Introduction to Photonics
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Photon Optics

Good morning and welcome to Introduction to Photonics. We started last week with the learning outcome of identifying fundamentals principles of photon optics and quantifying photon properties. Since this picture is drastically different from the kind of things that we have been seeing previously just coming from the particle nature of light, we have been spending little bit of trying, understanding what this means and of course one thing that helps in this understanding that this photons, it is one way of looking at them as particles but they do exhibit wave nature.

So they have a wave particle duality and through that duality we can bridge across and understand a lot of properties from the wave picture as well. It gives us an opportunity. But trust me what this picture also allows is to get a little more insight which cannot actually be explained so well using the wave picture. And that is what we are getting into in the next few weeks. We will talk about light emission and detection which as we will understand is a quantum phenomena, there is a certain quantised interaction that is happening and that is what we will read about.

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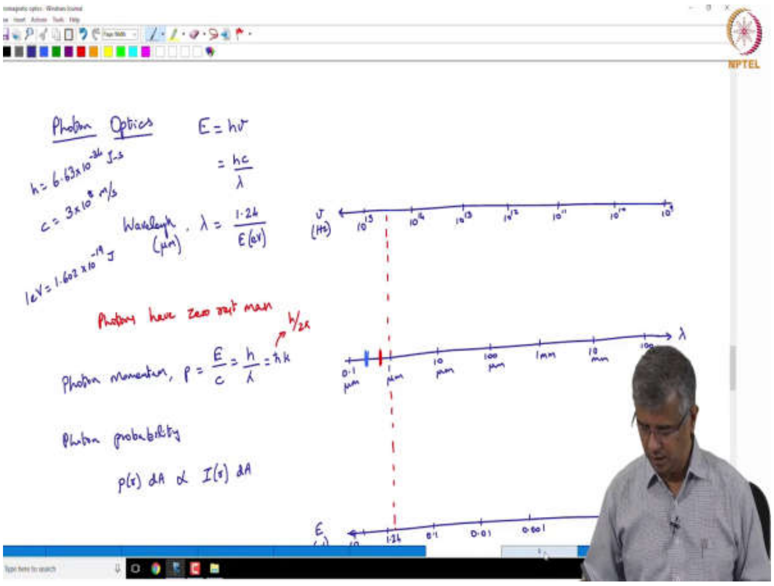

Now before we go on, I just wanted to clarify one particular thing. Of course we talked about in the photon picture that, you know, define an energy of a photon which corresponds to the frequency and we were looking at that relationship. We will look into that in a little more detail today.

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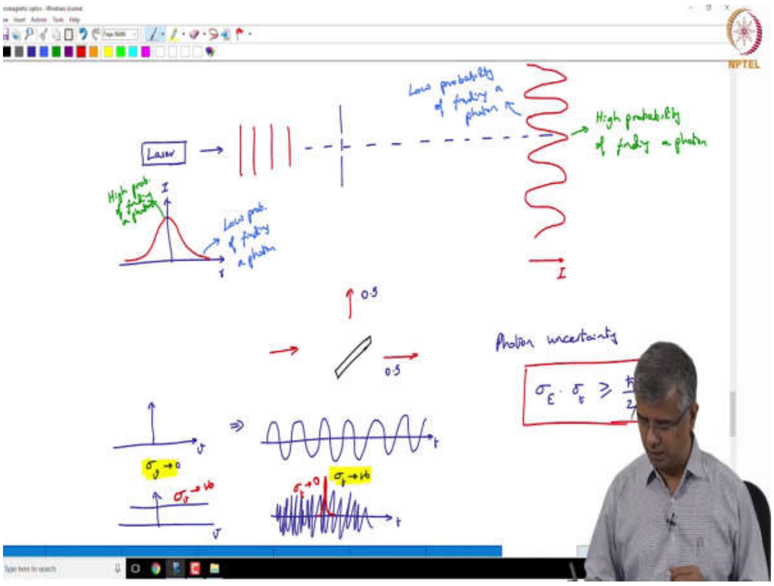

But before we go on I wanted to actually clarify something and this was actually something that was pointed out towards the end of or after the last session. So somebody was pointing out, this part is very clear that you know we have a monochromatic wave and to characterise that monochromaticity you have to observe for infinite time but the converse was not as clear. It was a specific comment. So to essentially clarify that let us just take a very short pulse.

