Introduction to LASER
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Lecture – 01
Scope and Contents

Welcome to this MOOC on lasers. The course is titled Introduction to LASER. I am M. R. Shenoy from the Indian Institute of Technology, Delhi. So, in this course we will discuss about the basics of laser. So let me show what we are going to do. So, in the first lecture today we will discuss about the Scope and Contents of the course.

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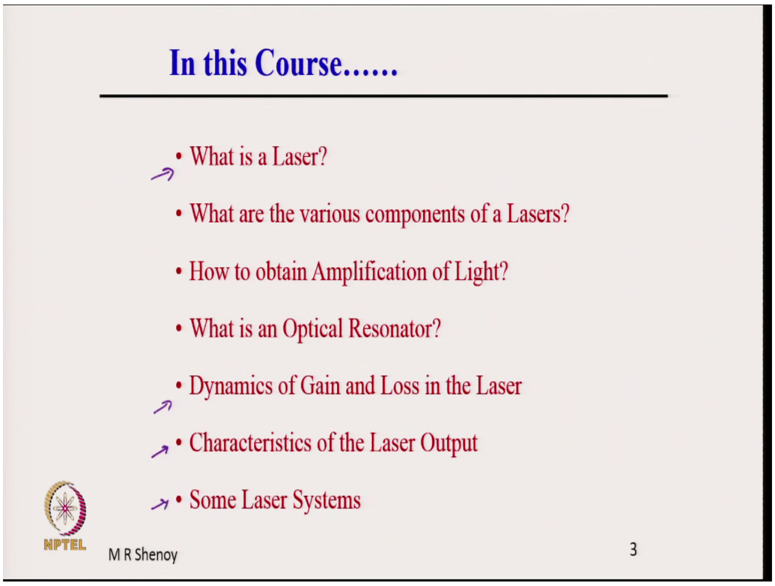

And in this course we will first start with trying to answer the question, what is a laser? What is a laser here? And then, what are the various components of a laser? How to obtain amplification of light? As we know that LASER is stands for Light Amplification by Stimulated Emission of Radiation and therefore, how to obtain amplification of light by the laser action? What is this laser action?

So, what is an optical resonator? Optical resonator is an important component of the laser. And therefore, we will spend some time to learn about optical resonators, and how they determine the properties of the laser.

Then we go to dynamics of loss and gain in the laser, the material has a gain then pumped appropriately and the resonator has a loss. And therefore, we will see the dynamics on gain and loss which will lead to a steady state output. Then we will see some of the important characteristics of the laser. And finally, we will discuss about some laser system some commonly used laser systems.

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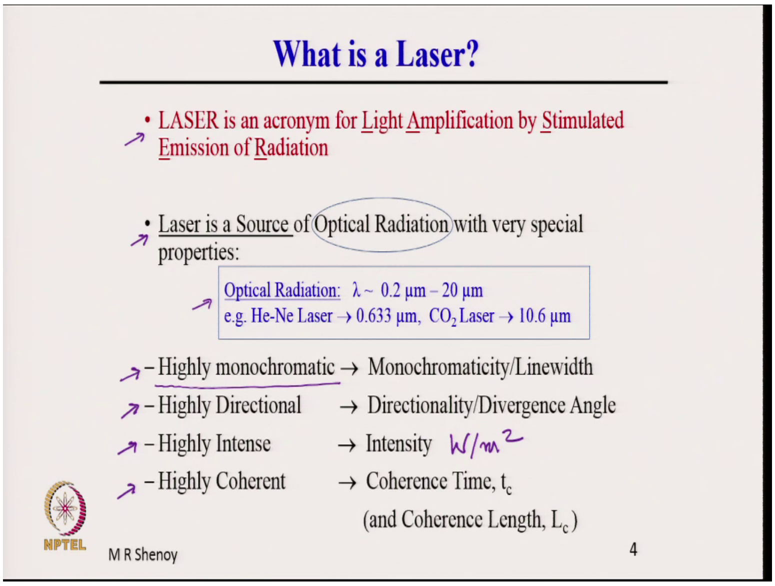

So, let us start with the basic question what is a laser. As I already mentioned LASER we all know that is an acronym for Light Amplification by Stimulated Emission of Radiation. But, what is a laser? Laser is a source so laser is a source of optical radiation with very special properties. As we go further we will see that laser can be defined in different ways, but here laser is a source of optical radiation with very special properties.

So, optical radiation, what is this optical radiation? Optical radiation is approximately the range of wavelengths of the electromagnetic wave with wavelengths in the range of 0.2 micrometer to 20 micrometers. For example, we know that a helium neon laser the wavelength is 0.633 micrometer; while a carbon dioxide laser the wavelength of emission is 10.6 micrometer.

So, we can see that it is a wide range of wavelength which covers optical radiation, it is not just the visible light; visible light as we know is from 400 nanometers to 700 nanometer or from 0.4 micrometer to 0.7 micrometer, but optical radiation covers a wider range.

Now, coming back laser is a source of optical radiation with very special properties; properties such as it is highly monochromatic. What are these highly? I have listed here highly, highly, highly. So, highly we will quantify. So, it is highly monochromatic and usually characterized by mono chromaticity parameter or the line width of the source.

It is highly directional so we will see what is this highly directional, again characterized by a parameter called directionality or divergence angle. The laser beam which is coming out has a finite, but very small divergence so the divergence angle is a parameter characterizing the directionality.

