Biophotonics
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Lecture No. 04
Nature of Light – Part – l (As Wave)

Hello and welcome. So, we will continue our discussion on the topic of bio-photonics, the introduction to bio-photonics. So, now since bio-photonics is as we all know by this time application of light to reveal biological matter to understand biological matter we need to refresh ourselves on the various properties of light, photonics is basically light technology, so let us refresh ourselves some well-known topics on the properties of light.

Now, statutory warning I need to give you here that I will not be discussing something completely new or entirely revolutionary, the idea for today's lecture is to refresh or revise some of the topic, some of the terms, some of the keywords that you should have learned in high school or in first year undergraduate. Now, if you are a student of physics, specializing in optics or optoelectronics or quantum mechanics, you can very well skip this part and just directly join us when I am discussing basic biology.

The idea for today's lecture is to cater for those students those participants who have lost touch with physics for a very long time, may be the last time they studied physics or they studied electromagnetism was in their high school or first year undergraduate, you are obviously welcome to stay irrespective of your background. But frankly speaking if your specialty lies in electromagnetism or if you are a doctoral student say in quantum mechanics, then this will look very basic to you. So, I would rather recommend you that you re-join us when we discuss biology.

This lecture is mostly catered towards medical students, dentistry students, students from biotechnology or other life sciences background. So, consider yourself warned.

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Now, let us discuss the nature of light, mankind have always been fascinated by what light is how it works and since time of antiquity Greeks and Indian philosophers have had discussed what light is, how it works, Greek philosopher Euclid thought that lights are beams of rays that human being shoot from their eyes. So, it is the other way around human beings shoot a light from their eye more or less like superman shoots laser, yes, I am a fan of superman.

Indian classical philosophies during the fifth century sixth century discussed that the nature is made up of 5 tattva, pancha tattva 5 elements, light being one of them and light and heater closely related and light governs the flow of several natural phenomena in Vishnu Purana in the Indian antic text there is a mention of 7 horses of the sun depicting seven rays, but throughout these old ages ancient ages ancient times, the discussion on the nature of light were more on a philosophical basis more on a philosophical term rather than a significant scientific discussion on what light is or how light works, there have been exceptions philosophers from middle east mathematicians have tried to discuss on the topic of the nature of light.

But usually these discussions to the best of our knowledge have been restricted to philosophy rather than science. Everything changed in around sixteenth century when Rene Descartes this gentleman, Rene Descartes the same person the mathematician who developed Cartesian coordinates, XYZ geometry that you know, 3-dimensional geometry also famous for this saying cogito ergo sum, I think therefore I exist you will see it in various bars, tattoos, etc.

Rene Descartes try to describe the nature of light and he came up with the answer that light is basically a mechanical property of the luminous body and there was a hint that light may sometime behave like waves. However, it was not fully formed, it was not fully fleshed out and that was the end of it, it was considered therefore the beginning of actual scientific studies on the nature of light.

Well, then came sir Isaac Newton, Isaac Newton was not a very big fan of the wave nature of light, Isaac Newton developed the corpuscular theory of light in which he described that light is made up of several particles and light goes in straight line, waves go can go beyond or can deviate from a straight line, but since light always go straight line according to him light can never be a wave it could be particle, however when light enters a sharp corner it can bend because some sort of interaction is happening between light and ether.

Ether or Aether is this mystic term which has confounded scientists for a very very long period of time it is considered this semi-conscious material that covers the entire universe envelops the entire universe we are all going on undersea of ether which obviously by the late 18th century has been proved to be completely bunkum.

So, Newton developed this corpuscular theory of light in which light are made up of particles and they go in straight line and these particles are strongly affected by gravity and he wrongly attributed that light, the speed of light increases because of the gravitational pull inside a dense material, we now know that it is opposite of that. So, though several theories of Newton are studied by every school going student in every country, you do not learn more about the corpuscular nature of light as proposed by Newton because it was correct.

Later stages, it was the Dutch mathematician Christiaan Huygens who discussed who actually gave some pretty good explanation of light as a wave, he described that light could very well react like water waves, how ripples are formed when you throw a pebble a stone into a pool of into a pool or into a lake, how the wave emanates from the centre of the disturbance, similarly light waves also behaves.

