Non - Metallic Materials
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Module - 06
Optical and Electrochemical Properties of Non - Metallic Materials
Lecture - 29
Optical properties: Refractive index, absorption and transmission of electromagnetic radiation, LASERS

Welcome to my course Non Metallic Materials and today we are in module number 6, Optical and Electrochemical Properties of Non-Metallic Materials. This is lecture number 29, Optical properties Refractive index, absorption and transmission of electromagnetic radiation and then we will introduce the concept of LASERS and optical communications.

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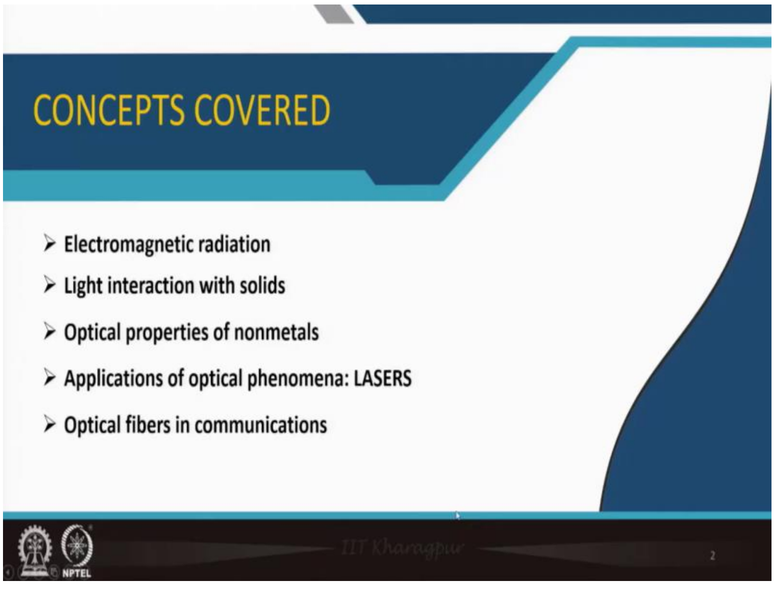

So, the concept that will be covered is the basics of electromagnetic radiation; then how light interacts with the solids, followed by optical properties of non-metals; then application of the optical phenomena, particularly in LASERS and optical fibers in communications, how exactly they work.

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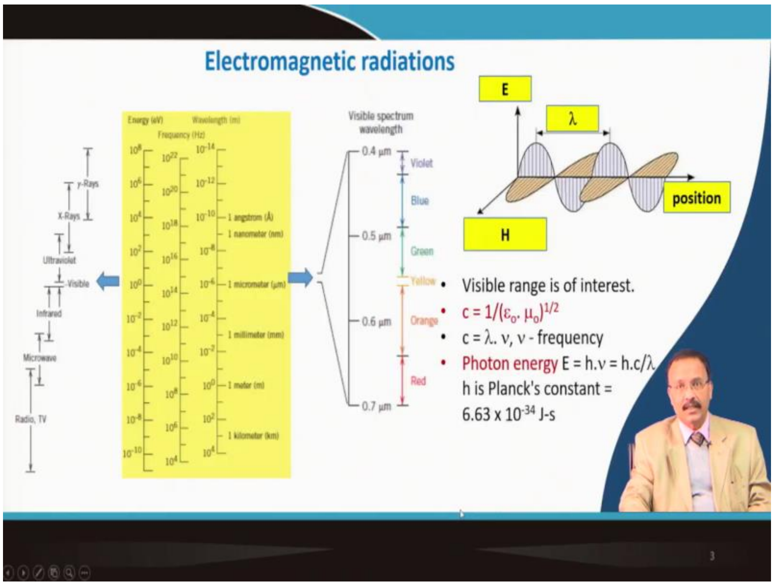

So, let us start with the very basic chart of electromagnetic radiation; as you can see, we have gamma rays, which are having wavelength which is pretty small and frequency is quite large and energy is also very large in terms of electron volt. And then we have X rays, ultraviolet, visible; we are interested in the visible region.

Typical wavelength is from 0.4 micron to 0.7 micron covering light violet, blue, green, yellow, orange and red. So, you know that this electromagnetic radiation it has two component; one component is the magnetic field component, which is in perpendicular to the electric field component and one can define the wavelength.

And the velocity of the electromagnetic radiation, that is dependent on the dielectric permittivity in vacuum as well as permeability in vacuum. And this is also, this velocity that depends on the wavelength as well as frequency, the frequency is defined as nu here.

So, you can calculate the photon energy, that is h into nu; that means h into c divided by lambda. So, smaller is the lambda, you have larger energy. So, as compared to radio wave, this energy is pretty large and it is related; this c and lambda is related with Planck's constant, which is having a typical value of 6.63 into 10 to the power minus 34 Joule second.

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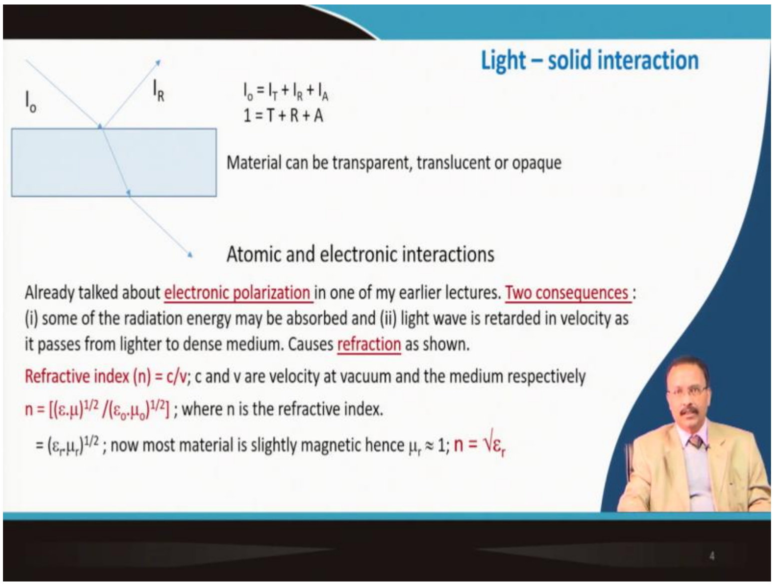

Now, it is important for you to understand that how light interact with a non metallic solid. So, you have one component incident light and part of it could be reflected. So, this is IR and part of it could be transmitted and depending on the optical density, you have a deviation of the light direction.

