Optical Fiber Sensors
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Lecture No. 17
Amplitude Modulated Sensors - 4

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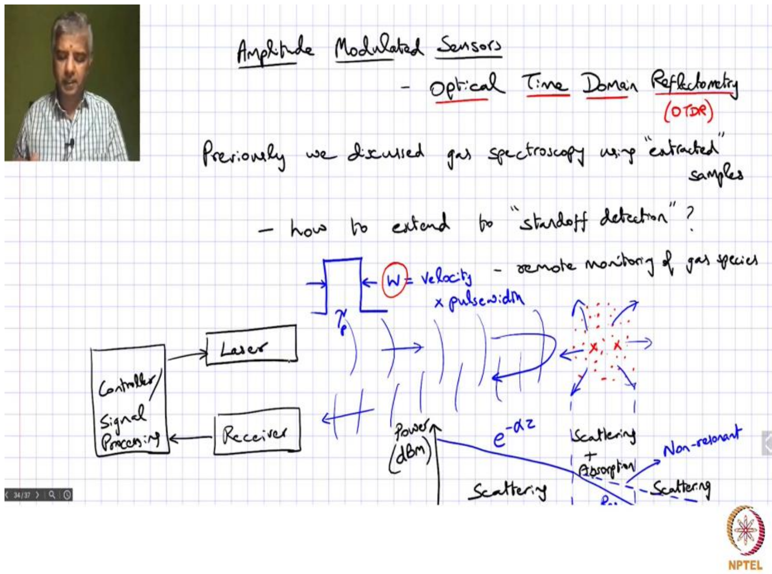

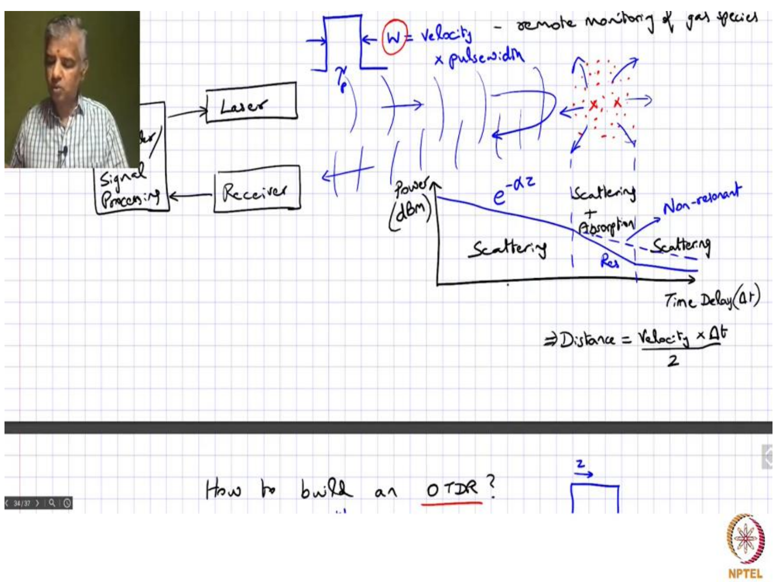

Hello everyone. So far, we have been looking at amplitude modulated sensors and we took the specific example of gas spectroscopy and then went on to ask the question whether we can extend gas spectroscopy for stand-off detection, that is actually, can we monitor gases from a remote location. And we saw in the last lecture that we could do this by going to optical time-domain reflectometry so, where we essentially have a laser that is sending a pulse of light and that is interacting with the remote location that, the gases in the remote location and because of that interaction, there might be some absorption happening to those pulses. And then the backscattered light, we are collecting using our receiver. We can actually see, some distribution like this with respect to a resonant wavelength and a non-resonant wavelength, we can actually do remote gas spectroscopy.

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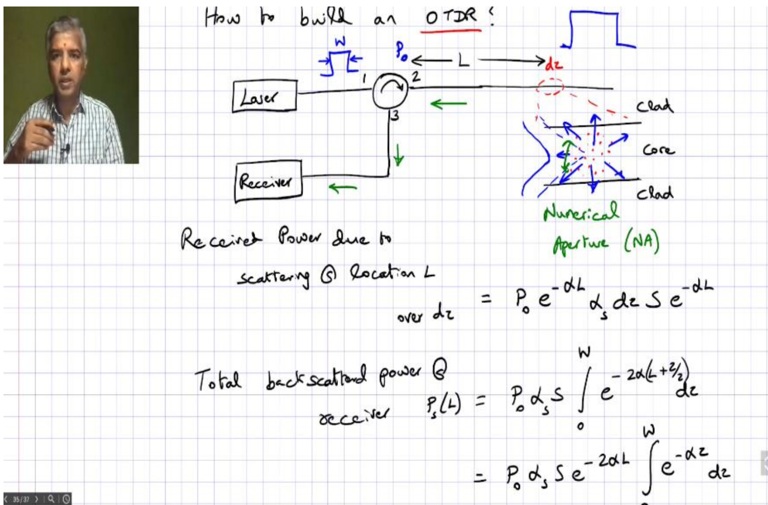