Similarly, lasers are highly intense it is intense because almost all the energy is concentrated in a very small cross section of the beam. The energy is concentrated in a small cross section of the beam. And therefore, the intensity which is power per unit area power is energy per unit time and power per unit area is the intensity and therefore, it is highly intense.

The unit of this intensity as we know is watts per meter square. So, watt is Joule per second and watt per meter square. It is highly coherent it is characterized by a parameter coherence time or equivalently coherence length.

So, we will see all these parameters a little later, but just to quantify a little bit at the beginning one quantity; let us say the highly monochromatic. What do I mean by highly monochromatic? Let us put some numbers and see what is highly monochromatic.

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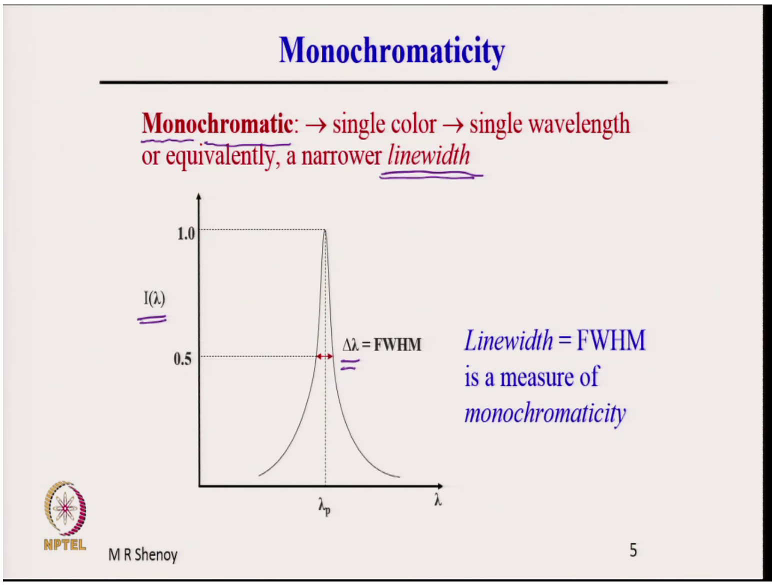

So, here monochromatic as the name indicates mono; mono is single and chroma is color. So monochromatic is single color or single wavelength because every wavelength has a different color; the red, blue, green they all correspond to different wavelengths; or equivalently.

There is nothing like as we go further we will see that there is nothing like a single frequency or a single wavelength in optics. And we can only define a certain line width for the source which determines the monochromaticity of the source. And therefore, the mono chromaticity is characterized by the linewidth of a source linewidth.

So, what is this linewidth? If we see the spectrum of a given source spectrum source spectrum. Spectrum means if we plot intensity here I as a function of lambda then we get a certain distribution for different sources. And the full width at half maximum of this distribution is delta lambda here indicated as delta lambda is called the linewidth.

So, linewidth of a source is the full width at half maximum of the source spectrum. So, spectrum here refers to intensity distribution in wavelength or frequency. So, it is a measure of monochromaticity of the source. Let us see some numbers for this.

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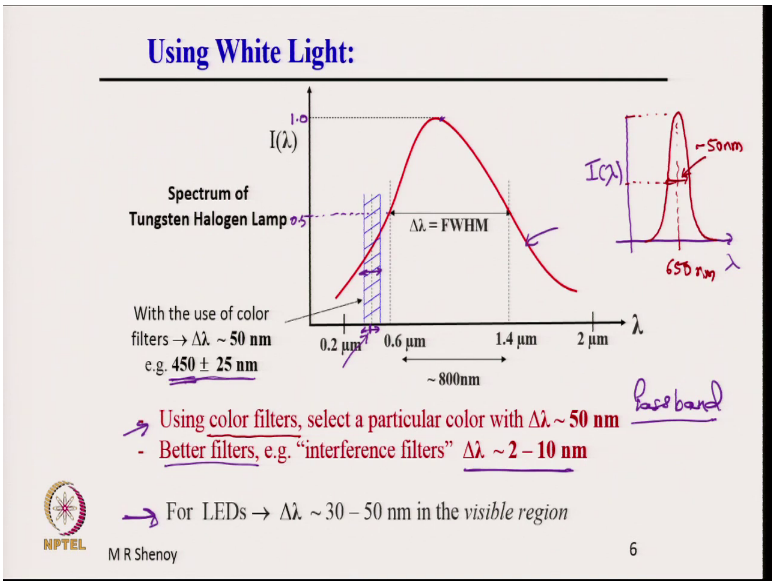

So, if we consider white light; white light has a broad spectrum. For example, if you take a tungsten halogen lamp. So, what I have shown here is the spectrum of a tungsten halogen lamp a typical spectrum. So, this is the spectrum of a; spectrum means, intensity distribution with wavelength. So, at different wavelengths the strength of the relative strength of the intensity is what is plotted.

So, arbitrary units I have not put the units on the y axis arbitrary units. So, what is shown is the spectrum of a tungsten halogen lamp, typical tungsten halogen lamp. So, it varies from approximately from 0.2 micrometer to 2 micrometer. So, if you see the full width at half maximum; what it means is the maximum is here so if you go down half the value 0.5 times here so 0.5 times the I max. So, what you have is the full width at half maximum. So, maximum is here so half the value; so this is 0.5 times the maximum.