You can see that in the dense medium, it comes closer to the perpendicular, if I draw a hypothetical perpendicular here. So, it comes nearer to it and when it moves from denser medium to lighter medium, again it moves away from this perpendicular.

So, already we have talked about the electronic polarization in one of my earlier lectures. So, when light interacts at that frequency range of optical radiation, then there are two consequences; number 1 some of the radiation energy may be absorbed and there are conditions apply when it will get absorbed.

And the second one is the light wave is retarded in the velocity as it passes from the lighter medium say in air to a denser medium and this causes as shown the refraction.

Now, one can define the refractive index which is the velocity in vacuum divided by the velocity in that particular denser medium. So, as I have already told you that, this two velocity is related to permittivity and permeability.

So, if I put back these numbers; then we can have the ratio of epsilon into mu divided by epsilon 0 into mu 0, and refractive index is given by this relative permittivity product with the relative permeability and most of the material they are slightly magnetic. So, we can assume that, that mu r value is very close to 1. So, that gives me the relation between the refractive index and the dielectric permittivity. So, n is equal to root over of the dielectric permittivity.

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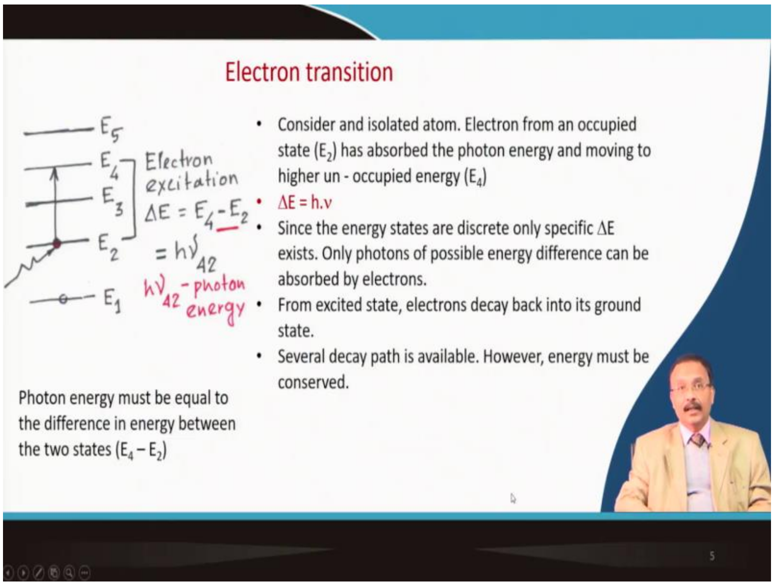

Now, if you consider an isolated atom, so electrons from an occupied state, say one electron is sitting in this occupied state; it can absorb some energy and excited and it can move to unoccupied state here. So, I have shown that from E 2 it is going to E 4. So, the energy that is required for this kind of transition is h into mu; so h is the Planck's constant. Now, this energy states they are discrete; so only specific value of del E that only can exist.

So, the photon which is having possible energy difference only that those photon can be absorbed by the electrons. Now, from the excited state, the electron cannot stay back in the excited state. So, they usually decay back into the ground state and several types of paths are available. So, this can be decayed either directly or by some other way and the main thing is that, the energy must be conserved. So, energy conservation should be followed.

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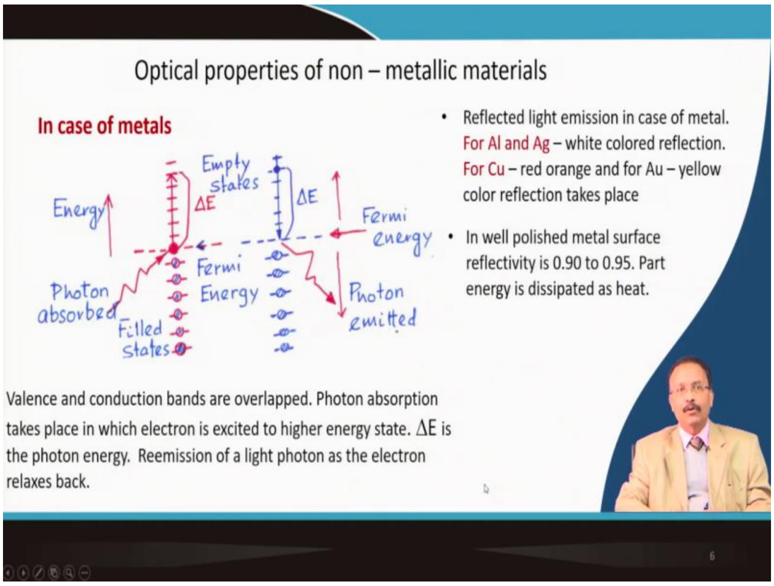

So, now if you consider in case of a metal, you know that the valence band and the conduction bands they are overlapped. So, the photon absorption that can takes place, where electron is excited to higher energy state as just I have shown.

So, the value of del E, that is the photon energy that is absorbed by that electron, go to the higher occupied unoccupied level and then they decay back. So, reemission takes place, when the electron actually relaxes back. So, this is done in case of a metal by reflected light emission.

So, if you consider aluminium and silver, you get a white colored reflection; for copper usually it is red orange kind of reflection; for gold it is yellow colored. So, when a metal piece is polished well, so that the scattering is minimized; then the reflectivity that can go up to 95 percent and part of this energy, this is dissipated as heat, heat energy.

