Fiber-Optic Communication Systems and Techniques

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Lecture - 59
Nonlinear effects in Fiber

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Design. In this module, we will look at an important effect that takes place in an optical fiber, when the power is large.

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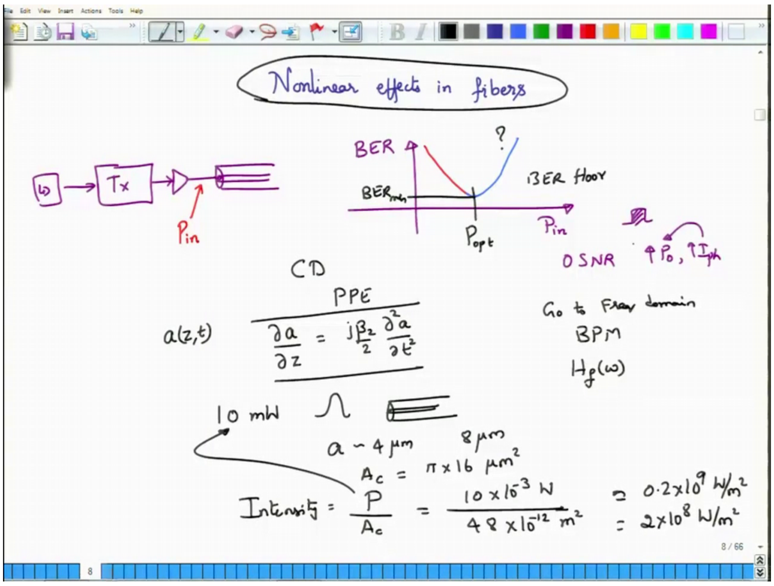

Now, in the previous module, we have seen that when you consider an optical fiber communication system, you will have lot of impairments. And what do those impairments do, they will actually increase the bit error rate of the system. So, when there is an additive noise or there is a phase noise frequency of it or any combinations of these which usually will be the case, they will all cause the BER to actually increase right.

Now, in traditional communication systems, you might have seen this type of plots, where we plot on the y-axis, the quantity which we call as bit error rate. And on the x-axis, we plot what is called as a signal to noise ratio. Now, if you keep the overall noise to be as the same, and in these cases I am assuming that we are dealing mainly with the additive White Gaussian Noise that is introduced by the optical amplifiers. The effect of phase noise is not considered in this graph. But, in general communication systems, which have noise, which is additive White Gaussian, which is what we have also assumed for the optical amplifiers.

If you keep the reference bandwidth, where you are calculating the noise power to be same, and then you essentially fix the noise power. Then to increase the signal to noise ratio or the optical signal to noise ratio or the electrical signal to noise ratio, we would have to increase the appropriate optical power or appropriately the photocurrent. And photocurrent increase would of course, depend on the increased optical power being incident on the photo detector. So, essentially what I am trying to tell you is that if you keep the noise level fixed, then instead of plotting on the x-axis, the signal to noise ratio, you can plot what is called as the launch power of the communication system.

What is this launch power, you have your transmitter, and then the transmitter after a first amplifier are called as the main amplifier or the amplifier that is just introduced after the transmitter to compensate for the losses. In the transmitter from the laser to the transmitter, whatever the losses that I have existed, you can compensate that one by placing this amplifier right. So, this corresponds to the transmitter of a single carrier system, this would go into the optical fiber. So, this is what will go into the optical fiber, and then begin to propagate to the receiver.

And when we talk about launch power, we are actually talking about the power that is launched into the optical fiber here. We are launching the power here, which we call as the launch power. And as you could of course, guess increasing the launch power would obviously, increase the signal to noise ratio, optical signal to noise ratio, which in turn will also increase the electrical signal to noise ratio, because you have more optical power being launched into the fiber.

Now, we do so, as I was saying you if you can look at traditional communication systems and look at textbooks or look at the literature, you will find that as the launch power P in increases, the bit error rate actually drops ok. So, this is something that you would also expect, because now if the input signal power increases the that means, it is now able to withstand more amount of I mean withstand the noise better than a system which has a lesser input power. Why is that so, because we have kept the noise level here and now increasing the signal power means you are moving away much higher in terms of the noise power.

