Photon Properties
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Introduction to Photonics

Ok, welcome to yet another session of introduction to photonics during the last couple of sessions we would been trying to get into this learning outcome of identifying the fundamental principles of photon optics and quantifying photon properties and to understand that it was essential that we introduce light as electromagnetic waves.

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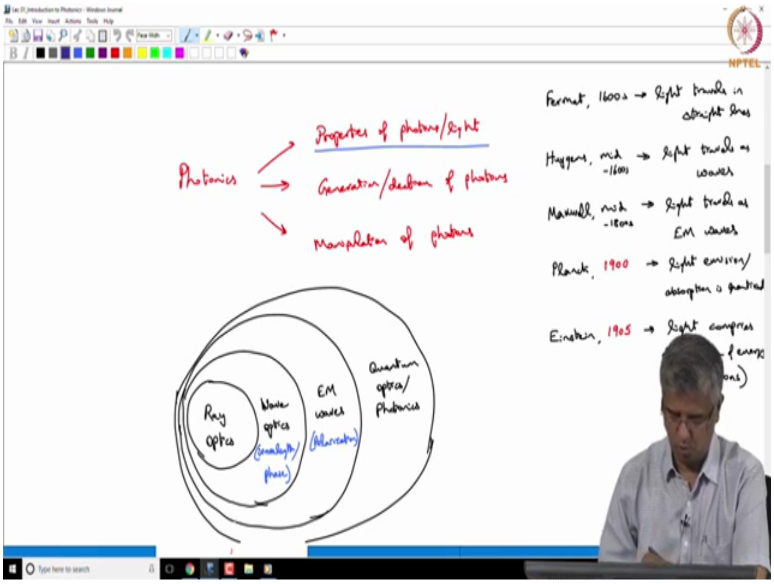

Fermat, 1600s → light travels in straight lines

Huygens, mid -1600s → light travels as waves

Maxwell, mid -1800s → light travels as EM waves

Planck, 1900 → light emission/absorption is quantized

Einstein, 1905 → light comprises … of energy … ons)

So if I go back and look at where we all where we started this all you know ray optics, wave optics and last couple of lectures we have been looking at light propagation as electromagnetic waves.

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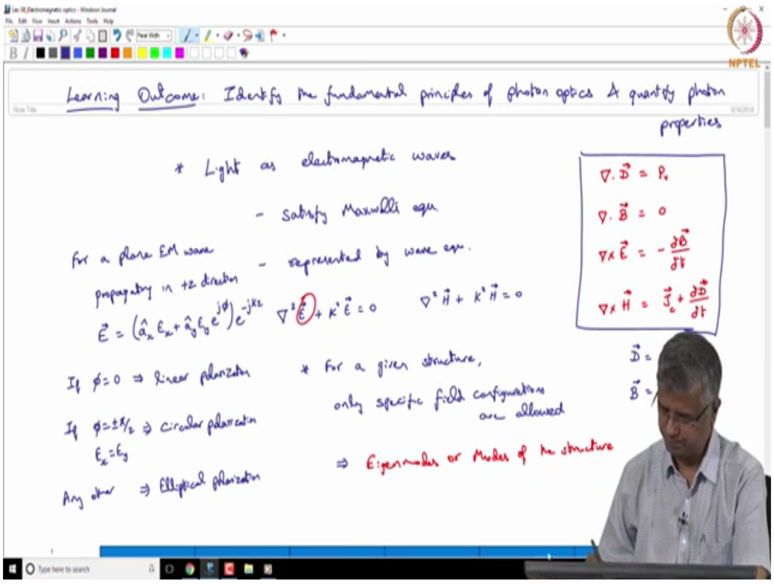

Learning Outcome: Identify the fundamental principles of photon optics & quantify photon properties

* Light as electromagnetic waves

- Satisfy Maxwell's eqn.

$\nabla \cdot \vec{D} = \rho_v$

$\nabla \cdot \vec{B} = 0$

$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

$\nabla \times \vec{H} = \vec{J}_c + \frac{\partial \vec{D}}{\partial t}$

For a plane EM wave propagating in +z direction - represented by wave eqn.

$\vec{E} = (\hat{a}_x E_x + \hat{a}_y E_y e^{j\phi}) e^{-jkz}$ $\nabla^2 \vec{E} + k^2 \vec{E} = 0$ $\nabla^2 \vec{H} + k^2 \vec{H} = 0$

If $\phi = 0 \Rightarrow$ linear polarization

If $\phi = \pm \pi/2 \Rightarrow$ circular polarization
$E_x = E_y$

Any other $\Rightarrow$ Elliptical polarization

* For a given structure, only specific field configurations are allowed

$\Rightarrow$ Eigenmodes or Modes of the structure

$\vec{D} =$

$\vec{B} =$

Now what we will do for today is session is actually consider light to be propagating as particles, ok these quantized electromagnetic waves that are known as photons, ok.

