Fiber - Optic Communication Systems and Techniques
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Lecture - 60
Four wave mixing, Loss measurement, Dispersion measurement

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. Let us continue the discussion in the previous module of nonlinearities, now we will look at another non-linearity which is called as four wave mixing.

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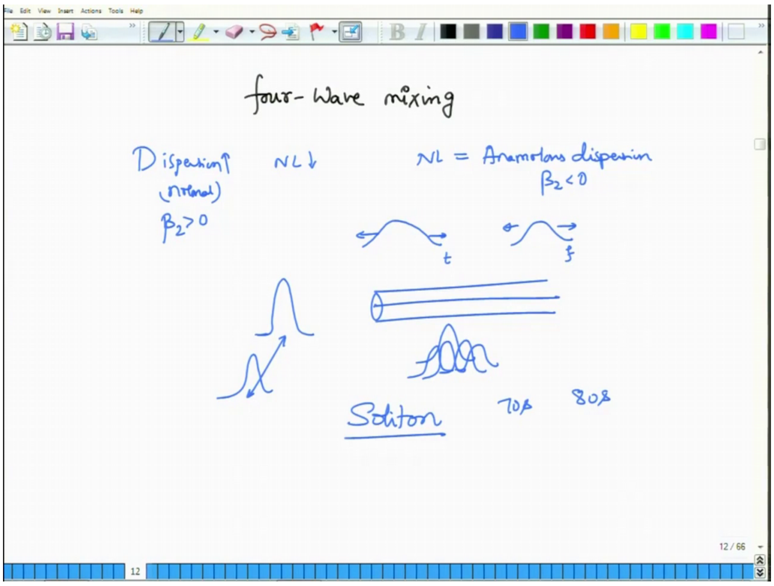

Now, before I get to four wave mixing, let me tell you and small other non-linearity as well or you know briefly one other non-linearity which actually is not just the non-linearity, it actually in the connection between non-linearity and dispersion. We said that non-linearity and dispersion can act with respect to each other, usually it turns out that whenever dispersion is present, non-linearity will actually go down ok.

And this happens when dispersion is actually normal, but in the case of anomalous dispersion things actually become slightly different. In that case what happens is non-linearity can exactly balance out the anomalous dispersion remember anomalous dispersion is where beta parameter beta 2 parameter is actually less than 0 whereas, for the normal dispersion beta 2 is actually greater than 0. So, in the normal dispersion case non-linearity is usually suppressed whereas, in the anomalous dispersion case, non-linearity can be enhanced and in fact, in some very special case non-linearity can exactly balance out the dispersion term ok.

So, while the dispersion act in a frequency domain, but it is effects are felt in the time domain such that the pulse tends to broadened the time domain, the non-linearity will act in the exactly opposite way non-linearity will tend to increase the spectral duration or the spectral width. Whereas, in time domain, it would not do anything, but when these two pair off with respect to each other balance out then you have an ideal or there is a pulse, which will effectively propagate in a lossless fiber without any change in the shape.

If I it is not just one pulse like this, if you take another pulse which is at a different wavelength, but it is also in the same anomalous dispersion regime having the same non-linearity. Then these two pulses can actually no propagate independently and even when one tries to overtake the other because of the dispersion difference and in the time of arrival difference they will simply pass through each other.

So, one pulse let us say is here and the other pulse will simply pass to the other one, without ever interacting with the other pulse ok. So, these are called as collisionless travel and this special pulse is called as soliton. In about this was actually discovered way back in 70s; however, experimental support did not turn up until about 80s and by late 80s everyone were predicting that solitons would be the next big thing in fiber optic communication system. And unfortunately that did not happen for variety of reasons

One of the reasons is that solitons require that the fibers be essentially lossless and dispersion and non-linearity be exactly balanced out. And if there was any perturbation in one of the parameters as it would happen in real fiber, then these pulses would lose their soliton nature. And then they will behave like any other pulse they will start to spread out they will start to talk to each other and all the advantages that you would have had that is pulses traveling without change in shape. And therefore, potentially be able to support many high data rate systems would simply not happen because of the real fiber characteristic. And in the fiber the dispersion is not constant along the entire length dispersion in fact, varies from point to point so, does non-linearity.