So, while noise does impact your bit error rate, the effect is not so in you know the effect is small, when the difference between the signal power and the noise power, which is essentially what the signal to noise ratio is you know that if the difference is actually quite large, then the effect of noise will be smaller. And therefore, the number of errors that you would make would also be reduced substantially. So, this is something that you would expect physically also that as I start increasing the power, which in turn increases the signal to noise ratios, whether I talk about the signal to noise ratio in the optical or electrical domain, my BER of the system should actually reduce alright. So, this is what one would expect.

Now, if you look at the same situation for an optical fiber communication system, and then you start increasing the launch power of whatever the channel that you are transmitting, something very interesting happens. The BER initially decreases from a value, which is high, which is of course as expected. And after reaching a certain minima, starts to increase again. Now, this is something that is very interesting right. So, this is the optimal launch power as we would call it, because at this point the BER of the system will be at its minimum. So, this is sometimes called as BER floor ok, because the BER actually goes to the floor or reduces to the minimum value, and then begins to increase again.

Now, why should this BER increase here, I mean there is there any reason as to why BER instead of decreasing as the power increases, actually leads to an increase in the BER rather than decrease in the BER. And the answer turns out that in optical fibers, we have so far assumed the fiber to be a linear medium right. So, all our impairment in terms of the actual fiber was by this chromatic dispersion, which we captured by equation of pulse propagation equation, which if you want to just refresh your memory is given by del a by del z, a being the pulse envelope correct; this is the complex pulse envelope. And I am of course, in this equation eliminating the carrier out there, and also going to all the you know retarded frame delayed frame will allow me to include the dispersion in a straightforward manner and dispersion as we know is acting in this particular way.

And of course, this equation is linear, this entire thing is linear, because the dispersion effect is also linear, I mean because of this linearity, we were able to go to the Fourier transform right or the frequency domain solve or account for the dispersion, and then go back to the time domain in our solution method called as beam propagation method. So, this is the linear description of the optical fiber. In this description itself, we were able to talk about the optical fiber transfer function as well turns out that this effect is true as long as the optical power is small.

Consider a simple calculation assume that we have 10 milli watt peak power pulse being launched into the fiber ok, and I am going to assume that this is a single mode fiber. So, the fiber core radius a is about 4 micrometer, the diameter is about 8 micrometers. And the core area which we will call as say A c will be about pi into 4 square, which is about 16 right, so 16 into pi micro meter square. So, this is what the core is.

Now, look at something interesting. We define the intensity of the optical signal as the power that is contained by that optical fiber divided by the area over which the pulse is spread out. For simplicity, we will assume that all of the power is actually concentrated in the core itself, although that is strictly speaking not true. But, we will assume that one, this is a good approximation for most cases that we are considering and then evaluate, what would be the intensity here.

Turns out the intensity for assumed peak power of 10 milli watt will be 10 into 10 to the power minus 3 watt divided by pi. Let me approximate it to be 3, so that I have 16 times 3, which is about 30 to 48 right. So I have about 48, this is micro meter square. So, converting that into meter, will give me minus 12 meter square. So, you can see that the units are all nicely matching; intensity is basically watts per meter square.

And you can see that even if you now make this approximation that instead of 48, you can take this approximately to be 50 that 0 and 0 will cancel with respect to each other, and then you have 1 by 5, which is about 0.2 into and then this 10 to the power minus 12 in the denominator will go to the numerator right. So, once that goes into the numerator, it would be 12 minus 3 that would be 9 into 10 to the power 9 watt per meter square right. Alternatively, you can express this as 2 into 10 to the power 8 watt per meter square.

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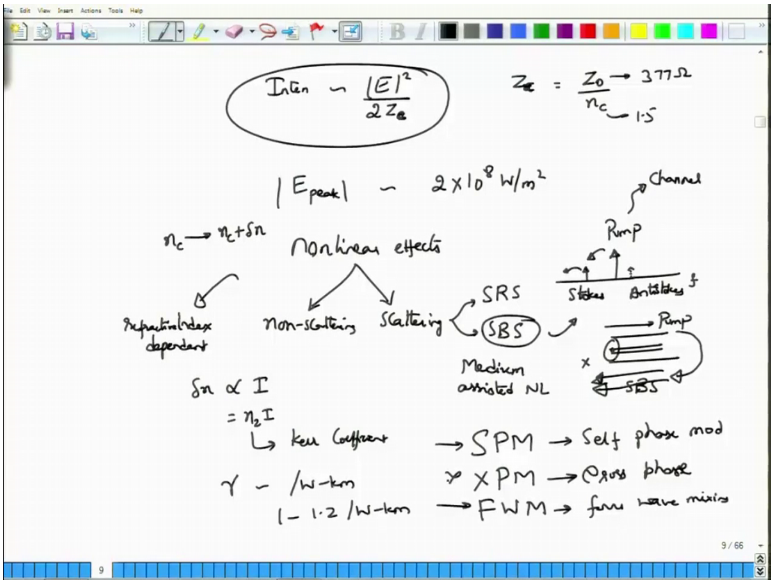