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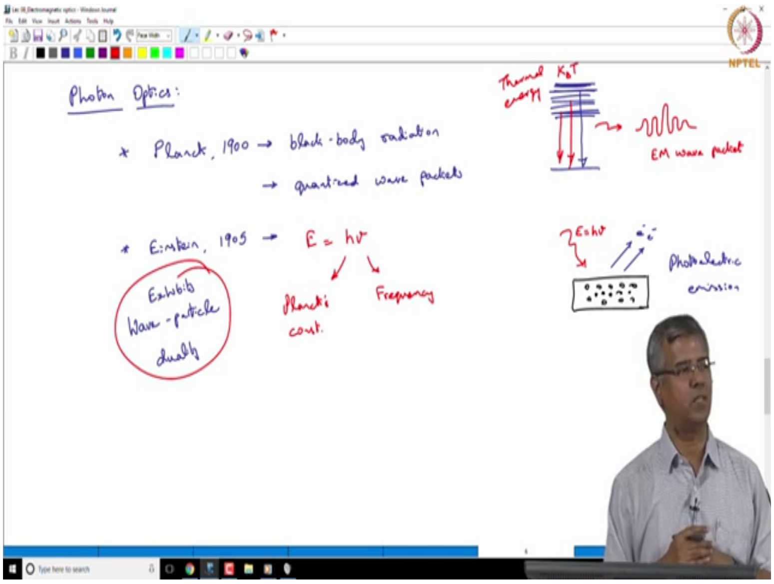

Photon Optics:

* Planck, 1900 → black-body radiation
→ quantized wave packets

* Einstein, 1905 → $E = h\nu$

Planck's const.

Frequency

Exhibits Wave-particle duality

So let us try to see what this is all about, the basis for a lot of this discussion came about when Max Planck was conducting his research that was to solve this problem of blackbody radiation when I say blackbody radiation what comes to your mind? What is blackbody radiation? Can you give any example of blackbody radiation?

Student is answering: (())(01:54)

Professor: The black holes more simply the light from the stars, closest star that we have?

Student is answering: Sun

Professor: Sun, so when we are looking at Suns radiation we can consider that as blackbody radiation. So Planck was actually looking at blackbody radiation and around 1900 when he was trying to explain blackbody radiation, he figured that light must be emitted as or this blackbody radiation must be coming out as quantized electromagnetic waves. So essentially he was figuring that light is emitted when an atom or more specifically an electron actually jumps from a higher energy level to a lower energy level when that happens he said you have this quantized electromagnetic wave packets that are emitted, ok.

So this electromagnetic wave packet he said this is one of those fundamental you know explanation for how we view blackbody radiation, so as you know blackbody radiation is something that could be spread over a spectrum, right and one of the simplest things of explaining that is by considering an hot object, so when an object is heated to very high temperatures it could emit light where do we use this principle for our lamps, incandescent lamps you know the light bulbs we do not see those light bulbs anymore, it used to be like a tungsten filament that is when you pass current through that it gets really hot and when you heat it up we know that we can get light, right from that.

So to explain some of those things Planck actually came up with this suggestion that there is there this emission is actually quantized, right. So quantized wave packets and Einstein followed it up, right so he is actually trying to piece together another puzzle which was quite you know it was attracting lot of attention at that time. Einstein was trying to explain photoelectric emission, right so what is photoelectric emission? Know somebody had projected that when light actually falls on some material consisting of all these atoms molecules, right.

And if you have in light of a certain kind, right for example if you have ultraviolet light the observation was that with that sort of light you could get electrons emitted from this material, ok. So that is what is called photo electric emission and so that was an unsolved puzzle at that particular time and Einstein looked at this and said as that is quite amazing actually 1905 it is a really famous year because Einstein came up with this for papers which spew out for different areas of research, ok.

So this is one of those for the photoelectric emission equal to m c square that came out of that year theory of relativity came out of one of those papers that year and explanation of Brownian motion was also or done in another paper that, yes. So four papers and you know decades of research following those papers, so that is just amazing, right. So that is why we worship Einstein when we think about scientists but this was one of those things and what he basically said was that if this was happening he pieced together what Planck had already said it is happening in a quantized manner.

