Optical Fiber Sensors
Professor. Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture No. 16
Amplitude modulated sensors – 3

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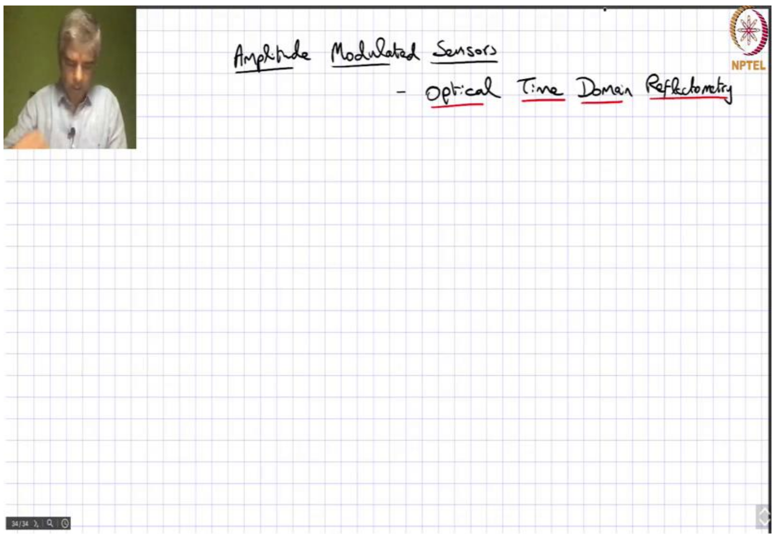

Hello, we have been talking about examples of amplitude modulated sensors. So we would like to now, extend one of our previous examples and see if we can cover optical time domain reflectometry. That is what we will try to discuss today. So, why do you need optical time domain reflectometry?

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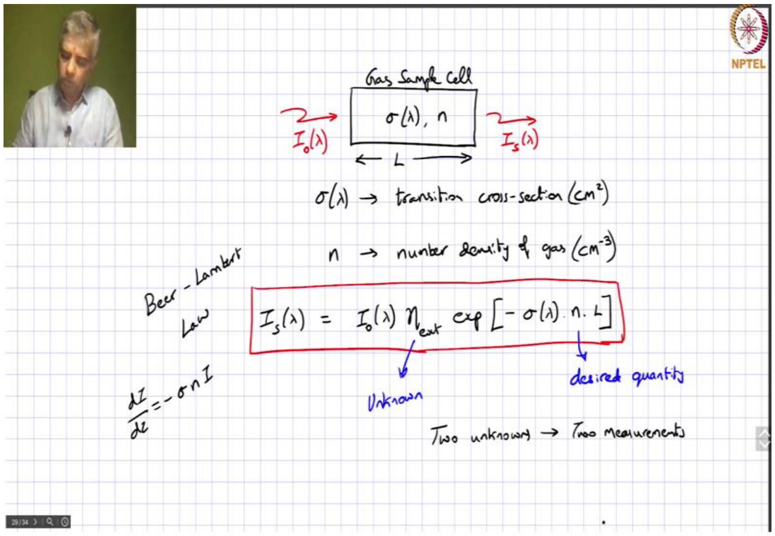

Well, we talked about gas spectroscopy previously and we talked about typically extracting a gas sample in an industrial environment this may be actually the gases the flue gases that are a byproduct of whatever manufacturing process that the industry has. And we extract that gas sample and then put it through a gas cell and we looked at how in that scenario, how we can use changes in the amplitude of light or the intensity of light because of absorption of the gas at a particular wavelength. We saw how using that measurement, how to extract out to get information about the concentration of the gas species and maybe even identify what is the gas species that is present.

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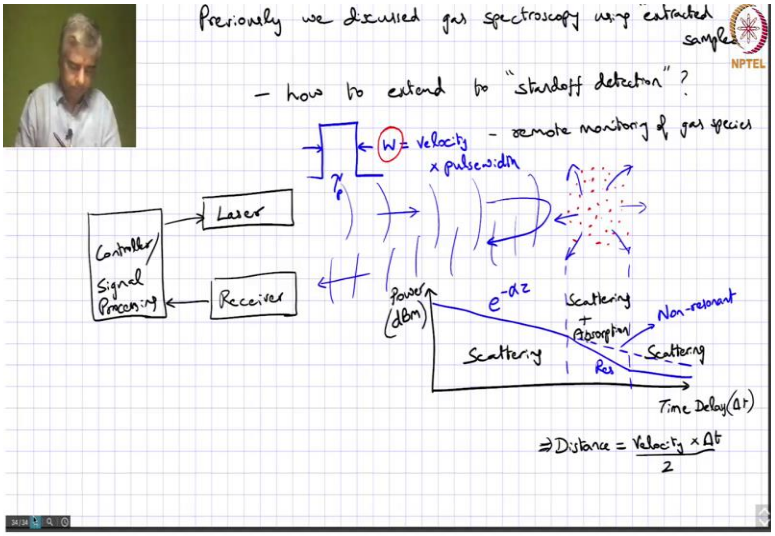

Now, the question is how do we extend this? So, let me just come back here. So, previously, we discussed gas spectroscopy or trace gas monitoring using extracted samples of the gas. So now, the question is how to extend this technique to what is called standoff detection. So, what is standoff detection? Well, standoff detection will essentially mean remote monitoring of these gas pieces.