Just to give you an idea of how high this intensity is. Let me tell you that intensity is kind of I mean is actually proportional to the peak electric field square magnitude of that one divided by 2 Z naught Z naught or Z c let us say. Z c being the core impedance, which is given by Z naught divided by n core right. Z naught is of course, 377 ohms, as we know from our electromagnetic courses, n c is about 1.5 for typical single mode fibers.

And what I would like you to do is to use this equation, and then determine; what is the peak value, magnitude of the peak value corresponding to an intensity of 2 into 10 to the power 8 watt per meter square right. So, you do this, and then you will see that the resulting electric field will be several kilo volts per meter, and if you condense that into a centimeter that will be enormous value or micrometers, as because the optical fibers are actually micrometer based sizes of those devices. So, you will see that there is enormous electric field that the fiber core needs to support in order to transmit as simple as about 10 milli watt of optical power right; that is a small amount of power by any measure that we normally think off, because our transmitters, RF transmitters or the wireless base station transmitters are running at 100s of watts or sometimes even kilowatts.

So, what is really happening, the difference between those systems, which use these high powers, and the optical fiber system is that all of this power, even though it is very small is condensed into an even smaller core area. And remember, this is only the single carrier case that we considered. In an optical fiber communication system, there are about 200

WDM channels DWDM channels. And if all of those 200 DWDM channels are going to give in just about 1 milli watt of peak power pulses, and if all the pulses line up simultaneously at the same time, which happens many times; in fact, it happens all the time. Then you will see that the total power density or the total intensity that is being sustained by the optical fiber is extremely large.

And this extremely large intensity causes the breakdown of the material itself leading to non-linear effects ok. So, this is what we want to look at in very brief things, because this entire thing to discuss non-linear effects would mean that we have to float a separate course for this, which we are not doing. So, we will just recap the main non-linear effects that will be necessary for us to understand optical fiber communication system.

These non-linear effects are usually classified into two types; one is called as the scattering effects. In the scattering effect, you have what is called as Stimulated Raman Scattering, and you have Stimulated Brillouin Scattering. In the Raman scattering, what happens is when you send in a wave, this wave is going to generate two additional waves; one wave is called as the stokes wave, and the other one is called as the anti stokes wave ok. So, this is in the frequency picture, stokes will have usually the lesser frequency, the anti stokes has a higher frequency.

In terms of the wavelength picture, they are actually different. And this power, which is optical power that we have transmitted is usually called as pump. These are all older terminology. This was in fact, discovered by Raman way back about 100 years ago. And this notation of using pumps stokes and anti stokes, actually comes from about 100 years old. What for our purpose is this pump could equally be a channel that is carrying information with reasonable optical power.

What it means is that, because you have put in this channel, because that there is a channel that is propagating exist in the core, it will actually give some amount of power to the stokes wave and results in the generation of the stokes. So, as I start increasing the pump power it turns out that, it will start to give more and more power to the stokes, the stokes will eat away or the stokes will start to give power back to another thing and then so on and so forth. And this is how your channel actually starts to lose power. And when you have multiple channels, each of those multiple channels will undergo Stimulated Raman Scattering, and start giving out power. In terms of the wavelength picture, the smaller wavelength signals are the pump signals, which are stronger, and they start giving out the power to the higher channel.

So, while you may have started off with all the channels at an equal power, which is now required for many cases in optical receiver operation. By the time, it has passed through the fiber, these powers are all become unequal, and then what you have is a system, where the gains of each channel will be different. And it will actually depend on what is the power in the other channel, and what is the propagation that has happened, and what is the power that you have presented in the principle channel itself. So, Stimulated Raman Scattering varying the stokes and the pump frequency shifts are quite large, they are about 10 to 12 terahertz. So, it is a large shift as we are talking about. But nevertheless, will impact our optical communication systems, because it starts to eat away the power.

