Introduction to LASER
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture - 26
Laser Output Characteristics

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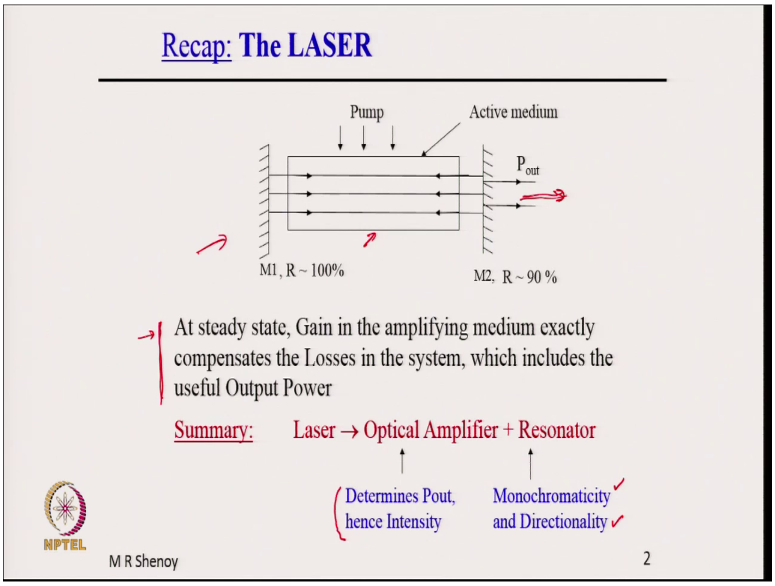

Welcome to this MOOC on Lasers. So, today we will see the laser output characteristics. A very quick recap of the laser, so, here is the laser, the gain medium, and the two mirrors forming the resonator. One of the mirrors may be around 100 percent reflecting, and the other one is partially reflecting. And output comes from here.

And we have discussed in detail that at steady state, gain in the amplifying medium exactly compensates the losses in the laser system, which includes the useful output power that is losses in the resonator includes the useful output power, or in summary laser is an optical amplifier plus resonator.

The amplifier determines the output power, the gain medium determines the output power, and hence intensity, whereas, the resonator determines the monochromaticity, directionality and so on. So, both amplifier and the resonator have important role in determining the laser output characteristics.

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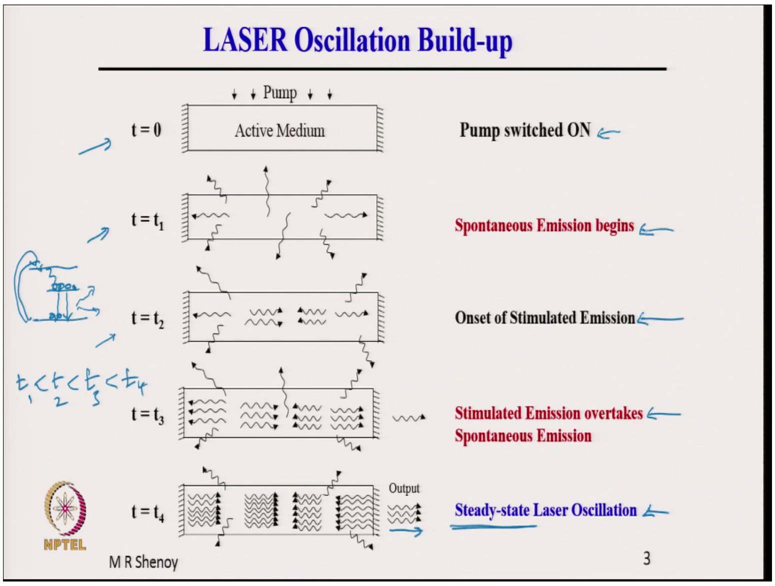

Here, what is shown is the final pictorial depiction of steady state laser oscillation. So, let us have a look first at t is equal to 0, so this is the active medium or the gain medium, and the mirrors are coated at the ends of the medium. There is a pump at t is equal to 0, the pump is switched on. So, pump is switched on at t is equal to 0. At t is equal to t 1, as the pump excites atoms in the system, atomic system in the active medium spontaneous emission begins, it starts with spontaneous emission.

So, if we have a three level system, for example, so at t is equal to 0, pump is switched on. So, atoms are excited to the upper state. And from there, atoms make rapid transition, and from here transition comes down further, to the ground state, giving out spontaneous emission, initially it is spontaneous emission.

So, there is no need of population inversion, for spontaneous emission. Excited atoms, when they get deexcited to the ground state they give out spontaneous emission. So, that is depicted here, spontaneous emission.

And note that spontaneous emission is in all directions, some going towards the mirror but some going outside in all directions. So, it is emitted in all directions. Now, some of those which are going towards the mirror will be reflected back along the same direction. And when it comes back along this direction, they may initiate stimulated emission provided a population inversion is built with the time t is equal to increasing time, so this is t 1 less than t 2 less than t 3 and so on.

With the increasing time, there will be population built up here, between the excited state and the ground state, let us say there is a population inversion.

And then those photons which are returning back, along the medium can excite further stimulated emission, and the stimulated emission starts building up in this direction as the photons get reflected back. The spontaneous emission first, and some of the spontaneously emitted photons may be refracted fed back into the system.

And if the system is in population inversion mode, by that time if the system has reached population inversion, then the stimulated emission will start and it will start dominating. And that is what is written as onset of stimulated emission, because for stimulated emission you need another photon to stimulate it. So, the fed back or back reflected photon can stimulate further emission of photons.

And as time increases, there will be a steady state population which will be reached. And there are more and more stimulated photons which are going back and forth, because by the property of stimulated emission the emitted photon is in the same direction as the stimulating photon. And therefore, more and more photons are building up in this direction. And soon stimulated emission overtakes spontaneous emission.

You can see that the spontaneous emission is all the while present, but the stimulated emission is building up along the resonator here, because the feedback comes from the mirrors. And as time increases further to t 4, soon there will be a steady state laser oscillation when gain is equal to loss. Note that stimulated emission has started dominating; and almost all the atoms which are getting de-excited to the ground state.

These atoms here getting de-excited to the ground state are being done, so by stimulated emission or by the stimulating photons. And therefore, the stimulated emission builds up in this direction along the resonator, and a fraction of it comes out as the useful output power. Naturally, because the light has been building up in this direction that is along the resonator, the output will come out as a parallel beam.

Note that spontaneous emissions are still present is ever present. If there is an excited atom, then the excited atom may make a downward transition by spontaneous emission or stimulated emission. Therefore, there will be spontaneous emissions always, but the stimulated emissions dominate, and therefore, the light output is primarily due to stimulated emission.

So, this is the laser oscillation buildup picture with time increasing time till it reaches steady state. So, this is steady state. So, at steady state most of the output which is coming out is primarily due to stimulated emission, although there will be some spontaneous emissions which will be present all right.