So, you can say this is basically remote monitoring of gas species. So, you may want to actually do this from a remote location you may want to actually shoot a light beam and try to get information from wherever these gases are and based on the backscattered light, you are actually trying to identify what type of gas species is present at distinct location and also possibly the concentration of the gas species.

So, how do we do that? Well, for that we typically take let us say a laser, because we are trying to shoot this beam over long distances, the LED may not have enough spatial coherence to support, sending pulses over long distances. So, you typically use a laser and you send these this light. So, it goes off into this into the far field and it might travel some distance and then let us say we have this environment where certain gas species is present.

So, how do we now identify this gas species, what type of gas it is? And then what concentration of gas is present as a function of maybe the spatial distribution also. Is it possible to do something like that, because that will obviously be very, very valuable information if we can do it in from remote locations or for example, we go on exploration of, like the moon and we want to understand whether the moon's atmosphere what gas species is present.

So, so, if you have one of these probes that are gone out, so, from that probe, you want to basically shoot this laser beam into the atmosphere of the moon and basically look at the constituents of that or we may want to actually get it right off the surface of the moon and so on. So, that is that is basically like a standoff detection that we are talking about. So, in this case, what we rely on is whenever there is a inhomogeneity in the propagation medium as far as the light is concerned, whenever it encounters a certain inhomogeneity, there will be scattering of light.

So, even as light actually propagates through our atmosphere the we know that atmosphere consists of various type of gases, even when we consider the Earth's atmosphere, it consists of various type of gases and there are density fluctuations in those in the atmosphere, whose scale is much lesser than the wavelength of light much less than a micron. If there are so, such density fluctuations, then all along the propagation, you will have certain backscattering happening.

So, certain part of the light will when it goes in encounters with it, the scattering is going to be happening in all directions, I will use the same color. So, the scattering might happen in all directions, but part of the light might actually come back. So, so if we look at that scattered light.

So, you capture a part of that backscattered light, using your optical receiver, right. That can actually this backscattered light can actually give us some very useful information about what is going on in this remote location. Of course, you would want to control all of this. So you have the back end controller and maybe also some signal processing that takes place, because the amount of light that you get may be very low, but let us say the controller is the one that is triggering this laser, and then it starts looking at what is back reflected.

Now the question is, how do we know that certain scattering is happening only from a particular location, we do expect scattering to happen all along. But let us say it is only in this region that this this specific gas piece is of interest for us that is present there. So, how would we localize the information that we received? Well, one nice way of doing that is by actually sending a pulse of light.

So, let us say a pulse, which extends for time with, say, tau P and that, that, within time will now correspond to certain within space, because light travels at a particular velocity, that is that that corresponds to the velocity of, in a light in free space was 3 to 10 power 8 meters per second. So, this time duration of the pulse that you are sending is going to correspond to a certain, it is going to occupy a certain spatial distance.

So, so that spatial extent, let us call that W. So, W is going to be equal to the velocity of your light multiplied by the pulse width. So, so that that is actually a very important aspect. So, at any particular point you are sampling the atmosphere only over this extent would so that that becomes the key point, you are sampling only over the W. And so at any particular instant, whatever you receive.

So, you, you send this pulse out, and then you are getting this back, whatever you receive at any particular time, that is going to correspond to a particular location in space. So, if I were to extend this, let me see if I can go down a little bit. So, let me try to extend this if I, if I am actually sitting at the receiver and I am looking at the received power. I look at the received power as a function of time, then, what do I see? Well, I get to see a certain amount of the received power initially, when I just shot it out let us say it is somewhere over here, and then it is going to let us say we are doing this in dB scale.

So, the power is actually measured in dB with respect to a milli Watt. So, it will, it will, it will keep going down, and it is a straight line in dB scale, that is because of the fact that it goes down as a function of e power minus alpha times z, where alpha is the attenuation in this medium. Now, that we will see the power will keep going down because it is getting more and more attenuated and then at the point where this species is present, at that point, you will see that it is actually corresponding to some extra loss, why is that extra loss?