He did several experiments, his work where seminal, he is considered one of the greatest scientists of his era as well as beyond and his work have tremendously influenced other scientists subsequently, Thomas Young developed the famous double slit experiment, Young's experiment

in which he proved that light waves can interfere both constructively as well as destructively and later century it was Maxwell, it was Maxwell, Scottish scientist who after in getting influenced by Faraday developed the laws of electromagnetism, the laws of electromagnetism describing light as an electromagnetic wave.

Strictly speaking light was considered only the visible portion that portion of the electromagnetic spectrum which our eyes can perceive that was strictly considered as light, now it is little bit of infrared and ultra-violet have been added we call it generally as well optical range or optical light, but overall there was during Maxwell's time or slightly before there was a confusion regarding whether light is electromagnetic wave or light is a separate entity.

It was the work of Maxwell which proved that light is indeed an electromagnetic wave a specific portion of the entire electromagnetic waves and it was also discussed in Christiaan Huygens time that these waves are not affected by gravity for say. So, life was good, life was okay till that time light has been described as wave and believe it or not by the late eighteenth century physicists were coming to this conclusion that everything that is there to know about natural philosophy that is physics how matter and we have react is known. Everything that is there to know is already known and few pockets here and there are remaining and that could be easily described by some rigorous experimental work and it is a trivial matter, everything that physics has to offer has already been offered and we should basically shut shop and go.

In the nineteenth some century something significant happened, there was this gentleman called Max Planck who developed quantum mechanics, in which it was said that light waves he was studying blackbody radiation that light waves have clumps light waves basically comes in packets or waves and they lump together and these lump depends on their frequencies and these frequencies have a specific discrete value, it cannot be continuous, this was the idea that was proposed by Max Planck.

That light is not just a continuous wave but it has a particle nature per se in which there are bits, computer students must know what bits are, so these are bits or clumps or they are lumped together into specific packet, these packets have a specific energy and these energy depends on the frequency, the famous formula $E = h\nu$, h Planck's constant was developed. And using that particular formula Albert Einstein was able to discuss or able to describe what photoelectric effect is.

Photoelectric effect could not thus far have been described by wave nature of light and he tried to describe it using light quanta packet of light. And it was during the 1920's or 1930's this famous physicist from Berkeley university of California, Berkeley, Gilbert Lewis in a letter to Nature the magazine nature the scientific journal very prestigious scientific journal Nature wrote a letter where he described this light quanta light packets discrete's packets of light as photons.

So, it was this gentleman at the very corner in the end Gilbert Louis university of California Berkeley one of the most prestigious chemist as well as quantum physicist who is responsible for coining the term photons as quanta of light. So, that was the historical perspective. Now, for this lecture, let us discuss light as a wave, we all know we have all studied in high school that light emanates or like exhibits both particle nature as well as wave nature, for the time being in this lecture let us describe light as simply a wave, let us make our life easy.

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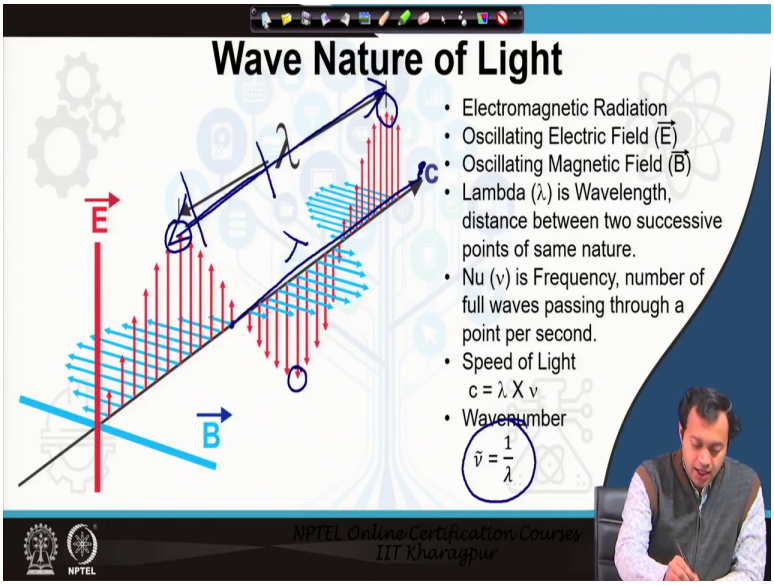

So, as we know that light waves or electromagnetic waves, light waves are a specific portion of electromagnetic waves are this waves that contains electric field and magnetic field perpendicular to the direction of propagation. So, if light is propagating in the z direction, in x direction there will be a magnetic field in the y direction there will be an electric field. These electric and magnetic field are both oscillating in nature. Now, opposite can also happen that the electric field is in this direction that is the x direction and the y direction is magnetic field as long as they are perpendicular to the direction of the propagation as I have shown in the figure.

