Advanced Optical Communications
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Module No. # 01
Lecture No. # 36
Solitonic Communication

In last couple of lectures, we are trying to solve the non-linear Schrodinger equation which governs the pulse propagation on optical fibers. We are taking different regimes different conditions, conditions under which only dispersion is dominant, non-linearity effects can be neglected. A situation in which the non-linearity effect would be dominant and the dispersion can be neglected and when both the effects are present.

So, we solved the non-linear Schrodinger equation for the group velocity dispersion neglecting the non-linear effects. And we saw that in that situation, the pulse broadening takes place and internally there is a frequency chirp develops because of dispersion. You also saw that for dispersion, the nature of the chirp depends upon whether you are working in the normal dispersion regime or the anomalous dispersion regime for a wave length less than 1300 nanometer where the dispersion is normal, we get a positive chirp. That means the frequency within the pulse increases as the function of time. Whereas, in the anomalous dispersion regime the frequency decreases within the pulse as a function of time.

So, whether we are working in anomalous regime or we are working in the normal regime the pulse broadening always takes place, the spectrum remains same, but different frequencies undergo different phase change. That is what was happening for the group velocity dispersion. In case of non-linearity, when we solve the non-linear Schrodinger equation, neglecting the dispersion term. Then, we find that the time envelope does not change, but the spectrum changes. The spectrum broadens, that means new frequencies get generated as the pulse propagates inside the optical fiber. Within the pulse again you have the phase change as a function of time which leads to change in frequency.

So, in this situation also we have a frequency chirping of frequency modulation. However, because of the self-phase modulation, the chirp is always positive. That means the frequency always increases as a function of time within the pulse envelope. Then we made a proposition, that if we create a situation where the dispersion is anomalous. That means the chirp of the frequency is negative and if the non-linearity also is present simultaneously. And if we adjust the parameters, in such a way that the chirp created by the non-linearity is completely cancelled by the chirp created by the dispersion then, the frequency modulation inside the pulse will vanish and then consequently the pulse broadening also will vanish.

Or in other words if you create a situation where the non-linear effects cancel the dispersion effect, the pulse can travel on optical fiber without broadening over much longer distances and that is the situation we called as a soliton. Then we solves a mechanical analogy, what really soliton means? And then we started analyzing, what should be the shape of the soliton? How the pulse (( )) evolves? What are the parameters?

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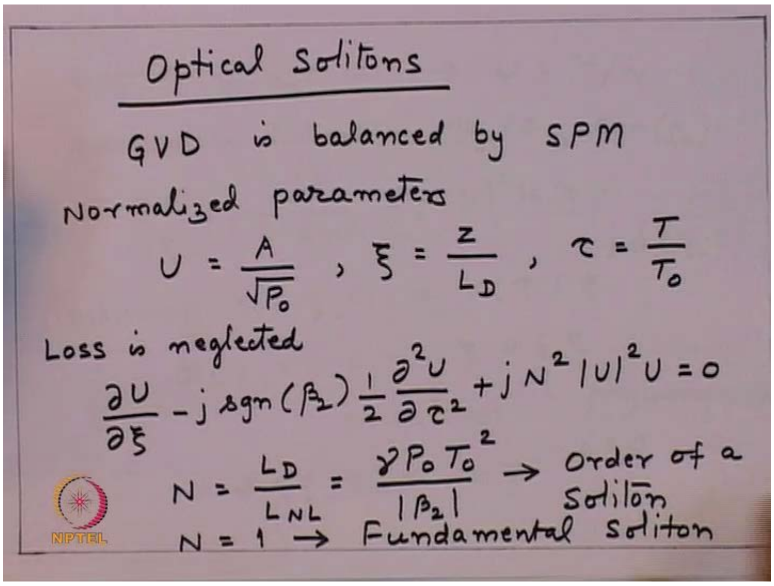

So, we continued with that analysis. So, we started with a non-linear Schrodinger equation and then in that equation then for the soliton we said now the GVD is balanced by the self-phase modulation. We define certain normalize parameters, we define the normalize distance which is normalize with respect to dispersion length. We also define time, which is normalize with respect to the pulse width.

We neglect the loss whether it will be discuss earlier, in the presence of loss as the pulse trans propagating the power in the pulse reduces in the non-linearity becomes weaker and weaker. One can also argue that at any point of time, if the non-linearity becomes weaker then what is required to balance the group velocity dispersion? The pulse will start broadening and when the pulse start broadening peak power in the pulse will come down. If the peak power comes down then the non-linearity will further weaken and then dispersion will further dominant in the pulse will start dominating further. So, it any point in this rays of non-linearity and dispersion, if the non-linearity losses through dispersion then it can never recover back, the pulse will go on broadening.

So, for this phenomena to sustain on optical fiber it is very important, that the power level in the pulse should be maintained in such a way that are no point of time the non-linearity losses against dispersion. So, as simple case to start with we are taking a loss less case. So, we are assuming that the loss on the optical fiber is neglected and then the non-linear Schrodinger equation in terms of this normalize parameters can be return like this. Where we define this parameter N, which we call as order of a soliton which is the ratio of the dispersion length to non-linearity length. And then we said when L d is equal to L N L and if the length of the fiber is much larger than L D N L N L then we get a phenomena, what is call the fundamental soliton, which corresponds to a N equal to 1.