So the pulse is such that your uncertainty goes to zero, tends to zero. When would the uncertainty tends to zero? When you have an extremely short pulse within which all your photon energy is present. If you have an extremely short pulse, what we find is that through the inverse Fourier transform you can or rather through the Fourier transform you can find that it actually corresponds to a large range of frequencies, so that is what we are talking about here.

So this uncertainty in frequency actually becomes infinity because we are representing by going for the short pulse we are representing a very large spectral band. To give you an example if you take a femtosecond pulse, you know people have actually demonstrated attosecond, hundreds of attoseconds pulses you can believe that right. But if you take a femtosecond pulse that typically corresponds to a spectral width of 10^{15} Hz.

So that actually fairly large range of frequencies and so you can essentially say shorter the pulse more will be the spread in frequency or more will be the uncertainty in determining a particular frequency, associating a particular frequency to this light pulse right, so that is the converse picture. Okay that was just a clarification from the previous lecture.

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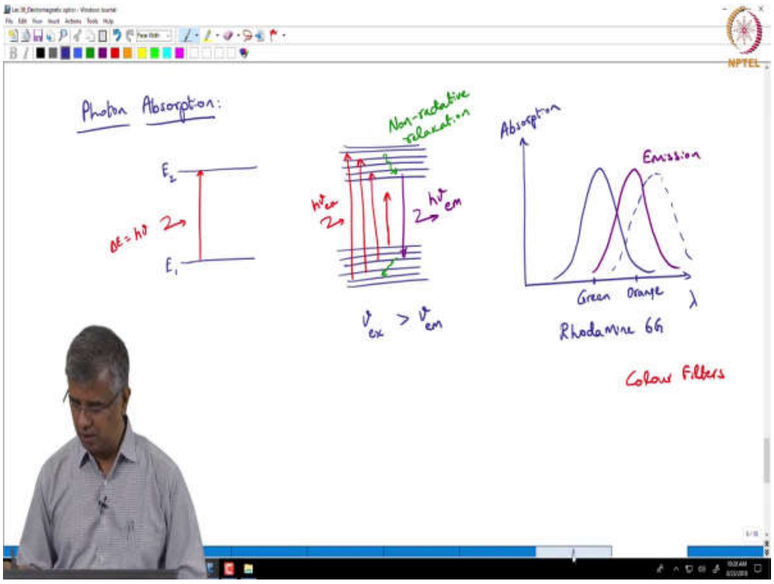

Let us just go on to this other topic: photon absorption. I am actually considering this topic, one side is to project the utility of considering energy of a photon, but the other side of it is also that you know this is going to be a demonstration that is going to be done this week. Let us see how light absorption happens. If you have two quantized energy levels and these energy levels, mind you, could correspond to two orbitals of an atom. In an atom you have all these electrons orbiting the nucleus. So these could be two orbitals, let us say the lower energy level corresponds to the valence orbital and a higher energy level corresponds to a higher orbital, higher energy orbital, outer orbital which normally is not populated. There are no electrons in that because all your valence electrons are at the lower energy level. In this case, what kind of light can you possibly absorb with this atom? Can you absorb any frequency of light? No, you can absorb only a specific frequency which takes the electron from one orbital to another orbital. All the other orbitals are forbidden as far as this atomic system is concerned.

So this will happen only if you have a energy of a photon which corresponds to ΔE, where ΔE corresponds to the energy difference. Only in this case you will have the absorption happen. Now if you are considering absorption in a collection of atoms, you are normally not isolating one atom and looking at the absorption; you are looking at a collection of atoms. When you are looking at a collection of atoms you may have this higher energy level may not be one energy level and the lower energy level, that specific energy level or specific orbital position may be different at different sites. Or you could also have this situation where when you have collection of atoms, they end up splitting that orbital. There is something called Stark's splitting that happens which allows you to go from one energy level to a collection of energy levels.