Now, here you need to understand that the wave nature of light considers that light has two hands, a strong hand and a weak hand. The strong hand is the electric field the electric hand and the weak hand is the magnetic field, most of the interaction of light with matter happens with this strong hand with this electric hand, whenever light decides to go from vacuum to a medium to any medium anything other than vacuum anything other than vacuum, it could be glass, it could be air, it could be water, it could be wood, it could be metal, firstly these two hands the electric hand mostly and the magnetic hand tries to see, if they can sustain themselves, if they can exist, if they cannot be completely diminish, if they will survive inside the medium.

If they can survive inside the medium in whatsoever form in a modified form no matter the field strengths amplitude et cetera will obviously change will obviously modify, but somewhat modification is okay as long as it is able to sustain itself. If the electric field and the magnetic field can somehow sustain itself inside the medium, light will enter otherwise, light will not enter, that is one of the basic of reflection transmission that we are going to discuss in subsequent courses. So, for the time being understand light has two hands stronger hand is sorry stronger hand is the electric field, weaker hand is the magnetic field and these two are the one in which light basically interacts with matter.

Now, here we will see that the electric field as well as the magnetic field is oscillating in nature. And since it is oscillating in nature, it goes from plus direction to the minus direction for a period of time and the distance between two successive points of the same nature, two successive points of the exact same nature is considered lambda **(λ)** . So, most of the time when we are describing the nature of light we try to describe it from the point of view of its electric field of the oscillating electric field it has.

If you have solved Maxwell's equation, or if you have discussed electromagnetism per se you will know that if we define electric field properly, we can generate the magnetic field component, if we on the other hand generate magnetic field component electrical component can also be described. We stick to electric field component because it is convention plus it is the most stronger of the effect most of the time that light emanates or light exhibits. So, if we are looking a distance from peak to peak of light that is lambda λ which is the wavelength, that describes a full turn, a full 360 degree turn of the propagation or of the oscillation of the electric field as the light wave propagates.

So, obviously if you in a very small length, if you can have this full turn 100 number of times, the full turn 100 number of times or in the same length the total number of full turn where crest to crest where it has come back to the original position which it is start with either it is like this or it is like this, the frequency changes, the frequency is basically determining how many times per second this electric field will oscillate within a given range, the range is that wave length.

So, basically within a second how many times the wave, the electric field component of the wave can come back to its original position it has started with. So, that is the definition of frequency. Very high-energy electromagnetic waves have very short wavelength, meaning in a very small period of time in a very small length also it can oscillate a large number of time, so understand this. Small wavelength that is very small length the data the entire wave has oscillated or gone through a full turn within a very small amount of time.

Whereas these are basically the high energy waves $E = h\nu$, so if energy is high, frequency is also high, wavelength is little less. These are basically the ultraviolet lights, physical lights, gamma rays, cosmic rays, x rays, etc. On the other hand if we are looking for electromagnetic waves which has which takes a long-turn to come back to its original position the wavelength is pretty large and the frequency is pretty low which means that in a period of time there are less number of oscillation.

So, that is the overall general definition of frequency as well as wavelength, you should already know matter what your background is you should already be knowing this this is high school stuff there is nothing extraordinary new that I am telling you that you need to worry about, wave number is basically one of lambda λ that is the difference between crest to trough.

So, crest per say is top the trough is actually the bottom, so the distance between this to this half of a wavelength is usually wave number or the reciprocal is wavenumber, $\tilde{\nu} = 1/\lambda$ the overall distance between the top position to the top, I the similar values is a lambda. If you want to take it from this point you have to go it to this point to get lambda. So, let us continue with our discussion regarding the wave nature of light.

