Fiber – Optic Communication Systems and Techniques
Prof. Pradeep Kumar K
Department of Electrical Engineering
Indian Institute of Technology, Kanpur

Lecture - 29
Modes in Optical fibers & Pulse propagation in optical fibers

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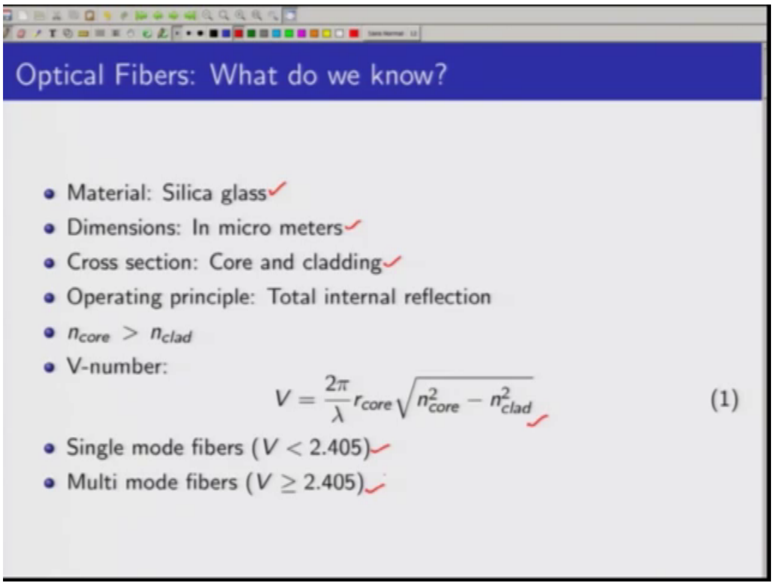

Hello everyone. Welcome to NPTEL MOOC on Fiber Optic Communication. I am Ashitosh and today I am going to speak about the topic Modes of Optical fiber. So, before we begin with the modes, let us discuss about optical fibers, and what do we know about them. So, what is an optical fiber, it is a made of silica glass and with a cross section of core and cladding with a dimensions in micrometers. And the optical fiber works under the principle of total internal reflection you know.

So, hence, in order to satisfy the condition of total internal reflection, the refractive index of the core must be greater than refractive index of the cladding. This is what we know about optical fibers. So, and there is one more property of the optical fiber which is very important, which is called the V-number, which is given by the equation 1 in here, which is 2 pi by lambda r core into square root of n core square minus n clad square. Here lambda is the operating wavelength, r core is the radius of the core, n core and n clad are the refractive indices of core and cladding respectively.

And these optical fibers are classified into two types; single mode fibers and multimode fibers. If the V-number of the fiber is less than 2.405, it is called single mode fiber. If it is greater than 2.405, it is called a multimode fiber. But, what exactly are these modes are, how do they look like. In order to solve for this, there are an analytical approaches, where we need to solve the equations and apply the appropriate boundary condition. But, today here we are going to see a numerical approach by using a software called COMSOL. And see how these modes actually look like, and what are the different properties of this modes under different conditions.

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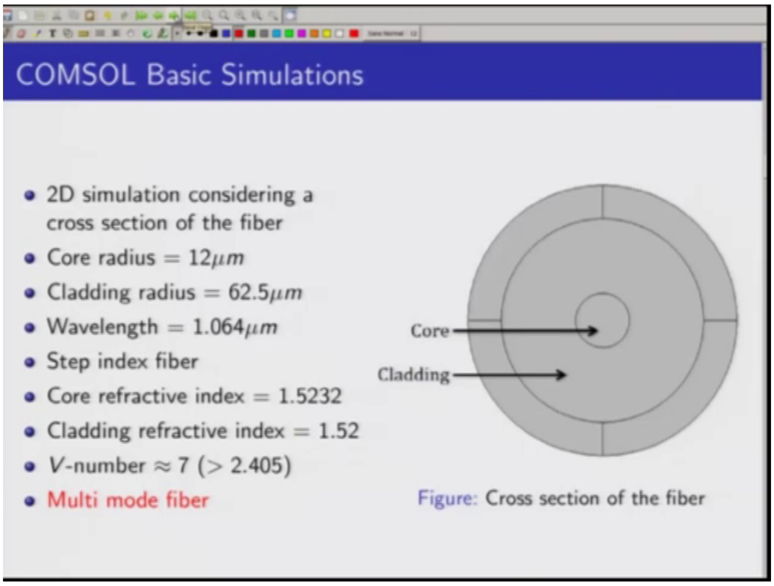

So, for that purpose, initially we need to set up the problem in COMSOL. For that, we need to design a geometry. As we have seen earlier, cross section of a fiber consists of a core and a cladding, which has been defined here in the figure. And the properties of this core and cladding that is the dimensions and the refractive index of this core and cladding are given here. Now, let us just take a moment and with whatever information we have given in this slide calculate the V-number. So, it would be appreciated, if you pause the video for couple of minutes, and look at these parameters and calculate the V-number. And then based on the value that you get comment if this fiber is a single mode or a multimode fiber.

Now, we are hoping that you have calculated the V-number, let us see what are the results that we are getting. Now, the V number for this fiber is approximately equal to 7, which is definitely greater than the value 2.405 that we have discussed in earlier slides. Hence, by seeing this, we can comment that this is a multimode fiber. So, now we have defined the geometry and also defined the properties of the geometry. Now, we have to set up the problem in COMSOL. For that, we need to say, what is that we are going to solve.

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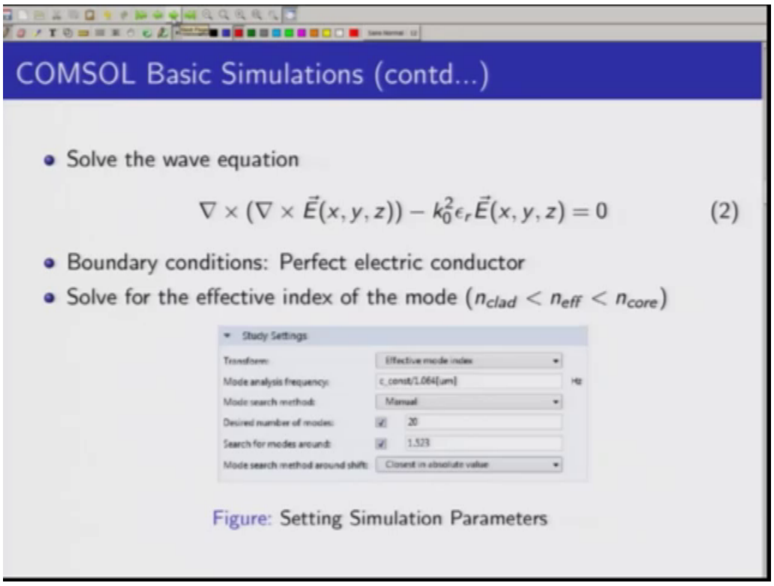

We are going to solve the wave equation. The wave equation is given here in the equation 2 and apply a boundary condition of a perfectly electric conductor. But, the question is what is that we are going to solve for, we are going to solve for modes. But, what is the property of the mode that we should have going to solve for, which is the effective index of the mode. Here if you see the screenshot that is given here, this is a here we are setting the simulation parameters in COMSOL, we are asking COMSOL to calculate the effective mode index and at an operating wavelength of 1.064 micrometer.