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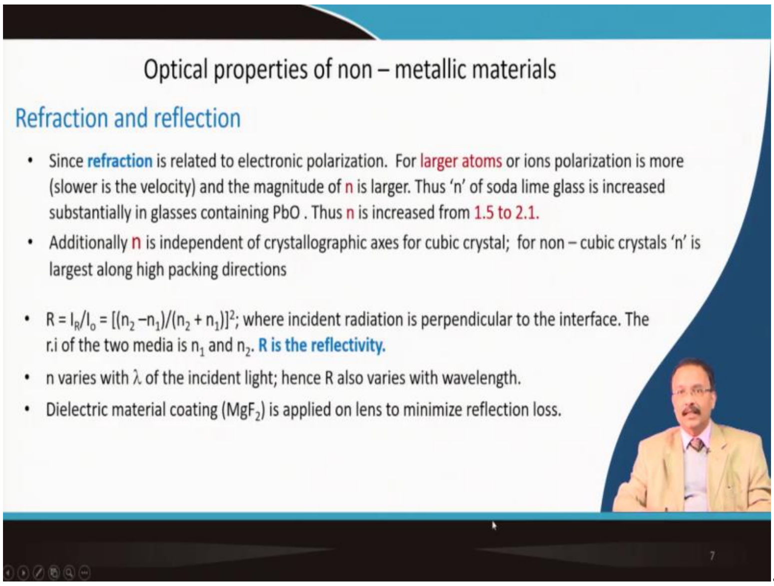

So, the refraction is related to electronic polarization. So, if you have a larger atom or larger size ions; the polarization is more, so that it is slower in velocity. So, the magnitude of the refractive index is larger so, if you compare soda lime silica glass and lead containing glass; then since lead is having larger ionic radii.

In lead containing glass, the refractive index is increased. So, for normal glass it is actually 1.5; so for lead containing glass it can go up to 2.1. This refractive index that is in case of a cubic structure, it is independent to the crystallographic axis.

So, everywhere it is same; but a non cubic crystal the value of n is larger, where the atomic packing density is high. So, n changes according to the direction. So, as I have mentioned the reflectivity is the intensity which is reflected as compared to the incident light intensity.

So, that can be given by this relation. So, n 2 and n 1 they are the refractive index in the two media. So, if one is coming from here, then certainly one of them will be 1. So, n 1 you can consider 1. So, this refractive index that varies with the incident lambda; so therefore, reflectivity is also will vary with wavelength.

So, sometimes a dielectric coating is given on the glass surface to minimize this reflection loss. So, typically magnesium fluoride kind of coating is used for this anti reflection characteristics.

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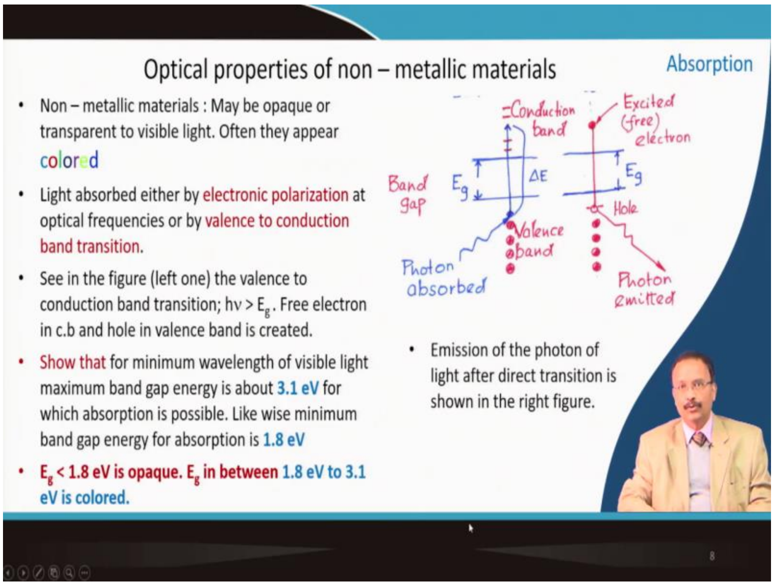

In case of non-metallic material, they may be opaque or transparent to the visible light; often they are also colored. So, usually light is absorbed either by electronic polarization, already I have told or by valence to conduction band transition; here in this case they are not overlapped.

So, if you see this figure, the left one; the valence to conduction band transition will occur when the photon energy is more than the band gap, so the free electron in conduction band and hole in the valence band that will be created. Now, it you can work it out that, for minimum wavelength of visible light, maximum band energy that is available is 3.1 electron volt, that you can work out from the energy equation which I gave earlier.

So, in that case absorption is possible. In the same way, minimum band gap energy for absorption you can calculate, that is 1.8 electron volt. So, if the E g value is less than 1.8 electron volt, then we call this is a opaque kind of non metallic material; and when E g lies between 1.8 to 3.1, then it could be colored. So, the emission of the photon of light after direct transition is shown in the right figure.

So, here you can see, initially it was excited from this occupied state creating a hole and then finally, photon is emitted when this relax back. So, direct electron to hole recombination also takes place. So, electron is going to the higher excited state, relax back. And then the hole created hole, it can react and it will give you energy. So, this is annihilation of electron and hole.

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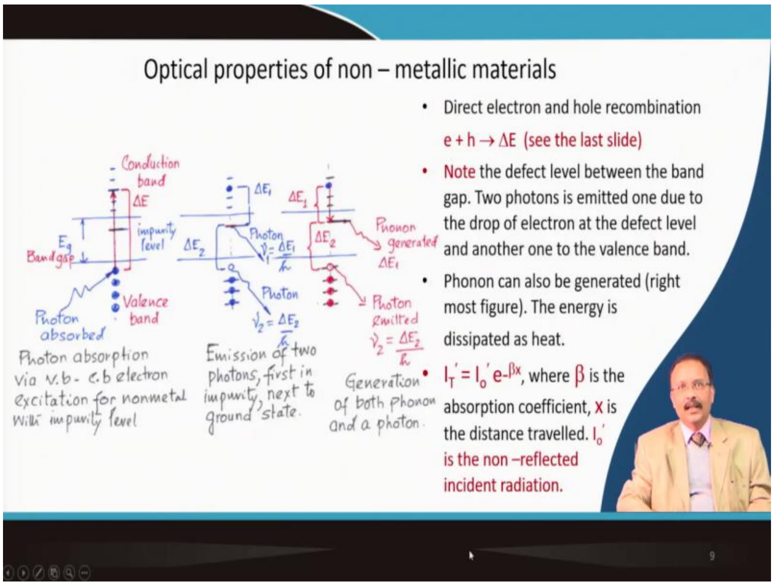

Now, additionally already we talked about the non-stoichiometry in oxide system; so there could be additional defect level between the band gap.