If I have a normalized distribution where the peak is normalized to 1 then we have at 0.5, if we measure the width of the distribution that is called full width at half maximum and that is the linewidth. So, if we want different colors traditionally for example, in a stage performance or somewhere where you need a certain color what do you use is color filters or color papers. So, color filters covering the white light will give you a colored output.

So, for example, if you use a color filter which has a certain linewidth of delta lambda approximately of the order of 50 nanometers. For example, you take a color filter around blue so this is around blue value 450 nanometers. So, the filter has a bandwidth of about 50 nanometers; 50 nanometer means, it passes light with all these wavelengths 450 plus minus 25 nanometers. So, this is the range of wavelengths which pass through.

So, in the same spectrum if I show then it would look like this; so it is centered around 450 with plus minus 25 nanometer here. So, the band which is shown here with the blue line is the transmission, it represents the transmission band of a blue filter or a blue color paper or a blue filter.

And therefore, the output would look blue all the rest of the colors are blocked and therefore, we see a blue color. Similarly if you use a green filter or a red filter then you can get the respective colors at the output. So, this is very common that we see in all stage performances where they put different colored papers, but these days there are also colored lights itself, because the emission is determined by the phosphor which is covering the bulk right ok.

So, using color filters select a particular color with the delta lambda that is the linewidth. So, delta lambda here refers to this width so this width is about 50 nanometer as the pass band, it is also called pass band. So, pass band means the filter will pass about 50 nanometer wide range of colors through it pass band.

But there are better filters available better filters. So, better filters such as interference filters; these are interference filters are dielectric filters with the multi layer coatings which have a line width could be of the order of 2 to 10 nanometers here; 2 to 10 nanometers means, narrower than this 50 nanometer here; which means, it is more monochromatic it is more blue or more blue in the sense more pure that is smaller linewidth.

Just to give you an idea if you take a typical LED Light Emitting Diode we see light emitting diode in various applications. So, red color yellow color green color are various colored LED's are available; and are typically the line width is 30 to 50 nanometer, just to give you an idea 30 to 50 nanometer is the line width of an LED.

What it means? So, this means if i plot the intensity distribution of a light emitting diode. So, here lambda versus intensity of lambda; let me choose a different color. Let us say red colored LED, then it will show a distribution somewhat like this centered around a particular wavelength.

So, let us say this is lambda is equal to 650 nanometer, a red colored LED and this width full width at half maximum. So, this is the maximum so half the value here. So, this is gives this gives us the full width at half maximum. So, this one may be approximately of the order of 50 nanometer.

So, typically this number is about 30 to 50 nanometer; you can measure this in a laboratory. If you have a good spectrometer then you can simply measure the intensity distribution of a light emitting diode and similarly you can measure the pass band of a color filter.

So, I was talking about color filters you can measure the pass band by passing the output through a spectrometer and scanning different wavelengths. So, that is how the intensity distribution is measured. So, we are talking of delta lambda of the order of a few nanometers or 10s of nanometers so let us go a bit further.

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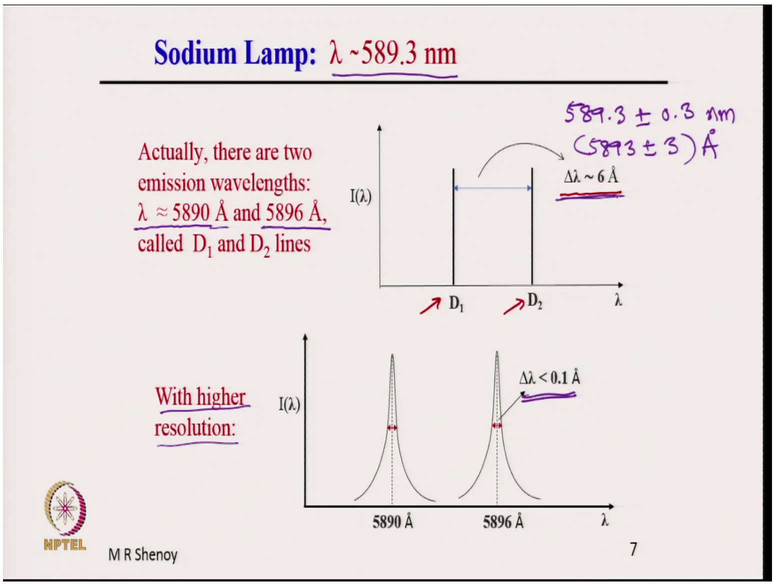

If you take a sodium lamp, the sodium lamp is the monochromatic source for us in our optics labs for example, in BSE or wherever we consider it as a monochromatic source. But we also know that it comprises of 2 lines which are called the D 1 D 2 lines here D 1 and D2, D 1 D 2 lines; we know this because in a spectrometer a grating spectrometer or using a prism spectrometer it is possible to see these 2 D 1 D 2 lines in the spectrum of a sodium lamp.

The output of the sodium lamp if you collimate and pass it through a grating diffraction grating then you will see the D 1 D 2 lines separated. The separation between them this separation delta lambda, this is separation between the 2 lines is about 6 angstrom. We know that actually there are 2; actually there are 2 lines here. So, lambda is equal to 5890 angstroms and lambda is equal to 5896 angstrom which are the D 1 D 2 line wavelengths.

