. The brag frequency corresponding to lambda b, so lambda b. So, lambda b is equal to 2 time n effective into lambda. So, nu b is c by lambda. So, nu b here is equal to c divided by twice n effective into lambda. This is the brag wave length, but actually you see that there are 2 modes.

If you see a practical structure and which has some more side modes, here side loads and there is an important parameter you will discuss. I will not go into the details of this, but this is slightly shifted the frequency nu, nu of the laser is given by nu b plus minus half q plus half into the free spectral range the free spectral range is c by 2 n effective into l, here into q plus half. Let’s a q is equal to 1 if q is equal to 0 it is the central 1 here. So, the 0’th q equal to 0 will have 2 values plus or minus.

So, you will have 2 modes instead of 1 at nu b this is the value corresponding to nu b, this is we thought that by taking a grating we will get 1 particular frequency nu b, but actually because of the coupling between the forward propagating wave and the backward propagating wave. A coupled mode analysis we will show you that it will support 2 modes the modes are given by this expression, which mean even if you put q equal to 0 then you have nu b plus minus half times this.

So, this is the expression for the which means there are further modes, which are separated like this, this is can be explained only by coupled mode theory, but it is possible 2 suppress this and make only make the laser to oscillate in the central mode and of course, the side lops will always be their, side lops are their because the structure is naught perfectly sinusoidal. So, you will always get side nodes in a perfectly sine out of the structure the Fourier component will be at one frequency.

But, if you take a step or if you take any other you are you always get the Fourier components at the harmonic frequencies. And therefore, that is why you get the side loads, and there is a parameter normally these lasers oscillate like this, these are calls side modes this is the repair mode. So, what I have plotted is the power let us say i of nu or i of lambda verses frequency.

The laser output if you see I said that these are the single frequency lasers is oscillating in one frequency, but actually practical devices will always have side modes coming here, but the power in these is much smaller compared to the power here, the power here is typically 30 d b down 30 d b means 1000 times smaller compared to the central load.

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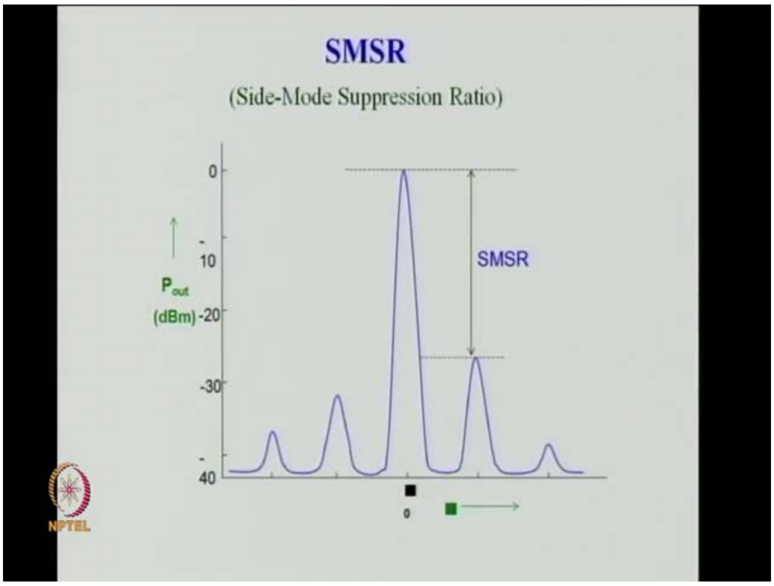

Typically, and this is characterized by a parameter we have I think I have shown here single mode, side mode separation ratio.