So, if this kind of defect levels are there; for example, the impurity level as you can see it is here. So, valence to conduction band transition it is taking place and there is a defect state there is in between. So, it is possible that two photons can be emitted; one due to the direct drop of electron at the defect level, and another one to the valence band.

So, additionally phonon can also be generated; not photon, but phonon that can be generated, that is shown in the right figure, you see the phonon can be generated and the energy is dissipated as heat. Now, this optical radiation that can also be absorbed with this relation; so this transmitted optical radiation this is absorbed here.

So, beta is the absorption coefficient and x is the distance through which this optical radiation is traversed. So, I naught dash is the non-reflected incident radiation. So, we will talk about it in a moment.

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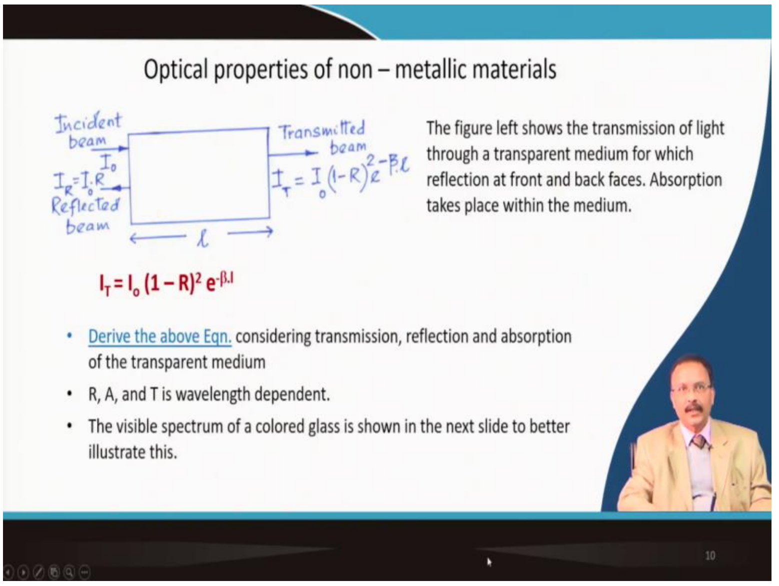

So, something similar to this is happening; it is showing the transmission of light through a transparent medium, for which reflection is taking place at the front surface, it can be in the back surface at well and absorption takes place within the media. So, I am leaving it on you to actually prove this relation. So, you have the reflectivity, you have the absorption; the equation already I have just shown you.

So, you can easily derive the transmitted light intensity and how it is related to reflectivity and the absorption coefficient. And remember this reflectivity, absorption, and transmittance they are all wavelength dependent.

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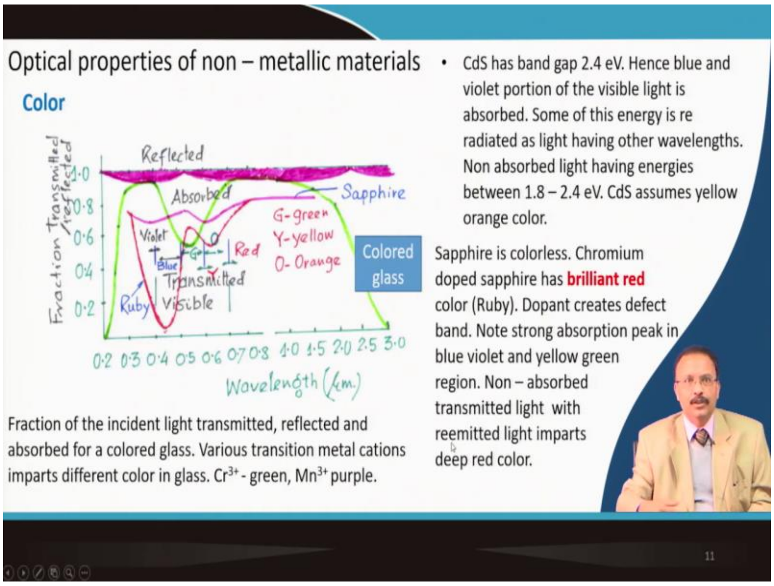

So, the visible spectrum of a typical colored glass is shown in this particular figure. You see here that, fraction of the incident light is transmitted, part of it is reflected and also it can be absorbed, right. So, various transition metal; you remember when we talked about the glass we told that, addition of the transition metal cation that is imparted in the glass batch to give different types of color.

So, if you have chromium plus 3, you will have a green color; if manganese plus 3 is there, you will have a purple color. So, coloration of the glass is due to the transition metal cation. If you take the example of cadmium sulphide, it has a band gap of 2.4 electron volt.

So, if you go back to the electromagnetic radiation table; you can see that, blue and violet portion of the visible light that will be absorbed. So, some of this energy what the electron will gain, they will be radiated at lights having other wavelengths, right. So, non absorbed light having energies between 1.8, because that is the lowest limit to 2.4 electron volt and if you see that, cadmium sulphide will radiate yellow orange color.

Another example you can take as sapphire. So, usually sapphire is colorless; but when it is doped with chromium 3 plus, sapphire usually give you brilliant red color, which we call ruby. So, this dopants create the defect bands I was talking about and strong absorption peak in blue violet, that you can see here, a blue violet region a strong absorption peak is there, and also there is another absorption peak in the yellow green region.

So, this non absorbed transmitted light, which I showed that part of it will get transmitted and part of it will be reemitted from this defect level. So, they will impart the deep, sorry deep red color in the ruby and this is used in laser, I will be talking it about.