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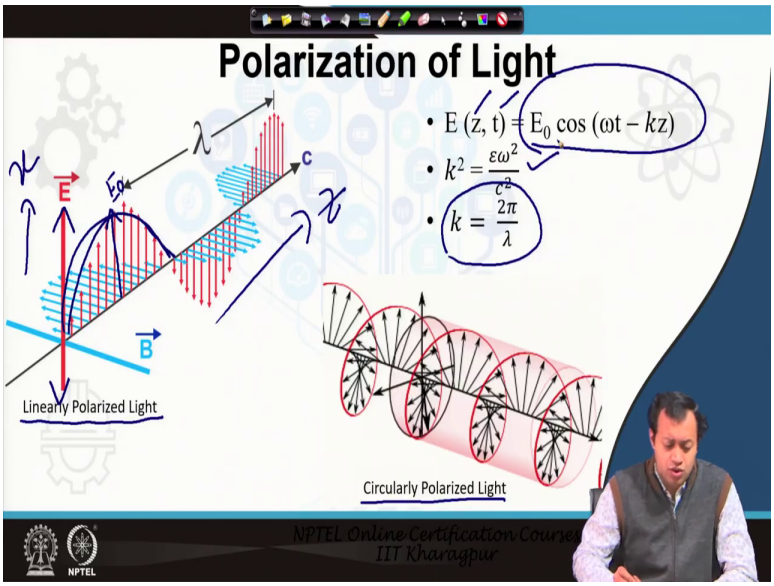

So, since we are mostly describing light from the point of view of it oscillating electric field, there comes the term polarization, polarization describes how the oscillating electric field behaves with respect to the propagation of the light. The two most important parts the two most important definition of polarization or the variety or the type of polarization that I want to discuss is linearly polarized light and circularly polarized light.

Let us, take them one by one. Linearly polarized light is the one in which the direction of the oscillating electric field remain constant, so if we have considered this to be x direction this to be z direction then as the wave propagates in the z direction, the direction of the electric field will forever remain in the x direction it can go plus x or minus x, but the direction of the electric field will it remain in the x direction throughout.

The spread, the amplitude of the field the overall amplitude of the field may diminish may change but the direction of the field will forever remains in one particular direction in our case it is x direction that we are considering. Remember for z coordinate both x and y are perpendicular, so, there is no restriction for E to be only in x direction it can go very well into the y direction, but when it comes to linearly polarized light we make sure we ensure that the direction of the electric field remains forever in one specific direction with respect to the propagation of light. And that is the linearly polarized light.

Something different happens when it comes to circularly polarized light, circularly polarized light the direction of the electric field with respect to the propagation of like constantly changes, constantly toggles in this particular case between x and y, so the direction of the electric field and circularly polarized light changes what remains constant is the spread, is overall amplitude of the optoelectric field.

So, again understand this, in linearly polarized light the direction remains constant, the overall amplitude the spread of the field changes. In circularly polarized light the direction is not constant the direction keeps on changing however the overall field strength, field spread the overall amplitude magnitude these terms more or less remains constant.

Propagating wave, a propagating wave which light wave electromagnetic wave which is moving in the z direction at time t can be described by this particular formula, where E_0 is the maximum value of the magnitude or the amplitude I use this term interchangeably whereas they are actually not the E_0 term is the maximum magnitude of the electric field, omega ω is the angular frequency, t is the time and k is the wave vector, k is the wave vector that describe the propagation of light in this particular direction given by $2\pi/\lambda$ and it can also be described using this particular formula. (refer the lecture here for better understanding)

$$E(z, t) = E_0 \cos(\omega t - kz)$$

Again high school physics, you should be knowing this, I am simply refreshing it, so that if you have forgotten it or you needed some more validation this is going to be the one that is going to provide you. So, this was the polarization of light.

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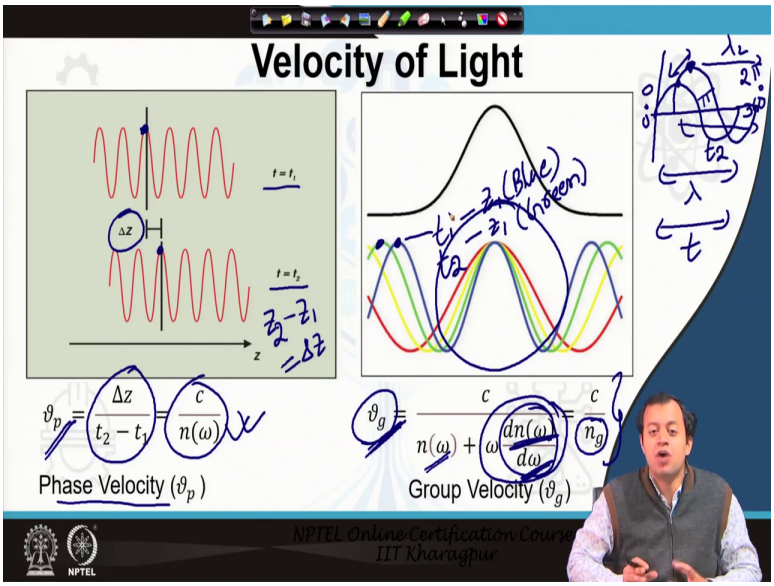