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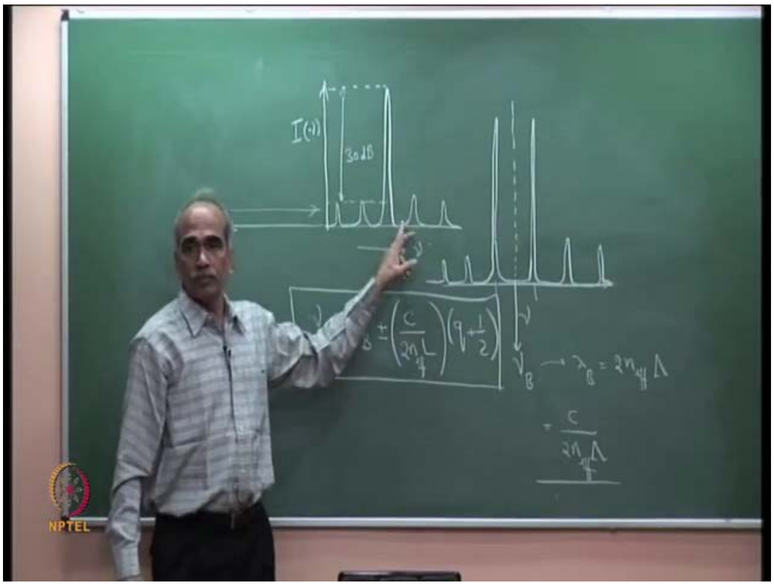

These are the side modes. Side modes separation ratio when you by a D F B laser there is always this specification will be even side mode separation ratio. So, side mode separation ratio for s m s are refers to the difference in power, here in d b between the required central mode that particular frequency and unwanted, unwanted side modes which come because of the periodic nature of the grating.

So, this is a parameter typically 25 30 d b orbital s m s are alright.

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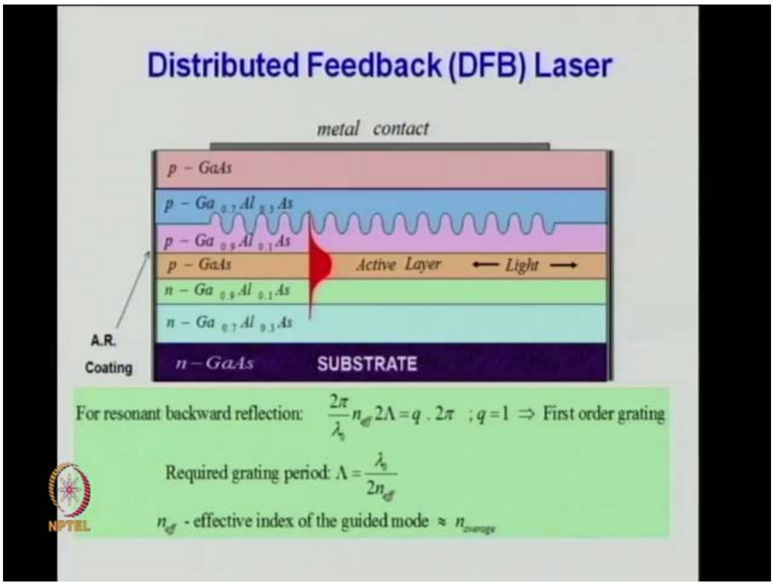

Let me go back to the D F B laser here. So, this is the structure and here is the spectrum just two illustrate.

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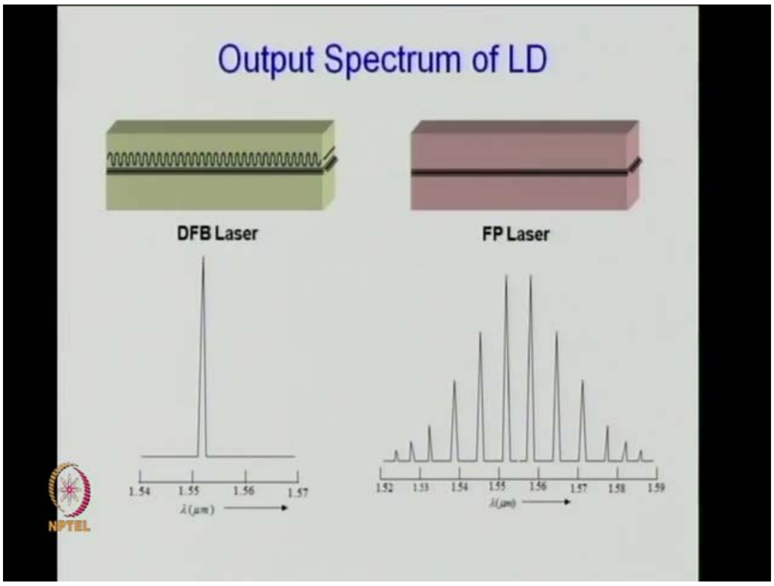