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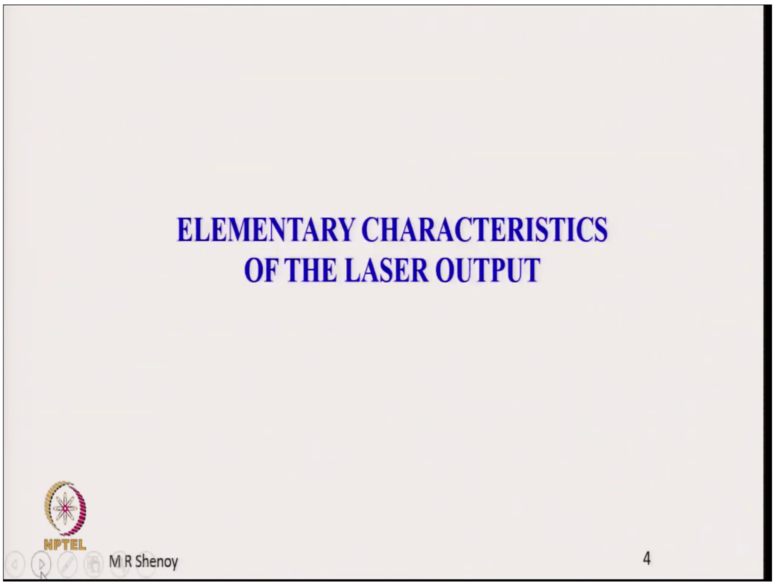

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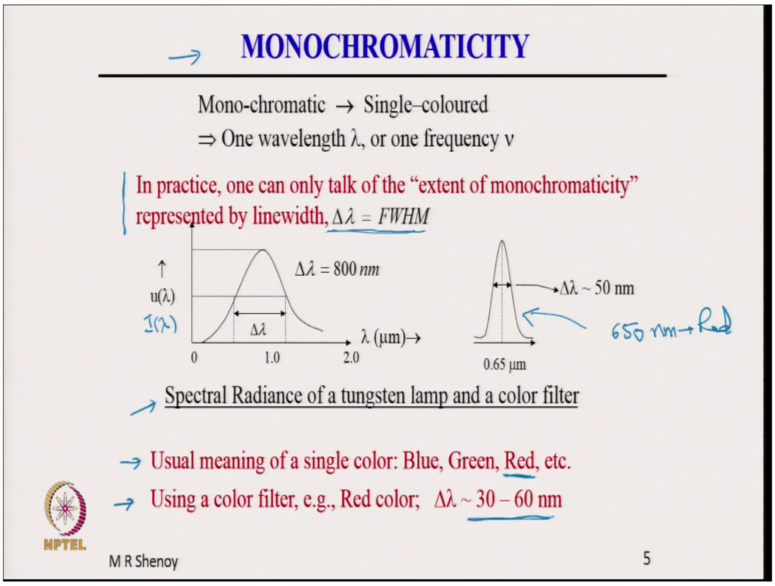

With this let us see some elementary characteristics of the laser output. First one, property is the monochromaticity. We have discussed this monochromaticity in the first lecture as one of the properties of the laser output.

And monochromatic means single coloured, I will go through it very quickly, or one wavelength lambda or one frequency nu. But as we have already discussed in practice, one can only talk of the extent of monochromaticity, there is nothing like single wavelength or single frequency. That light is emitted over a range of frequencies, and therefore, the line width of the source determines what is the monochromaticity. In other words, line width is the parameter which characterizes the monochromaticity of a source.

So, it is represented by the line width which is equal to FWHM. Here, we have shown FWHM of the output spectrum. What is plotted is here, so the density of radiation as a function of wavelength or it could be intensity I of lambda, this could be u of lambda or I of lambda as lambda, and you can determine the full width at half maximum. So, it is spectral radiance of a tungsten lamp and a colour filter

Now, the usual meaning of a single color, usual common meaning of a single color means when we say single color, we say blue, green, red, and so on. So, to obtain for example, if you wish to get red light from white light, use a color filter which is red colored, let us say red colored color filter, and as I have already discussed the line width of a color filter may be approximately 30 to 60 nanometer.

So, if we say 50 nanometer for example, it is shown here this is the output of a red colored filter, so 650 nanometer. So, 650 nanometer is red color. So, is red and the delta lambda could be approximately of the order of 50 nanometer. So, that is the single color in the common sense that we talk of blue, green, red, and so on.

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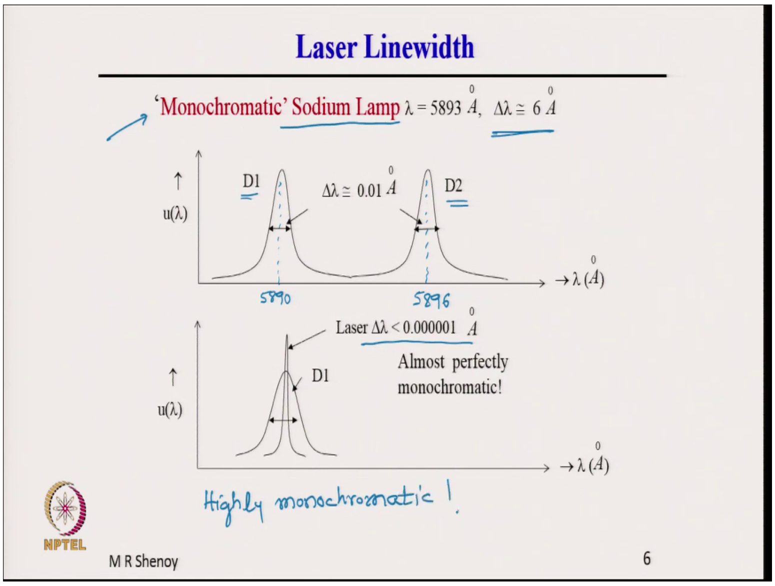

Then we discuss that the commonly used monochromatic source, which is the sodium lamp with a wavelength average wavelength of 5893 angstrom with a delta lambda that is D 1 D 2 sodium spectrum comprises of two lines D 1 and D 2; one at 5890 angstroms.

So, this is at 5890, and this is at 5896; D 1, D 2 with a separation of 6 Angstroms here. So, when we say in general the wavelength of sodium lamp, we say that lambda is 5893 actually at 5893 there is nothing it is the average wavelength which we are talking of.

And then we go down to laser, so the line width here delta lambda is of the order of 6 Angstroms, although individually these D 1 and D 2 lines have very small line width. In a laser, for example, the line width there are line widths which can be much much smaller than this, but typically if the delta lambda varies anywhere from 0.01 angstrom to 0.0001 angstrom.

Then the line width is extremely narrow. In other words, we say that it is almost perfectly monochromatic. So, this is what we had discussed and therefore, we say that lasers are highly monochromatic. So, highly monochromatic we have already quantified. So, monochromatic means the line width is extremely narrow all right.