And we take the average and say that in general sodium lamp the wavelength is 5893 angstroms or lambda is equal to 589.3 nanometers. This we use in our experiments for example, Newton's rings or a biprism experiment to determine the interference so, we use sodium lamps as the monochromatic source.

That is sufficient for that experiment, but the point that we need to see is that there is a finite separation of about 6 angstroms; in other words the source although it is 589.3 actually it is 58. So, it is 589.3 plus minus 0.3, that is it goes from 58 nanometers or you can write this as 5893 plus minus 3 angstroms in terms of angstroms.

So, there is if you see these 2 D 1 D 2 lines under a higher resolution spectrograph or a spectrometer then the 2 lines are further resolved. one line centered at 5890 angstrom. So, you have resolved with higher resolution and instrument with a higher resolution not the normal prism or the diffraction grating spectrometer.

But, with an instrument with a higher resolution; then you can see that they are they also have a finite linewidth that is there is a certain width and that width is of course very narrow, but you can resolve this. Now, let us go a little bit further. So, the sodium lamp that we have been using as a monochromatic source has a delta lambda of the order of 6 angstroms here.

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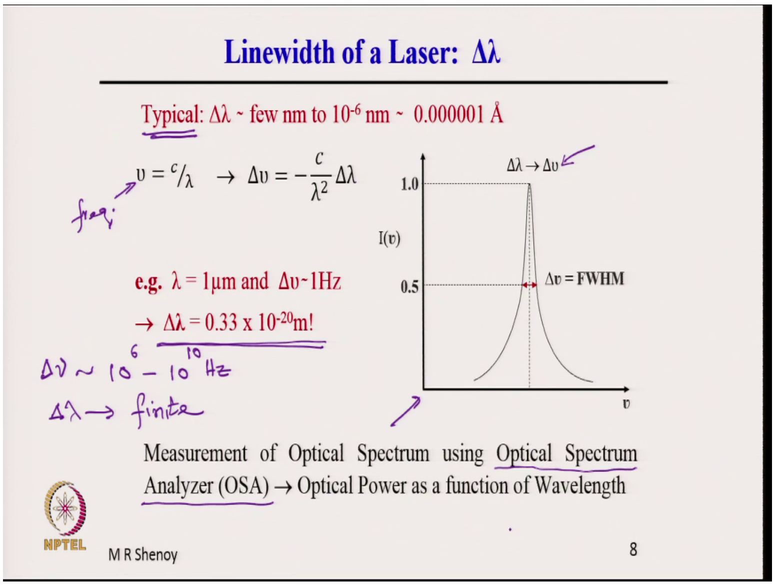

Now, let us see what about a laser. The line width of a laser typically, so typical line width of a laser delta lambda varies from a few nanometer to 10 to the power of minus 6 nanometers this is typical. A few nanometer to 10 power minus 6 nanometer, see that 10 power minus 6 nanometer means 0.00001 angstrom, not 6 angstrom as in the case of a sodium lamp.

Now, here we need to have a difference a relation between delta nu and delta lambda, which can be easily seen. This is nu the Greek letter nu for frequency, it is not v it looks like v, but it is frequency. So, frequency is equal to c by lambda therefore, delta nu you differentiate this then delta nu will be minus c by lambda square into delta lambda.

And therefore, delta lambda is related to delta nu that is what we want delta lambda is related to delta nu, if i give you a delta lambda you should be able to find delta nu and vice versa. For example if we take lambda is equal to 1 micrometer and delta nu is equal to 1 Hertz; I have taken delta nu very very small, normal practical lasers have a delta nu.

So, delta nu typically varies; normal lasers varies from 10 power 6 to 10 power 10 Hertz for practical lasers. There are lasers which have 10 power 3 Hertz, delta nu 10 power 3 and even as low as 1 Hertz.

So, just if you put a delta nu is equal to 1 Hertz see what is the delta lambda. This number is extremely small 10 power minus 20 meters, we know that the nuclear dimensions are 10 power minus 15 meters 1 for me, and this is 10 power minus 20 meter. So, what kind of monochromaticity we are talking of?

So, the monochromaticity of normal lasers is from a few nanometers to 10 to the power of minus 5 minus 6 nanometer, but there are lasers which can go down to much smaller linewidths, but the delta lambda or delta nu is always finite it can never be 0, is always finite. Quantum mechanics does not permit this to go down to 0 it can become smaller and smaller, but never 0.

Therefore, measurement of the optical spectrum using an optical spectrum analyzer is a very important instrument optical spectrum analyzer it looks like a CRO typical cathode ray oscilloscope. It gives optical power as a function of wavelength that is what we plot. So, the optical spectrum analyzer directly gives you if you connect the source to an optical spectrum analyzer it will give you the optical spectrum and you can easily measure the delta lambda or delta nu of a given source.

So, I have taken one parameter that is the monochromaticity and try to give some numbers which would give you an idea that what kind of numbers are we talking of for a laser. For a typical monochromatic source such as sodium lamp or maybe a red color, blue color light emitting diode which we use as one color when we go down to laser the linewidths are extremely narrow or they are almost like single frequency, almost like one frequency or truly monochromatic sources ok.