Now, if we go to some other properties of light, so now let us discuss another property of light and that is the velocity of light, before discussing velocity of light I need to describe the phase of light, what exactly does a phase when we talk about phase difference between two waves? What does the phase actually contribute? Phase basically means that particular specific angle of a specific point inside the wave which is travel, so let us try to understand it like this.

Suppose we have a wave that is traveling in a particular direction and this is its wavelength and it travels it at a period t, since the electric field is oscillating and circular in nature and it comes back to its original position after every complete turn, we can say that there is a 360 degree rotation. It starts from 0 degree and it has returned back to its original position which can be considered as 360 degree, if you have a protector looking to it and you will see 360 degree is returning to its original position. So, it has travelled a distance of lambda at a time t and it has come back to its original position, the full rotation, the full 360 degree rotation took a distance lambda and took a time t.

Now, since we can describe angles in terms of radian, generally we describe this as 2π and 0 and everything in between say for example the middle ground as π radians. So, if we are describing a particular point into the wave, we can very well described the angular position it has when it is moving a distance lambda at a period of time t. At the same time if we have a second wave, if we have a second wave that emanates from at a time t2 and it has a lambda of λ_2, not only we can

differentiate it with respect to the time it takes to come to a full rotation or the distance it travels to come to a full rotation, but also the angular position it has with respect to the original point that we have chosen as a reference.

And this gap this gap in angle from wave number 1 to wave number 2 is the phase difference that wave 1 and wave 2 suffer from. This could be $\pi/2$, $\pi/3$ anything that can be described as the phase difference. So, simply put phase is an angular position of a particular point of a wave, which is traveling a particular distance in a particular time. So, this distance travelled as you can see in a particular wave with $t = t_1$ it moves in a particular direction it is at a particular point.

And after the same wave has moved a value of t2 it has moved in the z direction and distance wise the original position to the moved position can be considered as z2 - z1 which is Δz which is basically this term that we are discussing. The phase velocity is described as the speed that this point takes, one particular point within the wave takes to travel from one point to another at a time t2 - t1.

Now, you have to understand that the speed of light depends on the medium on the particular medium it is moving, when we are talking about the fundamental speed of light that $c = 3x10^8$ m/s we are usually talking about the phase velocity, phase velocity is specifically a particular point of the wave that is moving a specific distance in a specific time. So, the distance moved divided by the time gives respect to the phase velocity.

Whereas interesting things happens when we try to discuss group velocity, what exactly is group velocity? Usually you will not have one single wave, wave travels as wave packets combination of several waves, which slightly different wavelengths, slightly different frequency case and point being the visible light, visible light white light or the light which our eyes can see comprised of 7 colours, colours basically represents wavelength.

So, different wavelengths have slightly different frequencies, if you have different frequencies, you have different energies, if you have different energies you have different speeds, so all of them travel with slightly different speeds slightly different times, so no matter what, a point in blue light for a time t1 will be at a position z1, however similar point in green light will not be at the same position in t1 and in z1. So, if you have to see so this is blue and this is green, we need

to know and we understand that since blue light and green light a different, so the in order to come to the exact same position the times will be different.

You can consider time to be a frequency as well, it is the reciprocal as such but the point that I am making here is that waves usually travels in packets like trains, like bogeys of trains, each bogey might have its own specific speed, but overall when you are looking at the speed of the train you are looking at the speed of the entire thing.

So, usually we discuss group velocity as the velocity of the entire wavelet, the entire wave package, the entire sets of waves which are of similar nature which are of slightly similar wavelength similar frequency similar speed and they travel with a speed which is given by this particular relationship. n here and n here are two different entities, the n that I have mentioned in phase velocity is refractive index.

Refractive index is simply the ratio by which the speed of light will diminish, when light enters from vacuum to a denser medium, it simply happens because the electric field and the magnetic field tries to modify itself in order to get sustained inside the medium in order to get itself sustaining inside the medium there is a modification in the electric and magnetic field the overall representation of how much the electric and magnetic field how much the strong hand and weak hand will modify will change is given by refractive index.