So he said this has to be light must have quantized energy wave packets with E equal to h nu where h quite rightly he called it as a Planck is constant because without Planck coming up with that previous observation he could not have possibly come up with this and new corresponds to the frequency of light, ok. So now the entire scenario changes quite a bit now so far you know I want you to think about this as if you are in around 1900 all you know about light is that light travels as waves, right and of course Maxwell came up with this fantastic observation that light can travel as electromagnetic waves, right.

And that is what people knew off and then Einstein came up and says no light actually travels as photons, ok so that was like completely disrupting the entire picture and then people are really stunned right and they are wondering this guy is pulling a fast one on us, right this cannot be true can it explain this can it explain that and so on, right so many of those questions were raised and as we know now most of those questions have been answered and this hypothesis at that time is now something that we consider as you know is a real thing but just to illustrate one of those you know answering one of those questions let us go back and look at this video, ok.

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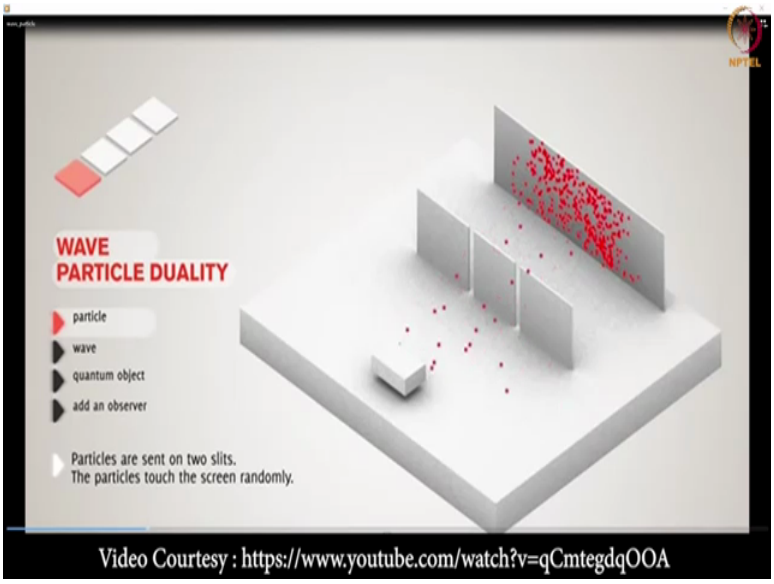
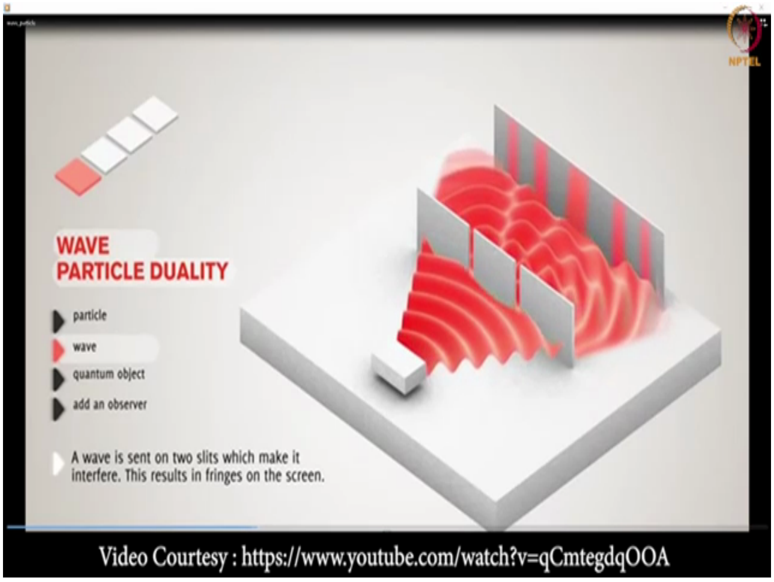


WAVE
PARTICLE DUALITY

Particles are sent on two slits.
The particles touch the screen randomly.