Here is the spectrum just 2 illustrate, if you take a febry perot laser is the same laser, you have the laser oscillating in multi longitudinal modes. And if you have a periodic grating here in the cladding to make it a distributed feedback laser it oscillate in a single longitudinal mode.

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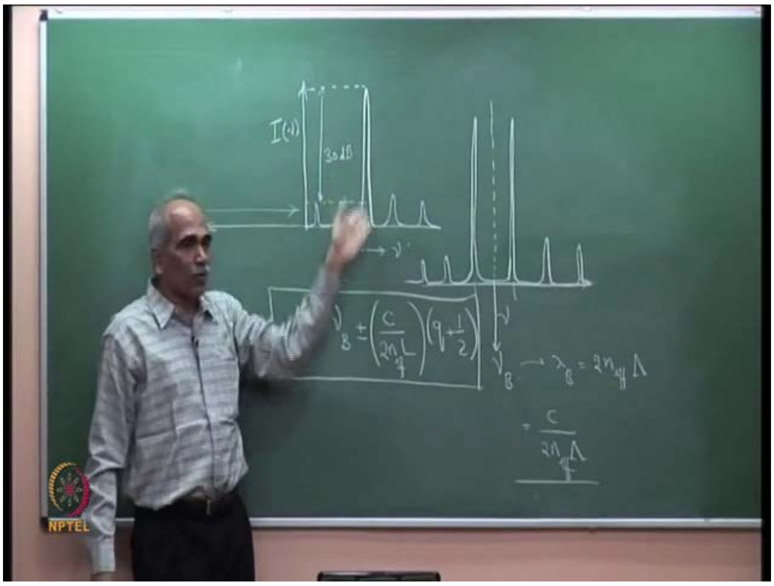

Normally if you keep the linear scale you will not see this if this is the k b 1000 times smaller, only if you keep log scale you will see this, in the spectrum analyzer if you choose the log scale then only you will be able to see this, otherwise the power here is 1000 times smaller.

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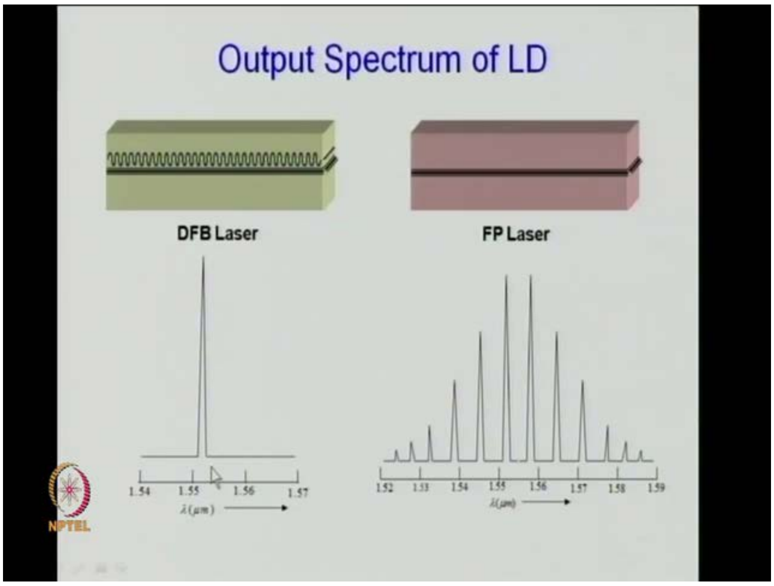

So, in a linear scale it will be just not there, that is why here I have not shown any of this, but actually there is a small amount. This is an illustration showing that it picks up one single longitudinal. So, D F B laser is a single frequency laser.