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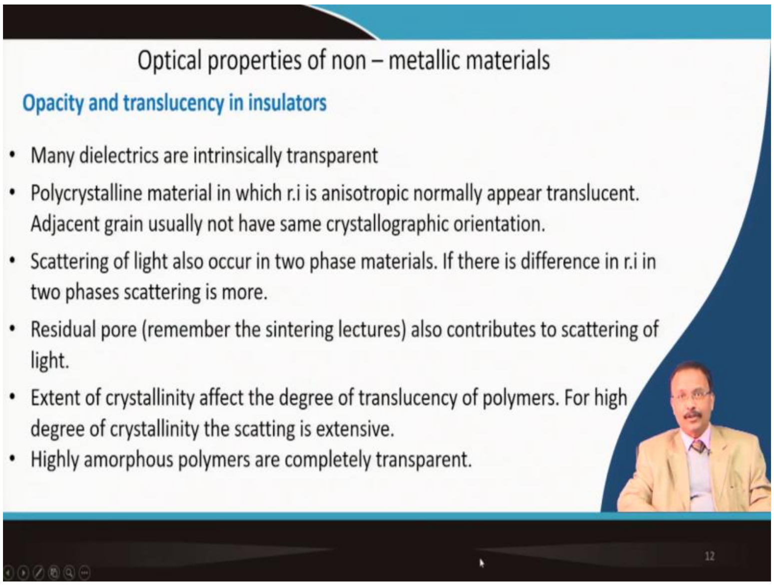

Next comes, the opacity and translucency in the insulating material, which is having a large band gap. So, many of the dielectrics they are intrinsically transparent, because of their large band gap. Now, if you consider a polycrystalline material, where the refractive index is anisotropy, they normally appear to be translucent; in the very first slide, I showed you that what is translucency.

So, it is due to the fact that in polycrystalline material, the adjacent grain usually they do not have the same crystallographic orientation and since the refractive index is dependent on the crystal orientation, so that will actually give this translucency.

Another effect which is important is scattering. So, scattering usually occurs when it is having a multi phase material. So, if there is a difference in refractive index in say the two phase material; if there are differences in the refractive index, the scattering is usually more.

Another aspect in sintering I was so much particular about the residual pore elimination; this is due to the fact as the as a optical solid, they also contribute, the porosity will also contribute to the scattering of the light and it will turn almost opaque, so extent of crystallinity that affect the degree of translucency in polymer as well.

So, if a polymer is having high degree of crystallinity, then the scattering is extensive. So, amorphous polymers they usually are completely transparent in nature.

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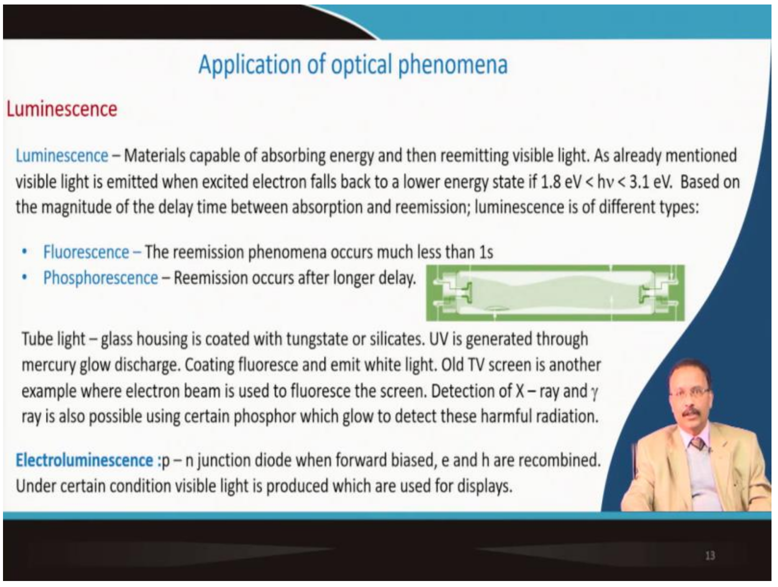

Another important optical phenomena is luminescence. So, this luminescence; in the luminescent material, they are capable of absorbing energy and then reemitting visible light. So, already I have mentioned that visible light is emitted, when excited electron falls back to a lower energy state.

So, band gap limit is 1.8 electron volt, which basically you can see the optical radiation from violet to red, so 1.8 to 3.1 electron volt. So, based on the magnitude of this delay time between this absorption and the reemission, luminescence can be of different types; the first one is called fluorescence, where the reemission phenomena occurs much less than 1 second.

So, one example is tube light, I will just be describing, the fluorescent lamp we call and another one is phosphorescence; so it occurs, the reemission occurs after a long delay. So, in case of this fluorescence light, you take a glass tube and this is coated with various types of tungstate or silicates and usually UV is generated through a mercury vapor glow discharge.

And this fluorescence coating is given at the inner surface of this glass and that emits the white light. So, remember the old TV screen is another example, where electron beam is used to fluorescence the screen and detection of X ray and gamma ray is also possible when you use certain phosphor.

So, otherwise you will not be able to see X ray or gamma rays. So, you have a coated phosphor, then it will glow and so, you can readily detect the presence of this harmful radiation. There is another term which is important, which is electroluminescence and it is applicable for p - n junction diode; for this course we are not taking semiconducting material, so I will just briefly tell you about it.

So, a p - n junction diode when it is forward biased; then electron and hole they are recombined. So, under certain condition visible lights are produced and which are also used for display. Nowadays you know the led display is very common, which has replaced your cathode ray tube which is used in older TV.