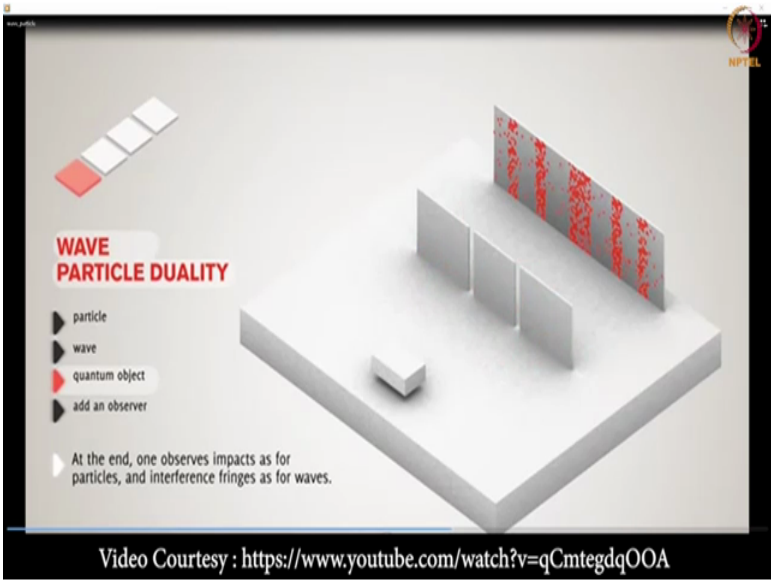
Video Courtesy : https://www.youtube.com/watch?v=qCmtegdqOOA



WAVE
PARTICLE DUALITY

A wave is sent on two slits which make it interfere. This results in fringes on the screen.

Video Courtesy : https://www.youtube.com/watch?v=qCmtegdqOOA

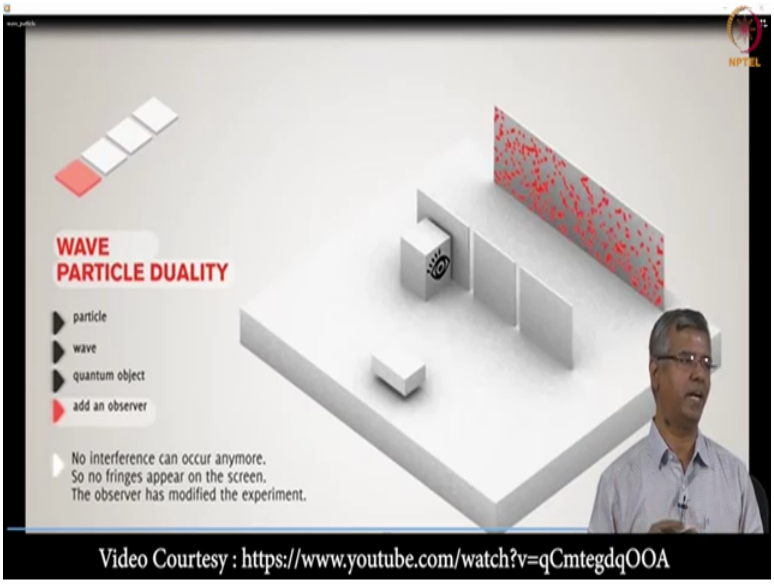


WAVE
PARTICLE DUALITY

- particle
- wave
- quantum object
- add an observer

At the end, one observes impacts as for particles, and interference fringes as for waves.

Video Courtesy : https://www.youtube.com/watch?v=qCmtegdqOOA



WAVE
PARTICLE DUALITY

- particle
- wave
- quantum object
- add an observer

No interference can occur anymore.
So no fringes appear on the screen.
The observer has modified the experiment.

Video Courtesy : https://www.youtube.com/watch?v=qCmtegdqOOA

Let us observe this video for a while and then we will go back and replay that and try to see this in a little more detail, let us see this video. So first we are considering a particle we are not telling what sort of particle it is, it is just some small balls that are bouncing around and they bounce around this interface and then you saw that picture what it creates and now it is a wave, right and this is the you can say is the Young’s double slit experiment we know what is supposed to happen, right so it's supposed to create these interference fringes.

And now we are looking at a quantized object, so it can be looked upon as a particle but it has wave like properties, right so when you observe it is a (pro) particle but this particle actually is exhibiting wave-like property. So let us go back and look at that once more. So when you observe that is observation screen you observe it as a particle but if you have multiple observations quite interestingly all these particles start making a pattern, it is a very fairly well defined pattern, just as the case of the wave, ok.

So what else what exactly is happening if I go back and look at this picture, right it is emitted as a quantum particle, ok but see how it is that quantum particle has got a certain wave associated with it from electromagnetic Theory you can think of this as some electric and magnetic field is carrying it is going as an electromagnetic wave, ok. It is a particle but it is got this electromagnetic wave that is associated with this propagation and because of that now you are seeing you know this interference effects because when you put a slit when you put a couple of slits between them then the secondary wave fronts now start interacting with each other and then it gives rise to this you know interference pattern which actually shows up as bunch of particles falling in different places, ok.