And then, we said, let us actually look at a simpler problem to understand this optical time-domain reflectometry, which is the key for this stand-off detection. And then said, let us actually learn to build a OTDR using an optical fiber configuration. And this, we will see, is useful for some of the other sensing applications that we will demonstrate later on in the semester but let us, just look at it from the perspective of understanding how an optical time-domain reflectometer can be designed. So, that is what we are going to do. How do you design such a reflectometer, such an OTDR instrument for any given application?

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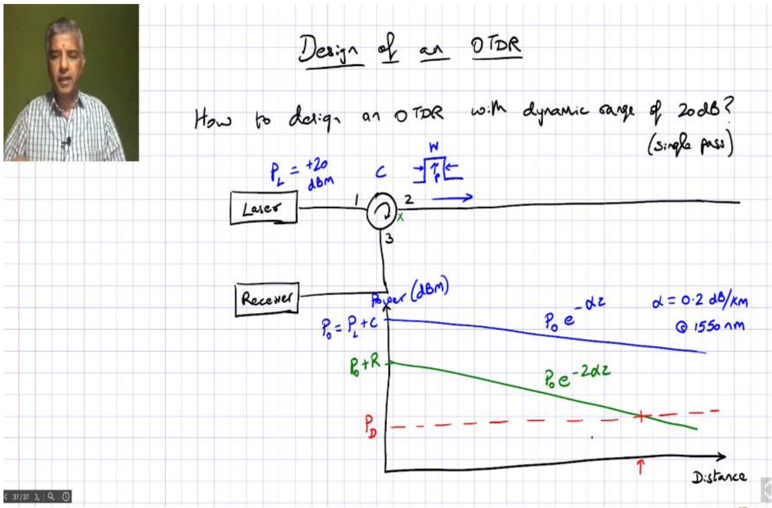

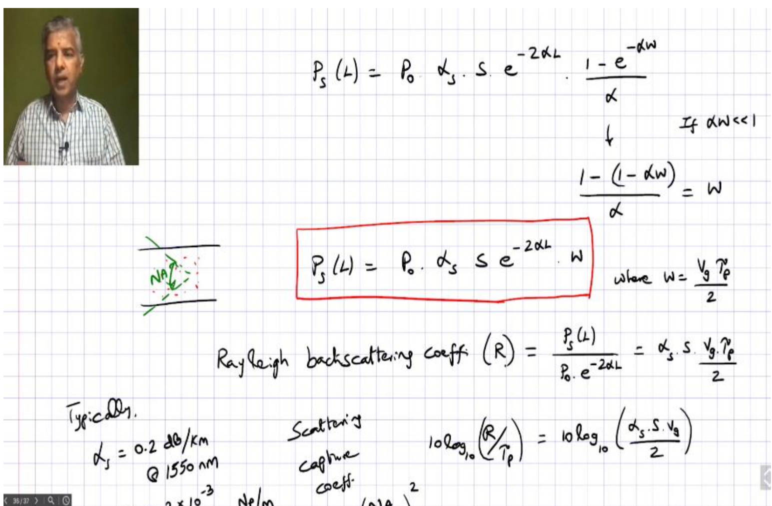

So, we ask the question, 'How to design an OTDR and let us say, when you talk about design, you need to adhere to some specifications. One of the key specifications as far an OTDR is concerned, is the dynamic range. So, how to design an OTDR with dynamic range of 20 dB. So, what is dynamic range? The, it is basically the range of power values that we can detect using your OTDR. And what power values are these? These are backscattered power values. So, we want to support a dynamic range of 20 dB, it is actually a factor of 100.

And we have to be careful about defining this because what we are typically interested in is the single pass loss. So, this dynamic range that we want, let us say, with respect to a single pass and of course, what you are seeing in your receiver, as far as an OTDR is concerned, is the backscattered signal so there is actually a round-trip involved. So, the overall loss that we want to support, maybe 40 dB, but as far as the single pass loss is concerned, that corresponds to a maximum of 20 dB. So, let us see how we will go about designing this.

Now, we saw that, of course, we, to design an OTDR, we need a laser, if it is going to be sitting inside an instrument, it better be a compact laser like a semi-conductor laser. And we are looking at the fiber coupled configuration, so we said, we typically use a circulator, which directs light from port 1 to port 2 and port 2 is where we have our sensing fiber. So, this is going to this distant location and getting information back from that. And then, any back reflected light we are collected at port 3 and we are directing it to receiver. So, this is the overall configuration that we want to support.