So, because of these variations you know affecting the overall system, the pulses will lose their soliton nature and that is the reason why it is never caught on as a replacement for traditional digital fiber optic communication system. So, although solitons were supposed to be the big thing, they unfortunately did not do very well in terms of an actual trial field trial although several successful laboratory trials were shown in the late 80s and early 90s, they did not simply materialize for the actual real transmission systems.

But, solitons are very important in an area called as pulse shaping because you want to go from say femtosecond lasers to a picosecond lasers one of the ways to do this one would be to use solitons. And you will see solitons if you were to study non-linear fiber optics which itself is used for many signal crossing and communication systems as well. So, you can actually mitigate all of those nonlinearities by non-linearity induced problems by actually using nonlinearities against them. So, that is something that we have only talked about in the sense that those are non DSP approaches for mitigating the impairments in the fiber anyway.

So, this was a brief idea about solitons, because it will come up in some discussion on optical fiber communication systems I wanted you to know what solitons are. But, please also remember solitons are not used anymore for optical fiber communications in fact, they were never used for optical fiber communications ok. Now, that we have put aside the single channels you know nonlinearities that is self phase modulation and two channel or more of the two channel non-linearity which are the cross phase modulation, what we have observed is that when there is self phase modulation the channel frequency the central frequency does not change right.

And when you have cross phase modulation between two different frequencies f 1 and f 2 cross phase modulation does not go and change the frequency f 1 nor f 1 will change the frequency f 2 not these two will introduce newer frequency terms right.

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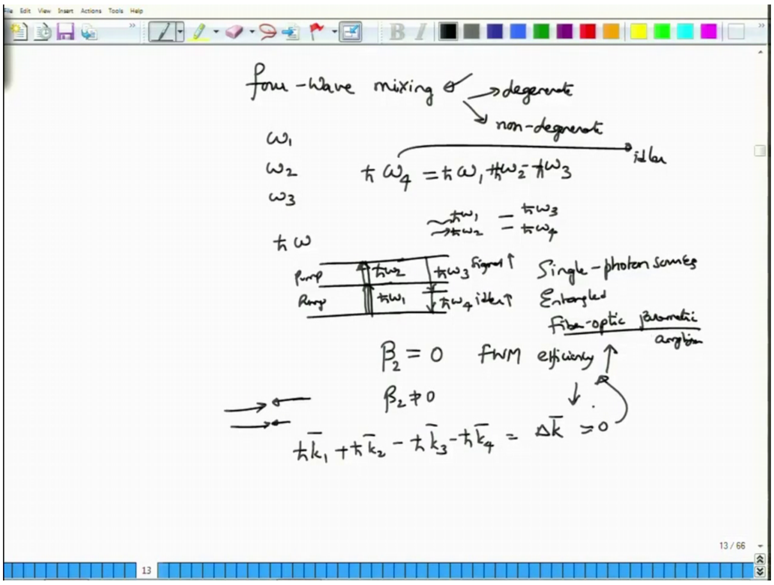

Whereas, four wave mixing as it is name suggests does exactly the thing right in four wave mixing you have three waves traditionally and in an optical fiber communication system sorry when optical fiber you can see that the minimum such mixing characteristic will be four wave mixing.

Although this further can be broken up into degenerate and non degenerate non degenerate case is the one that I am talking about right now there are three waves omega 1 omega 2 and omega 3 and these two will talk to each other, why are those nonlinearities that we talked about. And then result in a new frequency at omega 4 which is given by omega 1 plus omega 2 minus omega 3. Because, the energy of a photon is given by h bar omega multiplying throughout by h bar will also show you that this process of four wave mixing is actually a conservative process in the sense that the total energy h bar omega 1 h bar omega 2 will exactly equal to h bar omega 3 and h bar omega 4.