Now this is actually an advanced topic but just to complete the video let us go ahead and try to do this, ok. So what we have here is this person that is observing this wave like property, right. So there that eye is the eye of the observer, in this case it could be a camera, right that is trying to observe what is happening and so what do we see there no interference pattern, no wave like property.

So why is that happening the process of observation? What does that mean? If I am observing something an event related to light I am observing a photon, right so if I am observing a photon, if I am detecting a photon then it (exen) essentially collapses this particle nature of light rather it loses it is wave nature of light, right and then (bef) from that point onwards it is actually just propagating as a particle.

If I am observing I am actually intercepting, intercepting the photon, ok. So of course you would ask that if I am intercepting the photon then that photon cannot go past that slit, right so that is what is that so that particular photon is lost, it is already collapsed in that observation process, ok but the you know principle that is explained beyond that is that photon might have collapsed but other photons are coming up, right but just the fact that you have an observation and that observation is loaded on one side, right.

So it is actually starting to disturb this wave function that corresponds to the photon, right once is disturbed that wave function then it cannot proceed further with a wave like property, ok. So then it just goes has some random particle that is bouncing around, ok. So of course this is a fairly like I said the advanced concept that I do not expect most of you to get right away but nevertheless I think that the takeaway point from here is more of this, right.

So you can have emission of photons coming up and this emission if we go back and look at the case of an incandescent lamp right we know you heat up that filament, it emits photons ok and what Planck said was that is actually quantized particles that is not just some wave that is generated, right it is actually quantized particles that I emitted and quite interestingly depending upon the temperature of that blackbody it can emit multiple colours of photons, nu is not specific to one transition you could have multiple transitions if we go back and look at this picture that we have here this could be multiple transitions, right so you could have multiple energy levels and you could have multiple transitions of different colours with different energies, right.

So that is what we were seeing there and said that explains why an incandescent lamp looks yellowish, ok but it has got yellow, orange, red, spectral colours, a little bit of green also maybe, right. If you heat it up further so we are not able to heat it up normal in you know tungsten filament much more we not allowed to heat it up but if you heat it up further can you imagine what is happening what colour would it look like? Would it still remain yellow or would it be some other colour? So you would have maybe more number of colours but would it look a yellowish or would it look something else?

So what are you doing when you are heating up and a material you are building thermal energy, right? Thermal energy is quantified by K b T where K b is the Boltz, Boltzmann constant, right multiplied by T. So when you have higher temperatures you have higher thermal energies and because of that what happens you have building up of electrons at higher energy levels, ok and due to which what sort of photons do you emit? If my energy gap is really large, you can now have higher energy photons, higher energy means higher frequency and higher frequency mean is what is what in wavelength.

Student is answering: Shorter wavelength.

Professor: Shorter wavelength, so if it is a yellowish at a particular temperature if I increase the temperature what is it going to look like?

Student is answering: Closer towards the blue

Professor: Closer towards the blue, right maybe it will start looking greenish and then bluish and so on, right so that is what we are talking about here. So key thing is you know Einstein actually took something that Planck had done and then applied it to some other long standing problem and then said you know light consists of photons, ok. So light can be characterized like propagation can be characterized as you know as propagation of these particles known as photons but the key thing that we realized through this you know just this video that we saw what is it show? It basically says light or these photons exhibit wave particle (dude) duality, right.

So it can be thinking it can be characterized from the emission perspective it can be characterized as emission between two energy levels, right and so a mission of quantized electromagnetic wave packet which we are calling as a photon but that photon has wave like properties just because that electromagnetic feels that correspond to that photon are extending in the transverse direction, ok. So with this sort of a picture let us now see what should be the properties of the photon, ok.