Now, let us say that PL denotes the power that we are emitting from this laser. So, what is the typical type of power levels that we are looking at? If you are talking about a semi-conductor laser, it is usually a (())(05:52) laser. If you are looking at a pulsed semi-conductor laser, you can get power levels in the order of 100 milliwatts. So, this could be the order of plus 20 dBm. And then we go through some losses because of the circulator, there is a loss for light going from 1 to 2 and then again there is another loss for light going from 2 to 3. So, let us actually call that loss as C.

C is actually a negative value, mind you, because it is loss. So, you know typically it is like 1 dB per pass so C could be a value of minus 2 dB typically. So, now let us look at the power evolution along the length of fiber, so that will help us understand this problem that we are looking at. This design problem that we are looking at. So, this is as a function of distance, like the single pass distance. So, you measure this is a function of time and you correct it with the velocity and for, as well as the round trip time, so you can actually get this as a function of distance.

So, let us look at the typical power levels that we would encounter. Now, if you just launch this pulse, the pulse is going to, actually so this is what we are talking about is, launching a pulse of light down the fiber and as the pulse is propagating down the fiber, it is going to reflect some of the light. Let us say, the pulse width in time corresponds to tau P and the corresponding width of the pulse can be termed as W.

So, as it propagates down the fiber, so you are starting with a value, so this is actually in terms of power, we are tracking this, so you start with PL but PL plus C corresponds to the power level over here. We are saying plus C because C is actually a negative number, remember that. So, let us call this P naught. So, if you track P naught, so the, as a function of distance, of course it is going to go down as a function of distance.

So, how does it go down? It goes down exponentially because of the attenuation, you apply base law and you say, it goes to exponential decay in terms of the power level but then, let us say we are looking at this power in this dB scale, specifically in the dBm scale. So, reference to a milliwatt. So, we are looking at P naught, P power minus alpha z type of loss, where alpha is a typical value is about point 2 dB per kilometer if you take a standard single mode fiber, at a wavelength of 1550 nanometers, let us say we are doing all of this at 1550 nanometers.

So, this is actually the power that is present in the pulse. The pulse is decaying, remember the strength or the pulse is decaying, so that is actually tracking the power in the pulse as it goes to the distant location. But what we are really interested in is what is the power that is back scattered?

And when it comes to backscattering, we have to consider, basically this Rayleigh backscattering coefficient R. So, that actually defines the power that is backscattered. So, let us actually denote that in a different color. So, you say this is P naught plus R, once again I am using plus R because we have defined the backscattering coefficient, I think towards the end of the last lecture we defined it as a negative value, it is actually a very small fraction of the incident light, so that is why it is a negative value. And so, let us say that R is actually the backscattering coefficient.

So, this level represents the power that would be back reflected from the from the front end of the fiber, from this location here. But as it is propagating down the fiber, you will have lesser incident power, so correspondingly, there will be lesser back reflected power. But, specifically, if you are looking at the power that is reaching the receiver, that will be something like this. It will be a larger slope, how large? Well, it will be twice the slope of this line. Why is that? Because you are not only losing power as you are propagating towards the distant location, but also losing power for the back reflected light coming back to the receiver.

So, this is going to be corresponding to twice the loss. So, you will have P naught, P power minus 2 alpha z because this is, this basically the loss at the receiver which is corresponding to the round-trip propagation. So, that actually says, you have quite a, remember this is all in dB scale, so the amount of power that you get is, could be quite low and, and then you need to have a very sensitive detector to pick up this radiation.

Let us say the detector sensitivity is somewhere along this value. So, let us call this PD corresponds to the detector sensitivity, that is the minimum detectable power at the receiver, so that corresponds to that value. And we see that, we can actually pick up power values up to this point but beyond that it is actually, it is going in to the noise, so you are not able to retrieve any signal beyond this distance over here.

However, we know that we could improve this situation. How do we improve this situation? Well, we know that we could, since the properties of the fiber is not changing over a few minutes typically, you can afford to get one trace and then you shoot another pules, get another trace and shoot another pulse, get another trace and so on and add all these traces. So, we saw previously that when we add all these traces, we are essentially going through averaging.