So, one of the pictures that we used to think about this is that, there is a atom lying in one state by picking up a pump power it will go to another state and the amount of pump power that is necessary to go from one state to another state is given by h bar omega 1. And then one other pump h bar omega 2 will introduce another additional energy h bar omega 2, it will lead to the you know the atoms go one additional level up and because they will give out energy. So, they may not give out exactly equal energies so, they might give out equal energy.

So, h bar omega 3 photon will be given out and the remaining h bar omega 4 photon will also be given out. That is the reason why you have a minus sign here or you can bring this h bar omega 3 plus h bar omega 4 and then make it equal to h bar omega 1 plus h bar omega 2. This four wave mixing is very helpful for us it is actually helpful for us in realizing what is called a single photon sources.

It is helpful in performing entangled photon pairs; it is also helpful in performing fiber optic parametric amplifiers. So, that is to say you can use omega 1 and omega 2 as the two pumps and then use omega 3 as a weak signal and at the output you can obtain signal which is amplified and this fellow called as idler also amplified. So, omega 4 interestingly is called as idler wave. Again the terminology of signal idler pump goes back to about 100 or maybe about 75 years and interestingly this four wave mixing was first discussed in the context of microwave engineering not in optical communication systems or optical fiber.

But, it was in the late 80s about 78, that it was shown that four wave mixing can happen in optical fibers as well. And this efficiency of the four wave mixing is dependent on the dispersion beta 2. If beta 2 is equal to 0, four wave mixing efficiency which is basically the amount of amplified signal power to the power pump power that we have totally injected into the fiber, this four wave mixing efficiency increases ok. Whereas, when beta 2 is nonzero that is when there is significant dispersion, this four wave mixing efficiency will actually reduce ok.

Now, these equations which have given are called as the energy conservation equation for very obvious reasons, but in optical fibers because those are not only having energy, but they also have momentum why are there wave vectors. It is also important that we satisfy exactly the momentum conservation as well there is their h bar k values, k 1 plus h bar k 2 must exactly be equal to h bar k 3 plus h bar k 4 we will call this difference as delta k and this difference delta k should be almost equal to 0 for high FWM efficiency to occur. So, in all the parametric amplifiers you try to make this delta k mismatched as we would call to as much as close to 0 as possible in this system. So, this is this is what we actually want to do in four wave mixing.

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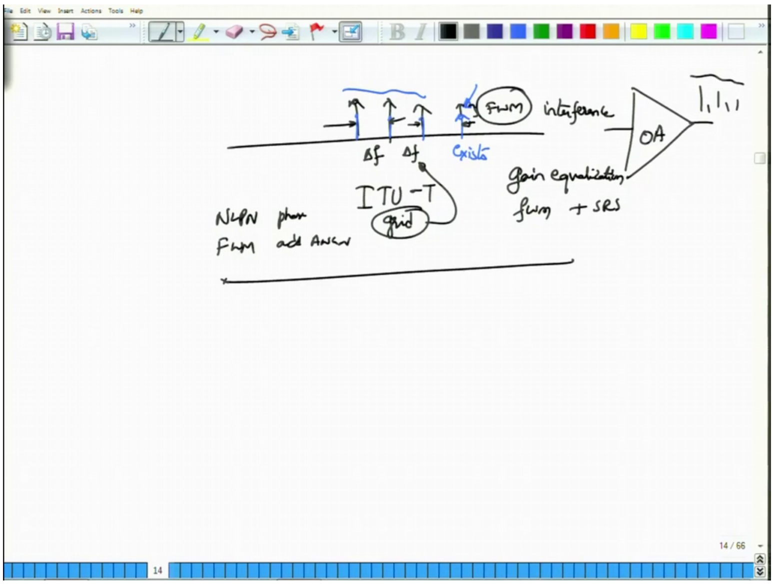

In communication systems why is it important? Well you now know that there are many many w d m channels right and if any of these three channels talk to each other and these channels are also usually spaced equally in frequency. Which means that the newly derived channel may actually fall into any of these original places itself or it may fall into one of the channels that already exists.