And then we are giving a mode search manually, where we ask COMSOL to search for around 20 modes around the value 1.523. This value of 1.523 is approximately equal to the refractive index of the core. Now, we have designed a geometry assign its properties. We know what is the equation that we are solving and we also know what for we are solving. Now, let us see what are the results that we get.

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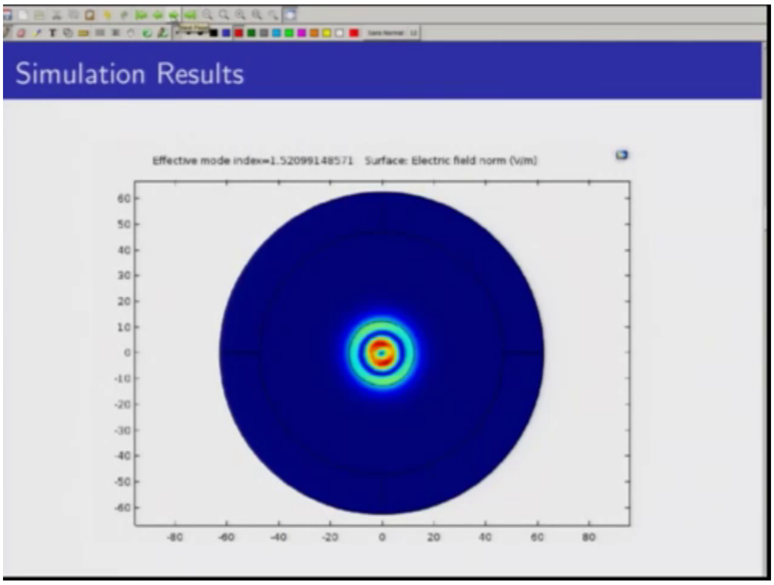

So, this is one of the mode that we see here. As you can see, we are plotting the norm of the electric field here. And this is how one of the mode looks like. This is probably LP 03 mode, and we can also see the effective index value on the top of it. Is this the only solution that we get? No, because we have discussed that this is a multimode fiber, and there are many modes that are supporting.

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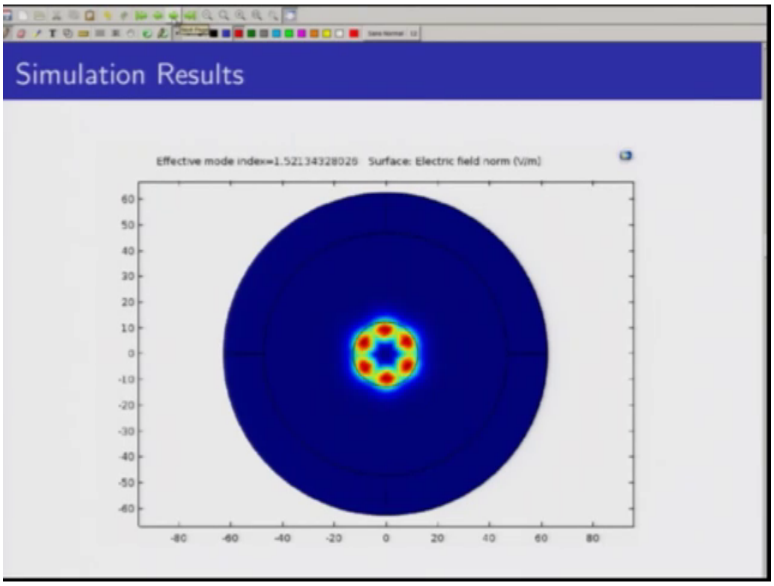

If you go for the next one, this is LP 31 mode, and it has a separate effective index value. One more point we can notice, almost do not have a equal same effective index, it changes based on the mode that we have. Is this is the second mode LP 02 mode, which again has a different effective index, which is probably this is we are going in the higher order of effective index value. And this is a LP 21.

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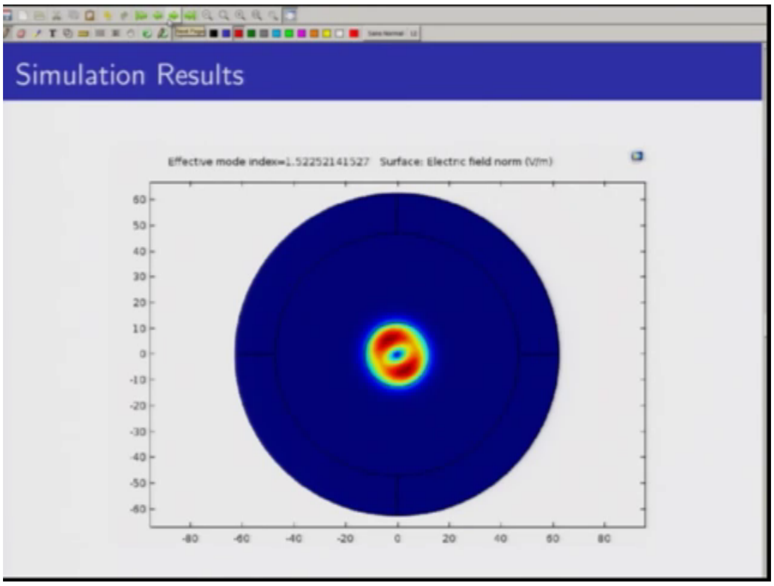

This is LP 3 1 mode.

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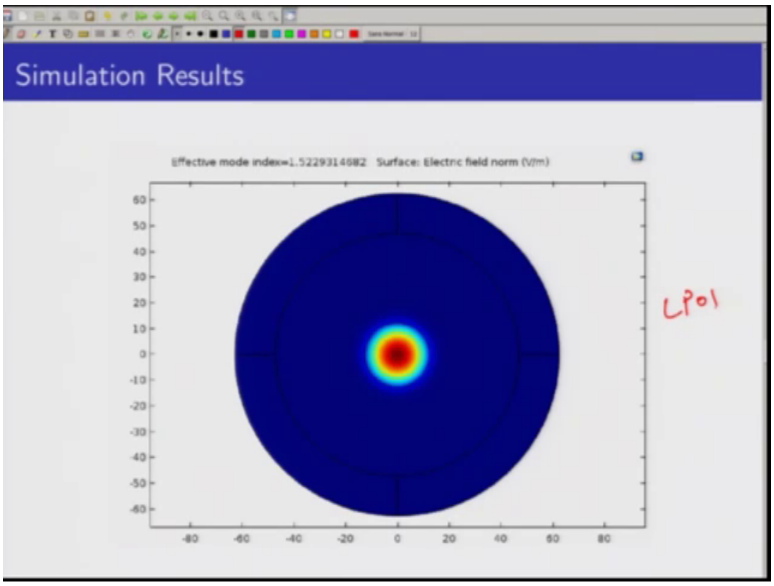

And finally, we reach the fundamental mode LP 01 mode. This LP 01 mode is the initial mode that gets excited in the optical fiber, and has a higher effective index. As you can see with this effective index is larger, when compared with the other modes that we have seen in the previous slides. And this is approximately equal to the refractive index of the core.