So when you consider a collection of energy levels, what does this represent now? You have a possibility that you could get absorption over a wide range of transitions. In effect when I am looking at absorption as a function of wavelength, in this case it would have been delta function: there is only one particular frequency or one particular wavelength that can get absorbed in isolated atom case. But when you are looking at collection of atoms, you have a band, a spectral band over which the absorption can happen and this is actually going a little more detail. We will actually come back to this at a later point but the point here is that all these transitions are not equal probability. If they were equally probable, the absorption would have extended from one frequency to another frequency and absorption would have been constant across that entire spectral band.

But there are some selection rules that come into the picture, it actually goes into the quantum mechanics of things and you talk in terms of, only in terms of probability of absorption and it so happens that this absorption would be spread over a bunch of frequencies. So whenever this absorption happens and electron jumps from one energy level to the higher energy level, at the higher energy level it is not allow to stay forever because the valence energy level is not filled, so it is the higher energy level is what is called a metastable state.

It goes up there, spends some time and then comes back. So in that process you might have some non-radiative relaxation happening. Actually it may lose some energy and then it would go through this emission and mind you when it goes through an emission process, two things to note: it is always from one energy level to another energy level, so what do you expect when that emission happens? The emission will be quantized okay, and that quantized emission is what we are calling as a photon with a very specific energy.

So let us say the absorption is characterized as $h\nu_{ex}$ corresponding to the excitation and now what we are saying is corresponding to the emission you have $h\nu_{em}$ right and since there is certain energy that is lost and that energy loss could happen above or it could happen below also in the ground level manifold. Since that energy loss happens you can basically say that typically the excitation frequency or the excitation energy is going to be larger than the emission energy; you lose certain energy in the process. You can also say that the excitation frequency is going to be greater than the emission frequency.

So if my absorption is happening in this broad spectrum, how do you think is your emission going to look like? That will be shifted to longer wavelengths because longer wavelengths represent lower energy. So because in the process of emitting it will be losing some energy, your emission would have shifted. Mind you, I have shown some regions where it is overlapping, what does that mean? Since it is actually a broad distribution in the higher energy level and a broad distribution in the lower energy level you could have photons that emitted and you could have, I mean photon that is absorbed and photon emitted both are almost having the same energy.

This week you will have a demonstration using a dye known as Rhodamine 6G that is a dye molecule. Rhodamine 6G has an absorption spectral band around green and emission spectral band around orange color. So if you come in with red color into this Rhodamine 6G what do you expect to happen? There will not be any absorption because red color in this case would correspond to some transition like this which is forbidden, so you do not have a corresponding energy level to go to. So because of that there will not be any absorption.

This part will be demonstrated to you that you will come in with red light and you will see that it goes straight through this Rhodamine 6G solution and if you have green light coming in, it will be strongly absorbed. You will be able to see the absorption. So what does strong absorption mean? Essentially if you have more number of these Rhodamine 6G molecules more will be the absorption right, so you will see that you will be given like three different concentrations and if you are asked to figure out which is what. You know what are the relative concentrations, you coming with green light right, hit that solution, let say you put it in a transparent cuvette you can see that absorption, with the highest concentration it will all get absorbed within a very narrow region.

Whereas with a lower concentration it will be absorbed less drastically, so it will actually, you may be able to see light, there some of the green light come through the other side. You will also see that whenever that absorption happens there is also a emission that is happening and you will be looking at this orange emission, you will observing that orange emission. One of the things that we will do as part of that is also use some color filters. You have already seen some color filters. What was the context in which we discussed color filters previously? We were basically saying that any of this interferometer you know is actually dependent on wavelength.