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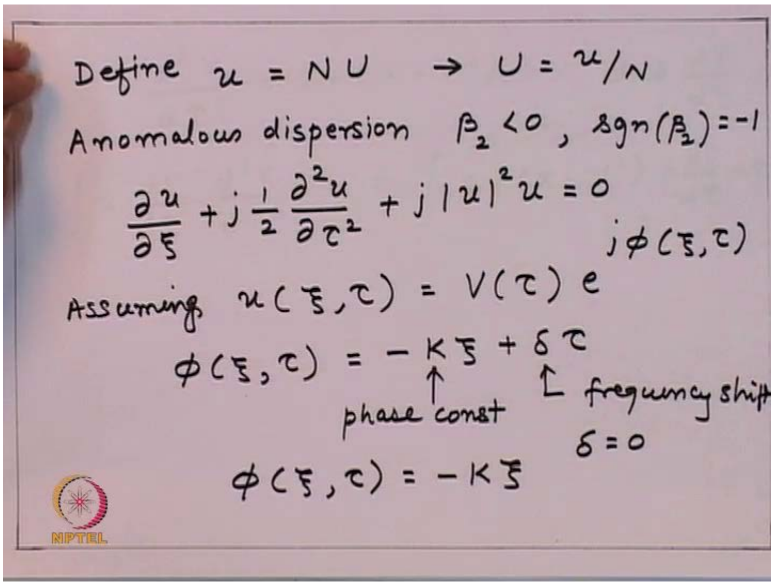

Than to solve this equation here to eliminate this parameter N, we define another variable the small U, which is this capital end times the envelope function U. And they may substituting this in the anomalous dispersion regime when beta 2 a less than 0 that mean the sign of beta 2 a minus 1, the non-linear Schrodinger equation then becomes this. And to solve this equation then first up all we note that once now the non-linearity and the dispersion are balanced, then the envelope does not change as a function of distance.So, you have envelope function which is a function of tau, but does not vary as a function of distance.

However, we have a phase function which can very as the function of time and distance. And if I take this now and substitute into this, you get 2 equations by separating real imaginary parts, one equation governs the phase other equation governs the amplitude. And for phase 1 can show that the soliton to the phase is given by this which is almost like a wave function kind of behavior. So, you are having a phase constant here this is normalize distance, this is the normalize time. So, this quantity is nothing, but the frequency shift. So, assuming that the frequency shifty is not there in this propagation one can take delta equal to 0. And then this phase function then can be return as a function of space with this k, which is constant quantity of in this form.

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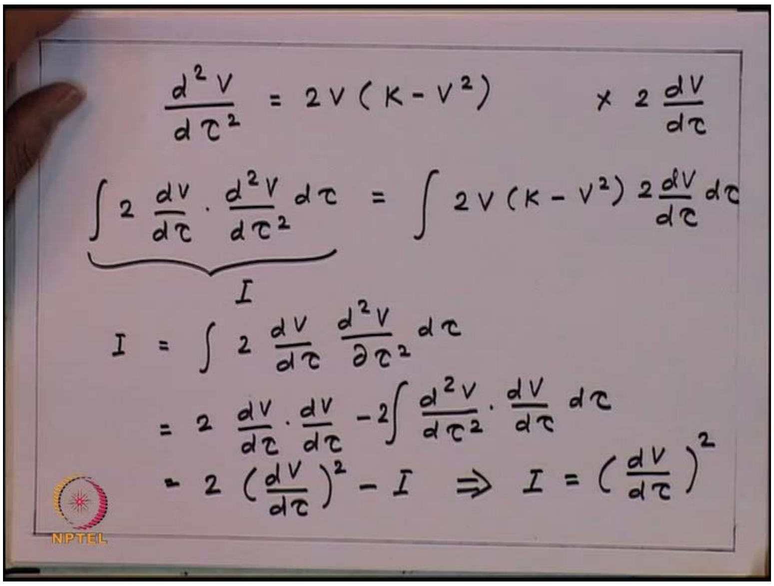

So, if I second equation than which we get, which governs the amplitude or the envelope that is given by this equation. So, v is the quantity which is the envelope function which is now not changing as the function of distance, which is governed by this equation. And to saw the this equation than one as some trick. So, let us multiply both the side by this quantity two times d v by d tau and integrate this as a function of time. So, that is where actually we stopped in our previous lecture that we have got this say equation which tells you the functional form of the envelope right which will sustain on the optical fiber without it is change in shape.

So, by multiplying this we got this quantity here. So, now, you will see how that takes will work. So, let us say this is the quantity which is given by some quantity I. So, the I is the integral 2 times d v by d tau, d 2 v by d tau square d tau. I can do the integration by parts. So, this will be 2 times, first function d v by d tau, d integral of second which will be d v by d tau minus integral of differential of first. So, that is 2 times (No audio from 11:18 to 11:25) d 2 v by d tau square into Integra of second. So, which is d v by d tau. But, this quantity if I look at this quantity, it is same as this quantity you have got 2 times d v by d tau multiplied by d 2 by d tau square d tau.