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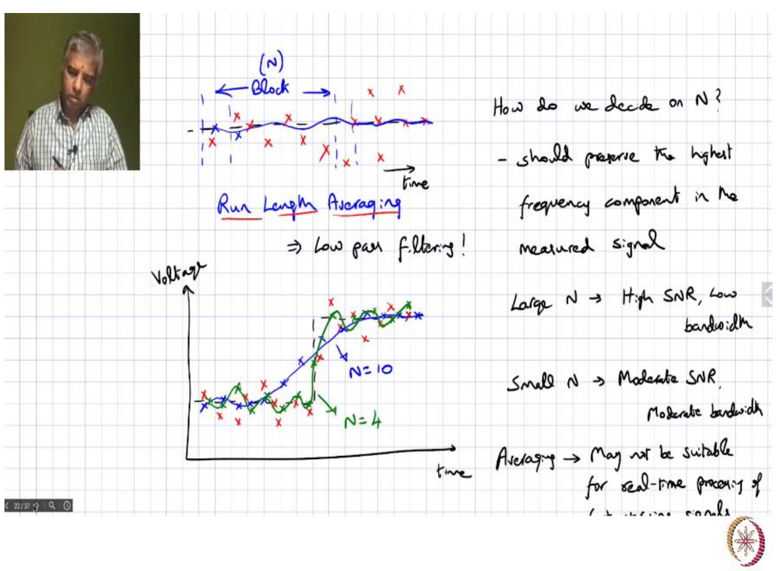

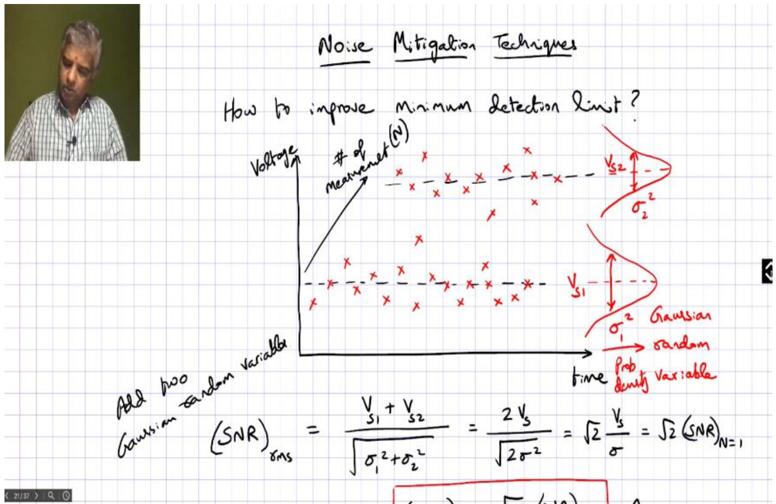

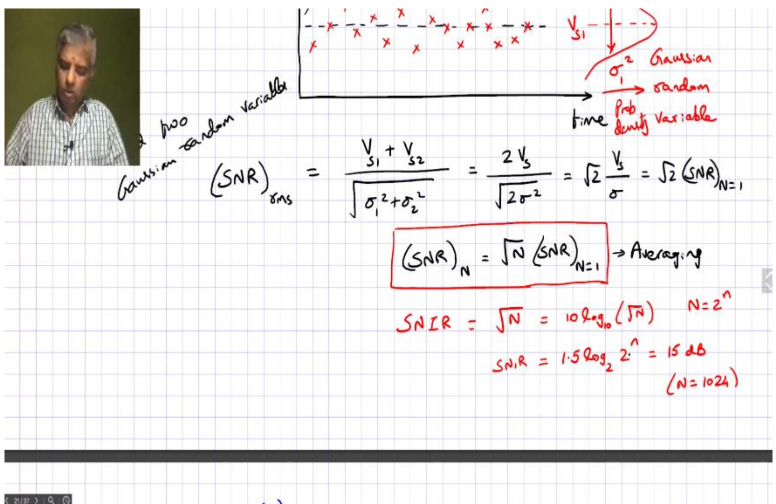

So, we can essentially get, we can do averaging over multiple traces and so, if you have N traces, your signal to noise ratio could improve by a factor of root N. So, if we were to write it as signal to noise improvement ratio, that corresponds to root of N. And that is in linear units, if you want to write this in log scale, basically you say this is 10 log, base 10 because we are dealing with power value, so that is where it is base 10 of root of N and it is convenient to do this N in terms of 2 power so many averages. So, then you can get a round number.

So, if N can be expressed as 2 power small n, then you can actually represent this in log of base 2. And if you do that, if you convert this to base 2, what you see this is, 1.5 log of base 2, 2 power N. So, let us just do a quick calculation here. So, let us say N is 1024, so well, we will pick a even, let us say 1024, so that corresponds to N, root of N will be somewhere around 32 or something. And log of 32 will correspond to a factor of 15. So, that will, this 10 log base 10 of 32 will correspond to 15 dB.

So, similarly 2 power N if you say, then 1024 averages will correspond to 2 power 10, so small n equal to 10. And then if you substitute that, you will get, this is going to be equal to 15 dB for N equals to, in this case, 1024, 1024 average. So, this SNIR can be expressed as this value.