The group index which is this particular thing the group index on the other hand gives an average rate of how the electric and magnetic field of the entire wave packet of the entire bogey of the train changes or modifies when this entire thing, entire wave packet enters a particular specific medium. So, that is group velocity. Usually when you are trying to do something fruitful useful say for example communication where you are trying to send information it is usually the group velocity that we are talking about, it is usually information are sent in wave packets rather than a single point of the particular wave.

Now, there is something very significant that can happen if you look at this figure, so group velocity is given by this particular formula where you have the normal refractive index of the material as well as this particular term which describes that the group velocity can be relatively modified or relatively changed if the refractive index part can be rapidly modified or rapidly change with respect to the angular frequency. So, if you have a medium in which the refractive

index is changing a rapidly over a very small frequency range, refractive index in this particular case, I mean the modification of the electric and the magnetic field of light inside that material is happening very fast very rapidly for a small period of time this part increases very much.

If this part increases Vg group velocity can reduce. What are the manifestation of such a thing in which the velocity of light is reduced significantly inside a medium? We call this as slow light something which you might not have read in your high school, but do not worry too much about it slow like is not part of our biophotonics course, so we will discuss this at a later stage, overall you understand phase velocity and group velocity as I will give you an analogy.

Consider a class like this particular class or any other class that you have attended, phase velocity is the result of one individual student, a particular student got first class or first class with distinction that is the marks that is representing phase velocity the speed of a particular point a specific point of the wave, group velocity on the other hand is the average result of the entire class, how many percentage of students got first class in that entire class in that particular year.

So, that is how I have tried to understand in my mind the difference between phase velocity and group velocity. So, that was the discussion regarding our velocity of light when it is individual points we are talking about phase velocity, when it is a wavelet a wave packet we discuss group velocity.

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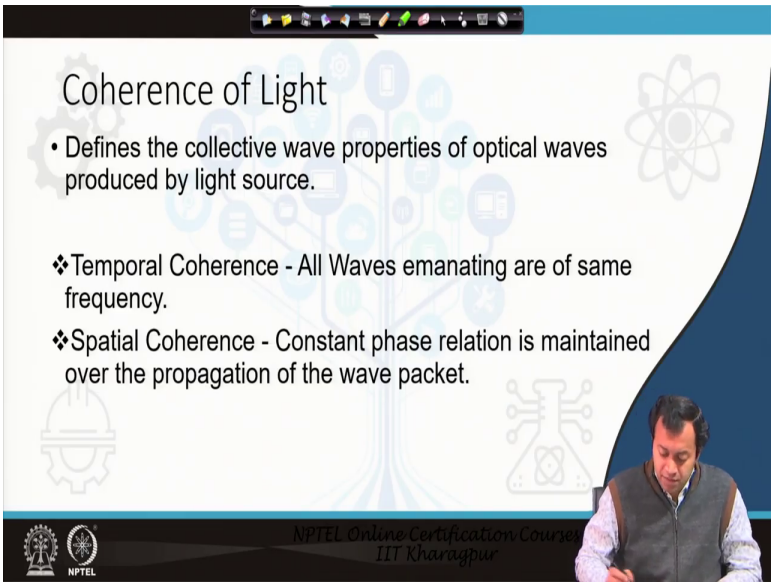

We also need to understand the coherence of light, coherence define that how the wave properties of optical waves are which are produced by light source, it can have temporal coherence, meaning the light that is emanating that light that is coming out from the source have the exact same frequency, it is not random in nature or coherence of light determines the spatial coherence where wave number 1, wave number 2, wave number 3, these are coming out from the source, they follow a specific phase value, they follow a specific phase difference from one another, they are not random in nature.

The natural light unfortunate as it is is random in nature, so natural light is not polarized we need specific things to polarize light because in natural light there is one ray going in this direction one ray going in this direction several all the randomly the light waves are emitted and therefore the electric field is also generated at random ways, but if we want to do something very very specific several times polarized light is required and polarized light needs to be produced, we cannot simply get polarized light from naturally available source, for example sun. Two most important thing two most important properties of light that we also need to discuss regarding coherence that utilizes it is interference.