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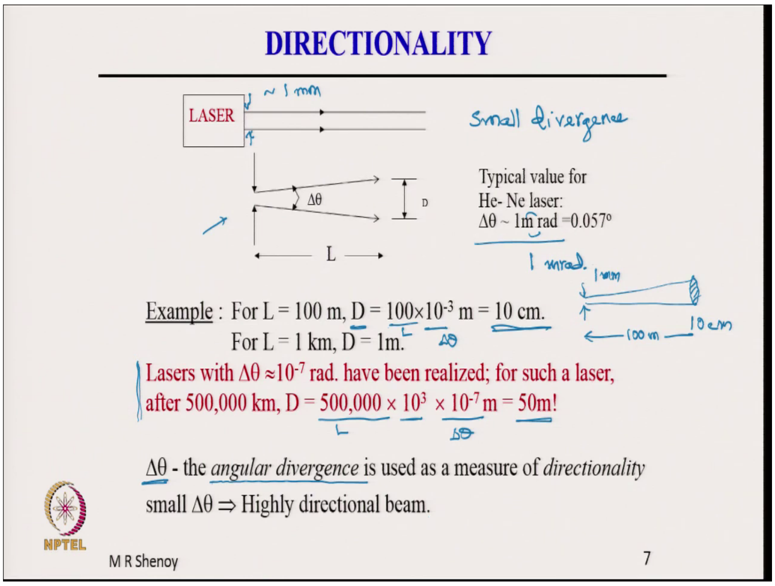

The second property is directionality that is we say that laser gives out parallel beams, but it is actually not exactly parallel, there is a small divergence. So, there is a small divergence angle, small divergence is not perfectly parallel. So, small divergence is present. And that is illustrated here that delta theta is the small divergence, which is now enlarged and shown here.

Typical value for a commercially available He-Ne laser, if you see that delta theta is 1 milli radian. This is to be written as 1 millirad, m rad, milli radian, so that is 0.057 degree. 1 radian is approximately 57 degree. And therefore, 1 milli radian is 0.057 degree that is the kind of divergence that you have. So, if you have an laser beam, the there is a finite divergence, but the divergence angle is very very small very much less than 1 degree. And therefore, it looks like a parallel beam.

Now, let us see if we want to see, what is the divergence how can we measure? For example, so you can take a laser beam and allow it to propagate for 100 meters. And at the other end, you can determine the diameter of the spot. In the lab, for example, the diameter of the spot here can be measured let us say this is approximately 1 millimeter. And then you propagate it through 100 meters and determine what is the diameter after propagating 100 meter.

So, we can find out the diameter by length into delta theta that gives the diameter. So, length is 100 meter, delta theta is 1 milli radian we have taken this, this is delta theta 1 milli radian and this is the length. Therefore, the diameter D is equal to L into delta theta which is about 10 centimeter. So, the beam after propagating 100 meters becomes a size of so here, it is approximately 10 centimeter in diameter. So, this is the distance which is 100 meter. So, here it was 1 millimeter. So, the diameter was taken here at the input as 1 millimeter; let us say, it has become about 10 centimeters.

Similarly, there are lasers with extremely small values of delta theta. So, for example, delta theta is 10 to the power of minus 7 radian that means; for such a laser after propagating through 500000 kilometers. Why do we take this number 500000? Because, the distance from earth to the Moon is approximately of that order 450000 or 500000 kilometers and therefore, if you propagate a laser beam from Earth to Moon, then you can calculate the diameter of the laser spot on the

Moon and that is calculated by this is the distance l kilometers; so, 10 to the power of 3 multiplied by delta theta. So, this is 500000 kilometers into delta theta is 50 meters means the spot size on the surface of the Moon is approximately of the order of 50 meters which is still which can be visible.

And therefore the conclusion is delta theta the angular divergence is used as a measure of directionality, small delta theta means highly directional beam. If you take any commercial laser, then they will always specify the divergence angle delta theta. So, it will be given in the data sheet. So, you can see for a typical laser, it is of the order of 1 milli radian ok.

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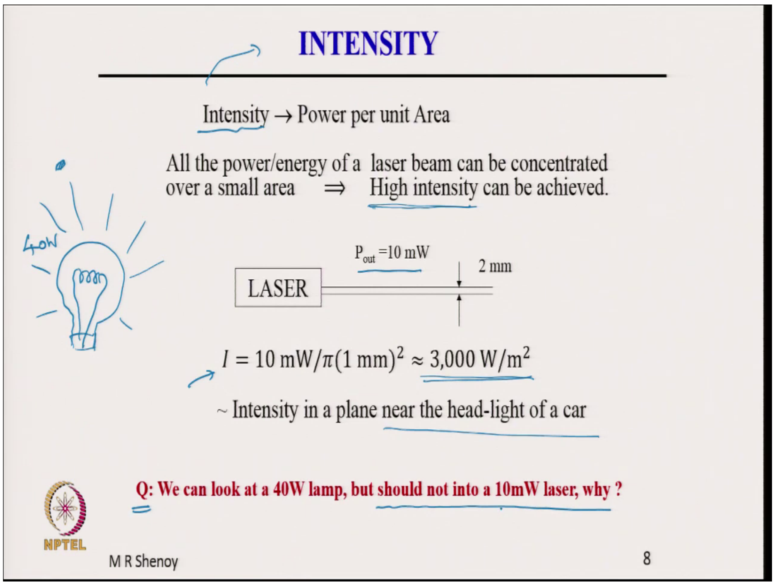

Now, we come to intensity you may remember that we had started in the first lecture that laser is a source of coherent radiation with very special properties. And one of the property, I listed was highly intense. So, what is this intensity? Intensity we know is power per unit area. So, in the case of laser, all the power of a laser beam can be concentrated over a small area and that is why we can get high intensities using a laser source.

If you take for example, an electric bulb let us say an LED bulb or a filament bulb, so a tungsten bulb. And let us say this is 60 watt or 40 watt, then note that light is emitted in all directions in all directions. And therefore, although the power is 40 watt but the power is emitted in all the directions. And therefore, if you take anywhere a small area like this, then the power per unit area will be extremely small.

But if you take a laser beam, we already said that the diameter here may be 1 to 2 millimeter. So, let us say this is 2 millimeter, a laser beam is coming here the output power is only 10 milliwatt. Remember this is 40 watt and this is 10 milli watt, so that is almost 4000 times larger power here. And this is only 10 milliwatt, but it is emitted the entire power 10 milliwatt is coming in a beam of diameter 2 millimeter.

And therefore, the intensity is equal to power per unit area, area is pi r square. And that comes out to be 3000 watts per meter square. This kind of intensity for example, just to compare what is this intensity this is of the order of the light intensity in a plane near the headlight of a car, 3000 watts per centimeter square that is very intense.

Now, note there is a question which is posed here. We can look at a 40 watt lamp. For example, in the room, you have a 40 watt bulb, and you are free to look at the lamp. But it is told to you that you should not look into a 10 milli watt laser. Why? So, please ponder over this, why we should not they are always tell you that do not look into the laser beam, although the power is 4000 times smaller between 40 watt and 10 milliwatt.