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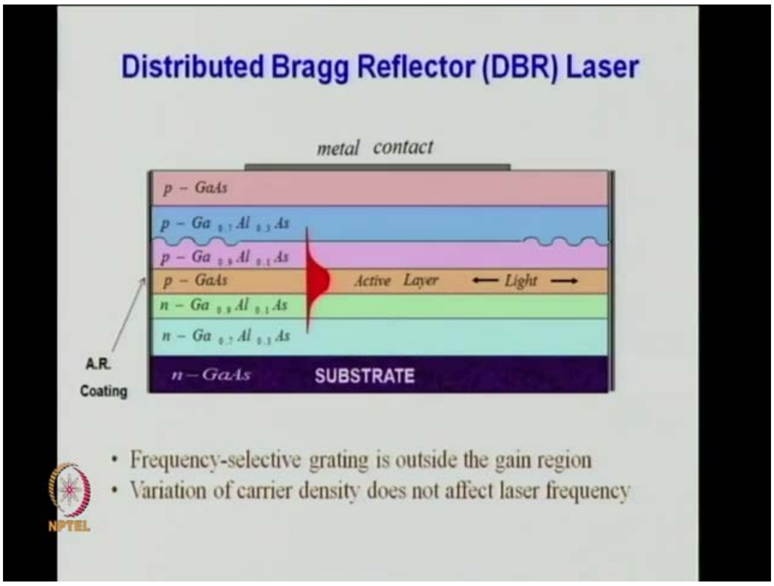

If you go to the extension that is Distributed Brag Reflector laser. This is not distributed feedback, but distributed drag reflector, what is the difference here, you can see the structure that there is a difference in the structure between D F B and D B R, I will not go into the details of this coupled mode analysis, but those of you are interested you can see the references.

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Recall the febry perot laser, the febry perot laser has reflection coming from here, from the 2 ends the febry perot. So, these are the cleaved facets, and therefore there is because it is a cleaved facet it is normally, not frequency sensitive almost all frequencies will get reflected because it is a mirror basically.

But, instead of this broadband mirror, broadband mirror means mirror which has a wide reflectivity over a wide frequency range. If you use a frequency selective mirror here, like the interfance filters, if you put a frequencies selective mirror or high reflection coatings for example, here if you put a periodic structure n high, n low, n high, n low and make a high reflection coating here, then that coating will be frequencies selective, it will be highly reflecting only at one particular wave length.

So, this is a possibility, but in practice it is it is not a practical solution in the considering the fabrication process. So, instead of this if you have the brag reflectors. So, this is structure here, if you have the periodic reflector which we had all along the length in the case of D F B only at the ends, we do not have anything here and here again we have the periodic structure. So, the mode is traveling like this back and forth, at the ends if there is a frequency selective grating here.

It is not a separate bulk layer, but it is with in this, this can be much easily fabricated by lithography. This is not by lithography you have to it is easy to show here, but in a practical situation taking the refer like this and depositing interference layers is very combustion process. And there forth this is monolithic process, that is on the surface you can do this lithography, lithography and epitaxial. That is etching and re growth both are required, but it is a much easier solution.

So, what you have is the reflector is a brag reflector here, in this section we have brag reflector brag comes brag means periodic immediately. So, there is a periodic structure which is providing reflection and that periodic structure is wave lengths selective and therefore, you have distributed brag reflector. So, these are the brag reflectors, at the 2 ends and the gain medium the gain providing contact electrode is only here.