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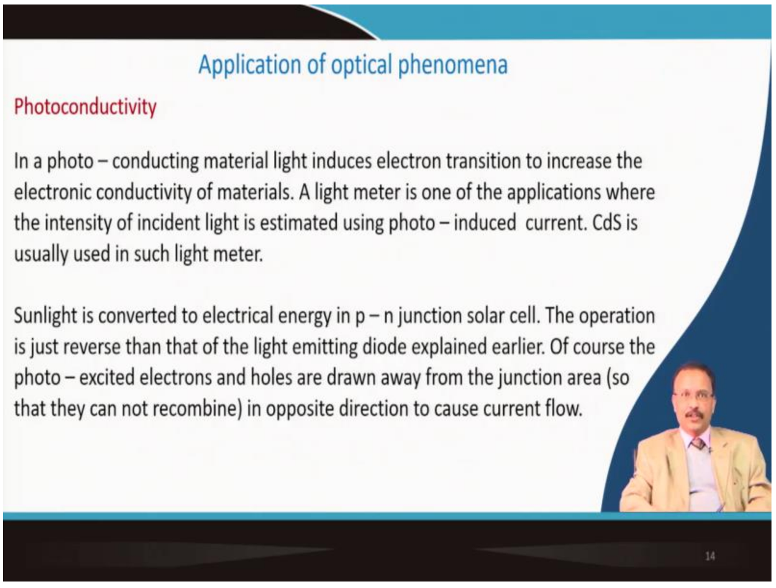

In a photo conducting material light induces electron transition to increase the electronic conductivity of the material and this phenomena is called photoconductivity. So, a light meter is one of the applications, where this can be used, where the intensity of the light that is estimated using this photo induced current. So, I just talked about cadmium sulphide; that is usually used to make this kind of light meter.

Sunlight is converted to electrical energy in p - n junction solar cell. The operation is exactly reverse than in case of the light emitting diode, which just I have talked about. And photo excited electrons and holes, they are actually drift away from the junction area; so they cannot recombine in opposite direction, so that a electric current can flow.

So, it is just the conversion of the light energy, renewable energy into electricity and which is used in the solar cell.

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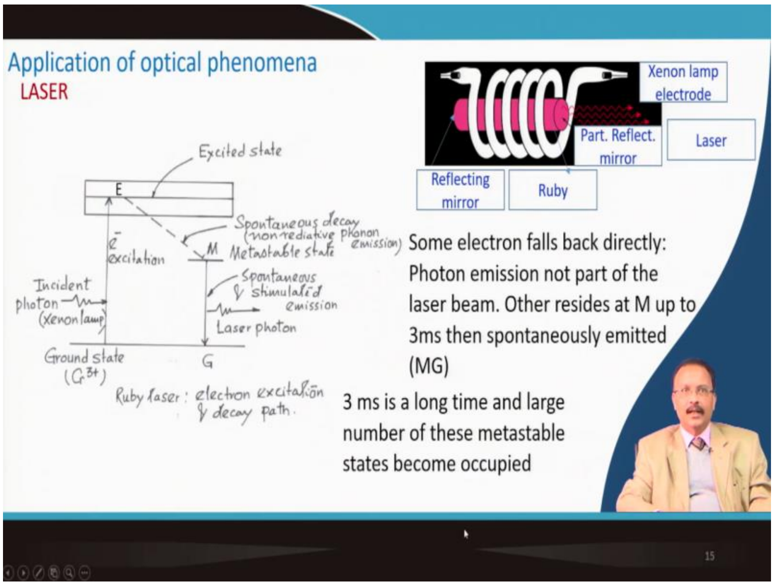

Now, this optical phenomena has a very important use in terms of lasing. So, let us try to understand what is this? So, you have a sapphire which is doped with chromium ions. So, that is a ruby laser and you have a xenon lamp, so that you can have a flash of light in this lasing material.

So, when the incident photon falls on top of it; then from the ground state, the electron goes to the excited state and a non-radiative spontaneous decay that occurs in this metastable state. So, this is defined as M and then a spontaneous simulated emission that takes place.

Now, these radiations some of the electron they fall directly; so photon which emission part of the laser beam, if in case of a direct transit transition that is not a part of it. So, whichever electrons are going to this metastable state, it stays there for 3 milliseconds. So, it is a quite long time and then they start to emit spontaneously.

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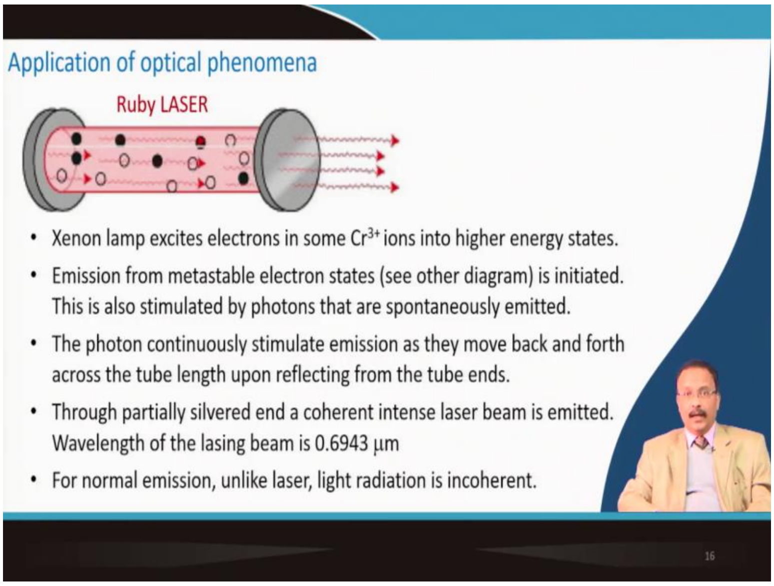

So, the actual case is something similar to this. So, first the xenon lamp excites electron in some chromium ion into the higher energy state it goes. So, emission that takes place from metastable electron states, the diagram that already I have shown; this is also stimulated by photons that are spontaneously emitted.

Now, the photon continuously stimulate this emission as they move back and forth across the tube length. And in this case, you see that one end is very highly reflected and this one is partly reflected, so it continuously go back and forth. And finally, a coherent radiation that is coming from this partially mirrored end of the laser.

And this is a single wavelength of light that you are getting; typically for ruby laser it is 0.6943 micrometer. For normal emission if it takes place, if it is not a lasing action; then light radiation is incoherent. So, very coherent monochromatic beam, you can get out of this process.