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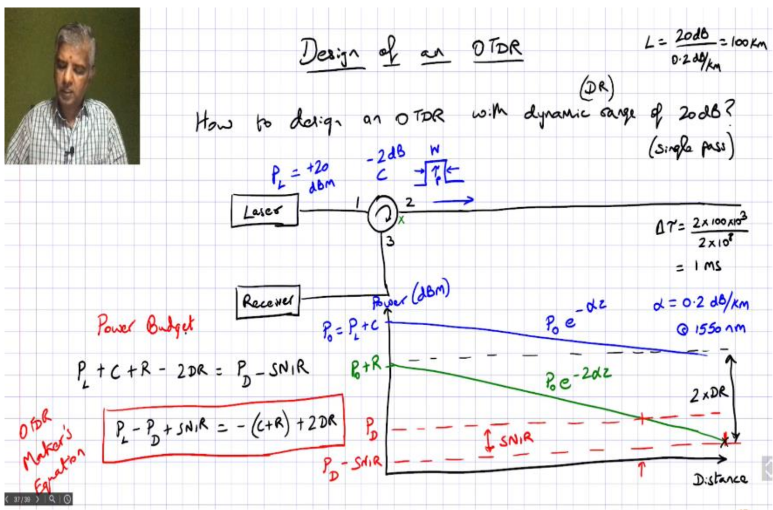

So, if you consider all of this, let us just go back to where we were. Right, so if you consider this situation, what we are saying here is now because of this signal to noise ratio improvement, you are able to bring down the level even lesser. So, this is actually PD plus SNIR. That will be even smaller number, I should say PD minus SNIR because it is, SNIR is the improvement. So, like we talked about, it is 15 dB improvement, so it will be even smaller value. So, this is a signal to noise ratio that you are, improvement that you are achieving through, for example, averaging. So, what is the effect of that? Now, effect of that is that you are able to pick up information up to this point.

Now, let us actually define dynamic range. So, dynamic range is corresponding to the range of values that you can detect reliably. So, you are able to detect values from, this is the maximum value that can pick up, because that is the maximum value from the closest end of the fiber and farthest end of the fiber from which you can pick up is corresponding to this distance.

But mind you, this is actually going through round trip, so this corresponds to two times the dynamic range as far as a single, so this dynamic range is, call it a DR. We want a single pass dynamic range of 20 dB. So, we will have to multiply that by 2 here, because everything is going through a round trip as far as this chart is concerned. So now, let us write an expression, you know, balancing all this off and that expression could be useful in determining, for example what is the receiver sensitivity required to support a dynamic range of 20 dB? So, let us look at that.

So, what we are saying is, we are starting with PL plus C plus Are, and minus, from this level you go minus 2 time DR, then you would have reached this point. This level over here which corresponds to PD minus SNIR. So, that is the equation that represents, how far you are going to be able to, what is the range of values that you are going to be able to support using this OTDR.

So, let us just rearrange terms. So, what we are, we can just write this is PL minus PD plus SNIR, that is equal to minus of C plus R, mind you both C and R are negative values. So, minus of this is going to just become a positive value. And plus 2 times DR, so this expression is what is called the OTDR Maker's equation. So, whenever someone is trying to make an OTDR, they essentially have to refer to this expression.

So, now, so we want to now define or basically design something for 20 dB. So, let us basically say that you start with plus 20 dBm and then C correspond to minus 2 dB, let us say is the value that you want to take for C. So, let us actually see how this will workout. Let us go to a fresh page for this.

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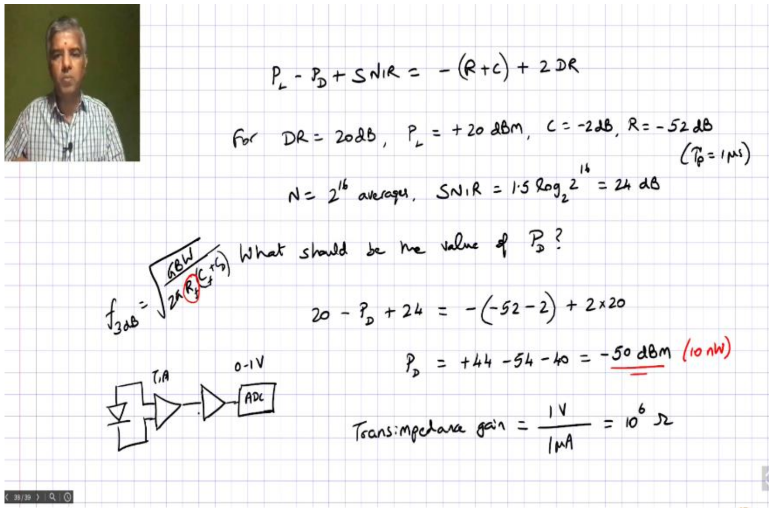