So, this quantity is nothing, but, the integral I it-self. So, you get here 2 times d v by d tau whole square minus the same integral I. So, this then gives I can bring this I on this said. So, it 2 I is equal to this. So, you get I which am this integral that is equal to d v by d tau whole square.

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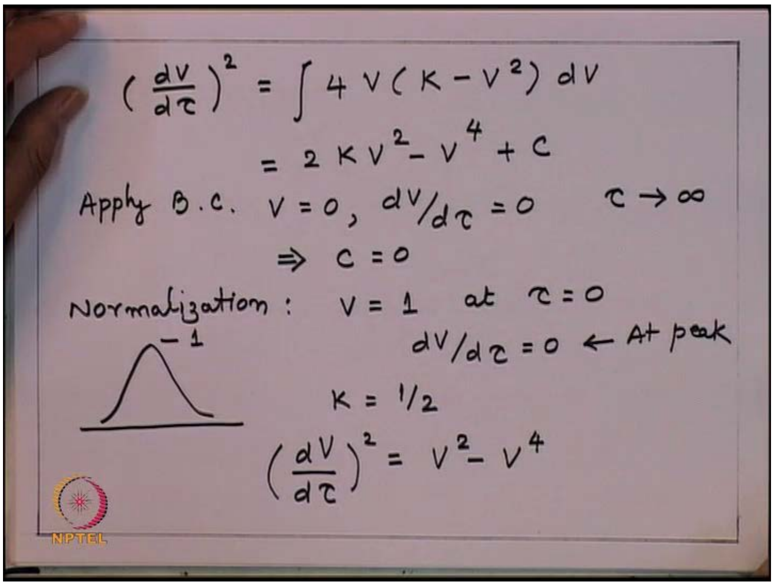

So, now, things are simple of this integral is this. So, I can substitute into this to get d v by d tau whole square that is equal to this one d tau will cancel will get d v. So, this is 4 times. So, I get here integral 4 times v k minus v square d v. So, I can this integrally very simple we can write this that gives you two times k v square minus v to the power 4 plus some constant of integration c. One can the new is the boundary conditions to get the value of c. So, if you apply boundary conditions and that is v is equal to 0 and also d v by d tau is equal to 0 when tau tends to infinity.

So, the envelope function is going to 0 and also the slope of that function is going to go to 0. If you apply this boundary condition on this then that will give this constant c is equal to 0. One can now also apply the normalizing condition for this and that is. So, normalization gives that v is equal to 1 at tau equal to 0. So, you take a pulse which is normalize amplitude pulse and a tau equal to 0 since we are talking about pulse which is speaking. So, just saying here you are pulse is like this. So, this value is 1 and the slope of this is 0 because you are in the top of this pulse. So, a tau equal to 0 we also have d v by d tau is equal to 0 at the peak. So, if I take this substituent into this, I can get this constant k and that k will be equal to 1 upon 2.

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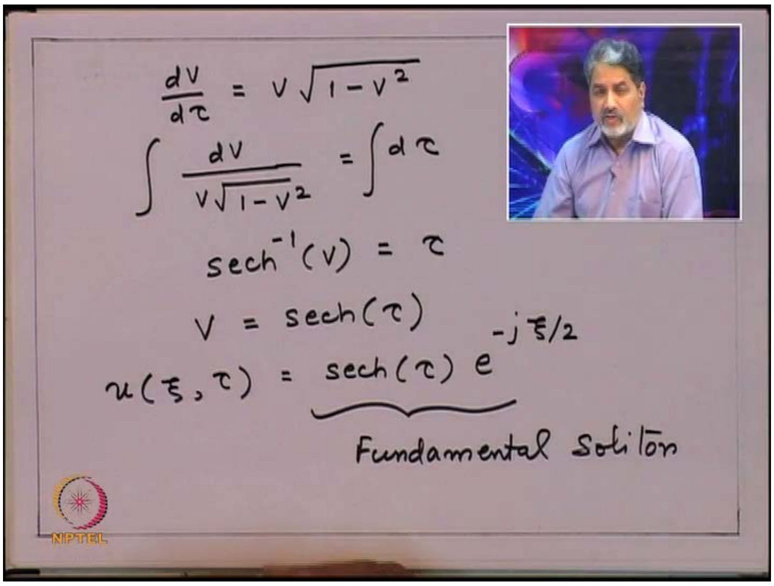

So, finally, then we got soliton of this equation which is the envelope is d v by d tau whole square that is equal to v square minus v to the power 4. One can takes square root on both sides to get d v by d tau is equal to v square root 1 minus v square. We can separate and the parts to get d v upon v square root 1 minus v square is equal to d tau. So, can integrate above sides and this is the started integral or which we have the hyperbolic sec inverse that is equal to tau.