But once the intensity at the retina, for example, if the laser beam enters our eye, there is a eye lens which focuses the laser beam to a small spot. And therefore, the intensity on the retina is power per unit area. The area of the spot is extremely small, and therefore, the intensity will be very high. We can put one can put some numbers and see that the intensity that you get is of the order of 10 to the power of 7 or 8 watts per centimeter square which is more than the damage threshold of the retina.

And therefore, immediately it will create laser spots or blind spots on the retina damaging the visibility.

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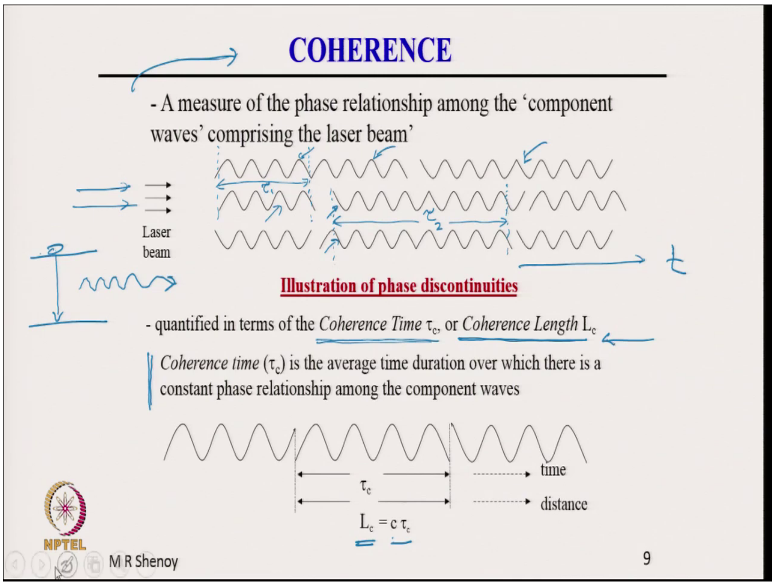

The next property, we also had written that highly coherent source. So, what is this coherence? These are elementary properties; some of you may be familiar with this already. So, coherence is a measure of the phase relationship among the component waves comprising the laser beam. Let me explain this.

There is a laser beam which is coming here. The beam comprises of a large number of component waves. So, what are shown are sinusoidal component waves, because please remember that when the atom makes a transition from excited state to the lower state, it gives out radiation over a finite duration till the atom is de-excited from the higher state to the lower state, or it can also be looked at as an energy packet corresponding to the energy difference between the two levels is given out.

And therefore, it is of a finite duration. And therefore, the beam comprises of large number of such components. And there is no phase relationship between individual components, such packets which are coming out. So, the coherence is a measure of the time duration over which there is a constant phase relationship or for example, any two component waves are maintaining a constant phase relationship.

And for example, if we see here let us look at this component wave and this component wave, so this axis is time, this time. So, from here, for example, from this time onwards till this end, we have there is a constant phase relationship between them. Because, all of them are of the same wavelength and therefore, there is a constant phase relationship here.

However, if you take this wave and this wave, then we see that over this period up to this there is a constant phase relationship, but afterwards here there is a gap and this wave continues still. And therefore, the constant phase relationship time duration is only this much; in this case the time duration is this much. So, let me call this as some tau 1 and tau 2. This is a very simplistic picture. And therefore, it is quantified in terms of coherence time tau c or equivalently the coherence length L c.

Let us look at the coherence time t c that is what I have been explaining. And therefore, the coherence time here is defined as the average time duration over which there is a constant phase relationship; constant phase relationship means the two are coherent among the component waves.

Coherence time is the average time duration over which there is a constant phase relationship among the component waves. For example, we can see it is now shown as a single wave, there is a packet, and there is a discontinuity, there is a wave here discontinuity and so on.

So, the phase is constant over a certain duration tau c as I have shown here corresponding to two different waves. And then we say that these two waves are coherent over the time duration tau 2. And if tau is the coherence time, then the coherence length L c is simply the speed multiplied by the coherence time, speed of light c multiplied by the coherence time.

So, this axis can be time or it can be distance at a given instant of time, this one and the same. That is why this one is in terms of length over a certain, duration here and over a certain length that we have constant phase relationship, that is why the coherence is in general characterized by either coherence time or coherence length.

Usually, the coherence time or coherence any one of them can be measured. In interferometric experiments, it is possible to measure this coherence length and calculate the corresponding coherence time.

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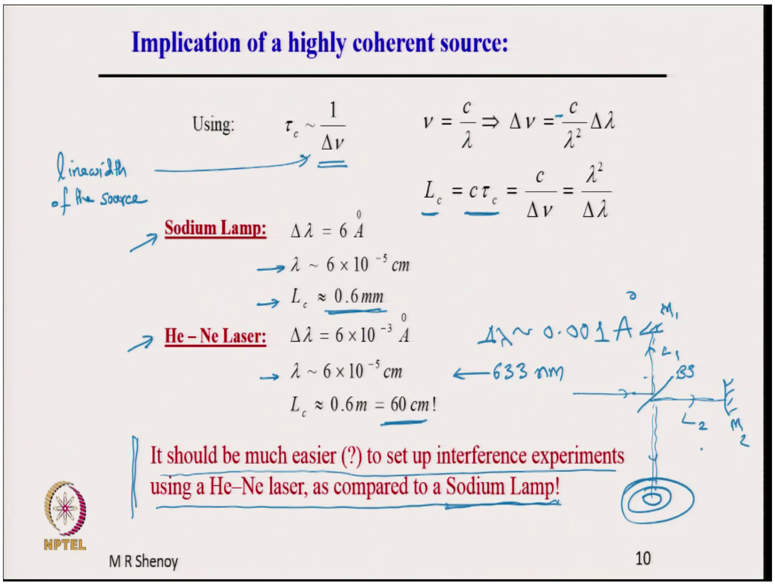

So, let me explain this putting some numbers here. So, the coherence time tau c, it can be shown that it is of the order of 1 by delta nu, where delta nu is the line width of the source. So, this is the line width, line width of the source. So, the coherence time is approximately of the order of one by delta nu. This can be shown; I am not going into the derivation here.

Now, nu is equal to c by lambda, frequency is equal to velocity by lambda. Delta nu, if you differentiate this, it will be c by lambda square into delta lambda, of course, there is a negative sign.

But we are interested in the magnitude and that is why, and L c is equal to c times tau c coherence length is equal to speed into tau c that is the coherence time which coherence time is 1 by delta nu. So, it is c by delta nu, and that is equal to lambda square by delta lambda. So, c by delta nu substitute here; c, c, cancels, and lambda square by delta lambda.