If we observe all the results that we got here, the effective index value is purely real and the mode is clearly confined to the core. Why, because this is like a ideal situation, where, we are not acting any external, there is no change in external environment such as temperature, or we are not adding an external pressure, or we are not even bending the fiber.

So, in all these cases, when there is no external pressure on the fiber, mode is confined, the effective index is the mode is confined to the core and effective index is purely real. Now, let us just take one of the scenario, one kind of scenario that we have discussed that is the bending of the fiber, and observe how this mode pattern looks like, and what happens to the effective index of these modes.

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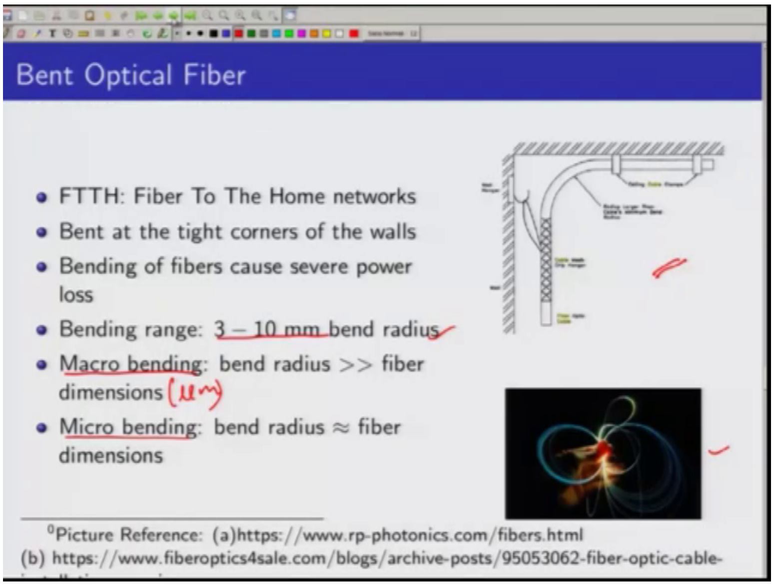

So, before that, let us discuss what is bending and where this bending happens. In a FTTH networks that is Fiber To The Home networks, these optical fibers are installed in into our homes, offices, and institutes in the form of optical fiber cables. And these cables are bent at the tight corners of the wall, as you can see in the figure here. So, what is the range of this bending, which is around 3 to 10 mm of bend radius. What happens when these fibers are bent, as you can see in the second picture here, when a fiber is bent or twisted, there is a severe power loss happening and the light is radiating away, which is a problem in a transmission networks. So, we need to see how what is the amount of light that is getting radiated away.

And these bendings are broadly classified into two types, macro bending and micro bending. As the name suggests, if the bending radius is greater than the fiber dimensions is much greater than the fiber dimensions, it comes under the macro bending category. And, if the bend radius is approximately equal to the fiber dimensions, it comes under the category of micro bending. And we have seen in the point number four here that the bending rate range for FTTH applications is 3 to 10 mm bend radius. So, clearly this mm is much value of mm is much greater than the fiber dimensions, which are in microns. So, these FTTH bendings comes under the category of macro bending. Now, we know this is an this comes under macro bending case. Now, let us see how are we going to solve this problem, or how are we going to approach this problem.

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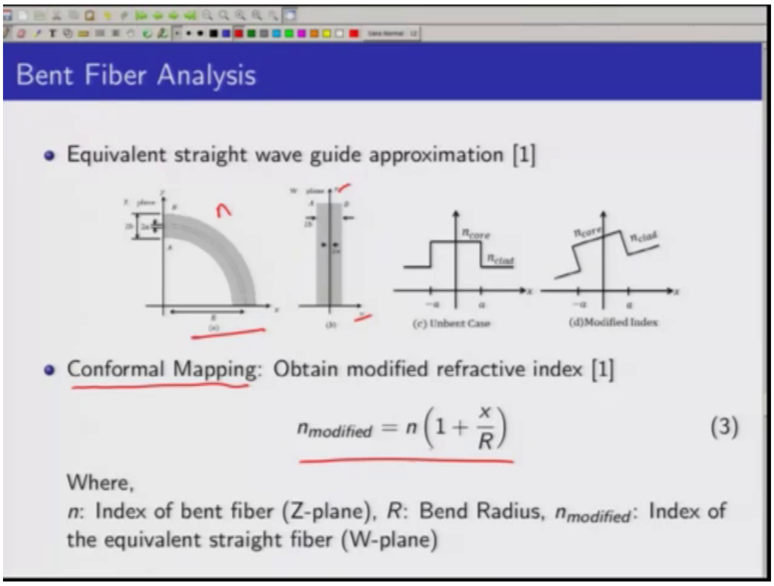

In a figure a that is here, we have a bent waveguide in an x y co-ordinate system or equivalently a Z-plane, where the fiber is bent, and it has the certain refractive index let us say n. Now, we are going to map this optical fiber into an equivalent straight waveguide in a new co-ordinate system u, v co-ordinate system. In this co-ordinate system, we have an equivalent straight waveguide. And we are going to obtain the refractive index of this equivalent state waveguide by following a technical conformal mapping. When we do that, we obtain the modified refractive index is given by equation

3, which is n into 1 plus X by R; n is the refractive index of the bent waveguide that is in a figure a, and R is the bend radius, X is corresponds to a co-ordinate system in the Z-plane.

Now, how does this refractive index looks like? If we consider a normal step index fiber, that we have seen in a earlier case as well. This is the refractive index profile that we see in an unbend case. When we apply conformal mapping technique, so we basically are adding a slope on to these refractive index profile. Now, we input this data, the slope the tilted refractive index profile into COMSOL, and see how actually our mode looks like. So, as we have seen earlier as well. Before going to the solution, we need to setup the problem.

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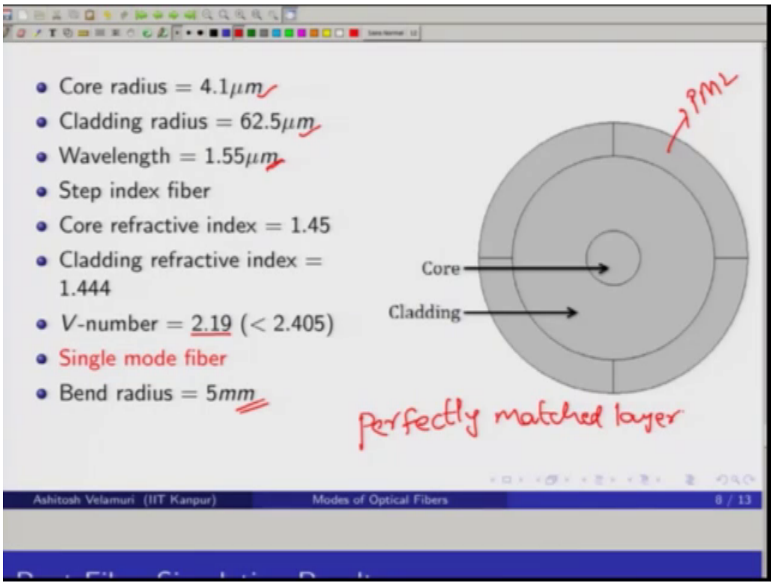

We are now defining a similar geometry, but with the core radius much smaller 4.1 micrometer, cladding radius is the same 62.5 micrometer, and wavelength is 1.55 micrometer. Yes, in the same we are considering a step index fiber with core refractive index of 1.45, and cladding refractive index as 1.444.