So, the soliton which we get for this is v is equal to secant hyperbolic tau. Then combining the phase function and the amplitude function the total soliton which we got for the non-linear Schrodinger equation tau is equal to secant hyperbolic tau e to the power minus j tau by 2. So, what this analysis has given us now is? That if we consider a situation of fundamental soliton; that means, if the non-linearity length is equal to the dispersion length, then the non-linearity and the dispersion will cancel each other. But this will not happen for any arbitrary function, this perfect cancelation will take place for a pulse which has the secant hyperbolic secant shape.

And there it has certain phase term. So, as the things move the this pulse will accumulate a phase a function of distance, but the envelope will remain intact as it moves. And this shape now is a very special shape which is a hyperbolic secant shape as the function of time. That is the one which will travel and distorted on the optical fiber. So, this shape now is the fundamental soliton shape. (No audio from 19:17 to 19:24) So, fundamental soliton has a very definite shape, it is the hyperbolic secant shape that is the one for which there is the perfect balance between the non-linearity and that is the dispersion. And that is the what which will propagate without any distortion on the optical fiber. So, thus very interesting analysis it is simply says that if you can create a pulse which as the shape, which is hyperbolic secant shape then this pulse can travel on the optical fiber and distorted in the form of the solitonic wave.

One measure wonder, how often do we have this kind of solitonic pulses which are actually generated into the system? Let us I have want to transmit some data on the optical fiber we have the pulse which are different shapes it could be simple rectangle pulses, it could be pulses which will look more like Gaussian pulses, lagrangian pulses whatever. But very rarely really we see a shape which is deliberately created which is secant hyperbolic secant shape.

So, one can then ask simple question, if I launch a pulse which does not have a hyperbolic secant shape then what will have happen. Would it form a soliton or would it not form a soliton or what will happen to the pulse when it starts from propagating? It is very interesting to see that is the non-linear phenomena which takes place in the optical fiber in the presence of dispersion it does certain reshaping of the pulse.

So, even if the pulse was not hyperbolic secant, but if the non-linearity was good enough higher than what is really required to form the fundamentals soliton. That is the initial phase there is some reshaping of the pulse takes place naturally. So, even if the pulse which is launch inside the optical fiber is not of hyperbolic secant type. There will be some readjustment of the pulse to form this hyperbolic secant shape. Whatever energy does not fit into this shape that energy may disperse, but a portion of the energy which can get shaped into this hyperbolic secant that one then thus propagate without any modification in shape in the form of the soliton.

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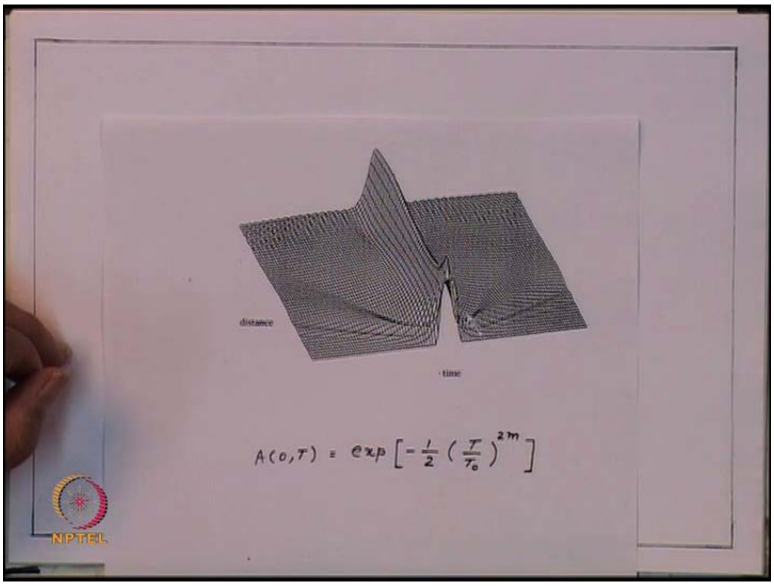

One would wonder that how often we create the pulses which have a shape which is hyperbolic secant shape. So, here the simulation which tells you how the pulse is going to evolve if the launch pulse is not having shape which is hyperbolic secant. So, what is done here is? A pulse which is launched inside the optical fiber is the supper Gaussian nature which is given by this function. So, you see here that if I put m equal to 1 then this is a simple Gaussian kind of distribution as the m increases you get the pulse shape which looks more and more flat on the top. So, when I am tends to infinity this pulses essentially becomes a rectangular pulse.

So, what is simulation is doing it is taking a pulse which is supper Gaussian in nature for different values of m as studies how the pulse is going to evolve as we travels on the optical fiber. It is also made sure that the power which is put inside this Gaussian is more than what is needed to form the fundamental soliton. That means, the power in the pulse is taken such that the non-linearity length is smaller compare to the dispersion length. So, this plot here shows now that if you take a pulse which is of supper Gaussian nature. Initially the some adjustment in the pulse shape takes place, but, finally, the pulse evolves into this shape which is a hyperbolic secant shape.

So, this stimulation show that is not important to launch a pulse which has a shape of hyperbolic secant. Even if the pulse shape was not of fundamental soliton nature, but if the non-linearity was strong enough. There is same readjustment of the pulse that the initial stage and the pulse will naturally evolve into this hyperbolic secant shape, which is the shape of the fundamentals soliton. Of course, in this process some part of the energy of the pulse may get distributed and which may not be balance by the non-linearity so, that energy will go into dispersive mode. So, a small fraction of energy actually made a get loosed into the dispersion. But substantial portion of that energy will go into the formation of the fundamental soliton.