So different colors separate out in these interferometers and the one case that we saw was actually a Fabry-Perot etalon consider of two mirrors we were looking at multiple dielectric layers from which this reflection was happening and we were saying that constructive interference happens for one particular wavelength and then or it transmits one particular wavelength whereas it reflects other wavelengths and so on. So we saw there was one type of color filter that could be done with that principle but there is other color filter which is essentially you dope it with two different dye elements okay and let us say the absorption for one like this, like Rhodamine 6G, and then the absorption for the other one if it is some other dye, it may look like that, then in between those two there is very little absorption happening.

So what that means is any color between these two will actually be transmitted, so you could have color filters made by a doping a polymer film with different dye elements such that you define which areas get, which spectral regions get absorbed, which gets transmitted, so you may be able to differentiate colors based on, such principles, so you will get to work with those color filters also this week.

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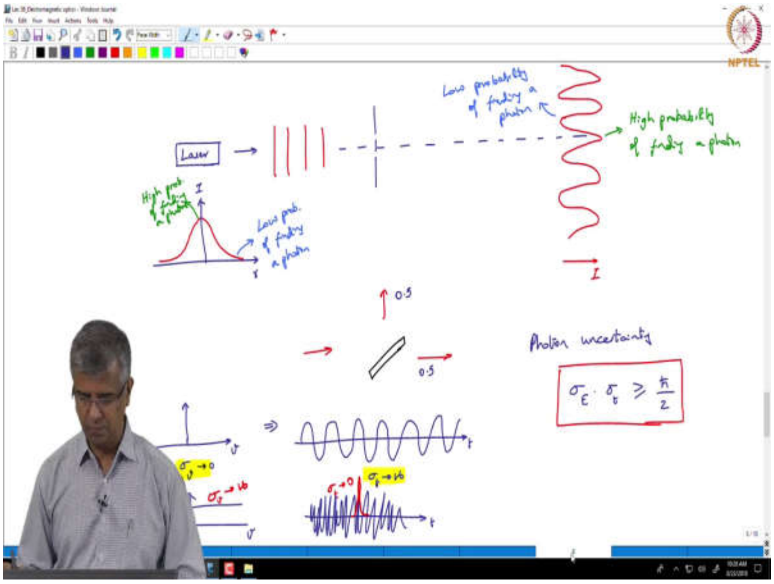

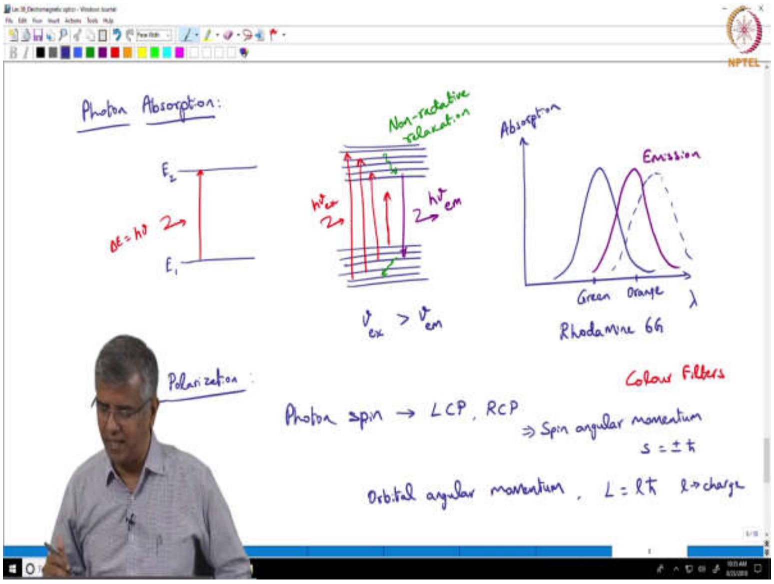

So when we were considering all the photon properties, so we were talking about that the photon has some energy, has zero rest mass but it has some finite momentum, probability of finding a photon and then we were looking at photon uncertainty, but there is one more property to the photon which I would like to address now which is called photon polarization. So what does photon polarization mean?