Now, if we calculate, if we consider these parameters, and calculate the V-number for this fiber, we are getting a value of 2.19, which is less than 2.405, hence this fiber is a single mode fiber, we only we will have a fundamental mode, not any other higher mode. Higher order modes that we have seen earlier. So and we are applying a bend radius of 5 mm, r is equal to 5 mm in this case. Now, we have a fiber geometry, its properties, and also its dimension. And we have seen how do we solve the problem, we solve the wave equation, and we follow the same process. And let us see what are the results that we get.

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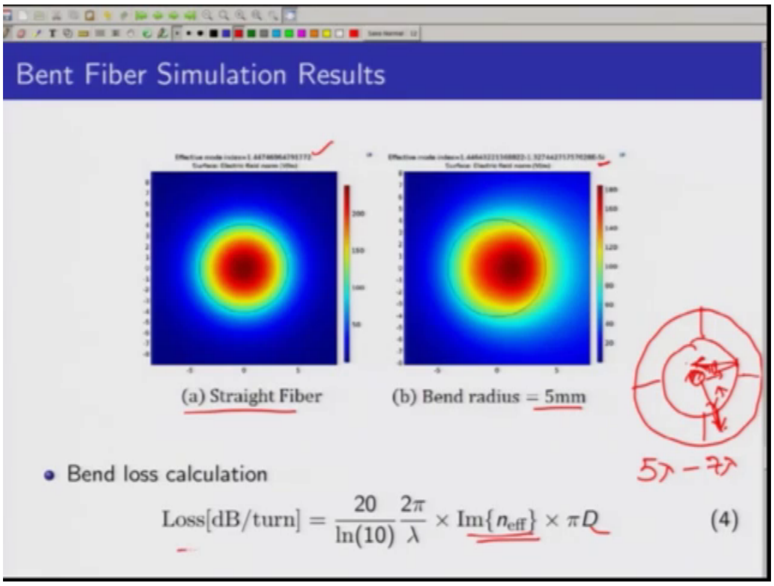

In the figure a, as we have seen in the earlier case as well, we have a more confined in the core for a straight fiber, where the effective index is purely real, and there is no radiation that is happening outside the core. But, when we apply the conformal mapping technique that we have discussed, and do the similar procedure for a bend radius of 5 mm, one we observe there is a shift in the mode towards the cladding that is the mode is radiating away from the core to the cladding. Because of which we have a imaginary part to the effective index, which from this, we can say if there is any radiation in the mode, we have a imaginary part in the effective index.

This imaginary part can be used as shown in the equation 4 to calculate the loss induced in the optical fiber. So, here D is the bend diameter, lambda is operating wavelength, and Im indicates the imaginary part of the effective index. Now, and one more important point that we need to see here is if we observe there is a third layer here, which is a PML, which is a short form of Perfectly Matched Layer. Why do we use this layer, is this really important? So, is this really important?

As we have seen here in the slide, there are some radiation that is happening from the core and this radiation will pass from core to the cladding. As let us see, if we consider this is the geometry, where we have core and we have some radiation that is coming out, this radiation will travel in this direction and hit the cladding boundary. And as we all we know, there is the radiation does not completely get transmitted, so there is some amount of radiation that is coming in a backward direction as well. When these radiation the backward coming radiation, there is a chance that may mix up with the mode that is confined in the core and distorting our results.

In order to avoid this circumstance, we add a third layer, which is called a PML layer. What this layer does is all the radiation that is coming from the core, it is will get absorbed in the PML layer, and there is no radiation that is coming out. So, we are basically removing unwanted radiation to reflect back, which will distort our final output, and we are protecting basically we are like protecting our results.

So, we also now the results that we have obtained here the imaginary part, you have after applying the PML layer, whose thickness which is generally 5 lambda to 7 lambda, where lambda is the operating wavelength, where lambda is the operating wavelength. Now, we have seen how the bending effects the mode pattern and the effective index, and we have also calculated the loss from that one.

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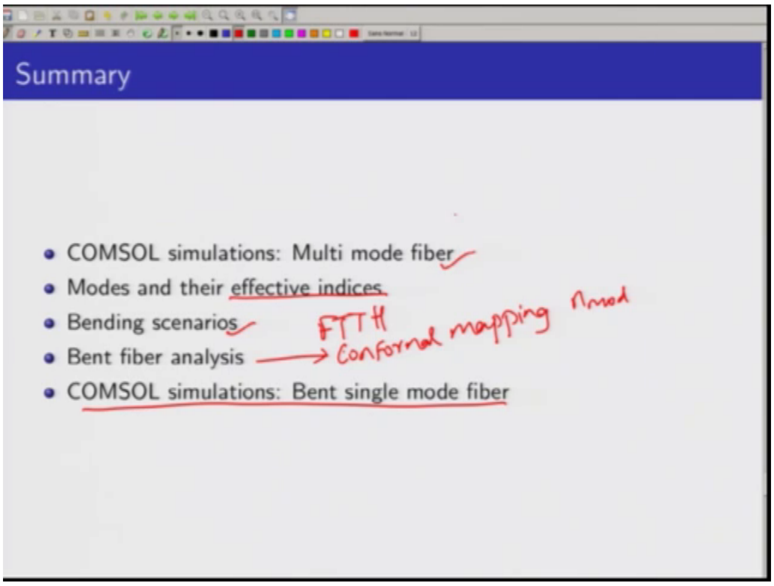

Summarizing what we have seen till now, initially we went through a COMSOL simulation for multimode fiber, and we have seen how the mode pattern looks like for different modes look like, and also made a comment on the their affective indices value. Then we have seen different the bending scenarios, one of the bending scenario is FTTH application. And we have seen the bending, what happens, when this is when it when the fiber is bent, and also we have also seen the classification of bending.

Then we went on to how are we going to solve this problem, how are we going to analyze the bent fiber, where we applied conformal mapping technique, and obtain a modified refractive index, conformal mapping to get n mod. We applied this n mod into COMSOL, and perform the simulation for a bend fiber. And have seen how the mode really looks like in a when a fiber is bent, and compared it with the initial results of a straight fiber.

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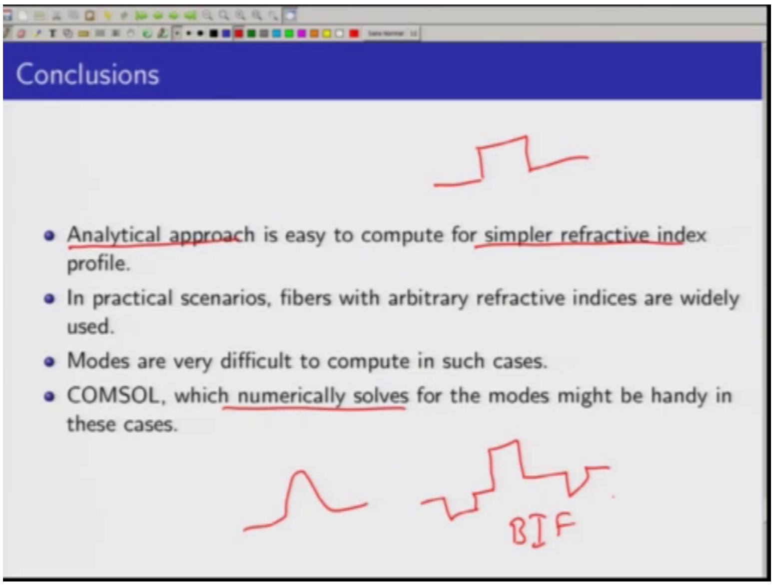

Now, what is that we are going to we have drawn from this one. As suggested earlier, there are we can fall an analytical approach as well to solve this problem of modes, but this can be applied in a case of simpler refractive index that is a case of standard one of the case is standard step index profile that we have considered here. But, in practical scenarios if we see, this type index profile is not much of a use, and there are many different profiles that are used in the optical fibers. And solving for those refractive indices let us say a parabolic index or a trench index, which is basically a bend insensitive fiber. Solving for these kind of refractive indices is very complex using the analytical approach.