So, these three can combine and fall into a new channel where a channel already exists right and for this channel this extra amount of four wave mixing that comes in is actually a noise kind of a thing as an interference it is an interference from other channels. And as the other channels also vary with respect to time the amount of power and the amount of thing that is injected or if there is interfering into the existing channel also will change.

So, this FWM is actually an interference for us, this is very similar to the interference that occurs in wireless communication system when you have a strong signal and a weak signal. The strong signal will start to give out or interfere with the weak signal and if you present both of them to the amplifier, the strong signal will actually eat up lot of power while the small signal or the smaller signal which is at a different channel will not usually have anything.

So, this is called as a blocking signal, and exactly same thing happens in four wave mixing. Because these channels are usually followed up with an optical amplifier the channel which has a higher power will start to saturate the optical amplifier that is the reason why gain equalization is so, important and this gain equalization which will not happen when there is FWM plus those scattering effects that I talked about SRS no it is not SPS.

So, when they change the gain right then they will lead to lot of problems because one channel starts to eat up the entire gain that is available for the other channel. So, there will be at the output all these channels which are not properly amplified and therefore, this gain inequality will also persist at the output of the amplifier. So, this completes our discussion on non-linear effects we would not have much to say anything about them except that FWM interference can also be modeled as an additive wide Gaussian noise.

So, on top of the noise that is introduced by the optical amplifier, you have to take into account an extra you know noise that comes in the form of FWM interference. And therefore, whatever that you do to suppress the noise in the optical amplifier case, you can try and do the same thing for FWM although it is not easy to do so. There is one interesting part about FWM that I would like to tell you because, the channels are equally spaced the pumps and the you know the three frequencies omega 1 omega 2 omega 3 when they interact with each other, they will result in another channel or they will result in a frequency, which is actually on the on one of the other channels itself right.

So, it is actually going and sitting on the channel that is already exists. So, one common sense way of removing this problem would have been to make the channels unequally spaced in frequency. So, that when three channels interact, the fourth frequency that is produced as a result of four wave mixing will not fall into the existing channel, but it will fall slightly away from the existing channel.

Why was not it done? It was not done because the ITU-T grid right or the ITU-T which is the International Telecom Union specifies the grid spacing or the channel spacing in terms of equal frequency spacing. You see that when we auction the spectrum; we auction a spectrum with frequency not with wavelength and that is the reason why today optical channels are all spaced equally in frequency leading to an enhancing of the provided; we do not say that four wave mixing is not going to be a problem and they just make them unequal frequency spacing.

It will be a problem, but the problem will be much less than what it would exist today. So, as I said we are done with non-linear effects and as I have told you non-linear phase noise will affect the phase modulated systems. FWM effect will affect everything it will add extra noise in the form of additive Gaussian noise. It may or may not be wide, but we usually make that assumption to be are clear about that work ok.

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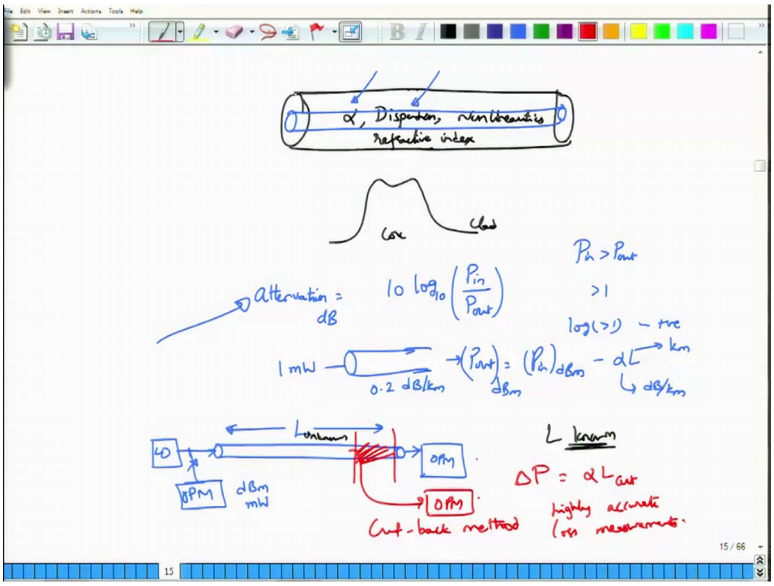