The current is flowing through this region, current is not flowing through this region, this is the structure of D B R, D B R laser what are the advantages or D F B it D B R laser is much more stable in frequency, a making a statement that a D B R laser is much more stable in frequency of the output. In the case of D F B laser alright let me go back to the D F B here D F B.

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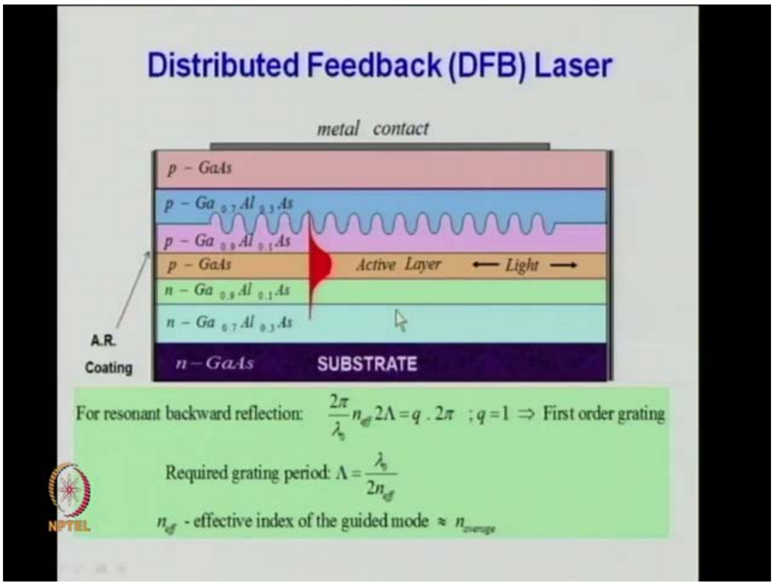

You see that the metal contact is here, carriers are flowing across, carriers are also flowing through the grating region. Carriers are flowing through the grating region which is selecting the frequency.

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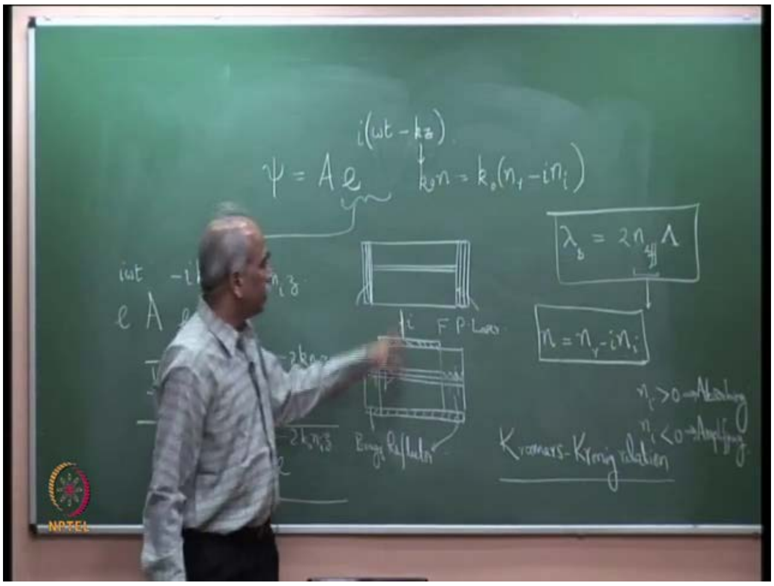

We have an expression that lambda b here, that is the frequency of which is selected is equal to twice n effective into lambda, lambda is fixed because once you have fabricated the corrugation that is it lambda is fixed; however, the refractive index of the medium here, is a function of the current which is flowing through. When carriers are injected the medium becomes has gain or loss depending on injection of the current, depending on injection of current.