So, what do we do, in those scenarios a software like COMSOL, which numerically solves the problem of modes might come in very handy and solves our solves our problem of very complex equations and equations and very tedious calculations. So, for the cases of bend very complex or refractive index profile, these numerical methods might come in very handy giving us accurate results in comparison with the analytical approach. Thank you.

Hello all. I am Shubham Mirg; I am the teaching assistant for the MOOC course Fiber Optic Communication Systems and Techniques. In the upcoming slides, we will see what are the dispersive effects on a pulse propagating in optical fibers.

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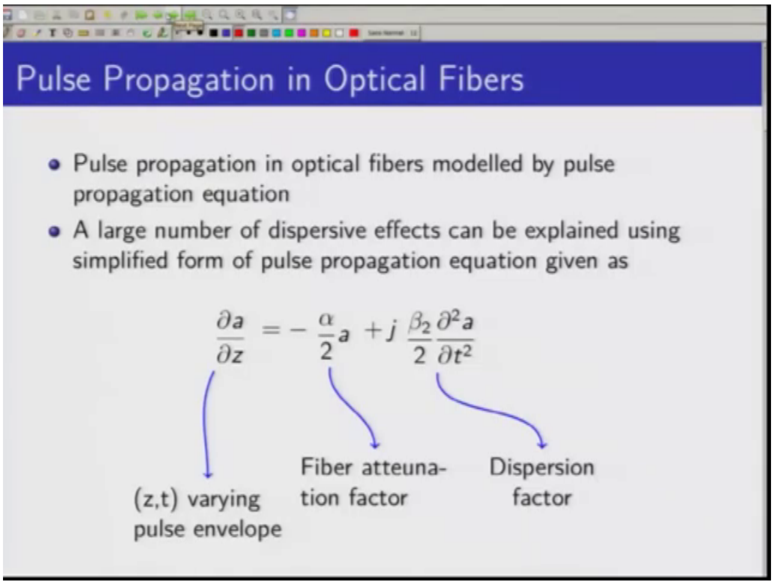

So, to start with, we will try to model the pulse propagating by using the pulse propagation equation. A large number of dispersive effects can be explained using a simplified form of the pulse propagation equation given us this equation. So, what a is the time bearing and as well as distance bearing pulse envelope, while the next term is the fiber attenuation factor, and the third term, we take care of the dispersion factor. So, the attenuation as well as the dispersion factor gets modeled into the pulse propagation equation.

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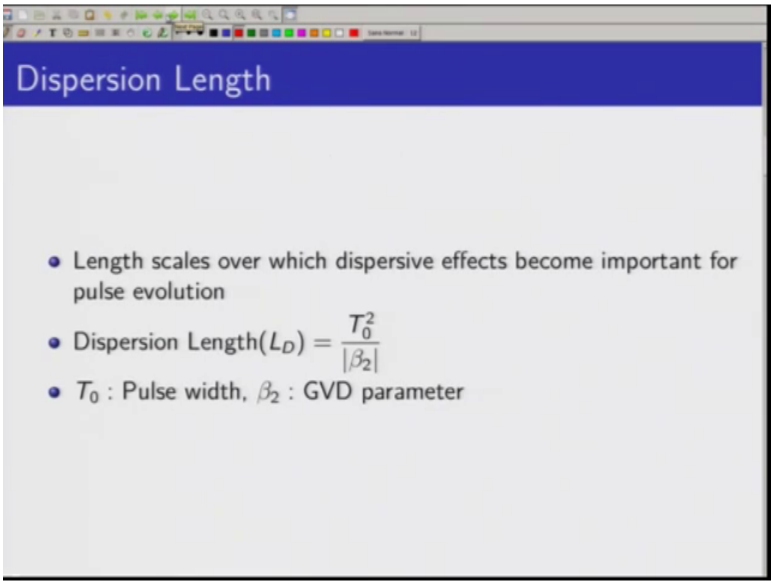

For the convenience, it is better to define a length over which dispersion effects become important for pulse evolution. This dispersion length is given by the pulse width (Refer Time: 16:40) beta 2. With this T naught is the pulse width, and beta 2 is the GVD parameter. GVD stands for Group Velocity Dispersion parameter.

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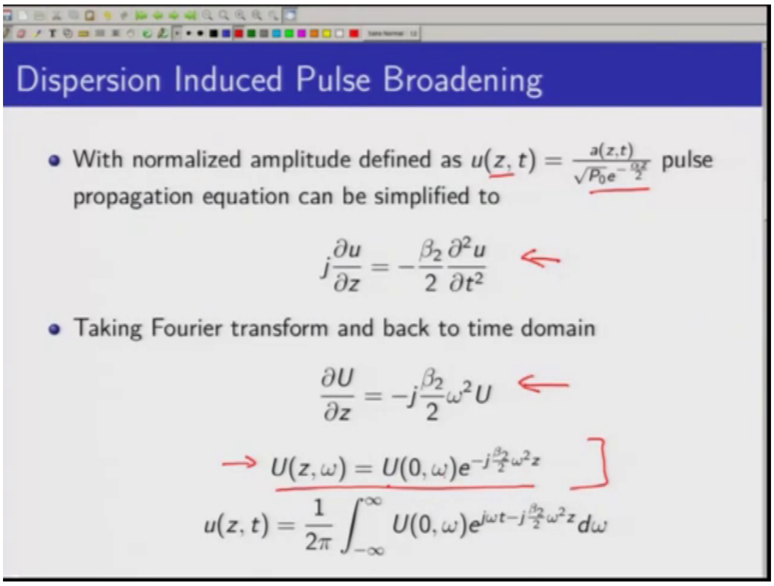

The next slide is dispersion induced pulse broadening. So, once we define a normalized amplitude which takes care of the attenuation, the u z, t is given by a z, t over square root of P naught exponential e to the power minus alpha z by 2. P naught is the peak power, so we get a more simplified pulse propagation equation, which is given by this equation. So, now to solve this equation, we will take the Fourier transform. Once we have the Fourier transform, we have an equation like this.

Now, we can see what U z, omega, which is the Fourier transform of u z, t would be. So, this equation is indeed very important, because we see that over a distance, when the pulse has propagated over a distance z, the pulse equation that we see from here is nothing but the incident pulse, which is U 0, omega multiplied by a dispersion factor, which is exponential minus j beta 2 by 2 omega square z. And to get back this equation in the time domain, we will take the inverse Fourier transform, which shows that the equation becomes, which is just the inverse Fourier transform of the above equation.