Now, you can very well appreciate, why we are actually going to have this BER rate increase rather than reduce. Because, as you start increasing the power of this channel, it will after a certain threshold is reached, these scattering effects actually have a certain threshold. After the threshold is reached, they will quickly transfer all of their power to the stokes wave. And the stokes wave will grow, stokes wave will need introduce additional stokes wave and so on, but the main channel which was our channel of interest has lost power.

Now, losing power means signal to noise ratio actually goes down, and therefore BER actually starts to increase again. Now, that may not be symmetric, because symmetric would mean that whatever the power increase is happening is the same as the case for the power decrease. So, it is not symmetric, because not only Simulated Raman Scattering is there, there are additional non-linear effects.

So, the other non-linear effect, which actually limits what is the maximum power that we can actually put into the optical fiber is called the Stimulated Brillouin Scattering ok. It is also very similar in nature. You have a pump, and then you have stokes, the anti stokes is usually very small and thermal dependent or temperature dependent, so we do not worry about that one.

But, the important property of Stimulated Brillouin Scattering is if in an optical fiber, the pump propagates in the forward direction or the channel starts to propagate from a to b, the Stimulated Brillouin Scattering signal propagates in the opposite direction. Now, this is the reason, why it is used in many sensor applications, especially for structural health monitoring of buildings, but it is actually bad in terms of optical communication system.

Because, as the pump power increases, once we have reach the threshold, all of the pump power will be converted to the Stimulated Brillouin Scattering, and this one will grow in the backward direction. And it will interact with the forward propagating signals meaning that we are actually going to lose lot of power here as well. And these are scattering effects, which require the fiber to assist them. So, these are sometimes called as medium assisted non-linear effects, because the medium which in the form of the lattice vibrations have to be involved in order to observe these effects.

Then there are what are called as non-scattering effects. These non-scattering effects are also called as index. When I say index, I actually mean refractive index. Refractive index dependent phenomenon, because these non-scattering non-linear effects will actually modify the refractive index of the fiber. So, the fiber refractive index, when there is nothing will be n c. But, after including these non-scattering effects, it will actually become some n c plus delta n, where delta n is proportional to the intensity. In fact, it is given by n 2 times I. And n 2 is called as the Kerr Coefficient or Kerr Refractive index term, and I of course, is the intensity.

And now, you see why intensity plays an important role not the power, because you may have a high power system. But if the area that this power is taking up is huge, then the power per area is actually quite small. Whereas, if you take the small amount of power, but try to squeeze it in into as narrow as possible, the space such as an optical fiber core, then the intensity becomes high. And the modification of that results or the intensity will result in the modification of the refractive index, which will give us to three main effects; one is called as SPM, the other is called as XPM. And finally you have what is called as FWM.

What is SPM, S stands for self phase modulation ok, and XPM stands for cross phase modulation ok, and FWM stands for four wave mixing. The strength of non-linearity in optical fibers is also given by the term gamma instead of n 2. A gamma is measured in per watt kilometer. And for a standard single mode fiber, this is about 1 to 1.2 per watt kilometer of these three effects. We will look at SPM and FWM, XPM being important, unfortunately we do not have time to look at that one. So, we are not going to look at XPM here.

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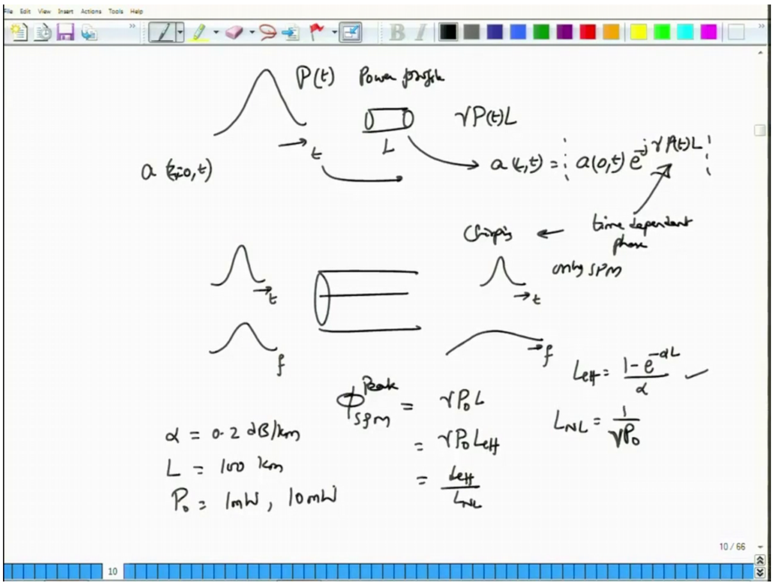