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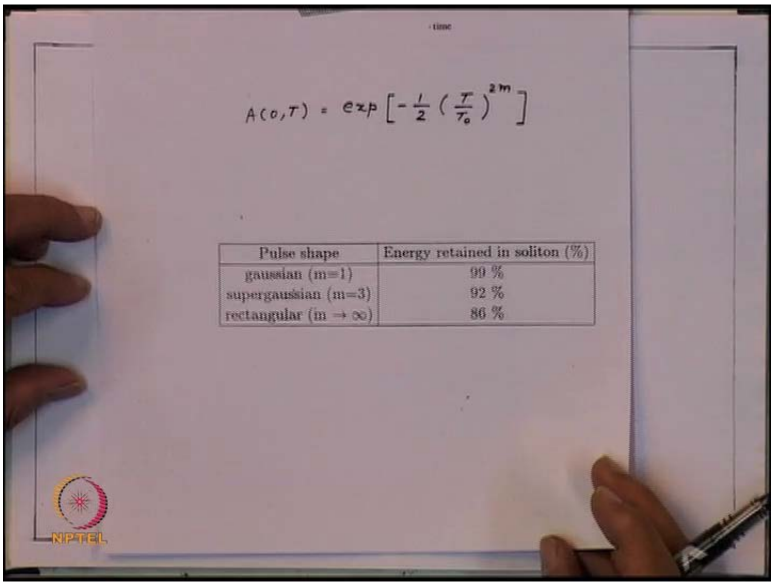

So, the simulation is done for different values of m. So, this table shows that if I consider a Gaussian pulse which is corresponds to m equal to 1. You can take a supper Gaussian for values of m equal to 3 and then rectangular pulses which is for m equal to infinity. You see that for Gaussian pulse almost the 99 percent of the energy gets adjusted into the hyperbolic secant pulse. For this supper Gaussian pulse 92 percent and rectangular pulse 86 percent of the energy essentially gets converted into the solitonic pulse.

So, it is not that you have to put two much higher power to for non-linear to dominant to for the formation of this pulse. Even about 15 percent of change or higher energy if you put way in the fiber then what is require to the fundamental soliton? The energy will get molded to form a the solitonic wave. So, that is a very interesting simulation we shows that we do not launch the pulses which are solitonic nature. It is the cyber the non-linear effects in the dispersion together they work in such a way that the pulse shape becomes solitonic shape. While this is a fundamental discussion on the soliton, the first order soliton, which looks secant hyperbolic shape the question one can ask is that when we are transmitting the data on the communication channel? We are certainly not going to transmit only one pulse.

So, the question one can ask is that if we have a train of pulses which are transmitted on the optical fiber? And let us say this train of pulses where in solitonic form. So, you did something initially some adjustment and now the pulses which are form which are of fundamental solitonic nature, but there are multiple pulses now which are one after another which are going. Would the propagation of this pulses get effected because the presence of multiple pulse and the answer to this is yes it does get modified. Infact, this solitonic pulse which is like a particle, but it behave more like charge particle.

So, if you are having particle which has a charge another particle which has charge another charge this two particle either can attract or they can repair depending upon what is the phase or what is the charge on this two particles. So, the light charges they will have repulsion the opposite charges they will have attraction and the similar kind of phenomena you see in the solitonic pulses also.

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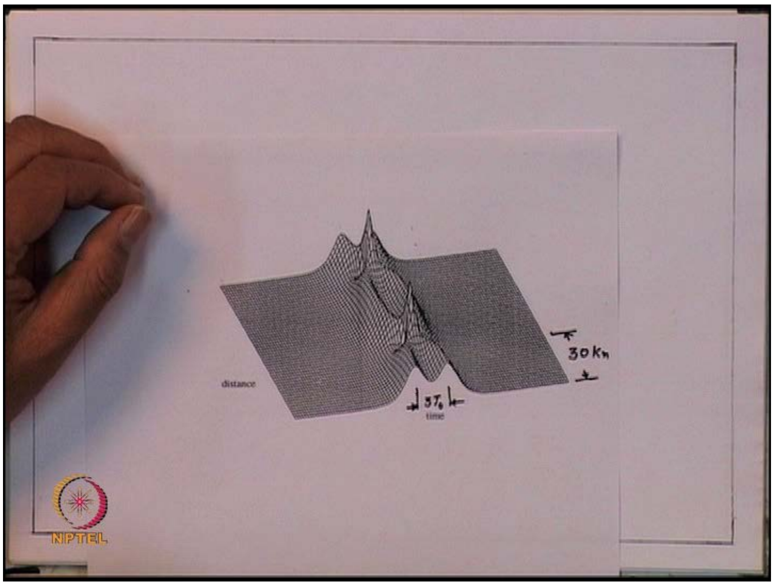

So, if you consider the multiple pulses which are propagating first just for demonstration purpose. Let us say you have these 2 pulses which are now propagating inside the optical fiber. So, you see this is a time and initially this are two Gaussian pulses which we are launched by separate by this distance, which is 3 times t naught. Where t naught is the standard deviation of the Gaussian pulse. And if you pulse start travelling now on the optical fiber this two pulses, you see what happens with this two pulses?