We have talked about optical fiber properties right, we have talked about attenuation, we have talked about dispersion and we have talked about nonlinearities how do we go and measure these properties? I do not have time to discuss all the measurement techniques. In fact, I would also like to discuss would have liked to discuss the refractive index profile measurement technique. How do I know what exactly the refractive index profile of the core and the cladding that I am going to get there are methods based on diffraction that you can use to actually measure the refractive index profile, we are not going to discuss that one.

But, I would like to tell you at least two methods because for most applications non-linearity will not be so, severe except for long haul communication systems. So, we are going to look at two parameters or two important properties of the fiber that we would like to measure. So, let say we begin with attenuation; attenuation is defined as you know in dB it is usually measured in del you know decibels dB, it is defined as the amount of power that is input to the fiber to the amount of power that actually comes out. Please note very important thing here P in is usually greater than P out obviously, right.

Because, if the channel is lossy, the input power will be always greater than the output power which means that this ratio in this bracket will be greater than 1 and log of a quantity which is greater than 1 will be a positive quantity. So, even when we talk of attenuation; even though we talk of attenuation or loss it is always referred to in terms of positive number. But, we do know that if I send in one milliwatt of power to a fiber whose attenuation is about 0.2dB per kilometer right then the output power will actually be equal to input power measured in d B m scale output also I measured in d B m scale minus alpha times L, where alpha is measured in d B per kilometer L itself is measuring kilometer.

So, the output power will be have to be subtracted by putting this negative sign right. So, please keep that in mind. How do we go about measuring attenuation? Well, there are a very standardized technique that we use in laboratories to measure and you will see some of these techniques in the demonstration video that we are going to upload with the course; what we do is we take a laser and then we measure the laser output through using what is called as an optical power meter.

So, let us call this as OPM. So, optical power meter will give you an optical power it will indicate the optical power usually in dBm scale or if you want you can also indicate that for in the milliwatt scale and you are directly measuring the optical power from the laser diode. Please note that we are not using any polarization device here because we want to capture all of the power that is coming from the laser diode right.

So, this is the first step that you are going to do. After you have done this step you are going to switch over this optical power meter ok. So, this will continue to go there and then you disconnect the optical power meter here and then you put the optical power meter here and then you measure the output. If you know the length of the optical fiber which again is a separate measurement thing that you need to perform using usually an interferometric technique. Then you know what is the output power that you are going to get and using this equation you can find out what is the attenuation per kilometer of this particular fiber?

But, again the drawback of this method is L should be specifically known alternatively you do not know what the length is so, fine no problem. So, you just say put this is length is unknown you measure the optical power here no problem measure the optical power here next what you do is you cut a known section of the fiber you cut off the known section of the fiber. And this can be done much more controllable manner, that is you can actually take a ruler and then line align it along and then get accuracies to just about few millimeters right.

So, you can cut this thing, and then remove the cut portion and reinsert the optical power grater ok so, to the original length. Now, you know what is the optical power that you have measured here you know what is the optical power measure that you have measured here. And the difference in the power should definitely be equal to alpha times the length of the fiber that has been cut this method is called as cut back method; obviously, the destructive method because, you are going to cut the fiber and the piece of fiber may or may not be used. However, this is used at the fiber plant to obtain highly accurate; highly accurate loss measurements

So, this is about attenuation measurement, you will see this attenuation measurement not with the cut back method, but with the standard referencing method that I discussed earlier in a demonstration video there is a second thing that we want to discuss.