We can make other either e f c minus e f v greater than e g or less than e g if it is greater than e g then only we have gain. So, what determines the injection current determines whether there is gain or not. Refractive index of a medium in general is given by n r minus i times n i refractive index of a medium in general is complex and because it is the complex art which will tell you whether the medium is absorbing or amplify is n i is greater than 0 here this means it is absorbing.

If n i is less than 0 it is amplify. This is basic optics I hope you understand that wave psi can be written as ampli, if you are looking a plane A wave e to the power of i k x that is i k z if it is propagating in the z direction into i omega t k z minus omega t of omega t or omega t minus k z whatever way that you want. So, you see that k here is k 0, k here is k 0 into refractive index n which is equal to k 0 into this refractive index is a real part minus i times n i part and therefore, you have minus this is this term here.

So, if you look at this turn you get e to the power i k 0 n r into e to the power the second part that is minus i square. So, minus minus is plus i let me write this other way because normally in optical wave guides in quantum mechanics we write this way, but in optical wave guide we write i omega t minus k z. So, k into z and this is here. And so the first part is minus i k n 0 into r there an oscillatory part the second one will be minus i into minus i. So, minus minus plus and i square is minus one.

So, you have minus k 0 into n i k 0 into n i into z, what I have written is an expression for plane wave this is a plane wave, propagating plane wave in the z direction psi is equal to amplitude into this, if the refractive index is complex. So, k is k 0 into n refractive index is complex as substituted here, the complex quantity then I just substituted back i omega t have left you can keep i omega t, so A into it the power of i omega t here.

So, you see that there is a term which is coming like this, this is exponentially decaying these are oscillatory. So, if you take, if you want to see the intensity which is equal to mode psi square which is equal to a square into this 2 terms organ and you have e to the power minus 2 k 0 n i into z. So, what is that mean the intensity is decaying with z the power is decaying with z that; that means, if n i is positive, then this is absorbing with z the medium is a absorbing, are you able to follow, that the this is z here therefore, as z increases this quantities exponentially e to the power of minus something which means one by e to the power.

So, it is greater than 1 in the denominator. So, this quantity drops down continuously, this a square i can write as i 0. So, I have i of z is equal to i 0 into e to the power minus 2 k 0 n i into the intensities continuously decreasing with z. If n i is greater than 0 that is what i have written here n i is greater than 0, means the medium is absorbing. If n i is less than 0 if you substitute n i as negative, negative, negative becomes positive. So, it is a amplifying, medium is amplifying.

When you pass a current here, the refractive index is this, when you pass a current n i decreases and it goes from 0 greater than 0 to less than 0. And that corresponds to gain by passing an injection current and maintaining the gain in the medium means n i has become less than 0. The medium is complex in general and amplifying and absorbing media are complex is general, have a complex refractive index, normally we do not consider this because we treat media which a transparent if you treat if you take glass and do all the optics then you consider that the glass is transparent, you are not considering absorption.

That is why you never use this part, transparent means this is equal to 0 n i equal to 0 is transparent. So, we only talk about the real part of the refractive index in normal optics, but if the medium is absorbing or amplifying it means the refractive index this complex. So, we come to the point here, as you pass current n i changes in the medium, n i goes from positive to negative that is the medium becomes absorbing then transparent at transparency carrier density and then it becomes amplifying which means n i is changing.

Through a kramars kronig relation some of you may not be knowing, but kramars kronig relation it relates the relative imaginary part to the real part of the refractive index kramars kronig relation. This is true for any real that it any complex quantity of a real system, that the imaginary part of the complex number is related to the real part of the complex number.

So, if this changes, this changes n r this if this changes, this changes through this relation, they are linked through this relation. If this changes the frequency changes because you see this, this was the real refractive index. So, this changes if the real part of the refractive index changes, the frequency changes and therefore, depending on the current here, if you have a larger current or smaller current the frequency of the light gets shifted. In the case of a D F B laser where in the case of a D F B laser here this is the D F B laser.