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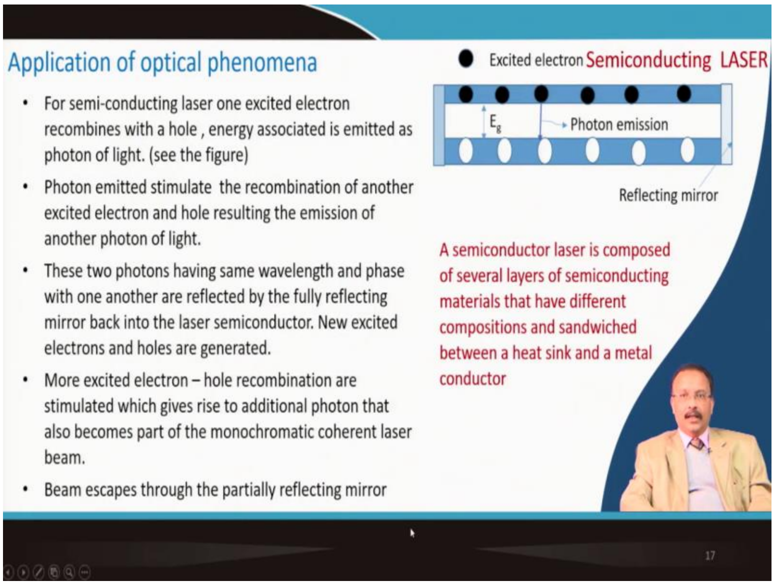

So, something similar is also occurring in case of a semiconducting laser. So, one excited electron recombines with the hole and energy associated is emitted as photon of light. So, that is shown in this figure. So, the photon which are emitted, they stimulate the recombination of another excited electron and hole, resulting the emission of another photon of light.

Now, these two photon, they have the same wavelength and they are perfectly in phase with one another. So, they are reflected by the fully reflecting mirror back into the laser semiconductor, and new excited electrons and holes are also generated. So, more number of excited electron hole recombinations are stimulated, which gives rise to additional photon and that also becomes part of the monochromatic coherent radiation.

And finally, the beam escapes through the partially reflecting mirror from one side. So, in practical case, the semiconducting laser is composed of several layers of semiconducting material; this is having different composition, which are sandwiched between a heat sink and a metal conductor.

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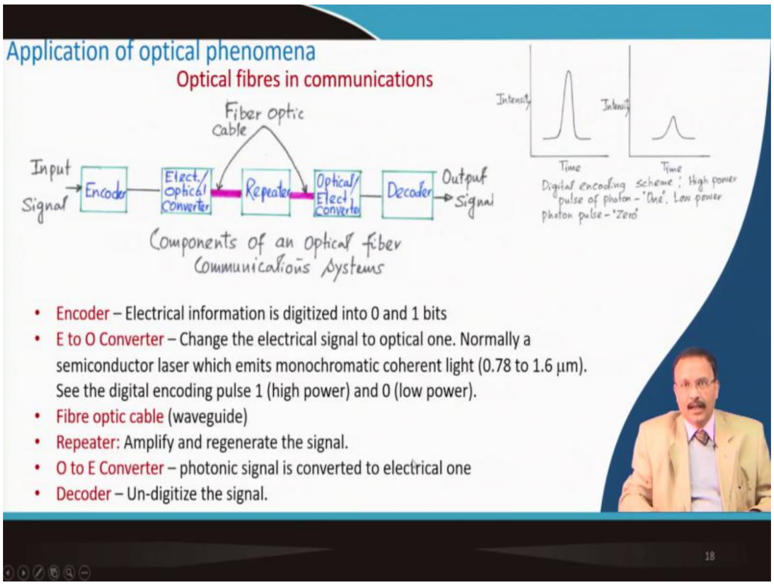

So, finally, you know about the optical fiber; the preparation I have already described in one of my earlier lectures. So, this optical fibers, they are now used for communication. So, no longer this metal wires are used; so this is done in the following way.

So, first the input signal you have a encoder, where this electrical information is digitized to binary digit 0 and 1. Then you have a electrical to optical converter that, basically change the electrical signal to the optical one. So, here normally a semiconductor laser is used, which emits monochromatic coherent light and having different types of lasers are used; so the wavelength is from 0.78 to 1.6 micrometer.

So, the digital encoding pulse something similar to this which is having high power they are considered as 1 and this one is 0, which is having relatively lower power. Now, the use of fiber optic cable, we call it is a waveguide that takes this information. Sometimes a repeater is used, which amplify and in some case regenerate the signal.

Finally, this is transmitted to a long distance and then there is a optical to electrical converter. So, here the photonic signal that is converted back to the electrical one and you have a decoder, which undigitize again from the digital form to analog signal. So, this is the actually heart of the optical fiber, which is used in the communication.

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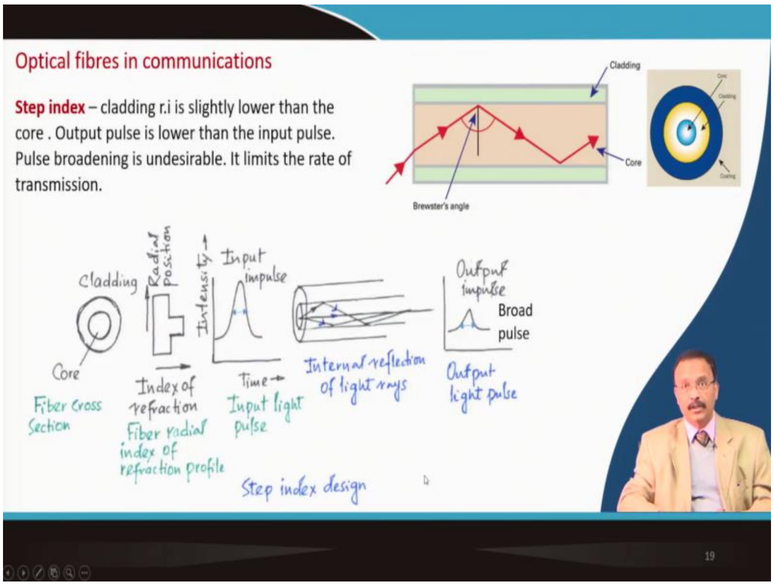

So, the main thing is the optical fiber and you can see the fiber is having a core and a cladding. So, the light is basically, internally reflected from this cladding area. So, if it is in the Brewster angle, from the high school physics you know that the light will not get out and it will be reflected back here.