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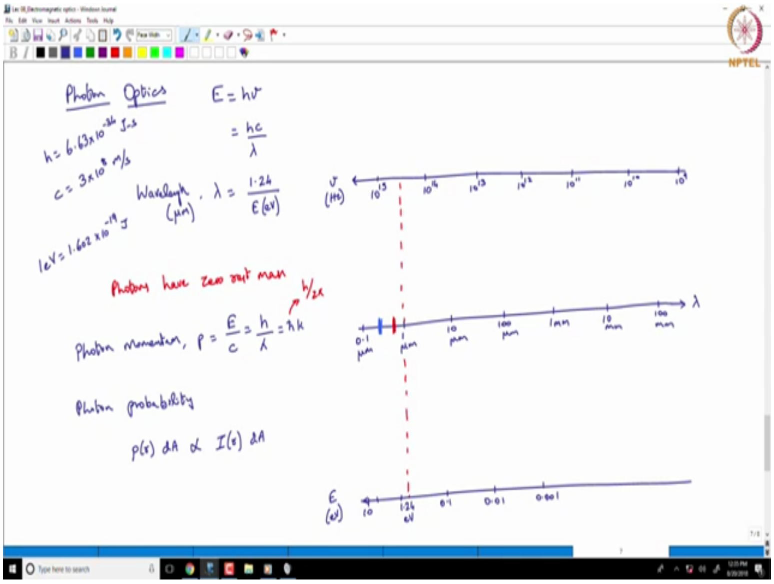

Photon Optics

$E = h\nu$

$= \frac{hc}{\lambda}$

$h = 6.63\times10^{-34}$ J-s

$c = 3\times10^{8}$ m/s

Wavelength (μm). $\lambda = \frac{1.24}{E(eV)}$

$1eV = 1.602\times10^{-19}$ J

Photons have zero rest mass

Photon momentum, $p = \frac{E}{c} = \frac{h}{\lambda} = \overset{h/2\pi}{\hbar} k$

Photon probability

$p(r)\,dA \propto I(r)\,dA$

So let us go ahead and try to look at this in a little more detail, so we said E equals to h nu, so to really understand what this means let us actually draw the electromagnetic spectrum and see how energy frequency and wavelength because if E is equal to h nu this can be right written as h c over lambda, right where c is the velocity of light in vacuum and if conversely if you are trying to find value of wavelength, wavelength in say in micrometer lambda can be written as since h and c are constants, h corresponds to a value of 6 point 6 3 into 10 power minus 34 joule seconds and c corresponds to 3 into 10 power 8 approximately 3 into 10 power 8 meters per second, the actual values to 2 point 999 and 8 something, ok but we approximated 3 into 10 power 8.

So since those are constants lambda can be expressed as 1 point 24 over the energy when the energy is expressed in electron volts, ok. So as far as the Planck constant is concerned we are using unit of joule seconds, so we are clearly the energy is expressed in terms of joules and here we are expressing energy in electron volts, so what does one electron volt correspond to?

Student is answering: 1 point 602

Professor: 1 point 602 and 10 power minus 19 joules, right. So just make sure you are comfortable with these different units, ok. So let us look at how these what these correspond to let us say this is new it is in frequency in Hertz, so we are going from 10 power 15 to 10 power 14, 10 power 13, 10 power 12, 11 power 10, 10 power 9, 10 power 9 is what we typically deal with, right. What is happening around 10 power 9 hertz around a gigahertz, your mobile communication right that has a carrier frequency of 10 power 9 hertz but yes you know expanding the scale all the way to 10 power 15 and let us actually also represent the wavelength lambda, right.

So this corresponds to it is point one micron or hundred nanometers and somewhere over here it is one micron here is 10 micron, 100 and then we get to the millimeter waves, one millimetre, 10 millimeter and 100 millimeter and then if we look at energy scale of course that is also going this way that is E expressed in electron volts, so 10 power 15 would correspond to a boat or one actually the scale is like this one micron, let us say is our reference one micron corresponds to roughly about one electron volt, right.

So if lambda equal to 1 micron then that corresponds to 1 point 24 electron volt, so one is somewhere over here so this is going towards 10 electron volt and so on, so one and then this is point 1, this is point 01 this corresponds to point 001 and so on, right. So in energy we are going down in energy as we go down in terms of frequency clearly, right. So to give you a feel for what we are dealing with normally we have basically blue happening over here and red happening over here, so blue wavelength around you know point 45 less than point 5 microns and red greater than point 6 microns, ok.

So the visible region happens over here and in the visible region the corresponding frequency is in the order of 10 power 15 hertz or hundreds of terahertz and the corresponding energy is you know going towards as we go to ultraviolet region you have higher and higher energy lower wavelength but higher energy so it is not surprising that when in the photoelectric effect was first looked upon they used ultraviolet radiation and they were able to see these electrons coming off, right. So clearly that radiation corresponds to fairly high energy, ok.

So we understand photon energy, ok so while we look at it what about photon momentum? What about what are the mass? Let us the photon have a mass associated with this, it is an electromagnetic wave, ok. So photons have zero rest mass, so you cannot like catch a photon and weigh it, right so photons have zero rest mass but it does carry momentum so when we look at photon momentum so that is going to be equal to is given by energy over c which can be written as h over sorry h over lambda and that can be written as h cross multiplied by k, right k is the is the wave vector 2 pi over wave number, 2 pi over lambda and h cross is nothing but h over 2 pi, right.