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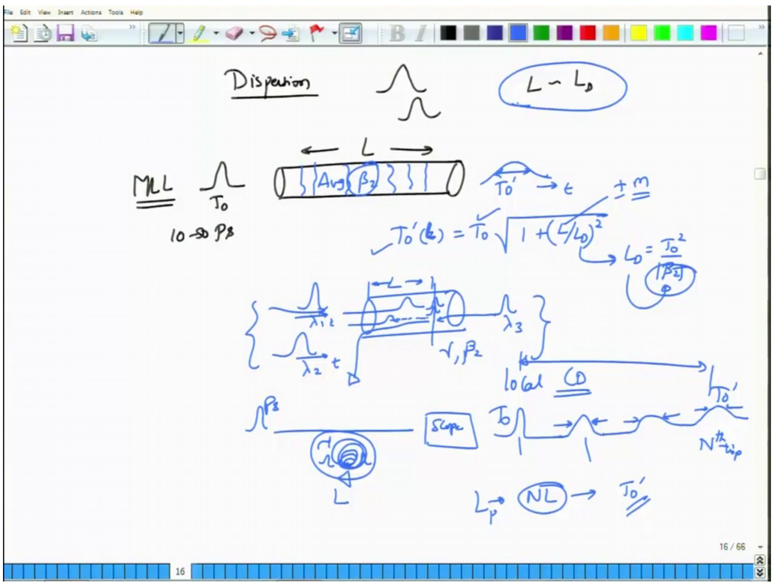

How do we measure dispersion right what is the effect of dispersion? The effect of dispersion that we are interested is the pulse broadening of the fiber or introduced by the fiber. So, one straightforward way is to actually put a fiber of certain length L and the length L should be appreciable quality of or appreciable fraction of the dispersion length itself right. If you do not have this L to be long than you usually do not be you are not able to when you cut the dispersion effects right.

So, we will see how to overcome that problem later on, but if you can get hold of an optical fiber which is about say 100 or 120 kilometers of length then what you do is, you send in a known pulse you know of known pulse width T 0 here. And you can do this by using what is called as a mode locked laser. A mode lock laser will actually emit pulses of appropriate duration and this duration of the pulse will be just about a few picoseconds.

So, may be about say 10 to 50 picoseconds of the pulse width that you are using. So, about 10 to 50 picoseconds pulse is what you transmit or you launch into the fiber. Now, after the effect of dispersion would be to actually broaden this pulse right, in the time domain it will broaden the pulse do not look at the frequency domain because ideally dispersion will not change the frequency spectrum. But, you now look at the time domain you know what is the new pulse width T 0 prime, you know what is the old pulse width T 0 and then you know that equation which says that T 0 prime of z is basically T 0 into square root of 1 plus length by L D whole square approximately right.

So, if you know the fiber length L and you know what is the dispersion length of the fiber that anyway you have calculated, then you can actually find out what is l d of this device or of this fiber by looking at T 0 prime, at the output of LT 0 and knowing what the length of the fiber that you have put in. Here, even if you are off by plus or minus few meters it is all right that does not change the dispersion too much.

And when you find out what is LD you know LD is basically T 0 square by beta 2 from this you can find out what is the magnitude of beta 2. So, this is one method which you can use to measure dispersion. The drawback of this method there are several drawbacks one of them is that it gives you an average value of beta 2, it does not really give you the local value of beta 2.

If you want to find out local value of beta 2 there is an interesting thing. You can actually sending one pulse at one wavelength lambda 1 you send in another pulse at a wavelength lambda 2 and because of dispersion they will travel at different times ok. And then you can actually is make them adjusting that time delay difference between them. So, this is with respect to time if you make them align at different times, then if your fiber is there.