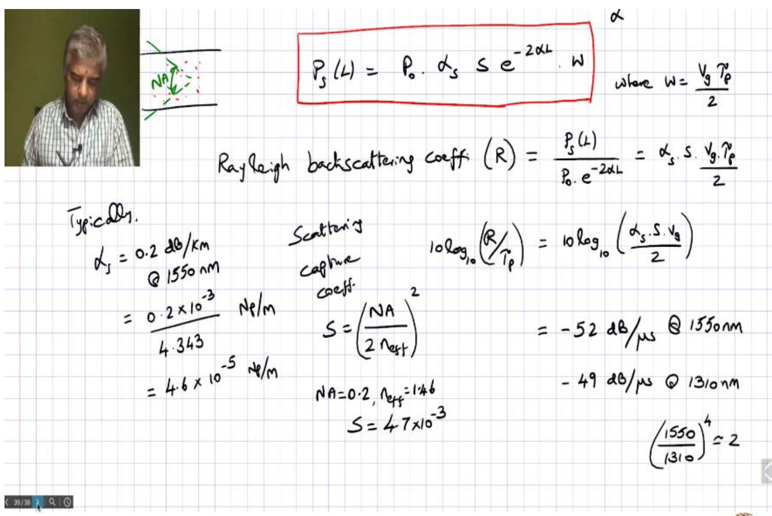

So, let me just write this expression one again. PL minus PD plus SNIR is equal to minus R plus C or C plus, whichever way, plus 2 time DR. So, what we need is for DR of 20 dB that is the single pass dynamic range that we want to support. We are starting with PL equals to plus 20 dBm. Let us say C equals to minus 2 dB. R is a value that depends on the pulse width. We saw that the R is the Rayleigh backscattering coefficient. Per unit pulse width corresponds to minus 52 dB per microsecond, that is what we were looking at at 1550.

So, let us say we, let us assume that we are using 1 microsecond, 1 microsecond pulse so that this corresponds to minus 52 dB. So, assume that the pulse width tau P is 1 microsecond. And let us say we are assuming N equals to 2 power 16 averages. 2 power 16 is indeed a fairly large number. So, 2 power 14 will be, 2 power 16 will be corresponding to 64,000 averages. You say that is actually a fairly large number of averages but then, if you consider the fact that you do these averages every, after every round trip.

So, let us just make some calculation here. If alpha is point 2 dB kilometer, what is the length of fiber that you can support with this 20 dB dynamic range? So, if it is a continuous length of fiber that would correspond to 100 kilometers. Because 20 dB, so length equal to 20 dB divided by point 2 dB per kilometer. So, that corresponds to 100 kilometers. So, to go 100 kilometers and then come back, when you look at the round trip delay corresponding to that, so that is basically, it is 2 into 100 kilometers, 100 into 10 power 3 divided by the speed of light in this fiber which we can approximate to 2 into 10 power 8.

So, then, if you do the calculation, you will find that this is corresponding to 1 millisecond. So, in 1 millisecond, you are able to go all the way down to the end of the fiber and come back. So, every 1 millisecond you can actually do an average. So, if you are talking about 64,000 averages, that will be done in 64 seconds. And of course, there will be some overhead processing and so on, so you will maybe have 100 seconds or 120 seconds, let us say, that is 2 minutes. So, in 2 minutes, you can actually do 2 power 16 averages. And if you do 2 power 16 averages, you can expect a signal to noise ratio improvement of 1.5 log base 2, 2 power 16. So, 16 multiplied by 2, 1.5 will be 24 dB. So, you can get a SNIR of 24 dB by doing this.

Now, the question is what should be the value of PD; the detector sensitivity, what is the minimum power that you should be able to detect? So, let us actually put all these numbers together in this expression. So, you have 20 minus PD plus 24 equals to minus of minus 52 minus 2, for R and C plus 2 multiplies by 20. So, all these, mind you, we are doing everything in dB scale. So, if you do the math, you will find that PD, this corresponds to 44 so you take it over there any this corresponds to 54, and that is a positive value. So, 54 minus 44 plus 40, that would correspond to, just do that, so this is minus 44 minus 54 plus 40, so that corresponds to minus 14 and this is 44. So, that corresponds to minus 58 dBm.

So, that is actually fairly small value. So, I think I made a mistake here. So, this is minus PD, so this is, when you are talking about PD, you are taking this, I think but then this will be plus and then, 44 and then this is minus 54 and this is minus 40, so if you do this, this is minus 94 plus 44, so this will be minus 50 dBm. So, that is actually the sensitivity that you require. So, minus 50, minus 60 dBm is actually 1 nanowatt. So, minus 50 dBm will correspond to 10 nanowatts of power. So, you are supposed to pick up fairly small value or power and not only that, suppose you are looking at building a receiver to pick this up, you want to build a receiver such that you have enough transimpedance gains so that the output of your amplifier chain fills the ADC.