So photons have zero rest mass but it can carry momentum in other words if a bunch of photons are illuminating a surface you could have certain energy imparted on the surface, ok so that is what we call as radiation pressure, we will not go into the details right now but basic point is that the photon can carry momentum. We will come back and qualify this in a little more detail in a few minutes but let us just move on with this picture for now, ok.

And then there is this question of probability of finding a photon, so you know we say that photons can be emitted at different time scales and in different directions and so on, so what is the probability of finding a photon? So photon probability is such that if you say probability of finding a photon at a particular location are, right so p of r over some unit area is actually proportional to the intensity of light in that location, ok.

So essentially it says that if you have higher intensity then there is a you know higher probability of finding a photon there. So let me just explain that insert a new page, ok.

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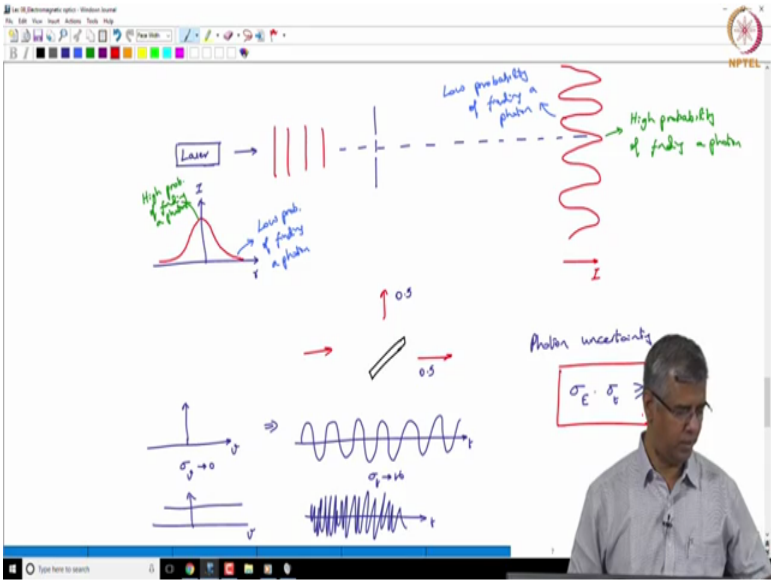

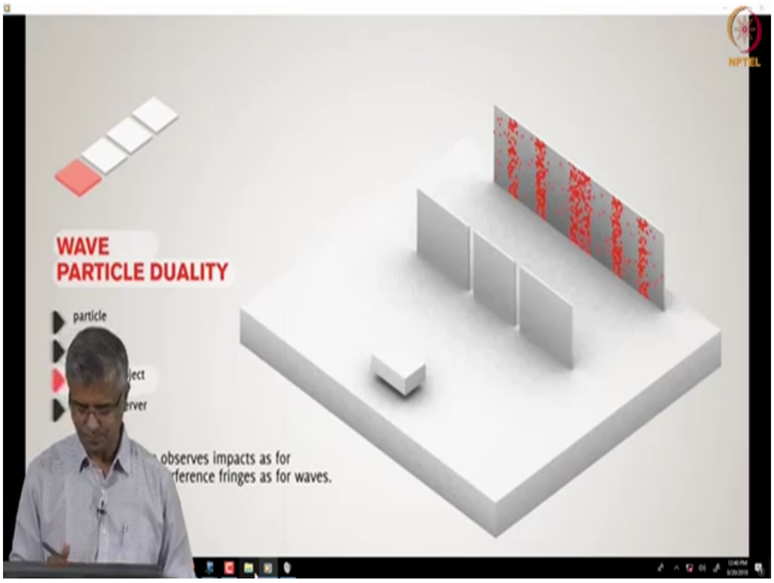

WAVE PARTICLE DUALITY

- particle
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observes impacts as for
ference fringes as for waves.

So let us just look at this, so in our previous lecture we looked at Gaussian beams, right. So you have laser, right which is emitting it is a plane waves and we said when we look at the intensity in the transverse direction that is the transverse plane, transverse to the direction of propagation that intensity was you know for a perfect light source with only the fundamental transverse mode operating, so that would have looked like a Gaussian function, right.