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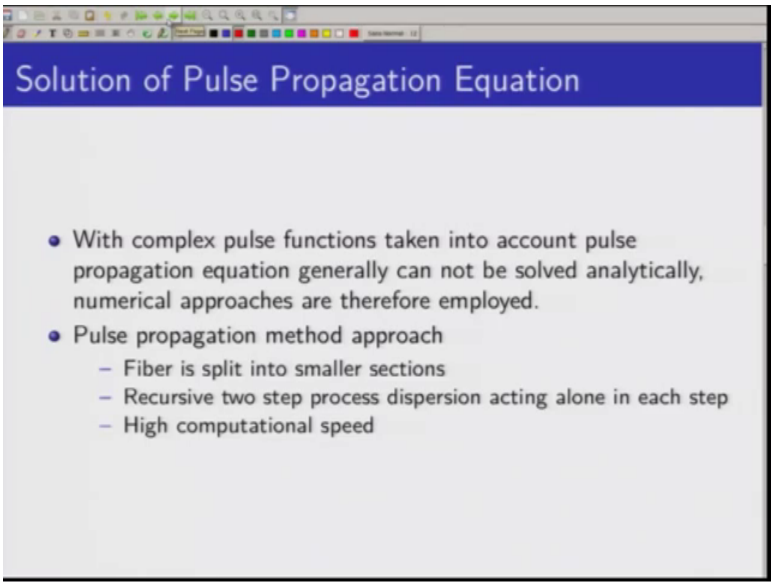

So, how do we go about solving this equation. So when we take complex pulse functions into account, the pulse propagation equation cannot be solved analytically, we actually need to have some numerical approaches. Pulse propagation method approach that we will see in the upcoming slides. What we do is we split the fiber into smaller sections, and it will be a recursive two step process, where dispersion would act alone in each step. The advantage of using this approach is that we get good computational speed.

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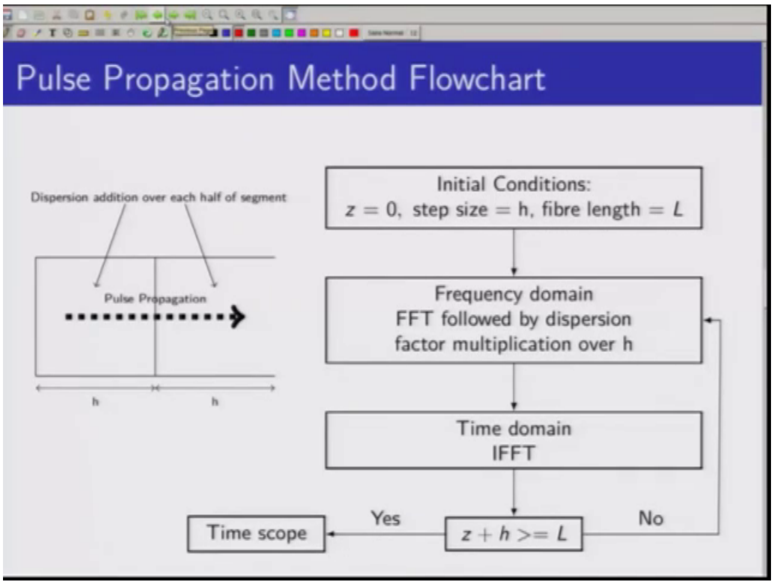

So, we have prepared a flow chart. First process, we will focus on this figure. So, we actually this is this is an optical fiber, and the pulse is propagating inside an optical fiber. And we split the optical fiber into separate sections of each length h. So, what we do is coming to the flow chart, we have an initial condition, where z is equal to 0, which is the start of the optical fiber, and then we have step size equal to h, and the net fiber length over which the pulse will propagate is given by L.

So, the next step (Refer Time: 19:17) taking the Fourier transform and multiplying it by the dispersion factor, which was given by in the previous slide as we pointed out by this factor. We will multiply by this factor for the section z for the section h, and here z is equal to h here. So, once we have that we will take the inverse Fourier transform, and we will ask if we have reached the end of the fiber by adding h. And, if the answer is no, we will go back to the frequency domain, we will again take the Fourier transform, and again the inverse Fourier transform and as and we will reach the end of the fiber.

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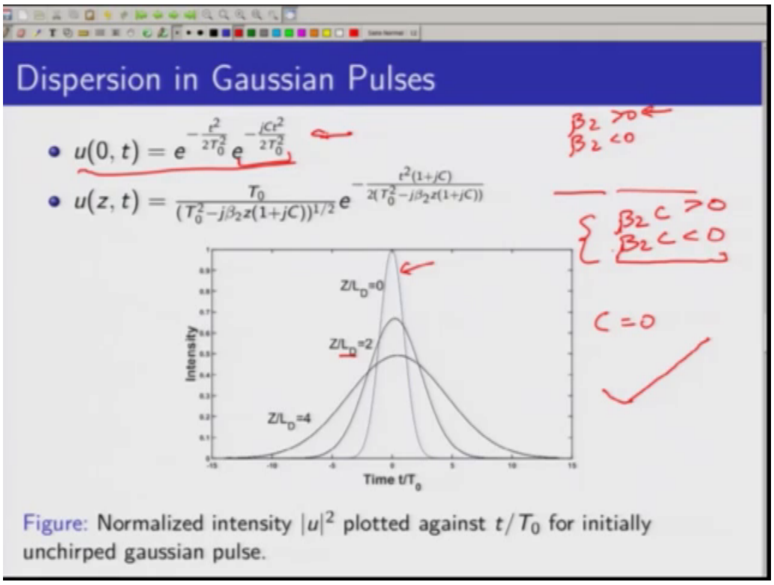

So, we have some examples in the upcoming slides. So, the one of the most used pulses are the Gaussian pulses, whose incident equation is given by this equation, which is u 0, t e to the power minus T square by 2 T naught square e minus j C t square by 2 T naught square, where T naught is the pulse width, and C is the chirp parameter. We will see what chip parameter is. In this scenario, because we know what is the Fourier transform, Gaussian pulses we can actually solve it analytically, and also by the numerical approaches we mentioned previously.

This figure shows for C is equal to this figure is for C is equal to 0. This is for initially unchirped Gaussian pulses, what happened, so the incident pulse looks like this. Now, as we move along twice the dispersion length factor, L D is the dispersion length. So, once we have moved two dispersion lengths, we see that the significant broadening of the pulse. And in fact, if we moving in further, we will see the pulse broadens even more. So, this is the effect that dispersion has one pulses.

So, if the pulse is initially unchirped, the dispersion induced chirp is linear. If this term is one, we can see the instantaneous frequency would come out to be linear over the time scale. However, if we have some chirping, then the things gets interesting, because then we will have to see what beta 2 C is (Refer Time: 21:25) greater than 0 or beta 2 C is less than 0.

Because, if beta 2 C is greater than 0, then we will still have a monotonically increasing chirp parameter, and that would signify that the pulse will still broaden. But however, if beta 2 C is less than 0, then the dispersion induced chirp and the initial chirping that we are providing the pulse will kind of counteract. And so, we will initially see some sort of compression, and then the net chirp becomes 0, and then again it starts monotonically increasing. So, for this case, for the initially chirped pulse counteracting with the beta 2 leads to compression to a certain distance, and then it starts again monotonically increase.