Let us say the ADC is about 1 volt full scale. So, the transimpedance, so what we are talking about is, you have the front end and then going on to TIA and then maybe, another set of amplifiers and then, voltage amplifiers and then you are going, getting to the ADC. If the ADC is actually 0 to 1 volt, you need to fill the ADC. So, the transimpedance gain that you require is basically 1 volt, should be the output of your voltage amplifier, divided by whatever you have at the input.

And let us say, if you are using a PIN photodiode, a PIN photodiode at 1550 will typically give you a responsivity of 1 amp per watt. So, for 10 nanowatts, you will gt 10 nano amps as the photocurrent. So, you get about 10 power 8 ohms. So, that is the requirement as far as the transimpedance gain is concerned. So, you need to actually have a fairly large gain so that you can, represent this, the what do you call the lowest power with fairly high values. So, of course, it may be actually a little less than that because of the fact that this is corresponding to the power that we have at this location and so your, that is the minimum power that we have.

The maximum power corresponds to the power that we have at this location. So, at this location, and this is what needs to fill the ADC. So, at this location, it is basically 20 dBm, minus 54, so that is about minus 34, so that is about a microwatt, something of the order of microwatts of power. So, in reality, if you consider that aspect then maybe you do not need to have this high a transimpedance gain. So, you, let us say you have something in the order of 1 microwatt from the closest end of the fiber, then you can just say this is corresponding to 1 microamp of current and then in that case, the transimpedance gain value need not be more that 10 power 6. So, it helps you a little bit in that sense.

So, that is still a fairly large value so you need to design it such that the TIA takes up most of your load in terms of the gain. So, you may want to try to achieve as much gain as possible from the TIA stage itself. Now, the question is can you just achieve this transimpedance gain with just the TIA feedback resistance 1 megaohm? Can possibly, but what is the constraint there? We know that, when you talk about the f 3 dB of TIA, we saw that previously that corresponds to the gain bandwidth divided by 2 pi Rf plus Cf plus CD and so on, so all the other capacitances.

So, it is limited by the gain bandwidth of the op amp that you are using here. So, you may not be able to actually get 1 megaohm transimpedance gain from this stage itself because in that case, you f 3 dB can be quite limited. So, then you ask the question, why do you need a large f 3 dB? Well, you need to actually pick up the pulse, the backscattered pulse. So, you want to represent the pulse as well as possible. So, let us actually look into that aspect in little more detail.

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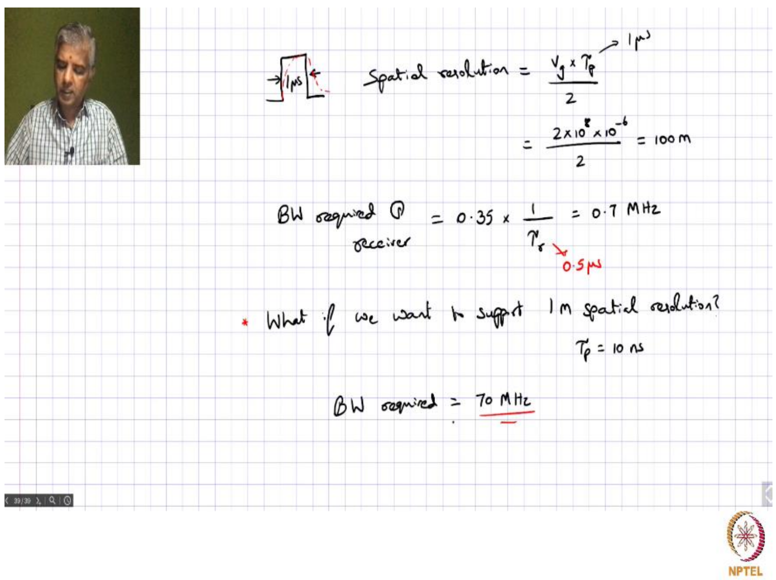