SPM is very simple. Suppose, I have this pulse ok, which is a function of time, then because of the non-linearity what will happen is this pulse or the pulse profile P of t this is the power profile ok. So, please remember, this is the power profile that we are talking about. What will this do is that it will change the refractive index by a factor of gamma P, and it will also make the refractive index dependent on dependent on time. And if you propagate this pulse over an optical fiber of length L, then you will see in the absence of any attenuation, you will see that this would be the total phase shift that the signal would suffer will be given by gamma P of t times l.

So, if you started off this one as a of z equal to 0, t by the time you reach at L, you have a of L t being equal to the original pulse amplitude multiplied by e power minus j gamma P of t times L. And as you can see, this is a time dependent phase. And we know that when this time dependent phase exist, then chirping will also exist right. And gamma in this case is positive for an optical fiber, so the chirping that you will actually find will be of the nature that will be opposite to the dispersion.

So, when there is dispersion, the chirping introduced by the dispersion will oppose, the chirping introduced by the self phase modulation, they will eventually one of them first we will one of them will be stronger. Usually the non-linearity will be stronger, so SPM induced chirping will be larger. And then as the dispersion takes over, it will reduce the amplitude and the power of the pulse that is propagating, because dispersion spreads out signals in time. And because of this reduced power, the non-linearity will go down.

But, because non-linearity has already introduced chirping, which means it has introduce newer frequency components, they will talk to the dispersion, and then they will again in increase the dispersion in the time domain further. So, these two actually talk to each other. And it turns out that when you have both dispersion and self phase modulation, they will actually reach a equilibrium at some particular point, and then the fiber bit I mean then the pulse will actually starts to propagate.

So, initially non-linearity will dominate. Non-linearity please remember, will not change anything in time domain. So, the pulse with respect to time domain will be the same. This is the frequency domain picture at the beginning of the fiber, but now as it propagates. If there is only non-linearity that is if there is only SPM, then the pulse will not change in time, it will maintain its shape, because you know you can look at this one. Take the magnitude of this magnitude of this one will actually be equal to a of 0 t magnitude. So, with respect to time nothing has changed, but because there is a time dependent phase that will lead to chirping, and it will lead to expansion in the frequency.

So, you can see that newer frequency components have come in the frequency domain, and this is the main effect of self phase modulation. The maximum phase shift that the signal will experience is given by gamma P 0 times L in the absence of attenuation. If there is attenuation, then that would be gamma P 0 into L effective, where L effective if you recall is already given by 1 minus e power minus alpha L divided by alpha.

Interestingly L NL, which is called as a non-linear length is defined as 1 by gamma P 0, this is defined with respect to the peak power that we have incident. And therefore the peak phase shift that you are going to get. Let me just write this as peak phase shift is given by L effective to L NL ratio ok. And you can calculate what would be this ratio for alpha equals 0.2 dB per kilometer of a fiber; and for one span, which is about say 100 kilometer. So, you can calculate what would be L effective from this equation. Calculate what is L NL; assuming that the peak power is about 1 milli watt or at about 10 milli watt right, and then you can find out what would be the peak phase shift that is induced because of the SPM. What is the effect of this SPM on communication systems?

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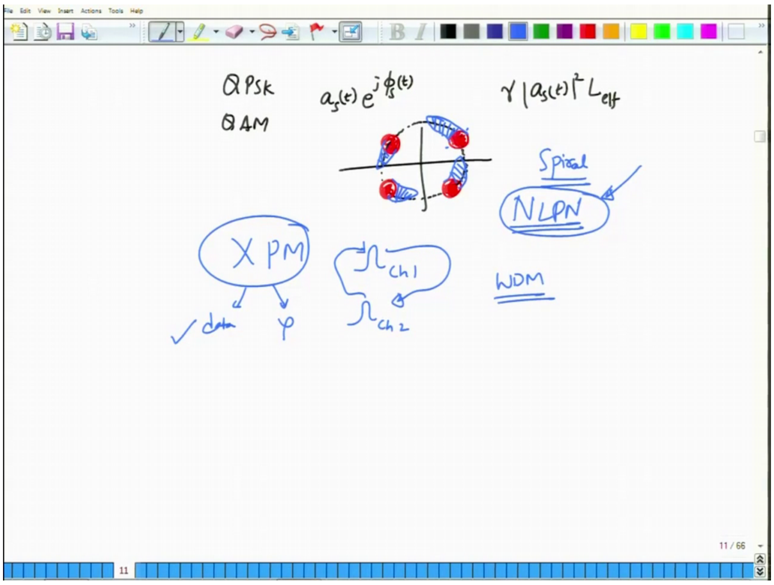