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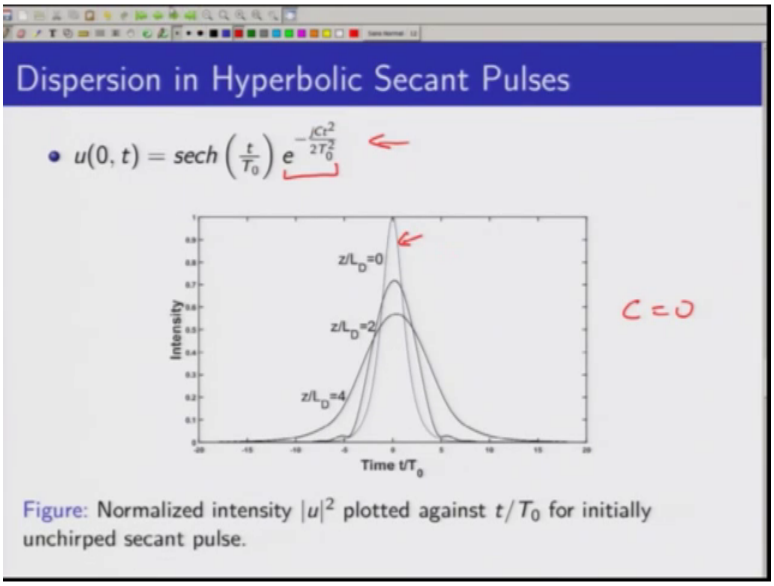

Now, we will come to more complex pulses, for example the hyperbolic secant pulses, whose equation is given by this u 0, t is equal to sech, T naught is the pulse width, and then there is this chirp factor. We plotted it for initially unchirped, again this C is equal to 0, and this is the initially incident pulse. And as we see as we move along two dispersion lengths and 4 dispersion lengths, there is a lot of dispersion induced broadening. And another see so, the pulse the secant pulses are narrower than the Gaussian pulses. So, the instantaneous frequencies are much more, and hence we see some sort of distortion at the ends of it, because that the instantaneous frequencies in this scenario are higher than the frequencies in the Gaussian case.

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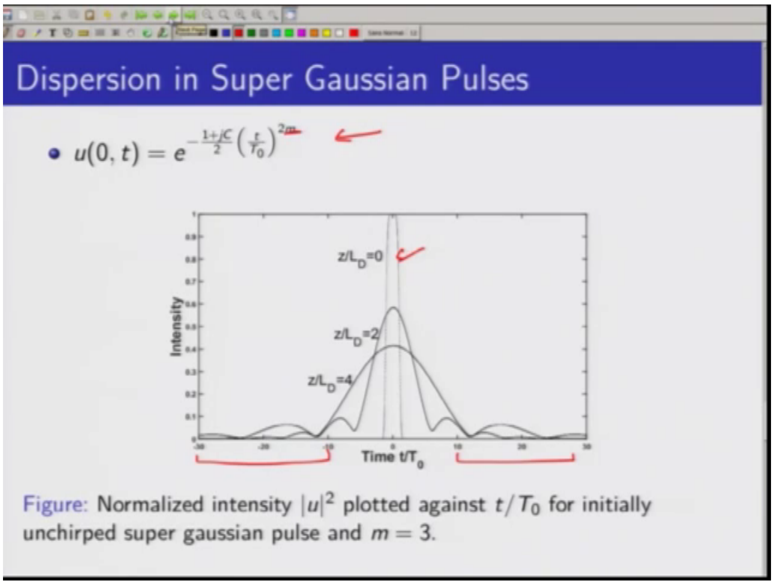

Now, in fact, to even make them more steeper, we will take the case of dispersion super Gaussian pulses, whose incident equation is given by this factor. We see is again the chirp parameter T naught is the pulse width. And it is similar to the Gaussian pulse equation, but we have another factor m here. So, the pulse looks like this, this is the case for m is equal to 3, and again initially unchirped super Gaussian pulses. As you can see, it is even much more steeper than secant or the Gaussian pulses that we saw before.

And the instantaneous frequencies get really high, because it is an it is there is an instantaneous jump at the edges, so there is much more distortion here. As you can see at the trailing edges and the leading edges, this the pulse as it propagates into the fiber. The trailing edges and a leading edges start distorting, and the pulse starts losing its shape. So, in a communication system, this would be very problematic for us. So, it is really important for us to study these effects, and to probably find techniques to mitigate these effects.

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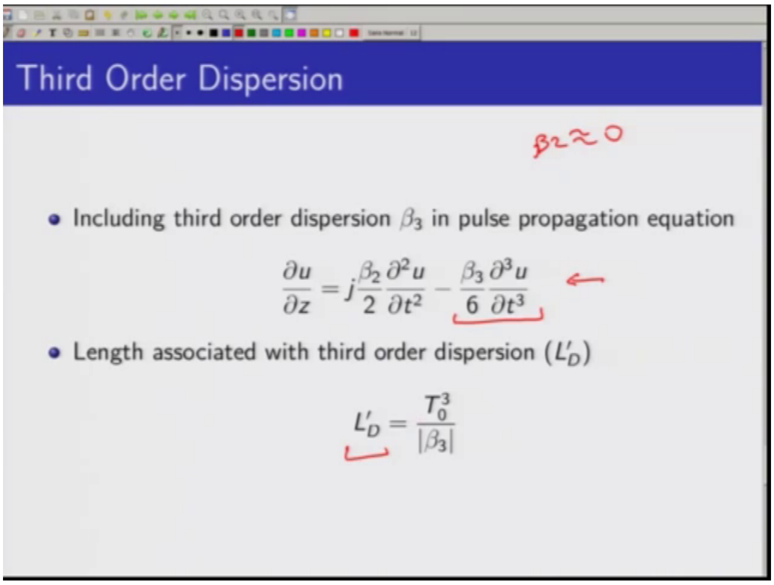

The other factor is the third order dispersion. Now, usually beta 2, the second order dispersion dominates in most of the practical cases of interest. However, if our operating wavelength is really close to the 0 dispersion wavelength, we have beta 2 goes to around 0, then beta 3 actually comes into play and we study the effects of beta 3 on the pulse propagating in the optical fiber.

Also another case would be, when we have very narrow pulses, then again also beta 3 effects come into picture. Otherwise, in most of the practical cases, we do not usually consider third order dispersion. However, if above you any of the above following cases, we do have to consider beta 3. Then the pulse propagation equation that we study previously becomes this way. We (Refer Time: 24:59) another term, which is the beta 3 by 6, so beta 3 partial cube u partial t cube. And again for convenience, we will define the third order dispersion length, which is given by pulse width cube by beta 3, which is the third order dispersion parameter.