Something interesting happens, slowly this are similar identical pulses. So, slowly then get attracted to each other. So, the separated by this slowly the separation between them decreases. They almost merge into 1 pulse and then again slowly this sort of separate out and they become 2 pulses, again after certain distance they get the collapse into 1 and so on. So, you see that this some kind of a periodic behavior which takes place on the optical fiber. The 2 pulses when the propagate they become one of the sometime this is collapse into 1 then the against separate out, after certain distance again collapse into one. So, if I look at now the pulses that the travelling if I look at this location I see 2 data pulses 2 pulses. If I go to this distance here the 2 pulses will not appear like 2 pulses, this 2 pulses we appear like 1 pulse because they have been collapse into 1 again at this distance the 2 pulses were appear like 2 pulses.

So, you see that if you put multiple pulses then the behavior of this is very different than a single solitary pulse or a single soliton. And this behavior that the pulses collapse into 1 and then the separate out is not very good from the data point of view. So, we have one more simulation here we said start with 3 pulses and the separation again is about 3.5 a t naught or t naught is the standard deviation of the pulse. This 3 pulses they collapse into 2 the collapse into 1 then again the separate out become 3 again the collapse 2 into 1 and so on.

So, this multiple pulses when you are having they show this periodic behavior of collapse into different pulses and this phenomena of merging of pulses separating out at as a function of distance is certainly not a desirable phenomenon from the data point (( )). Because, if the data bits keep on sort of merging into each other in certain losing their identity, you will not be able to recover your data. So, this solitonic pulses through it looks when the single pulse was going it can travel for long distance without any distortion and so on, does not really true if you are transmitting multiple pulses.

So, the question one can ask is if there is some kind of attraction or repulsion which is going to take place between these pulses? This should depend upon how much separated they are, because we know if there was single pulse; that means, 2 pulses where separated by infinite distance then there is no possibility of this collapse. So, 1 can there ask a question how much we should separate out this pulses so that this effect of attraction or repulsion becomes negligible. And the simulation show that you require about 8 2 10 times t naught separation between 2 pulses 2 make this effect of attraction or repression negligible small.

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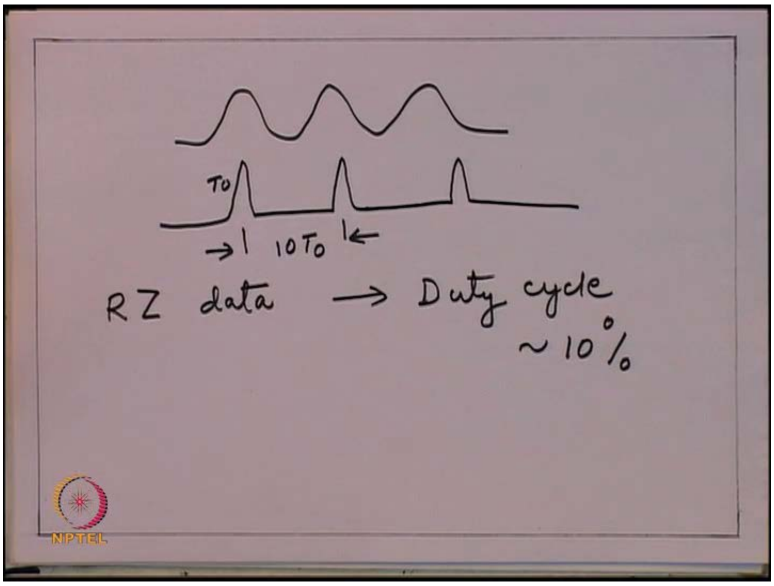

But what; that means, is then that the data which we are transmitting is naught of this type. We are saying that we should have a pulse which is like this the second pulse should be separated by distance which is about. So, this is if this is t naught the width of this is t naught the separation between this should be about ten times t naught then the like that. So, first thing if you are looking for solitonic communication first thing becomes clear that since we are going to talk about this pulses, the data has to be in the form of r z. The N r z data which cannot give you this pulse which we are getting train of the long once you will not be able to get this pulse nature into the data.

So, the data has to be r z kind of data for solitonic pulse generation. Second thing it is clear that the duty cycle of this r z data has to be only about 10-20 percent. Because, if it was more than that than there will be attraction and repulsion between this r z data pulses. So, we look for duty cycle or this is order of about 10 percent only this situation then we can create the propagation which is a solitonic propagation. Or another words what it means is that if you want to send that 10 gigabits of data, the pulse width would correspond to 100 gigabits because the pulse width is going to about one-tenth of the what about data rate you are transmitting.