Well, we are talking about QPSK or we are talking about QAM signals in which information is present both in terms of its amplitude right, as well as the phase phi s of t. In the QPSK case, phi s can take on these constellations right: we will assume that this is the QPSK constellation. And what would be the effect of SPM alone is that it will start to increase right or it will start to rotate the constellation.

And why should this constellation be rotated, because the amount of power that is present in the transmitted signal, which is proportional to this magnitude square of the envelope will impact with respect to gamma and L or L effective will impact what would be the face. In fact, this would be a kind of dependent on the amplitude as well. If there is no other noise, then this will result in only rotation along the same circle. So, eventually you may have such large non-linearity that they will start to cross over into the other decision regions, and thereby create the errors.

But interestingly, what happens when you have noise is that the additive noise itself will be you know distributed around each of the constellation points in this way, and now look at something very interesting. Those points, which are at this edge, have a higher power compared to the points, which are at this outer edge correct. So, let us call this as one edge here, and another edge here. The power that is on this edge here of the top one is actually more than the power that is here, because the radius is actually smaller here right, because of the noise subtracting the amplitude, this have come inside.

Now, what would happen to this one is that, it could actually start to increase, while this will also increase, but not so much right. So, you will actually see that it will turn out to be a kind of a spiral pattern, I am not showing you the pattern correctly, but I will give you these patterns in the assignment, you can actually do it for yourself. And then see that you will actually get spiral patterns because of the combination of noise that is present in the amplifiers contributed plus this particular noise. And in fact, this noise is called as non-linear phase noise. And eliminating or compensating non-linear phase noise is an important topic in today's optical fiber communication systems.

And how do we go about compensating this NLPN, we go about this one in the same manner as we have tackled the phase noise problem. Remember, phase noise also rotates the constellation points. Here the rotation is dependent on the noise power as well, where in the other case, the rotation was independent of the noise power, and therefore, phase noise could actually be eliminated by increasing the power there. But, in this case, you cannot do that, because the rotation that will actually introduce the spiral kind of a characteristic to the phase noise problem, the non-linear phase noise is dependent on the amount of the signal power as well as the noise power.

A proper analytical detail could actually be done, but you know we do not have time for all that. But, please do remember that non-linear phase noise is an important effect, and it can be compensated by techniques, which are similar to phase noise compensation techniques. But, there are specialized techniques, which are suited to take into account the non-linearity characteristic. And those things again we cannot discuss in this course, we will discuss them in some other course ok. So, this is about non-linear phase noise and something that has been done, I mean there is something that is the result of you know self phase modulation. And self phase modulation means the phase of the signal is modulated because of its own power is what is the self phase modulation is.

Very quickly XPM would obviously be if you have two channels say channel 1 and you have another channel 2, the power of channel 2 will impact the face of channel 1; the power of channel 1 will impact the face of channel 2. So, this is the reason why we call this as cross phase modulation. And clearly for a WDM system, where there are many channels. Cross phase modulation is an important topic right, so that has to be taken care.

Turns out that XPM can be data dependent and data independent. In the sense that if I know the data completely, then XPM in principle can be corrected, same is the case for SPM also. So, if there is no noise anything else apart from only SPM, then it could be corrected. But, because there is noise, which is interacting with the non-linearity of the fiber resulting in what is called as NLPN, you cannot correct NLPN in the in a deterministic manner. So, this is a random noise, whereas the XPM if the data is known can be corrected in principle, because that is a deterministic non-linearity.

However, in most cases, you do not know data, or the data could be completely random, one of the channels could be using QPSK, the other channel could be using QAM. So, all of those means that you know XPM is a harder problem than the reasonably simple self phase modulation, or non-linear phase noise. Interestingly, non-linear phase noise is also called as Gordon Molenaar noise, because it was you know it was kind of first studied by these two people Gordon and Molenaar ok.

Anyway, we are left with four-way mixing. We will give a short introduction to four-way mixing in the next module.

Thank you very much.