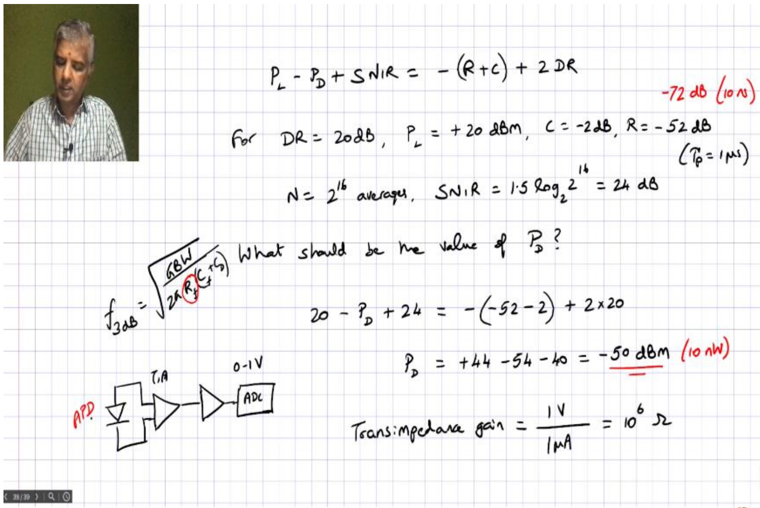

So, let us say we are having a pulse, like we have talked about, like we have so far assumed this is actually a 1 microsecond pulse, so what is the corresponding width of the pulse? Or rather, what we are interested in is what is the corresponding spatial resolution? What is the minimum distance that you can resolve between two different evens? So, that will correspond to vg, that is the group velocity of light in the fiber, multiplied by tau P. But because it is actually a round trip configuration, you have to divide that by 2. So, vg is 2 into 10 power 8 meters per second. Tau P is 10 power minus 6, so divided by 2, if you do the math, so that will correspond to 100 meters.

So, you can get 100 meter spatial resolution provided you have a bandwidth in your receiver that can capture this 1 microsecond pulse. So, let us actually calculate the bandwidth required at the receiver to capture this pulse. So, then you say the, for a linear transform limited pulse, your bandwidth is given by 0.35 multiplied by 1 over the rise time, right? The rise time that you are trying to support.

Now, to get a 1 microsecond pulse, you do not need to get the entire pulse but I mean, you do not need to see the square pulse, because if you want to get the square pulse then your bandwidth required will be very large. But even if you have some representation of the pulse, that is probably okay. So, if you are able to get something like this, that is still good enough. So, let us actually assume that tau R corresponds to half a microsecond, nominally. And if you consider that, then 1 over tau R corresponds to 2 megahertz multiplied by point 3 5 so that corresponds to 0.7 megahertz.

So, what you want to do is, you want to see if 0.7 megahertz is supported with the, when you substitute in this expression. So, what is the maximum value of Rf that you can support and still maintain, point 7-megahertz f 3 dB? So, that is the question. So, in some cases it maybe, that you are not able to get this much transimpedance gain from a TIA itself because of this limitation and so you will have to go to one more stage beyond that to actually get this total transimpedance gain.

So, that is actually the typical issues that goes into design of a OTDR. Now, I will just end with just one last thought. What if we want to support, let us say, 1-meter spatial resolution? If you want to support 1-meter spatial resolution, then your pulse width, the round-trip, considering the round-trip propagation, the pulse width should be 10 nanoseconds. Here, we have pulse width of 10, 1 microsecond is what we considered. But if you want to have much finer spatial resolution then tau P has to be 10 nanoseconds and, in this case, the bandwidth required will be, a factor of 100 more so that will correspond to 70 megahertz.

So, if you want to actually support 70-megahertz bandwidth, then you go back and you look at this and then you say, if you want to get 70-megahertz bandwidth then my transimpedance gain as, the gain that you can get from a transimpedance amplifier is going to be even lesser. And so, in that sort of a design, you may need one or maybe even two more amplifiers beyond that and that is to make up for this transimpedance gain that you are trying to achieve. And so, what is the downside of that?

Well, the downside is that with each amplifier that you are adding, you bring in extra noise figure. So, that degrades the signal to noise ratio, that degrades the PD value that you can achieve. So, and of course, you also have to recognize that if you have 2 microsecond pulse width is, you have minus 52 dB, but if you have 10 nanosecond pulse width, you have minus 72 dB. So, already your PD is actually going to be minus 50 dBm, minus 70 dBm, if you are considering 1 meter spatial resolution.

So, that is actually putting more burden on the receiver in which case you do not have a choice but to go for a APD receiver over here, APD base receiver, so you can at least get a gain of 20 from the APD and then of course, you have to have more amplifiers. So, if you do all that calculation, you will probably find that if you want to get 1-meter spatial resolution, you are not going to be able to support 20 dB dynamic range. Maybe you will be able to support only 10 dB dynamic range and so on. So, you need to have that trade off in all of this.

So, those are the typical issues that we face when we face when we go about designing and OTDR. And these concepts are once again relevant to the case of doing a free space OTDR.; instead of a fiber, you launch light into free space. There again, you have to do a power budget like what we did here, whatever we did here, this is actually a power budgeting. So, you do the power budget, you do the rise time budget, just like you do for a communication application. And then you can actually achieve the end result after going through this process. So, that will be the same if you are doing it in free space as well.

And of course, we will come back and look at a OTDR from the perspective of distributed sensing later in the semester when we go to RAMAN and Braun OTDR and all that. That is it for now.