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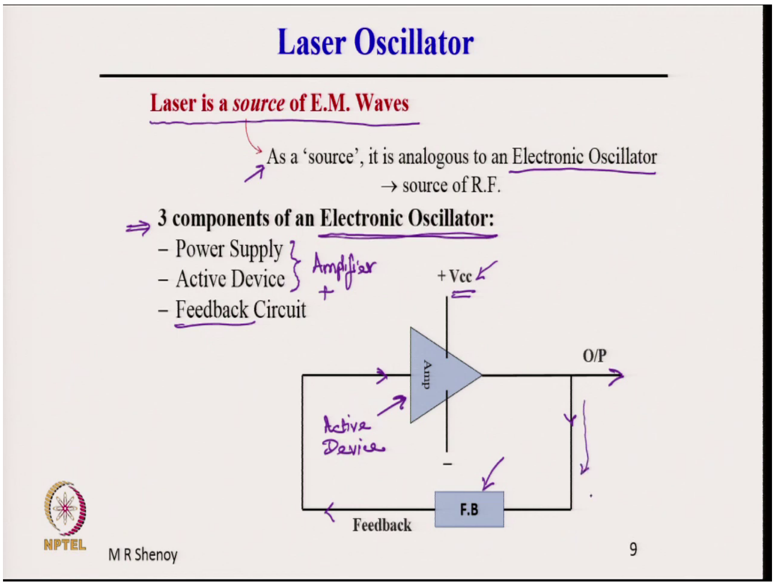

So, the laser; now I slightly raise the level and come to a different context that is the laser is a source of electromagnetic wave. We had said that it is a source of optical radiation; optical radiations are electromagnetic waves. So, laser is a source of electromagnetic wave.

As a source; as a source here it is analogous to an electronic oscillator an oscillator an electronic oscillator, which we widely use in electronics which is a source of radio frequency it is a source of R F an electronic oscillator. So, exactly like that laser is a source of E M waves in the optical in the domain of optical radiation.

The 3; let us just look at the 3 components of an electronic oscillator. The 3 components of an electronic oscillator here are 1 so, what is shown here is a schematic of an electronic oscillator, there is an amplifier here which is powered by a supply voltage supply and then there is a feedback circuit, a feedback component or a feedback circuit. This is a general schematic of an electronic amplifier and we have the output which comes out here.

So, what is shown is an amplifier an amplifier with a feedback circuit. The amplifier itself the amplifier itself here comprises of an active device, an active device such as an active device; such as an op amp, a transistor or any of the active devices which would amplify the input. So, this is the input so this is the feedback loop, the input is amplified when it is supplied a suitable power; power supply a Vcc voltage is applied to an amplifier an electronic amplifier then it amplifies the input.

Now, a part of the amplified output is fed back to the input and this is the basic configuration of an electronic oscillator. We are discussing an electronic oscillator the schematic of an electronic oscillator. This feedback this device the active device may be different types of active devices it could be an FET field effect transistor, it could be a normal transistor it could be an op-amp so any of the active devices.

Similarly, the feedback here the feedback component it could be an RC circuit and then we call it an as an RC oscillator. It could be a Colpitt oscillator it could be an Hartley oscillator depending on what type of feedback circuit that you have the feedback components; whether, you are using inductors capacitors so you can use a suitable feedback loop here.

So, it comprises of a feedback circuit, an active device and the power supply which makes this active circuit into an amplifier. So, the power supply with active device forms an amplifier so it is an amplifier plus feedback. So, amplifier plus feedback is what we have in an electronic oscillator.

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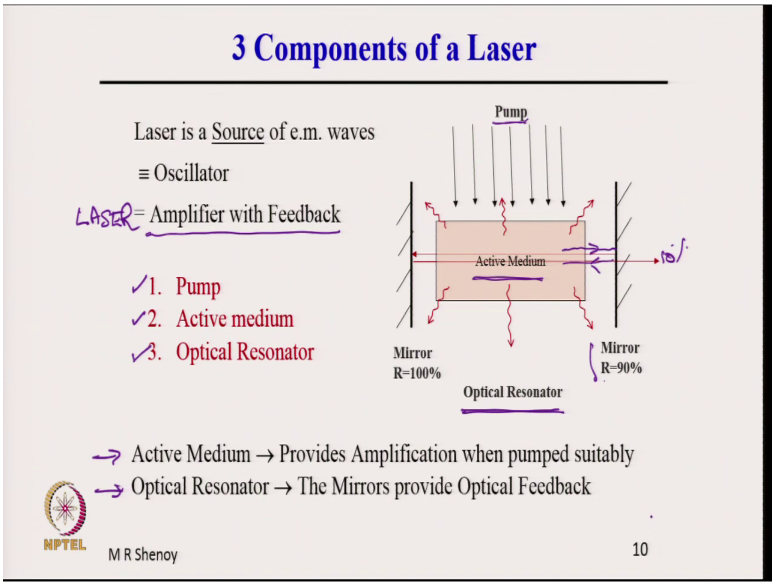

Now, let us see what is the case in the case of a laser. The 3 components, why are we saying 3components? Because here also we had 3 components power supply, active device and feedback circuit. The 3 components of a laser, the laser is a source of electromagnetic wave therefore, as a source is it is identical to an oscillator and an oscillator is an amplifier with feedback.