So you can look at photon as a particle right and if the particle is spinning around its axis while it is travelling, it is spinning around its axis it can either spinning clockwise or counterclockwise Those spin would essentially mean that the electric field corresponding to that is also spinning as its moving right. So just that spin itself since it is just a single particle that we are considering that field would actually correspond to a circle okay.

So you could have basically a photon spin which would represent either left circular polarized light or right circularly polarized light depending upon which way it spins and correspondingly it will have what is called a spin angular momentum which is defined by $s = \pm\hbar$, so $+\hbar$ for LCP and $-\hbar$ for RCP okay, so photon polarization can be quantified in a natural manner through the photon spin.

Now you want to ask the question what does linear polarization mean then? So the linear polarization you can represent it as a certain collection of particles that are doing the left circular polarization and certain other particles that are doing the right circular polarization. Based on that mixture you can define linear polarization. So since any polarization can be expressed in terms of right and left circular polarization, it is easy to say that, you know collection of these photons, photons that are spinning one way and photons that are spinning the other way can be used to describe the any other polarized state and in reality that is what it means as well.

So linear polarization is just in this case equal probability of left and right circularly polarized photons but the other intriguing part about this photon picture is this concept of orbital angular momentum. So what does this correspond to? Orbital angular momentum corresponds to the fact that the photon can actually go on a sort of a helical path as it is travelling right. If it travels in a sort of a helical path then you have spin associated with that photon and then there is also another momentum that imparts, it is like very simplistic example of this is that you want to put a nail on the wall right, you take a nail hammer it through the wall that is one way of doing it.

The other way of doing it is you have a threaded nail and you impart a spin to that right, sort of a corkscrew motion and through that you are able to go into the wall right, which one is easier, the second one why? Because you do have linear momentum and then on top of that you are imparting certain angular momentum in this case what we are looking at it as orbital angular momentum.

So these photons which have orbital angular momentum can actually carry a momentum which is defined, which is quantified as $l\hbar$, where l corresponds to charge, so basically $l = \pm 1, \ldots, \infty$. It could have multiple charges and clearly what this is telling is that if you go to the higher charge, you know photon with a higher orbital angular momentum charge then it would actually be constituting momentum.

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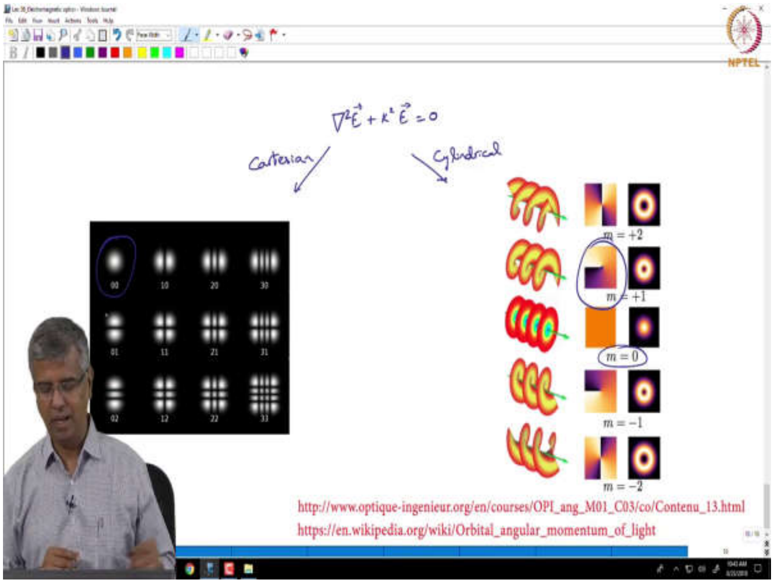

$\nabla^2 \vec{E} + k^2 \vec{E} = 0$

Cartesian

Cylindrical

http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_13.html

https://en.wikipedia.org/wiki/Orbital_angular_momentum_of_light

So is this some fiction that we are looking at? Not really because you know if you go back to Helmholtz equation which is the starting point for all things that we have looked at before, you solve Helmholtz equation in Cartesian coordinates, you get these solutions right, which are at a fundamental is like a Gaussian beam solution and then as you go to higher-order solutions you have multiple lobes, or multiple fringes, that can be solutions.