Let us take the sodium lamp. If you put some numbers, it will give a very good feel. Delta lambda just now, we have seen is 6 Angstroms between the D 1 D 2 lines, and that is considered as the line width of the sodium lamp. Wavelength is approximately 5893. So, let us say 6000 Angstroms which is 6 into 10 to the power of minus 5 centimeters. And therefore, L c the coherence length comes out to be lambda square by delta lambda. If you substitute, it comes out to be 0.6 millimeter, 0.6 millimeters

Let us look at a helium-neon laser. All of these are typical numbers. Delta lambda is I had already said that it is of the order of 0.001 Angstrom for a practical laboratory helium neon laser delta lambda. So, I have taken here for a particular laser 6 into 10 power minus 3 Angstrom that is 0.006 Angstrom. And lambda here is again helium neon is actually 633 nanometers, so 633 nanometers which comes out to be 6 into 10 to the power of minus 5 that is 600 nanometers, 6 into 10 power minus 5 centimeter.

And coherence length L c in this case comes out to be 0.6 meters or 60 centimeters. Here, it is 0.6 millimeters, this is 600 millimeters. So, almost 1000 times 0.6 millimeter, and this is 600 millimeter that is 1000 times more coherent. I have made a statement here. Therefore, it should be easier much easier to set up interference experiments using a He-Ne laser as compared to a sodium lamp. This is something very interesting. I would request you to give thought about this.

Let me give a hint torrent, some idea what do I mean by this? If you take, for example, if you want to set up a Michelson interferometer using sodium lamp, the standard Michelson interferometer, so, most of you would have seen a Michelson interferometer, where you have a source which comes here there is a beam splitter which splits it into two towards two mirrors. So, there are two mirrors here and then of course, the reflected beams interfere here.

Both of them to give you depending on the position of the mirrors and the source that you use, you may get here nice ring pattern. Those of you have done a Michelson interferometer experiment, know that the two arms have to be nearly equal, first of all the two arms that is the arm here L 1 and L 2 the length from the mirror to the beam splitter, so this is the beam splitter BS. And from beam splitter to mirror here, so let us say this M 1 and M 2.

Then the L 1 and L 2 should be nearly equal; otherwise, you do not get using a sodium lamp, it is very difficult to get the fringe pattern. But, if you use a helium-neon laser, it simply does not matter whether L 1 is equal to L 2 or L 1 and L 2 are different by several centimeters. Why? The only difference is helium neon laser is more coherent has a longer coherence length. You can think over more about this, and understand what this statement means all right.

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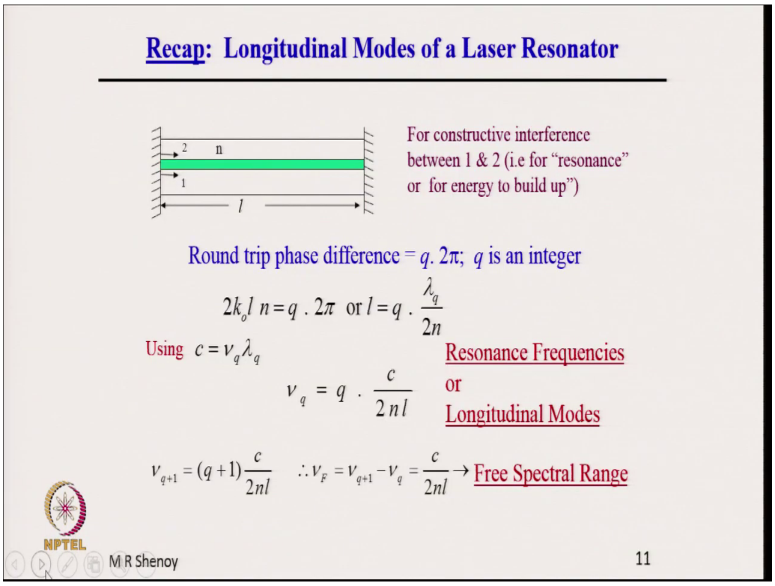

Now, let us come to the longitudinal modes of the laser resonator. We have already discussed this in detail that is why I have written it is just recall here. And we know that the modes are determined by the condition that round trip phase difference is equal to integral multiple of 2 pi, and that gives us the resonance frequencies.

We have seen these all in detail. The qth order resonance frequency nu q is equal to q times c by 2 n l. l is the length of the resonator; q is an integer; n is the refractive index of the active medium; c is the velocity of light. So, these are the resonance frequencies or longitudinal modes of a laser. And then if we simply replace q by q plus 1, then nu q plus 1 is given by this. And the free spectral range nu f is equal to c by 2 n l. We have seen this in detail.

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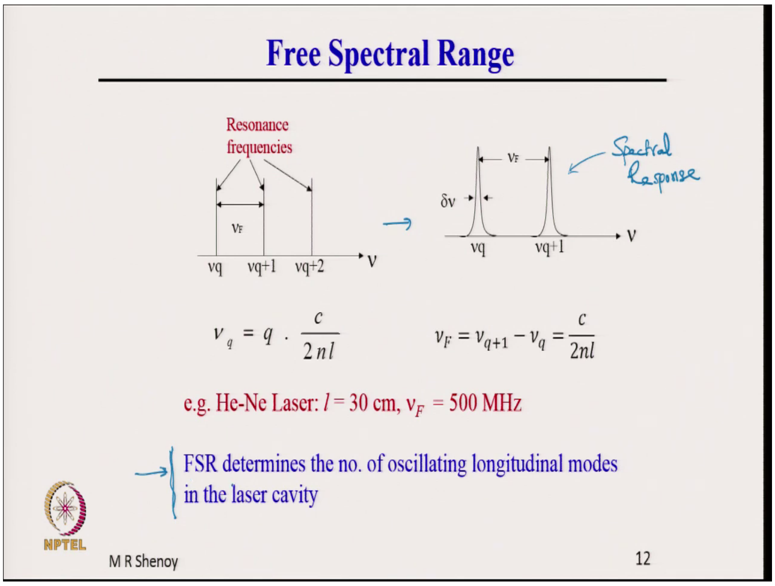

Now, what is shown here is the frequency axis and the position of the resonance frequencies or the longitudinal modes. We know in practice, so this is just the positions only. But in practice if you see the spectral response, there is a finite width of each of these resonances. So, this is the spectral response . And we have already seen that the line width delta nu of the resonances is determined by the losses in the resonator. Smaller the losses narrower will be the sharper will be the resonances, and smaller will be the delta nu.

Now, for a helium neon laser, let us say the length of the laser is about 30 centimeters then the nu F comes out to be about 500 megahertz. Statement here, says the FSR determines the number of oscillating longitudinal modes in the laser cavity. The free spectral range determines the number of oscillating longitudinal modes in the laser cavity not just FSR, but FSR also determines the number. So, let us try to understand what is this.