So, the 3 components of a laser is 1, the pump; the active medium and the optical resonator. What is shown schematically here is an active medium; in this course we are going to discuss these 3 components in detail and how it forms a laser. That is why the schematic here simply says an optical resonator which comprises of 2 mirrors, the active medium and a pump what are these we will discuss in detail.

The pump the active medium when it is pumped suitably acts as an amplifier and the mirror provides the feedback because we are talking of optical radiation. So, the optical radiation which is going towards a mirror will get reflected. If the mirror is partially reflecting let us say 90 percent then 10 percent will go out every time, out of the 100 percent which is incident 10 percent goes out and 90 percent gets reflected back.

That is a part of the output from the amplifier is reflected back exactly analogous to this. A part of the output is, a part of the output is fed back to the input. So, this is the same thing which is happening in the case of a laser. So, the mirror here the 2 mirrors forming an optical resonator we will discuss optical resonators in detail.

So, the 2 mirrors forming an optical resonator acts like a feedback circuit and the active medium when pumped appropriately; what is this active medium and what is this pump we will see in detail forms an optical amplifier. So, an optical amplifier with the feedback is what a laser is that is the source laser.

The active medium provides amplification when pumped suitably and the optical resonator here is formed by 2 mirrors which provides the optical feedback. So, with this context with this basic idea about a laser and the 3 components of a laser I would like to present to you the course contents of this course. So, let us see the course contents.

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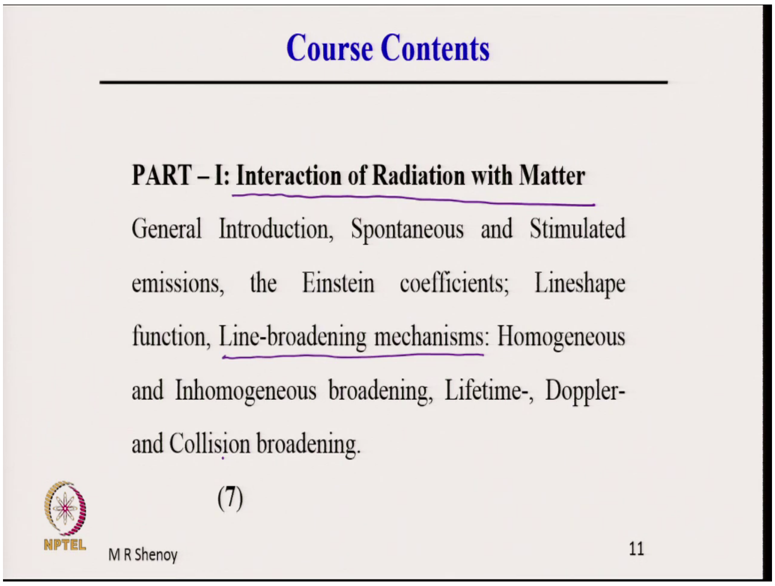

The course is in 5 parts in the first part we will discuss interaction of radiation with matter, interaction of radiation with matter part I here. So, we will start with spontaneous and stimulated emissions in a medium, the Einstein coefficient; the lineshape function, line broadening mechanisms. We will see these in detail; these are the mechanisms which are responsible for the finite world linewidth of the source.

There are two types of line broadening mechanisms homogeneous and inhomogeneous broadening. And we will briefly discuss lifetime broadening, Doppler broadening and collision broadening as examples of broadening mechanisms. So, approximately 7 lectures we will cover part I.

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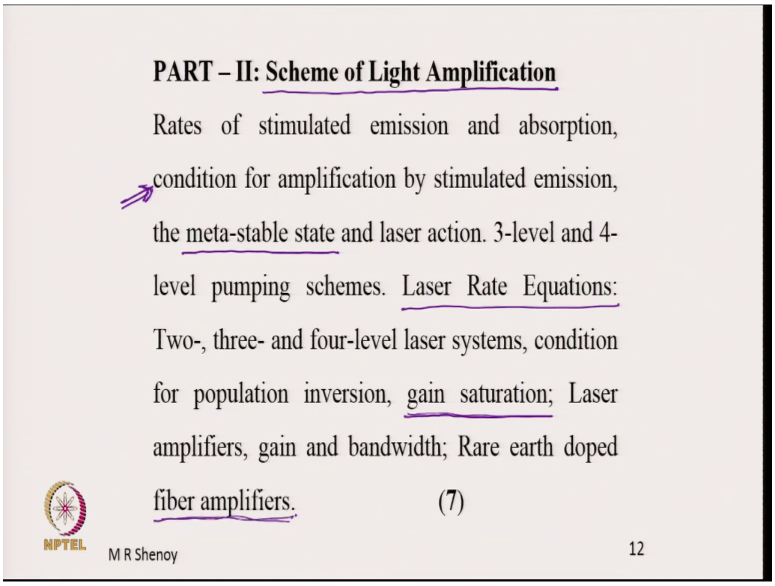

In part II we will discuss the scheme of light amplification. So, here we will discuss the rates of stimulated emission and absorption; we will obtain the condition for amplification by stimulated emission. Then, we will see that what is a meta stable state and how it helps in laser action. Then, we come to we will see that 3 level and 4 level pumping schemes, in laser physics there are 3 level and 4 level lasers.