So, earlier when we are transmitting the analysis data the bandwidth required by this system would be about two times something like that for the data of the data rate. Whereas, now when we are going to transmit this kind of pulses bandwidth which is required is order of magnitude higher than the data rate. And that is the reason we will naught able to push the data rate very high because the total bandwidth required by this is going to be much larger compare to what the data rate is. So, when we are looking at a solitonic communication it might appear now that since the soliton is a pulse which can travel and distorted over a very very long distance. We can arbitrarily create a very narrow pulses and very high speed data large bandwidth data can be transmitted. But, unfortunately that is not true because the band width which is required is order of magnitude higher than what the data rate you can transmit.

So, that brings as back again to the data rate may be typical of the order of about 10 gigabits at which even in the sol tonic pulse form you will not be able to increase the data rate much larger than that. So, that is one issue, that when we are taking about sol tonic communication. Then you have to generate the data in the r z format with a very low duty cycle. That means, much larger bandwidth requirement then what the N r z data normally would require for the normal communication.

The second aspect which is which is again important is that for this to happen as we mentioned earlier for the solitonic communication to take place and thing to go and distortion. The non-linearity should keeping role, it should keep dominating what the dispersion. If the non-linearity loses at any point of time then the dispersion will dominate non-linear will become further weaker and then the game is loosed that the pulse will go on broadening after that. So, that means, at every point we should make sure that the non-linearity length is always smaller than the dispersion length.

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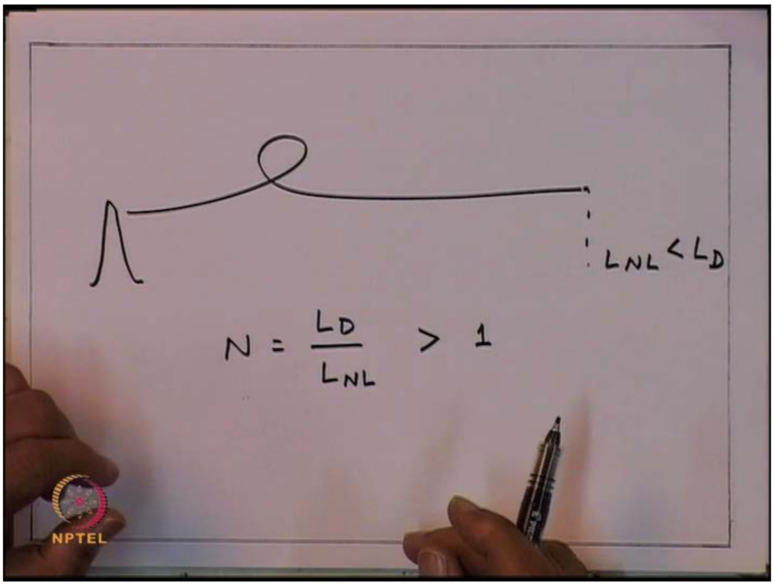

Now, when we include the loss on the fiber the non-linearity length will go on increasing because the power level go into come down. So, we are saying now that if pulse is launch inside the optical fiber. So, we have this optical fiber with the pulse is launched you launch a pulse in this of a such power that even after loss at the other end of this fiber, the non-linearity length should still remain smaller than the dispersion.

So, if I consider a typical loss of that us say 10 d b or something like that on the fiber even a very modest number. What that means is? The power which is required for the fundamental soliton to sustain at this location, the power at this has to be order of magnitude higher or non-linearity length now has to be much smaller compare to this length. But if that is a situation at this location would we get the soliton which is fundamental soliton? And the answer is no. In that situation the parameter N which we define which is L d by L N L is greater than 1. So, it will be 2 3 4 and depending upon this than you will have the higher order solitons. And if we do the analysis of the of the equation, you will see that the higher order soliton do not have a simple shape like hyperbolic secant.

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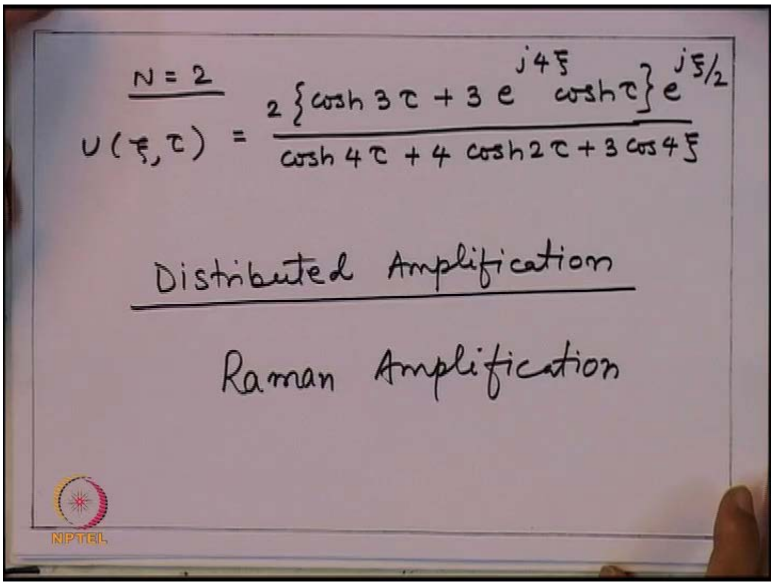

For example, if I consider the second order soliton. So, if consider N equal to 2 the shape of the soliton will be given by this 2 times.