Now in terms of photon probabilities what are we saying? We are saying that the intensity is high than this corresponds to a high probability of finding a photon and similarly this region represents a low probability of finding a photon, ok. So that actually explains some of the randomness associated with light, now we are starting to talk about finding a photon in terms of probabilities, ok.

So the classical measure of light has been the light intensity, so now what we are saying is based on that measure if you look at you know the photons we will find that certain regions where there is high larger intensity of light you have better probability of finding a photon and if you extend that to something that we did earlier into a Young’s double slit experiment and we said, ok the Young's double-slit experiment what we expect to see in the far field is some intensity pattern like this of constructive and destructive interference over there and what we are saying here is this high intensity, if you say that the intensity is increasing this way manner here we have a high probability of finding a photon, ok and similarly this is indicative of low probability of finding a photon, right.

So that actually you know reverts back to this picture over here so clearly we see that in this picture you have certain regions where you can the photons are denser, you know when you and you have large number of observations of course if you make much many more number of observations you will find that these bands are very (niar nea) nicely formed but that just corresponds to the fact that you have high probability of finding a photon, you have low probability of finding a photon in other areas and there is it is not like there is zero probability, right.

So you always say high and low but you could always find one of these photons showing up in the so called dark band so unless it is absolute zero intensity you cannot rule out the possibility probability of finding a photon there. So the question is you know the total probability does it correspond to one, so we will just go back and look at the issue of what you already experienced previously which is 50, 50 beam splitter, so 50 percent of the light goes here, 50 percent of the light goes here and what we are saying is in terms of photon probabilities if you have one photon 50 percent, we are not splitting a photon by the way, ok it is got 50 percent probability of going one way and 50 percent the other way, right.

So what that means is if you have multiple observations you will find 50 percent of the photons have ended up there, 50 percent of photon other, 50 percent has ended up here. So the question is if the total intensity is so it is, so first of all we are saying that probability is proportional to that intensity, if the total intensity is not conserved is the photon probability conserved actually that is a hypothetical situation because the intensity if you have a certain intensity you either have reflection, refraction, scattering, absorption but you have to account for all that intensity, right.

So as long as energy is conserved we are saying, ok the photon probabilities need to be adding up to 1, right so we are not introducing anything new here, ok. So in terms of finding a photon we are saying that it is a probabilistic event and from that perspective this actually leads to this other principle which is called photon uncertainty, ok just like in quantum mechanics you have an uncertainty principle what is the uncertainty principle?

Student is answering: (())(40:52)

Professor: Heisenberg's uncertainty principle which states that the error the uncertainty in finding the momentum multiplied by the uncertainty in finding the position is at least h bar over 2, right. So similarly the photons have an uncertainty associated with them that is the r m s error the root mean square error in finding an a energy of the photon multiplied by the r m s error in determining the time at which photons there at a particular point that is got to be greater than h bar h cross over 2, h crosses basically h over 2 pi, right.

So what does this mean? What is the implication of this? And this is something that we have already in certain ways seen also, ok. So what is this photon uncertainty mean? Lake let us take the example of a single frequency, so monochromatic source, ok. So you have a if you have a monochromatic source let us call this new, right. so it has it is a single frequency source, so if there is something called a single frequency source the uncertainty associated with determining that frequency goes to zero, ok.

But in time what is this represent? When can you tell through observation in time that you have a monochromatic source? if you are observing it with time, so if it is characterized by a periodic waveform then you say that is monochromatic but to absolutely say this sources monochromatic at all times you essentially have to make an infinite observation, in this case unless you can go to an infinite observation you cannot characterize this as a monochromatic source, right.

So if your uncertainty in frequency goes to zero the uncertainty in time goes to infinity, ok so that is what we are talking about as far as the photon uncertainty is concerned, of course you can play the other way also you could have a source which actually exhibits you know polychromatism and then you essentially take a sample of that and you look at it in frequency space you would find that it has got multiple frequencies, ok which is something that we already saw from perspective of this Wiener-Khinchin theorem, we were saying that you know we were saying there we were saying in more in terms of the power spectral density and an autocorrelation but here what we are saying is for a for a polychromatic source if you take a sample of that wave front and look at it in some sample of that wave in time and we look at the frequency content it will have multiple frequency content, right.

So this photon uncertainty is once again saying that, ok what we are dealing with is a quantum particle, right. So it exhibits all this quantum natures that you associate as we have seen in quantum mechanics, ok but here we are talking more in terms of energy and time determination, ok. Where of course energy is related to frequency so it is basically frequency and time relationship and what we are looking at talking of time I think we run out of time now so let us stop here and we will continue from this in the next lecture.