Now you do the same with cylindrical coordinates, you can actually get solutions once again which are you know at the lowest level, I said l there, l is the same as m over here okay, so when $m = 0$ that just corresponds to your plain old Gaussian beam propagation, it does not have any orbital angular momentum but when m or l actually increases in value then it corresponds to this helical motion and interestingly what you will find is that helical motion happens around a center. So at the center, the phase is not perfectly defined. It is actually the phase grows from 0 to 2π, so you would have an intensity pattern which will be like a doughnut. It will have a null intensity at the center and then bright fringe around it. And as you go to higher and higher charges, you will see that the diameter of that ring would increase, it corresponds to the helical path that the photon is taking while it is actually travelling.

Interestingly this over here, that actually represents the phase variation in the azimuthal direction or in the transverse plane. Like I said at the center, the phase undefined, it is going to 0 to 2π but when you go off center it actually goes from 0 to 2π okay, so basically within one wavelength of propagation the phase would have evolved from 0 to 2π. Just for comparison, look at this picture for $m = 0$. What you see is actually a planar wave front, this is what we have been so far looking at a plane waves right.

So that is the same as what you would see in this case for your fundamental Gaussian beam okay, you have a plane wavefront but here it is actually like the wavefronts are if this is my propagation direction the wavefronts are actually going through sort of a helix, it is defining the path of a helix and interesting thing is you are told that for any electromagnetic wave, so for whatever you have looked at, your field components are transverse to the direction of propagation right, that is what Poynting theorem tells you.

So if this is my direction of propagation electric and magnetic fields are you know mutually perpendicular, perpendicular to the direction of propagation, now what are we saying? Does Poynting theorem holds good for this case also? It should, right, after all it is an electromagnetic wave, it should, so but what we are saying now is by the phase front actually going off axis, off the transverse plain, what we are saying is that the Poynting vector is pointing not in the direction of propagation, slightly away from the direction of propagation but it is going like this.

So the average Poynting vector is still pointing at the direction of propagation, that the direction of propagation that we are looking as far as the beam is concerned but the instantaneous Poynting vector at any instant, it need not be pointing the direction, it may be slightly off what it is following a sort of a helical. So from the wave picture and that is the picture that we are painting, from to the photon picture what we are saying is that the photon actually is taking a path that is in a helix okay.

So if this is like really new to you and you never heard of this do not be surprised because this is new to lot of us as well. This field of light having orbital angular momentum was first discussed in detail only 25 years ago and people are still trying to figure out what it means in different context. We do research projects where we are trying to amplify beams, these vortex beams because it actually looks like vortex right. The very crude example is water in a sink, well that is not so crude but maybe I am getting recorded I will not say this now.

Okay, so you have seen vortices and so these beam actually you know behaves like a vertex as it propagates and so we will not, you can breathe a little easily, we will not go into much more detail in this as far as this course is concerned because that requires much different way of building it up and discussing that, we will not go into much details but I just wanted to let you know but that when you consider photon polarization, you have this spin angular momentum which is normally what we track but it could also have orbital angular momentum which could be very useful for certain applications.

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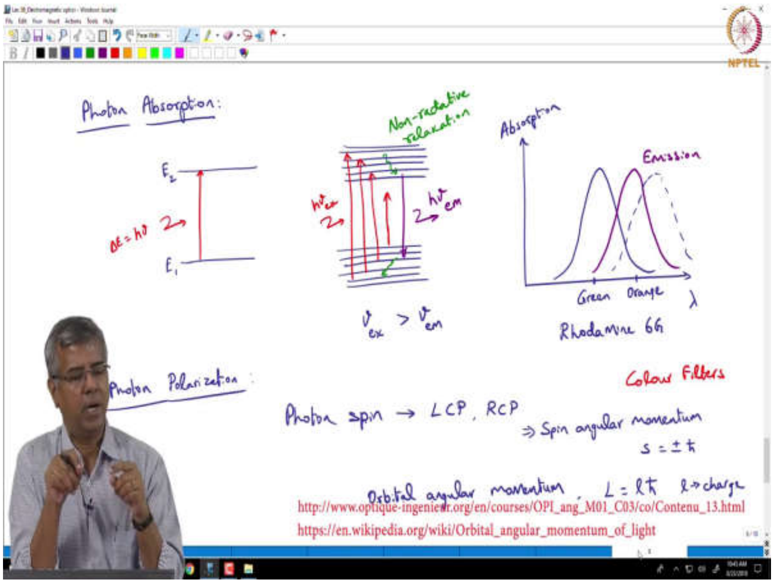