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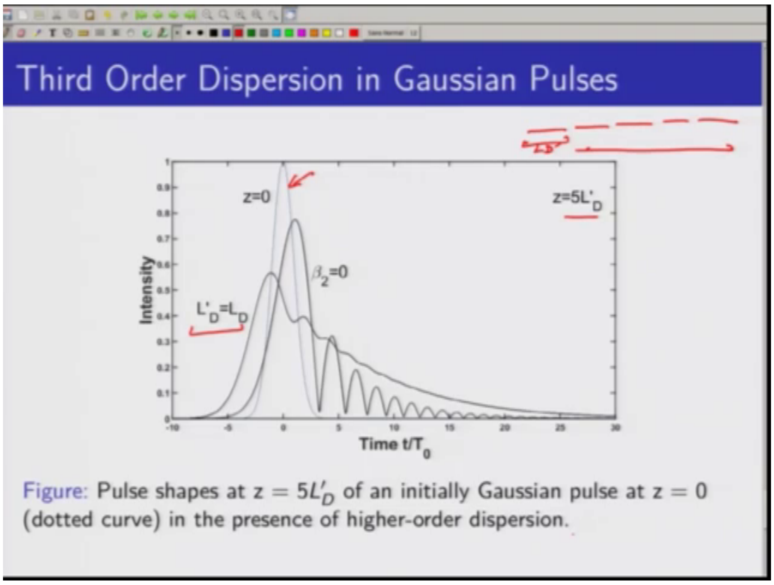

The third order dispersion in Gaussian pulses. So, previously we saw the equation for the Gaussian pulses was this. Again, we will take the chirped parameter to be 0. So, the incident Gaussian pulse looks like this. And for the case, when we say that the second order dispersion is equal to 0, we see that the pulse not only loses its shape, it becomes asymmetric as it propagates, it also starts oscillating at the edges. And when we take both the effects and both beta 2 and beta 3 and make them comparable, for where (Refer Time: 25:51) the dispersion second order dispersion length is equal to the third order dispersion length.

Then we will see that the pulse broadens a lot, because of the beta two parameter as we saw previously as well as the pulse becomes asymmetric and distorts because of the third order dispersion parameter. And this was for the case of z is equal to 5 L D dash, so they we are propagating it to five-third order dispersion lengths. So, 5 L D dash means (Refer Time: 26:17) 5, so this is L D dash. So, the net length of the fiber is 5 times this. So, as you can see, it significantly distorts as well as makes the pulse asymmetric as we propagate along the fiber.

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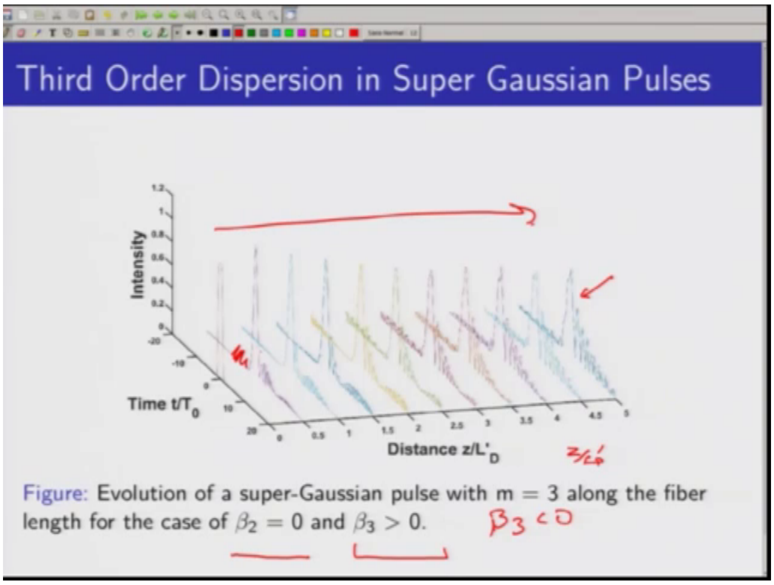

The other case is the third order dispersion in super Gaussian pulses. We will keep the super Gaussian pulses unchirped as well as the m, m would be equal to 3 and so and beta 2 is again kept to be 0, and beta 3 is greater than 0. So, as we see as we move along the distance, so this is the distance measured by L D dash. So, this is 0.5 L D dash, so 1 L D dash and 1.5 L D dash and move so all.

So, as we see as we are moving along the fiber, so we see that the pulse is initially not distorting, as we move even at 0.5 L D dash, which is half the third order dispersion wavelength, we see significant distortion in the trailing edges of the pulse. And as we move ahead, we see that the pulse starts even get distorted more and more, and we also see some pulse broadening happening. As we move along the dispersion lengths, and there is no much more distortion. Due to the fact, that it should be super Gaussian pulses are much more steeper than normal Gaussian pulses.

So, we see significant amount of larger distortion as compared to the previous case, where this case. As you can see this case, and the last case here, this case has much more significant, much more distortion as compared to the previous case, and this the we see a lot of oscillatory behavior at the trailing edge of the pulse. So, this another thing that beta 3, the sign of beta 3 if we are operating in the region, where beta 3 is less than 0, then the effects on the trailing edge would reflect on the leading edge of the pulses. So, if we are having a facing distortion here in case of beta 3 less than 0, we will see distortion in in this sides.

And similarly, in the previous cases, when beta 2 is greater than 0 or beta 2 is less than 0, we do not the pulse will always broaden in the case of a unchirped, it the does not depend on the whether we are operating in the normal dispersion regime, which is beta 2 greater than 0, or the anomalous dispersion regime, which is beta 2 less than 0. However, if we induce some sort of chirping, then the sign of beta 2 becomes important as seen here.

So, to summarize, what we did here was we started, we had a pulse that was about to propagate in an optical fiber. The first step was the model, how it will propagate, we actually added the effects of second order dispersion by the pulse propagation equation. And then we saw that there is a possible analytical solution, but it would be really difficult, if we are not able to calculate the Fourier transform of an incident pulses.

So, for something like Gaussian, where we can actually calculate the Fourier transform, we do get an analytical solution, and however as we move to much more complex pulses. This we cannot really have a very straightforward analytic solution to it. So, we put in the numerical approaches, which are much more easier to compute.

And as we see Gaussian pulses have a significant amount of gardening. And these as we much more narrow pulses in hyperbolic secant pulses, there is also as with broadening, there is some distortion as well at the leading as well as the trailing edges of the pulses. And pulses maintain their symmetry here in the cases of beta 2, where beta 3 is not affecting the pulses, and beta 2 is dominant factor here.

As we moved along into the super Gaussian pulses, we see much more significant amount of oscillatory behavior at the trailing and the lead leading edges of the pulse, as the pulses moved along the fiber. And then we saw the effects of third order dispersion, we saw the cases we have third order dispersion can come into play such as very narrow pulses, and operating wavelength to be near to be the 0 dispersion wavelength. And we associated a length with the third order dispersion as well.

And then we saw what third order dispersion does in the absence of in the case, where beta 2 is equal to 0. And we also saw, when beta 2 and beta 3 both come into play and they are comparable, then what happens, which is a significant above broadening as well as the pulse becomes asymmetric. And it also has some oscillatory behavior at the leading or the trailing edge depending on the sign of beta 3.

And the last case, we studied was dispersion in super Gaussian pulses. We saw the evolution of the pulses in this 3D figure as it moved along the fiber. And we saw significant amount of distortion, and oscillatory behavior, and pulse becoming asymmetric, as it moved along the fiber as compared to the simple Gaussian case. And the next step in the future lectures, we will also see what non-linearity parameter does to the pulse propagation equation.

Thank you.