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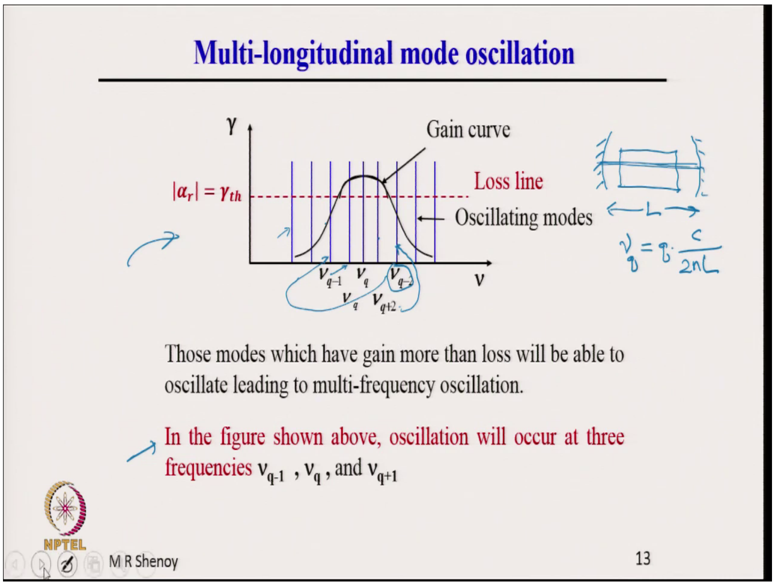

Now, let us come back to this picture here, where the black curve here is the gain curve and the blue lines here represent the cavity resonances. Please, see cavity resonances means you have a passive cavity here. And this cavity is characterized by resonance frequencies. And if this is L, then nu q any resonance frequency nu q will be c times 2 into n L. So, what is shown here are the positions of those resonance frequencies; this is the gain curve around the lasing transition. This axis is frequency axis.

Although, the resonator permits oscillation or buildup of these resonance frequencies, in this diagram when the medium is placed inside the resonator, no doubt the medium is characterized by a gain curve, but the resonator is characterized by a loss line. And we have discussed in detail that only those longitudinal modes for which gain is more than the loss will be able to oscillate.

And therefore, in the figure shown above there are three modes 1, 2, 3 which corresponds to nu q, nu q plus 1, and nu q plus 2. So, nu q minus 1, so this is nu q, this is nu q minus 1 here, and this is nu q plus 1. Actually, this plus 2 the positions have moved. So, we should have nu q. So, this position is nu q minus 1, and nu q I do not know how these positions have changed.

So, this should have come here nu q minus 2 is this, so, nu q minus 1 nu q minus 2 nu q this is nu q plus 1, and this one is nu q plus 2. So, this one is nu q plus 1.

Now, in the figure shown above oscillations can occur at only three longitudinal modes. For other frequencies although the resonator permits them to build up, but at those frequencies the gain is less than the loss. And therefore, they cannot oscillate in the laser cavity.

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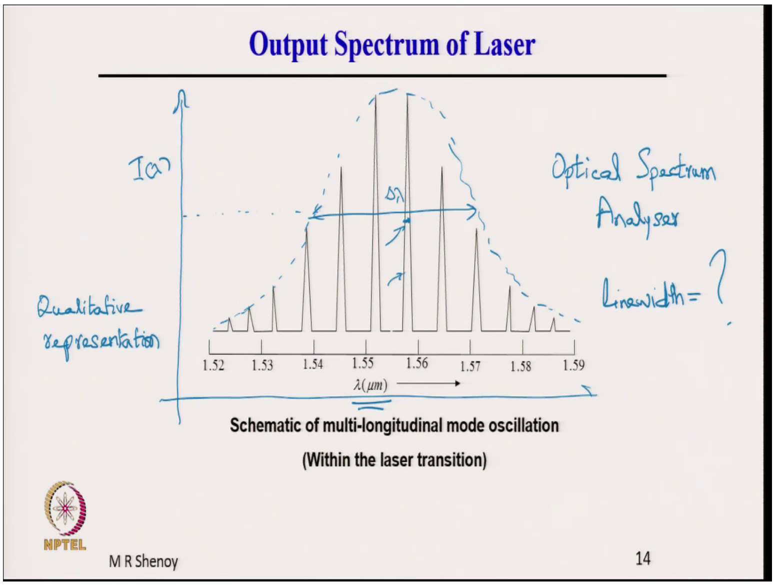

And therefore, in such a laser this is a schematic this is a qualitative picture. So, qualitative representation, this is a qualitative representation of the intensity of what is plotted is either power at those modes I of lambda by lambda. So, this axis is already pointed out it is lambda, it is the intensity.

So, you have this kind of variation here, so power variation, because we have already seen that the power in any particular mode, any particular longitudinal mode will be determined by the difference will be determined by this difference gain to loss this difference. So, larger the difference we have discussed this in detail, the intensity should build up more to pull down the gain to the loss, because while the laser is oscillating in steady state gain must be equal to the threshold gain coefficient.

So, this is the spectrum if you see on a optical spectrum analyzer, so I will try to show you this a typical diagram optical spectrum analyzer. I will show a photograph for a typical multi-mode laser you will see like this, so intensity versus lambda. Now, if this is the spectrum of a particular laser, what is the line width? So, line width for this laser. Line width by definition is full width at half maximum of the spectrum. The envelope here shows the spectral dependence.

And therefore, if you take at the half point here, full width, for example, this is delta lambda or line width of this particular laser that is full width at half maximum which is quite a bit in this case. Now, let us see suppose, I want highly monochromatic source, if I can somehow have only one longitudinal mode oscillating, then I would have got the full width at half maximum is only this much.

Because, the output would have looked like this and the full width at half maximum would have been this if it was a single longitudinal mode or a single frequency laser. How to get this? That is our discussion now.

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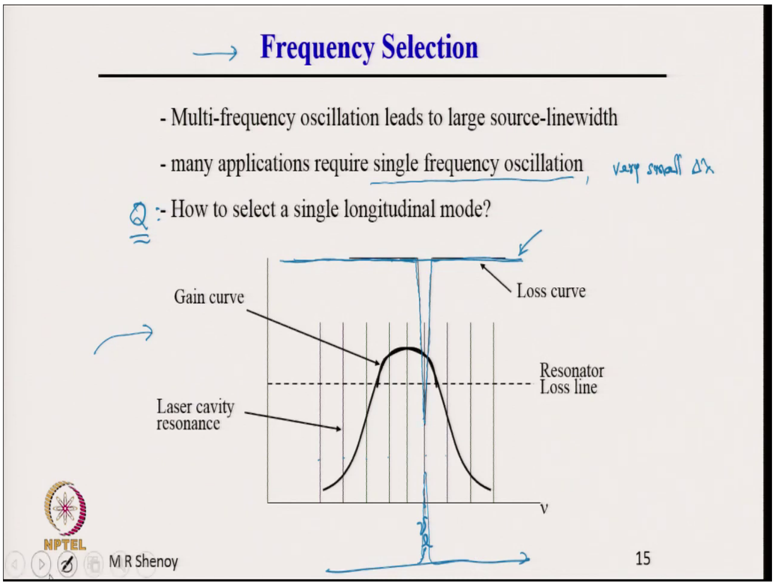

So, that is the topic called frequency selection. Multi-frequency oscillation leads to large source-line width. As I have illustrated here, this is the line width of a multi-longitudinal mode laser output.