Photon Absorption:

Photon Polarization:

Photon spin → LCP, RCP

⇒ Spin angular momentum $s = \pm\hbar$

Orbital angular momentum, $L = \ell\hbar$ $\ell \rightarrow$ charge

Colour Filters

http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_13.html

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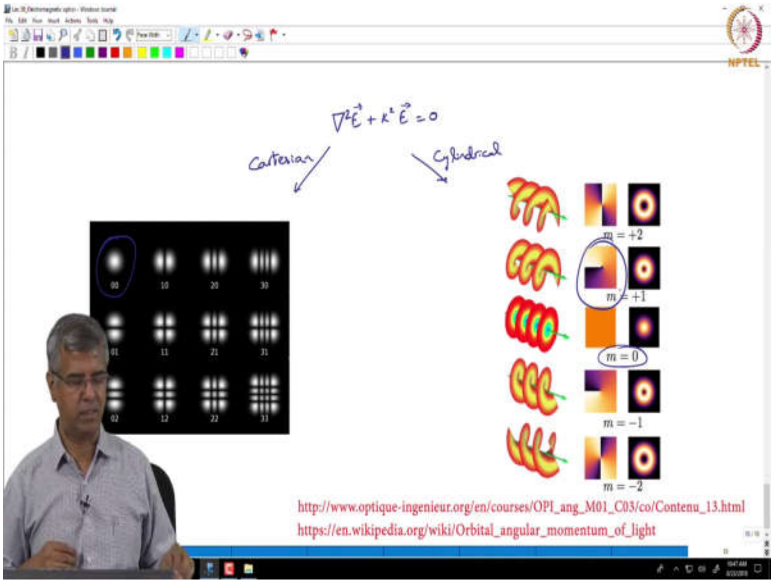

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So the question is the photon is a boson, so how does it have different charges? so essentially what we are saying is that this is consider, we are essentially saying that okay the photon is spinning around an axis and axis is travelling okay, so the fact that it is a boson is related to how it is emitted. But in terms of its propagation, we just characterizing the propagation how it is spinning while it is propagating, that spin or that orbit that it takes because I want to make sure that is different from the spin as in this left circular polarization, right circular polarization, we are talking about the orbit that it takes that actually depends on how you have manipulated that photon right.

So a simple example is this. You have a circularly polarized light and then you are actually going into an element which is graded in phase like this, like how we have, that circle that we are pointing out on $m = 1$, it is graded in phase like this, meaning the glass plate is thicker by a λ or it gives optical length of λ in certain regions compared to the other regions. So then what it does is, it sort of delays the phase or it sort of skews that phase front as it is propagating and that skewed phase front depending upon the incoming polarization can actually corresponds to either a skew that corresponds to positive charge or negative charge it is something that we are imparting on this boson right.

So does that answer your question? Well, that is an interesting thought. I should go back and look at that in little more detail as well, you had a question okay. So we running out of time but maybe it is okay we will stop at this point. I wanted to talk about, how do you quantify propagation of a stream of photons? So far we have been looking at single photon sort of characteristics but how do you characterize a stream of photons? That is what we typically deal with. Most of us do not do single photon experiments right, so the laboratory things that we have, demonstration that we have shown so far, they all involved multiple photons propagating together, so let us look at that little more detail in the next session. Thank you.