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So, you see the shape which we got now for the second order soliton is extremely complicated shape. So, the data if you want to try to launch and if the fundamental soliton is not launch if it is higher order soliton then it is not the simple data pulse. The function becomes extremely no extremely complicated the function.

So, what the situation then means is? That if you want to transmit the data in the form of solitonic pulses and if you do maintain the soliton here at this location which is the other end of the optical fiber, I cannot excessively increase the power here to compensate for the loss. Because if I just increase the power here which is just of set this loss this power will become excessively large. Then for that power the fundamentals soliton the higher order soliton will get excited and which will have a shape which will not be simple pulse like shape. So, I will get a lot of distortion I did not do into data pulse.

So, increasing the power level here, so that the non-linearity keeps dominating over dispersion at every location of the optical fiber is not the solution to have a sustained Solitonic communication on the optical fiber. Because here then you get a higher order soliton. So, it becomes upper end then the, if you want to make the solitonic communication feasible, workable then we are not looking for a mechanism which will simply jack of the power per location.

We are looking for a power or looking for a mechanism which will just of said the loss which will compensate for the loss. So, that the power at in location it does not become excessively large to excite the higher order soliton. Or in other word what we are saying is we are not looking for an amplification process which is lamped at the location. We are looking for some kind of distributed amplification mechanism which will just keep on compensating for the loss.

So, the amplitude of the pulse practically remains constant any travels on this. So, in no situation the annual go more than more than 2, it will always remain less than 2 so that the higher order soliton cannot get generated. So, for a solitonic system to become a realizable system, we have to look for a distributed, amplification mechanism. So, in a long how will communication link, we cannot really say that periodically VCP amplify the signal by using some lambda amplifier and then the soliton will propagate and when the non-linearity become weak again we can amplifier the signal will so on. We can do that because that is going to create higher order solitonic problems.

So, only soliton now is to device a mechanism which gives distributed amplification. And as we have seen earlier the erbium doped fiber amplifier are the lumped amplifiers. The data travels on optical fiber when you have a single to noise ratio problem. At that point we introduce this EDF erbium doped fiber amplifier the signal is amplified and then again it propagates, attenuates on the optical fiber. Again when the single amplitude goes down they can amplified do periodic amplification. We keep doing all the normal optical link here, we are saying that if we have to use the sol tonic communication then we have to have a mechanism which will keep maintaining the power in the optical pulse. Whatever the loss is it is simply compensate for that loss and that this distributed mechanism is provided by what is called the Raman amplification.

So, Raman scattering is the another non-linear effect and that effect will discuss that effect is use to create the distributed amplification inside the optical fiber the many other characteristics of Raman amplification. But, from sol tonic point of view the most important thing for Raman amplification is that it give the distributed amplification. And once you are a get distributed amplification one can always make sure that at every location the power in the pulse is such that only fundamental soliton is maintained and higher order solitons are not excited. So, a distributed mechanism like Raman amplification is the keyword if you want to make the sol tonic communication possible. Experimentally people have demonstrated the propagation of soliton inside the optical fiber not in the real system, but, creating the loops of optical fiber. And sort of periodically maintaining a power in the optical pulses, the optical solitons have been demonstrated in the laboratory the optical solitons have to come in the life.

So, as a times moves and as the distribution distributed amplification becomes more and more use a bill in the system. You will see that we will have the propagation high speed data communication which inside the fiber will be in the sol tonic.

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So, let be summarize what we have done? We are looking at different non-linear effects and dispersion effects on the optical fiber. So, we made a simple formulation of the wave equation approximated it, linearism it. And we got an equation what is called non-linear Schrodinger equation which gives the evaluation of a pulse on the optical fiber in the presence of dispersion and non-linearity. We saw in the dispersion domain the pulse broadens the spectrum remains intact in the non-linearity domain which is selfish modulation. The pulse envelope remains intact, the spectrum broadens when you are having both of this to together then we have a phenomena what is called soliton. And in this case the pulse neither broadens nor contracts it does not get internally frequency modulated. So, this phenomena travels like a particle, but, then we saw that if you have multiple solitons travelling next to each other. Then they behave like charge particle form that means, they have a behavior the charge particles have, they have a force of attraction repulsion

So, when the multiplied pulses start travelling in the form of solitons they show collapse of two pulses, again separation some periodic behavior which is not very attractive. So, then we saw that two have multiple pulses transmit in the sol tonic form. We have to create pulses which have a very low duty cycle; they are in the r z format low duty cycle. So, that the attractive or repulsive force between this two solitons become negligibly small and this pulses can keep travelling in the form of sol tonic pulses. Then we also saw that two make at more practically realizable the distributed amplification is most important. Because the lambda amplification if you use for periodically for a compensating for the fiber loss, it will create possibility of higher orders solitons which are not simple in shape.

So, by using distributed amplification the power level inside the soliton can be maintained and then the pulse can propagating in the system fashion in the form of fundamental soliton through there are practical demonstration of this, but, sol tonic communication still has to become a reality realize, but, as time use we will see the sol tonic communication happening a reality in future.