And many applications require single frequency oscillations, because they need delta lambda, very small delta lambda or highly monochromatic delta lambda; highly monochromatic, because there are applications which require highly coherent output from the laser. How to select the problem is the question that we have now, address is how to select a single longitudinal mode? A schematic idea is depicted in this diagram here.

So, note that these vertical black lines are the cavity resonances this axis is frequency, and this is simply showing the positions. And the dark line is the gain curve. And I have already explained that these three modes would oscillate in this case, when the resonator loss line is here. Suppose, the loss line was here, let us say the loss line without any dip let us say this is the loss line, the blue line is the loss line.

If this were the loss line with this amplifier, no mode will oscillate the laser cannot operate it cannot oscillate in any longitudinal mode, because loss is much higher than the gain. But suppose, by some mechanism, the loss curve has a dip corresponding to one permitted longitudinal mode of the resonator.

Let us say corresponding to one frequency here, let me call this as nu l where the loss curve behaves like this. It is like a notch filter at this point there is a dip in the loss. Then for this frequency, the loss is here and gain is here. Therefore, gain is much more than the loss and that frequency will start oscillating. And if you see the output spectrum, you will get simply one longitudinal mode like this at the frequency nu l. And this is called single frequency laser or single frequency oscillation.

Now, how to have such a situation where the loss is very small at only one frequency? Let us see.

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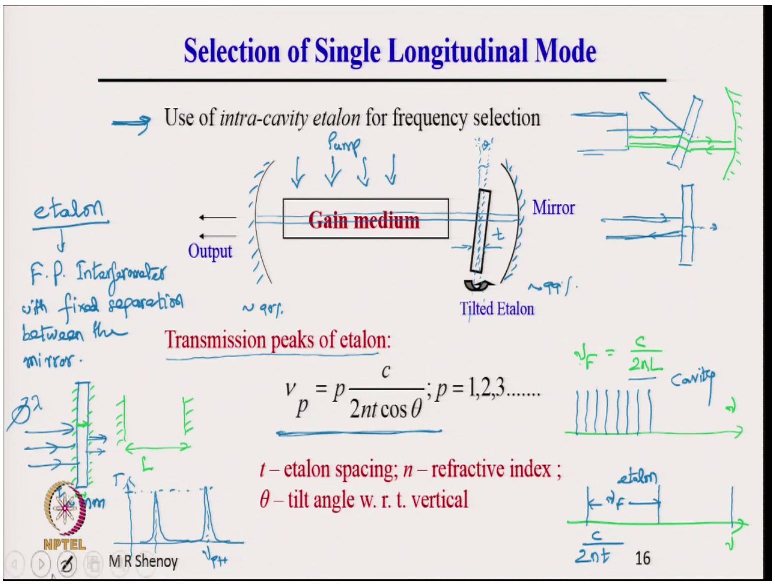

So, selection of a single longitudinal mode, there are different techniques by which we can achieve selection of a single longitudinal mode. I will consider here one of them one of the common techniques is use of intra cavity etalon for frequency selection. It is simple to understand and, but used only in bulk lasers one cannot use this in a compact laser like semiconductor laser.

But let us try to understand the principle and let us see whether the principle depicted in this diagram does it apply to this particular case. So, what you have is a gain medium, this is a laser which is pumped this is the pump, and it has two mirrors here. So, this is forming the cavity. This is a partially reflecting mirror, which gives some output. Just for example, this is 90 percent and this is 99 percent or 100 percent, let us say and it says use of intra cavity etalon.

What is shown is an Etalon. And its intra cavity means it is inside the resonator, inside the cavity laser cavity that is why intra cavity etalon. What is an etalon? Those of you are not familiar etalon is nothing but, etalon is a Fabry perot interferometer it is a fabry perot interferometer with a fixed inter with a fixed separation between the mirrors between the mirrors.

Usually, the separation is very small, a few millimeters. And it is realized by taking, for example, one takes a glass plate of let us say, certain millimeter thick let us say millimeters 1, 2 millimeter thick and on the two ends. So, if you coat mirrors on the two ends, this forms a fabry perot interferometer or a resonator basically, an optical resonator where light can go back and forth and build up here. It is the same short version of the laser resonator which I showed in the first slide.

So, if we see the first slide here, so a resonator here for example, where the gain medium ok, let me show the first one, yes. So, we have a resonator. So, maybe this one; we can see the active medium and there are two mirrors coated at the end. It is the same thing. But in an etalon usually, the separation the length of the active medium or the separation between the two mirrors is very small. And therefore, easiest way to realize an etalon is by using a plate and coating them with the mirrors.

So, that this forms an interferometer fabry pero interferometer. So, the normal fabry pero interferometers comprise of two mirrors separated by a distance L here. And the separation can be usually varied. In the case of an etalon, the separation is fixed, and usually it is very small. Now, why we use such a resonator? We know that the free spectral range nu F is equal to c by 2 n L. Where L is the length of the cavity, in this case, L is very small here; here L is very large.

So, if we have a small L, that means, so in a normal fabry pero if we had resonances, so let me show nu. And in a normal fabry pero if we have resonances which are close like this with a certain nu F; then in the case of an etalon, we will have well separated resonances, because nu F is large. So, this is nu F for the etalon. So, this is for the etalon. The nu F, the free spectral range is large, because the length is small. So, we now understand what is intra cavity, inside the cavity, and etalon.

And there is a tilted etalon. This is tilted with respect to the vertical axis. So, it is if this is the axis of the etalon. So, we use a tilted etalon, tilted with respect to the axis with a certain angle theta. Then if light is building up like this, going back and forth in the resonator, then we can show that the resonance frequencies of the etalon is given by c by 2 n t cos theta.

This is the resonance frequencies of the etalon, the transmission peaks of the etalon that is etalon is a fabry pero interferometer. And we know that if you have an incident spectrum a broadband source, which is incident from here, then we get corresponding to this transmission. So, there are resonances corresponding to the resonance frequencies there is transmission. What am I plotting transmission? Transmission means the light that is transmitted here.

So, this is a variable lambda source, let us say this is a variable wavelength source or a broadband source. Then only at certain frequencies nu p, and nu p plus 1 and so on, so nu p plus 1, we have transmission which comes 100 percent 1.

So, the transmission is 1 at the resonance frequencies, so that is what is meant by transmission peaks of the etalon are given by instead of q, we have used nu q for the resonance frequencies of the resonator, nu p is the resonance frequencies of the etalon, where p is an integer of course, p into c by 2 n t cos theta. If theta is equal to 0, cos theta is 1.

And it is the same as c by 2 n L, t here is the thickness. So, this is t, t is the thickness of this plate or thickness of the etalon which is here, so, this is t. If the thickness is t, then you can show that the resonances are given by c by 2 n t cos theta. Note that t is not variable, but theta is variable.

So, by slightly tilting the angle theta, we can change the resonance frequencies, the position of the resonances can be tuned by tuning the tilt angle theta. So, t is the etalon spacing, n is the refractive index, and theta is the tilt angle with respect to the vertical which I have already shown here.