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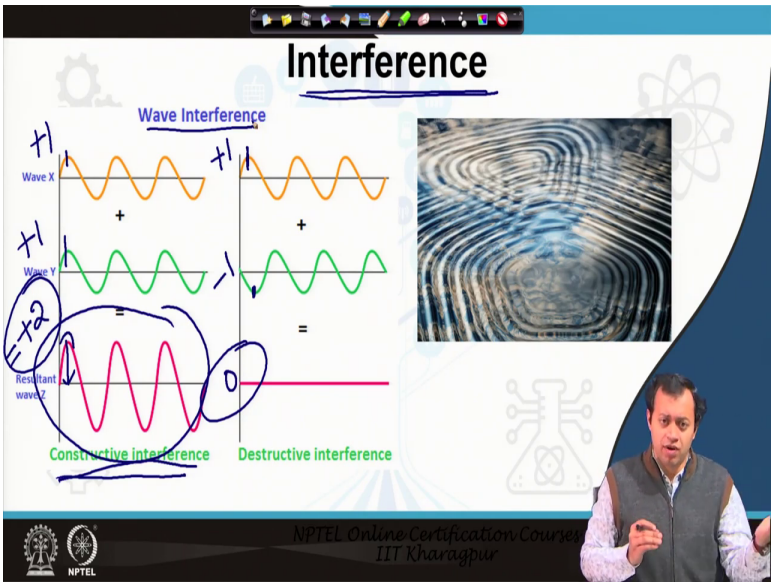

Interference was discussed quite a lot by Christiaan Huygens and later by Thomas Young which states that just like waves of water ripples of water wave can interfere among each other and there happens to be a summation or a linear superposition, meaning waves which are of the same nature similar frequency similar phase they can interfere with one another and this interference could be constructive.

Say for example in this particular case where the crest and the crest matches and you have the resultant summation where the overall amplitude overall magnitude of the wave has increased, this is a constructive interference where if you consider this as plus 1 and this has plus 1 the resultant is plus 2, magnitude wise at the same time if there is a destructive interference whereas the crest the top of this wave number 1 is matching with the bottom of wave number 2, so if you consider it +1 and if you consider it as -1 you got 0 value. So, this is the maxima and this is the minima and you can have several combinations in between.

So, interference basically meaning that of all the waves that are emanating from different areas they can combine together constructively or destructively, obviously to completely dissimilar waves with different amplitude different frequency different wavelengths we will not have that much of an interference that we are looking for it, usually when we are talking about wave interference, usually we talk about similar type of waves when I talk when I say similar, it basically means similar wavelength and similar frequencies.

Because otherwise the wave is taking a long-term to travel a particular space whereas one wave has taken very very small amount of time to travel into that space there will be obviously a mismatch of wave number 1 and wave number 2 to interact and match because they are time wise separated from one another. So, interference pattern we see in nature as well water waves these mix and match.

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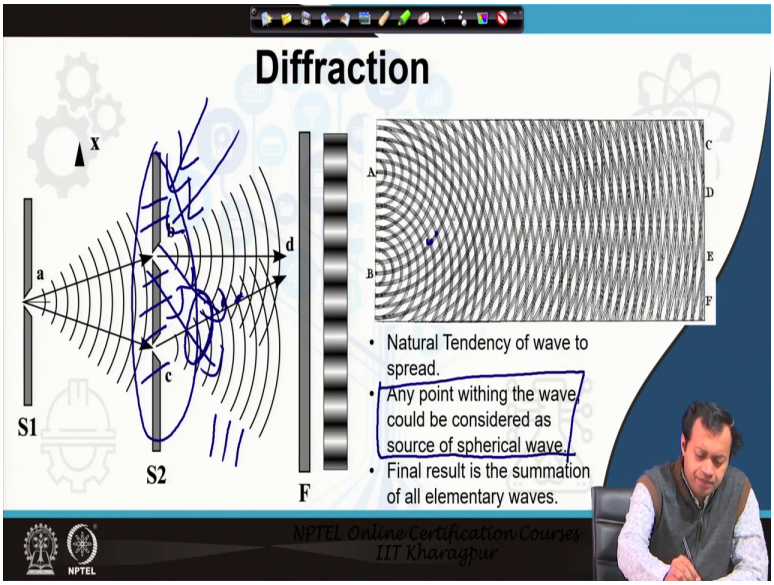

The basic idea of interference was significantly utilized in this concept of diffraction, diffraction basically utilizes interference you know this experiment already every high school student have studied it this was the very famous Thomas Young's double slit experiment nature publication I think has considered this to be one of the most beautiful scientific experiment of the last few centuries where Thomas Young try to produce a similar source of light and passed it through two slits and the light spread out and the interfered forming a constructive and destructive interference constructive interference give you bright bands and destructive interference give you dark band.