These are basically schemes which help in obtaining the laser action and therefore, we will see 3 level and 4 level pumping schemes. We will write down the laser rate equations for 2, 3 and 4 level laser systems and obtain the condition for population inversion; because here we would show that the population inversion is the necessary condition for amplification by stimulated emission. And therefore, we will see under what condition we can achieve population inversion.

Then we will see gain saturation which is fundamental to steady state laser oscillations. And before we go to the laser oscillator part we will first discuss laser amplifiers; practical laser amplifiers I will take an example of the neodymium: YAG laser and erbium doped fiber amplifier; erbium doped fiber amplifiers are very very important with practical applications.

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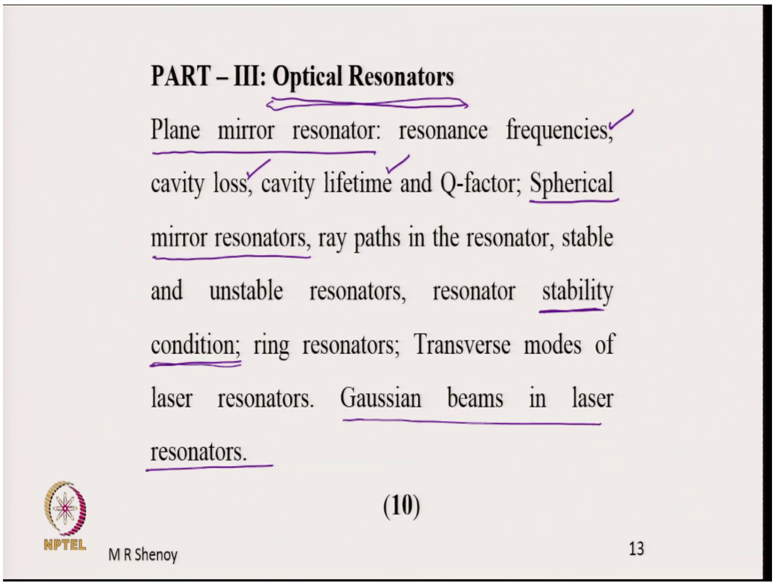

In part III we will discuss optical resonators. Optical resonators a study of optical resonators is very important in the study of lasers because that characteristics; the output characteristics of a laser system is primarily determined by the optical resonator. And therefore, we will discuss these optical resonators in a little bit more detail, we will start with the simple plane mirror resonator.

Plane mirror resonator means a resonator an optical resonator comprising of 2 parallel plane mirrors. And we will obtain expressions for the various parameters which characterize a resonator such as resonance frequencies here, the cavity loss that is the resonator loss the cavity lifetime which is also called photon lifetime; that is how long lights can survive inside a resonator. And the quality factor all of these are related actually to the resonator loss.

And then we go to spherical mirror resonator, spherical mirror resonators are most of the practical lasers use spherical mirror resonators. So, we will use here ray optics to trace ray paths in the resonators and obtain a condition called stability condition. A given resonator what is the stability condition, given a pair of mirrors can you always form a resonator? What should be the separation between the resonators resonator mirrors?

So, this is discussed in the stability condition; the stability condition tells us whether we can form a resonator of a certain design given a set of mirrors. Then, we discuss about the modes, transfers and modes of resonator. And finally, Gaussian beams in laser resonators because Gaussian beams are very important and therefore, we will discuss specifically Gaussian beams in spherical mirror resonators.

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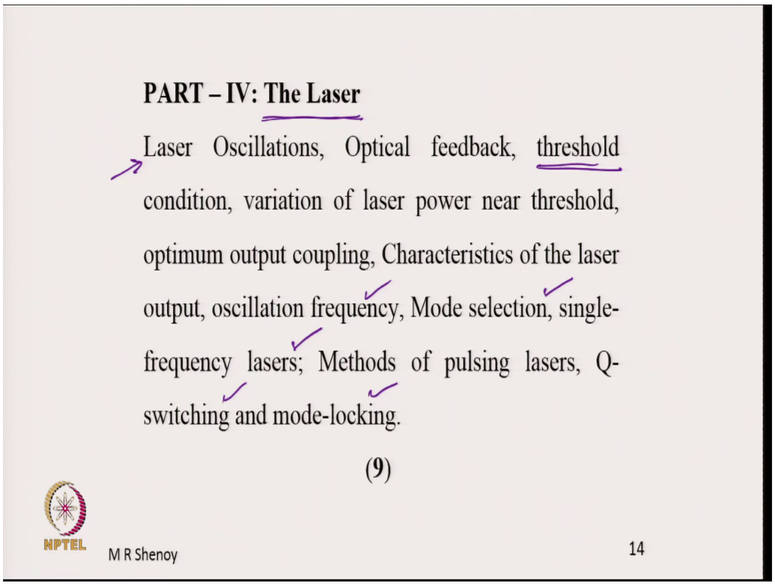

In part IV we come to the laser, in part II we discussed about the amplifier, in part III we discussed about the resonator and in part IV we will place the amplifier in the resonator and realize the laser. So, laser which is amplifier with the resonator and we will see the condition for laser oscillations, condition for laser oscillations; optical feedback, the threshold condition and how the laser power varies near threshold, why this name threshold?

There are certain other parameters of the resonator such as the optimum output coupling; that means, for a given pumping power what is the maximum output power from a laser that you can get. Then we will see elementary characteristics of the laser output the oscillation, frequency, mode selection, the transverse modes longitudinal modes and then single frequency lasers.