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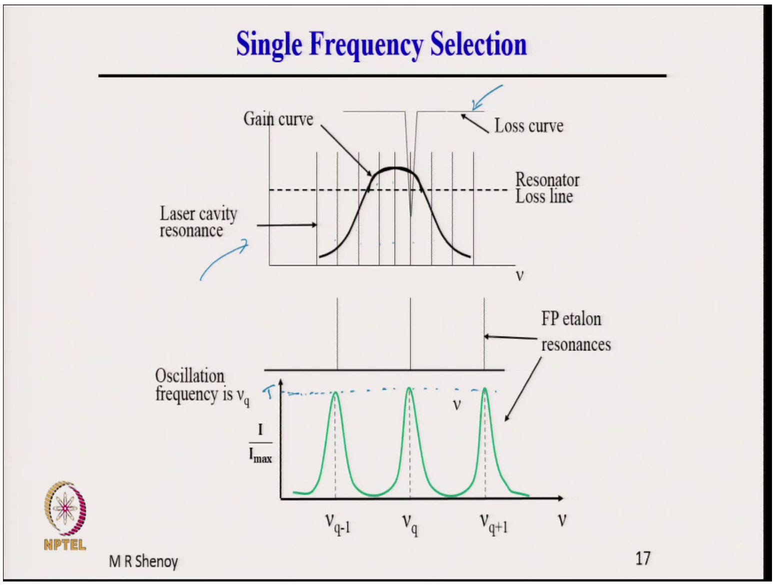

Now, let us try to understand the principle of this again. So, this is the idea which we want to implement. Now, if you take the very same laser here. This is L and this is t, the resonances due to the laser are what I showed here, because of c by 2 n L. And this is c by 2 n t, let us say it is not tilted then it is c by 2 n t and n t is very small. And therefore, the nu F is large. So, these are the resonances of the etalon; these are the resonances of the cavity.

Now, let us look at the other diagram. So, that is what is shown here. These are the resonances of the cavity. And we saw that three of these modes have gained more than the loss. And therefore, this laser without the etalon would have oscillated in all three modes.

Now, when you place the etalon inside the cavity, these are the transmission peaks of the etalon.

So, transmission is one here. So, this is the transmitted intensity, so, t is 1. So, these are the transmission peaks of the etalon, what I have shown here in the previous diagram, transmission peaks. At these frequencies, the etalon is completely transmitting which means it is as if this is completely transparent which means the light would go back and forth, back and forth as if there is no etalon at these frequencies.

What about for the other frequencies? At all other frequencies, other than the resonances, for example, these frequencies the etalon does not transmit at all, the transmission is very low in the etalon. And therefore, transmission is low means at those frequencies, the loss is high. If the transmission is low means the light is not allowed to go to the resonator, or it does not see the reflector.

It does not see the reflectivity of the mirror. It means for all other frequencies other than those frequencies which the etalon permits to pass through, there will be no feedback. Because, there is no reflector r 2 or the second mirror at all. And therefore, the loss in the resonator is very high.

Now, let us see this the loss is very high here, because light at these frequencies do not pass through the etalon; only light at this frequency passes through the etalon. And therefore, the loss of the etalon is very low at one particular frequency corresponding to the resonance of the fabry pero etalon. And now, we exactly have this situation which we depicted earlier as an idea, but that idea is implemented using an intra cavity tilted etalon.

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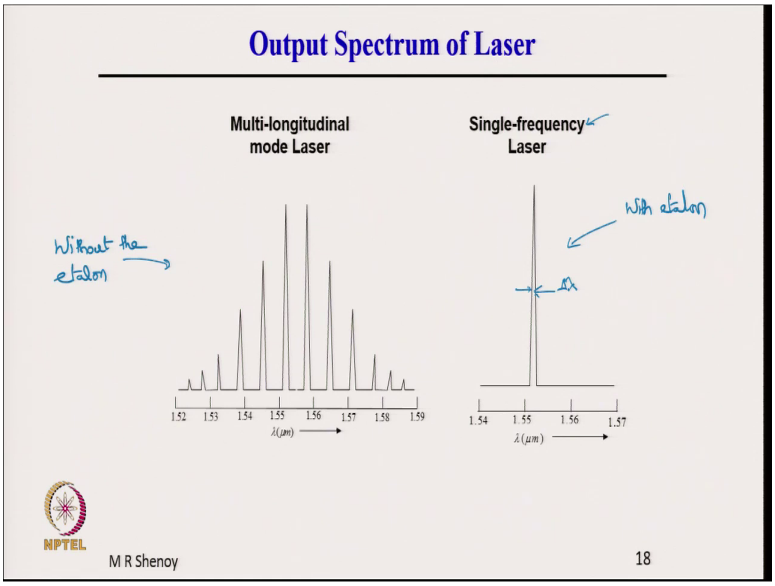

And if we use this then the now, we see the spectrum. So, this is with the etalon, this is with etalon; and this is without the etalon. So, we see that without the etalon, the laser oscillates in multi longitudinal mode. And with the etalon, it oscillates at a single longitudinal mode or it forms a single frequency laser. Of course, single frequency here, I have repeatedly said does not mean it is at one frequency, but it means it oscillates at one longitudinal mode with a certain delta lambda.

Now, of course, the delta lambda is very, very small. The line width of this source is very small and we call it a single frequency laser. A small question here is why do we use tilted etalon? We use tilted etalon for two reasons. One, it may so happen that the resonances do not coincide. For example, if this resonance happened to be here, then for none of the frequencies we can achieve this low loss condition.

By changing the angle theta, we can shift the resonances. For example, if we had like this, then for none of the frequencies it would have coincide. It is coinciding only in this position. And therefore, by changing theta, we can shift these we can shift these and adjust such that one of the resonances of the etalon coincides with the resonance of the cavity, and that is why one uses tilted etalons.

Second, if we do not tilt the etalon, then if you have a laser beam which is incident on the etalon, it will go back reflected along the same line behaving as a reflector. So, it would go back along the same line. But if you use a tilted etalon, I am enlarged exaggerating here then the laser beam which is incident here, although it does not pass here. It does not pass through, because the frequency is does not correspond to the resonance, but it will reflect back, because of 90 degree incident, normal incident.

In this case, the incident laser beam would get reflected in a different direction and would not go into the gain medium, because of the tilt. But if this is transmitting, let me show the with a different color, if the etalon transmits, then it would come here, it would bend, it would go like this. And from here the reflected ray, I will show as a ray picture ray would come back, and then it would come back into the laser. Provided the etalon is completely transmitting.

But any other ray which is incident here, which does not correspond to any other frequency, which does not correspond to the transmission peak would be reflected back in a different direction and would not cause any interference in the gain medium all right. So, there we have seen what is a single frequency laser, and one of the methods to choose a single longitudinal mode to realize a single frequency laser. We will continue with other properties in the next lecture.

Thank you.