So, diffraction is basically the natural tendency of waves to spread and the important point that you have to understand that diffraction determines that any point within the wave any point within the wave could be considered any point within the wave could be considered as a source of spherical view. So, what does that actually means? First and foremost, diffraction simply

means that light waves can bend around sharp corner, it is not always straight line, it can bend around sharp corners because light wave spreads.

At the same time while it is spreading and it is interfering with other waves, the interference will depend on the nature of the wave on the amplitude of the wave on the phase of the wave at that particular point it does not matter what it has started from, it can start with phase and amplitude a1 and z1 or a1 and phi 1, but say it has moved and it has modified itself to a2 and Φ2, Φ2 being phase and Φ being phase and a being amplitude it has moved to a specific point and it has changed. And when it is interfering with the other wave then it is a2 and Φ2 that will represent or that will matter or that will determine the outcome, rather than what it was before.

So, diffraction simply is considering the interference pattern or interference phenomenon to a large extent. Many books have considered diffraction and interference to be same and interchangeable, but as Richard Feynman stated when we are talking about interference, we usually mean just a few waves couple of waves combining with one another, constructively or destructively and everything in between and as a result the overall resultant is a combination of these two.

Diffraction when we talk about large quantity of waves, large quantity of waves have come together combined together and they formed a specific pattern. Several of optical phenomenon or several of optical properties are at the end of the day could be boiled down to diffraction, could be boiled down directly to diffraction. When you hear about the fancy terms like meta-materials of metal surfaces or frequency selective surfaces at the end of the day what they are doing, they are creating materials such as this, where light will fall and light will reflect while reflecting light the property of light which is falling and the property of light which is scattered or reflected will be different, you can modify their property.

And the final light can interfere among each other to produce patterns or produce effects of your light, you can customize this particular material on which the light is falling and thereby you can generate the output the reflected light or the scattered light according to your own will, this is the basic matter the basic understanding of all those frequency selective surfaces meta-materials metal, meta-surfaces, optically selective surfaces, there are obviously some more to it. There is frequency, there is some amount of gain medium, but overall to a large extent several optical phenomenon could be described from a diffraction point of view.

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So, that basically covers the very basic of the properties of light, we discussed the wave nature of light, we discussed polarization, we discussed phase, phase velocity and group velocity and how interference and diffraction are. Remember interference and diffraction is are very very similar, interference is two waves mixing two or three waves mixing that overall result is the linear summation diffraction when a large number of waves are mixing, they are spreading together, they are spreading out, they are moving around the corner and each point in the wave can be considered as a source. So, that is the overall very quick half an hour description that covered all of the topic that you should have by this time.

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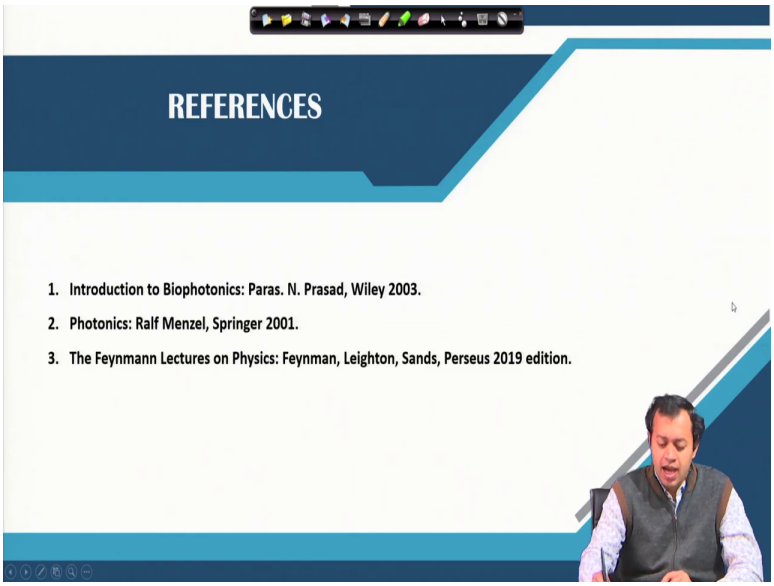

So, these are my references and I thank you and I will see you in the next class. Thank you very much.