So, after as the pulses start to propagate at some point they will actually meet and you can control the point where they meet and then you can also put in one more signal on the from the left hand side. And then selectively amplify this pulse on the lambda 3 signal you can amplified and as the amplified lambda 3 comes out, we can take this thing out. And then by knowing what is the length which you can anyway calibrate properly you can know the attenuation of this lambda 3 that or the signal that it has undergone the attenuation, you can remove that attenuation and then by looking at this particular point where they are you know interacting you can find gamma as well as you can find beta 2.

The exact way of doing this one is something that we are not going to look at any more detail, but this is a very interesting example which has been used to measure local dispersion. So, local values of beta 2 can be measured by these schemes that was the first problem average dispersion. But, you can overcome the average dispersion problem by taking a shorter length of the fiber and then measuring the local dispersion. The bigger problem if you know if you do not want to know local dispersion, but you are only interested in the average dispersion would be to actually find a piece of fiber of length L which is closer to the dispersion length.

So, that you can observe the pulse difference or rather you can observe the way in which the pulse is actually spreading out right. So, you can there is another problem with that one. There is a way to overcome that problem and that would involve looping the fiber you sending the pulse you send the pulse in there and then you can put an amplifier just. So, that you are covering up the losses in this particular span and as the pulse which is about a few picosecond long, you start looking at the pulse at the output so, you have a scope here. First time the pulse will go in portion of the pulse will go into the loop a portion of the pulse will come out. So, you are going to look at the pulse here, then as the pulse goes through and then comes up it will suffer one span propagation.

So, after a certain delay you will see that the pulse that would come out is slightly longer. And then again as it keeps on making these loops and loops, eventually you will see that the pulse you know broadens and by looking at the delay you can find out what is the delay in the loop, I mean by knowing the delay in the loop. And after certain calculations you can actually see that the dispersion induced in the fiber after a certain round trip propagation you know what is the nth trip propagation, by knowing the delay between the first one and the nth output and therefore, it has propagated a total distance of NL,

And in this NL the pulse has broadened to T 0 prime here compared to the original T 0, and then you can actually take this as the length of propagation and then calculate what would be your from the pulse width that you know you can calculate what would be the average value of beta 2.

In fact, you can do this even for shorter fiber lengths, but then you will have to wait for a long time for these pulses to actually come out ok. So, local dispersion also can be measured in this way, but it is not as successful I mean you cannot do it as successfully as the earlier method that I discussed because, shorter fiber length means you have to wait for longer round trip times.

And you will also have to know see that if you are using a periodic source, then this pulse that you are sending should not emit another pulse or you should not send one more pulse until after sufficient round trip time has. So, this would call for very short pulses, but with a very long repetition times right. So, to the preparation rate should be very very small.

Again these are something that is actually useful in the femtosecond regime case because, you can find femtosecond lasers with just about one kilo hertz of no repetition rate. And within that one millisecond you can have many such round trip after round trip propagation many many such after loop propagation many such pulses whose width you can use as a parameter to actually measure the bandwidth sorry measure the dispersion coefficient of the fiber.

In fact, by using self phase modulation that is by actually transmitting a set of known signal. So, let us say q p s k with only a single constellation and then accumulating at the output what is the constellation points you decode them, under the output you actually once you get sufficient number of points, you can put up a constellation diagram. And by knowing how much this has moved you can estimate what is the variance of the noise induced because of the phase shift or self-phase modulation.

And because self phase modulation corresponds to the movement by gamma P into L, knowing what is the peak power that you have used knowing what is the length of the fiber you can even find out what is the value of gamma which is the non-linear coefficient or sometimes called this square non-linear coefficient.

So, these are some of the methods that you will use in characterizing an optical fiber, these are very important if you are especially a fiber manufacturer they are also equally important whenever you are under taking any experiments in laboratories which make use of optical fibers.

Thank you very much.