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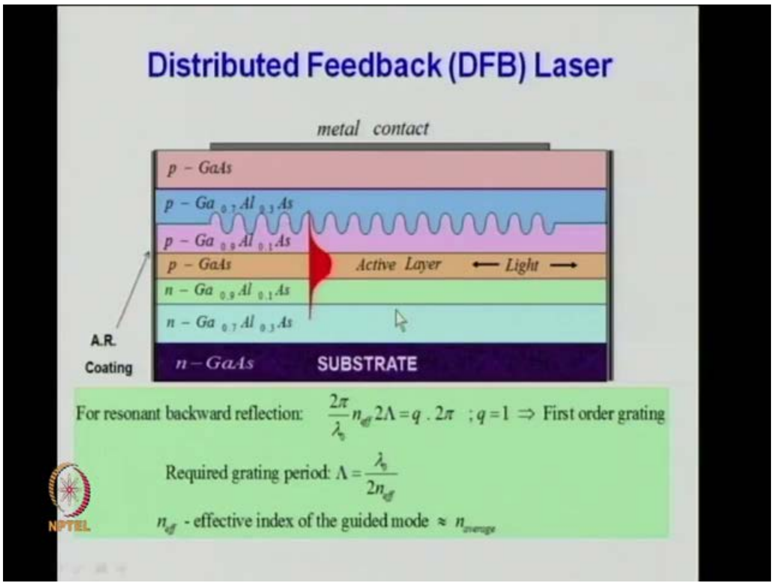

The current is passing through the grating which is selecting the frequency because the refractive index of the medium here changes due to injection current the frequency also changes with injection current in a D F B.

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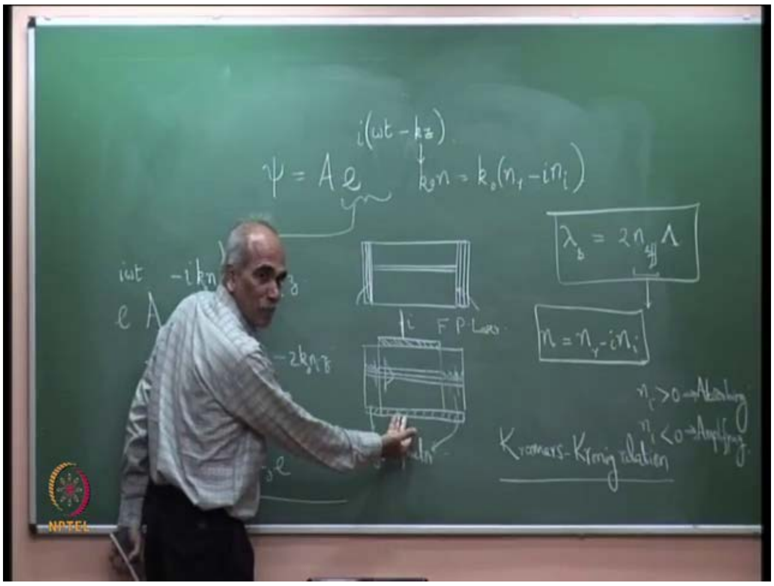

In a D B R here is the D B R structure, the current is passing through the active medium where there is no frequency selection. Frequency selection is done at the ends and therefore, that is not effected the refractive index here is not affected because the carriers are moving here and therefore, the frequency remains stable irrespective of the current the frequency remains stable, this is the main advantage of a D B R laser over a D F B laser.

However, it is a little bit more difficult to fabricate this at the ends and normally unless you really require then application unless you really have an application where you require extreme high stability of the laser frequency then to use d D F B lasers. Therefore, in communication we normally use D F B lasers because we use the current system at least uses the on of keying or intensity modulation scheme and therefore, it is not a issue. However, if you use coherent systems then this will become an issue. The frequency shift will be then issue, we will stop it is time here. So, we will stop here and continue in the next class.