What are single frequency lasers? Then we come to pulse lasers and we will discuss the methods of pulsing lasers; two very widely used methods are called Q switching and mode locking so, Q switching and mode locking. So, we will discuss these in part IV of the laser.

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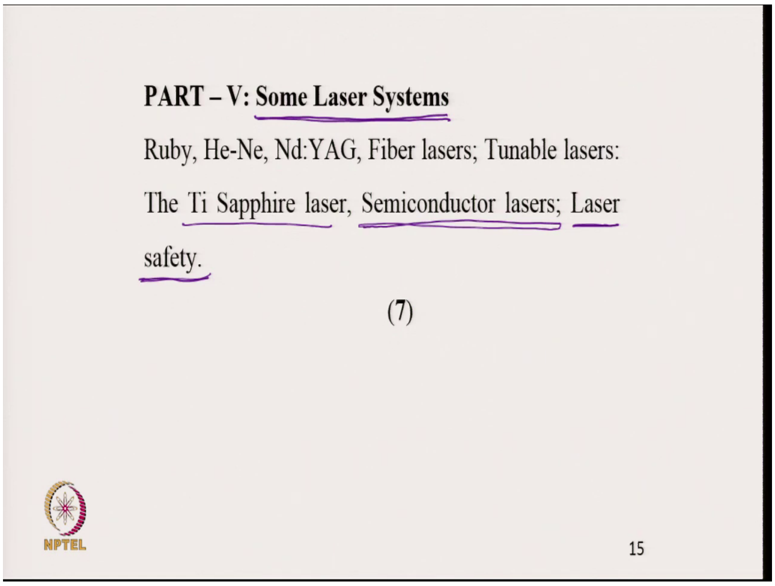

And finally, I come to part V where we will discuss some practical laser systems. We will start with the ruby and He-Ne, ruby because traditionally this is the first laser which was realized. And then helium neon laser which is even now widely used in laboratories. The ND YAG lasers the fiber lasers with the enormous applications in industry, defense and various applications since science and technology.

Tunable lasers where the output wavelength can be tuned one example that i would take is the titanium sapphire laser it is a solid state laser and then I will just discuss a little bit about semiconductor lasers; semiconductor lasers actually for a different class of lasers, but I would like to discuss this laser system as well which will give you a favor of how the semiconductor lasers are different or related to the general lasers that is the bulk lasers such as helium neon lasers, ND YAG lasers and so on.

And the last topic will be laser safety, last but not the least it is of paramount importance to know about laser safety in using lasers in laboratories, as well as for various applications. So, that would complete the course contents of this course.

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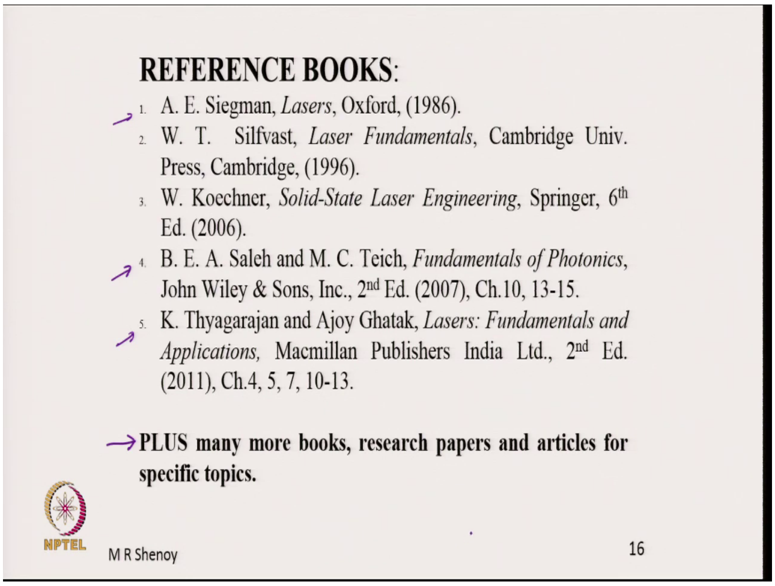

Now, finally, I will show a list of references here. These are actually classic references Siegman lasers these are; as you can see it is a little dated it is a little older references, but for a introductory course these are still the classics and they give a very good description of the fundamentals of lasers.

And so Koechner, Solid State Laser Engineering, Saleh and Teich fundamentals of photonics has several chapters relevant chapters. There is also book here by Professor K. Thyagarajan and Professor Ajoy Ghatak lasers fundamentals and applications. So, I have; in these 2 books I have marked specifically chapters so that for students who are following the course it would be easy to follow.

Whereas, in the first 3 references I have not marked any chapters because they are more like reference books, which gives a wider perspective of the lasers. Plus of course, many more books recent research articles, research papers for specific topics that we would cover.

So, that brings us to the end of this 1st introductory talk, introductory lecture. The basics which is expected of a student who does this course is some basic knowledge of optics, electromagnetic wave propagation and a little bit of mathematical physics; although we do not have any higher level mathematics in this course, electromagnetic wave propagation, light fundamentals so these would be required and maybe a little bit of electronics nothing more is required.

A typical graduate level undergraduate level exposure to these courses basic courses is sufficient for this background because this is this itself is an introductory course on lasers. So, we will start with the 1st topic in the next lecture.

Thank you.