So, the cladding refractive index is slightly lower than the core. So, the output pulse is usually lower than the input pulse and the pulse is broadened, if you have a step index kind of design in the optical core. So, as you can see that, input pulse is broadened here, intensity also goes down which is not desirable.

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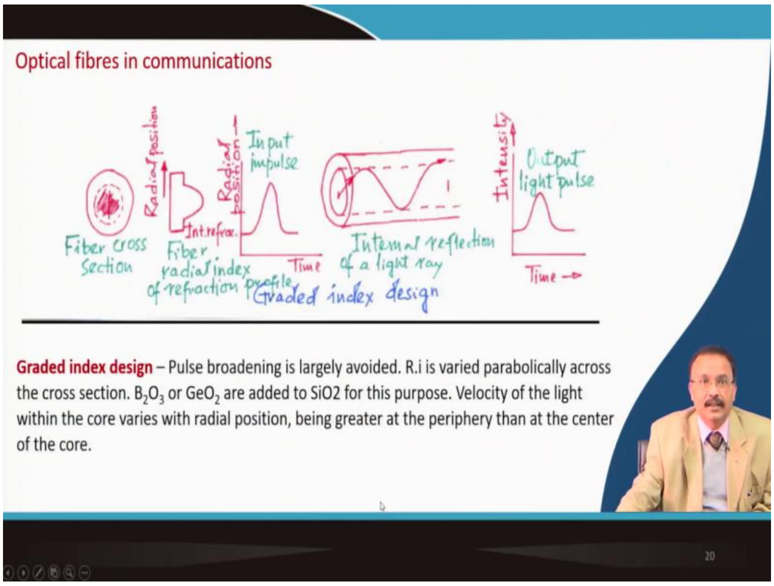

So, this design is usually changed in a graded index type of design; so where the refractive index is continuously changing. And here in such case, you can see the input pulse is not very different from; the output pulse is not very different in terms of broadening as compared to the input pulse.

So, pulse broadening should be avoided, so graded index is used. And in this case, the refractive index is varied as has been shown parabolically across the cross section. So, usually boron oxide or germanium oxide are as added to silicon dioxide very high purity glass fiber; so to make it graded, they are actually used.

So, velocity of the light within the core varies with the radial position; so it is largest at the periphery than at the center of the core. So, in this way the broadening is avoided.

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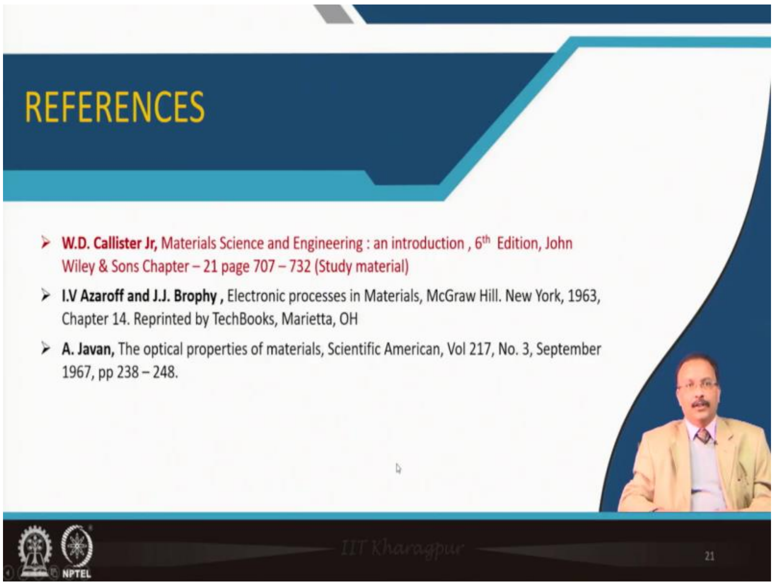

So, the reading material for this part of the lecture is from the book by Callister, chapter number 21 and in addition the book by Azaroff and Javan can also be consulted.

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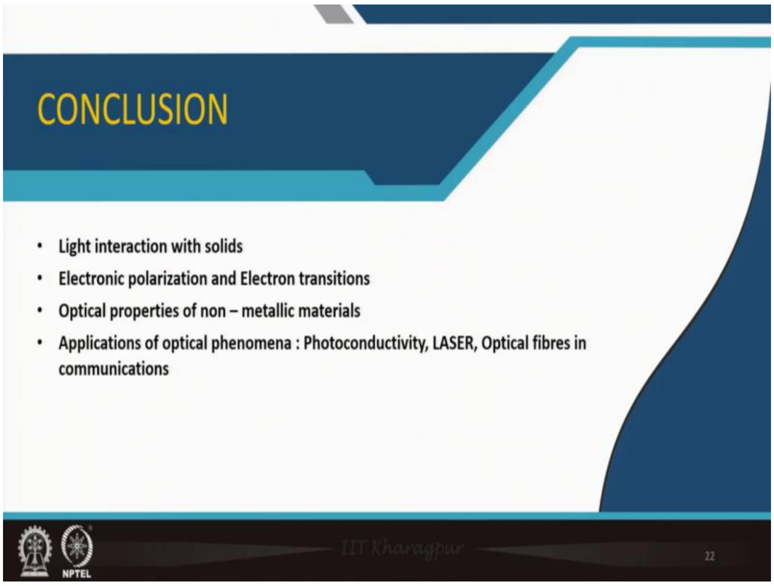

So, in this particular lecture, we talked about the light interaction with the solids; then we talked about electronic polarization and electron transition in particular; then optical properties of the non-metallic materials are described. And finally, the application of this optical phenomena in terms of photoconductivity, LASER, optical fibers and communications have been highlighted.

Thank you so much for your attention.