Because normally you have the scattering happening, but at this point, there is actually further loss because of the absorption. So, then at that particular point, it will actually take a different slope rate corresponding to this region, it will be a different slope and then then it will flatten out again corresponding to regular losses in the atmosphere. So, so, what is happening here in this region, there is scattering, just scattering related losses and this region also that is just scattering, general atmosphere scattering related losses.

But in this region you have both scattering as well as absorption. So, the rate at which the power is decreasing is going to be more than the other regions. And, of course, to actually identify a particular species, you know that each of these species has a particular wavelength at which it is absorbing. So, you tune your laser to that wavelength and then you launch a pulse and then you what you find is at that wavelength this this absorption is happening.

And just to verify that it is because of absorption, you may want to just slightly detune and send another pulse, and if it is off resonance, then what you get to see in that case is something like this if I were to just represented dotted lines, so that will be that will be maintaining the same slope. So, this is basically the resonance and that corresponds to non resonant backscattered light.

So, by doing differential absorption spectroscopy essentially, you can actually figure out what is the level of absorption that you are having at that, at that particular point. So, the key to all of this is, of course, one thing you want to note here is we are doing this as a function of time. And what we are really interested in this, absorption as a function of distance, so you need to convert this time to distance and that we know.

So, if you say that the time delay, what you are essentially plotting here is the time delay. The time delay, let us call it delta t, time delay with respect to the time that we initially shot out this pulse. So, you shoot the pulse and you start counting 1, 2, 3, 4, 5 and so on. So, that that is essentially the time delay. So, if you want to convert that to distance, so you will say that the corresponding distance is going to be the velocity, velocity of light multiplied by this delta t.

So, then you would actually have the distance is that all well, you have to be careful about this. The time delay is actually the round trip time delay, because the light actually goes out. It gets scattered and it is, it is actually coming back. So, the time delay that that you are measuring here is actually the round trip time delay. But if you want to identify the location from which this this reflection came, you have to divide that you have to divide that by 2. Because it is, it is gone and come back. That is what this time delay corresponds to.

But if you want to just say, where this absorption this cloud of gases present, then you have to, essentially say that divided by 2 corresponds to the single pass distance. So that is actually very, very important to understand. So, that is actually a very nice way of doing absorption spectroscopy at a farther distance. But of course, you want to actually quantify how much power you are getting. And, and of course, what are the what are the system parameters? How do you actually go about designing this this entire system which, how do you decide what wavelength?

First of all that depends on the gas species, then, how much power should you have? The output to the peak power or the pulse? What should be the pulse width? What should be the receiver characteristics? What type of receiver do you use? What type of photodiode you use? Then we are talking about, what is the minimum? What is that? What is the minimum power level that you can detect using the receiver? Does that actually support? Detecting gas from a, such a long distance?

Let us say it is something that is happening at 1 kilometer away, are you able to capture some absorption that is happening 1 kilometer away? So, you know, what, what are the receiver characteristics? So all of this, we need to understand. So essentially, we need to build an instrument, this OTDR instrument. And so that is what we want to look at next.

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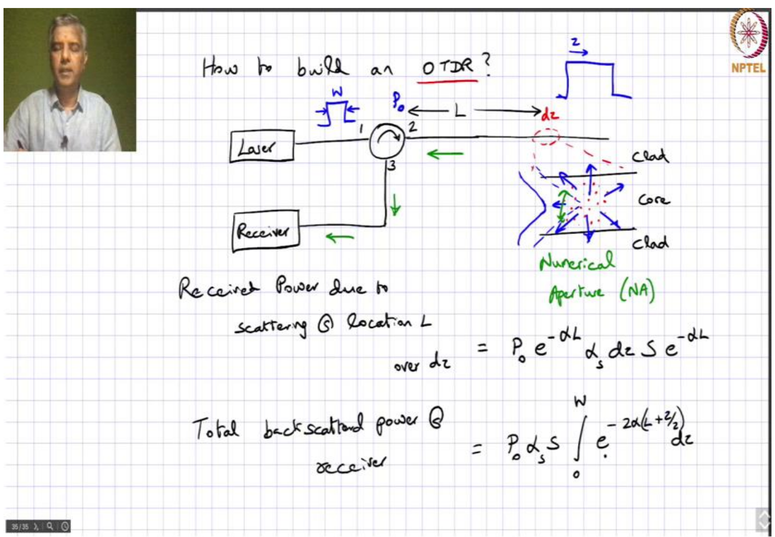

So, the question we want to ask is, how to build an OTDR? The OTDR is what we said here corresponds to optical time domain reflectometer. I mean, the technique is called reflectometry. But the what we are building is actually an instrument. So it is called a reflectometer. So, how do we go about building that OTDR? And to build that OTDR let us actually make things a little,

little more easier for us. So, let us actually look at a case where, instead of sending light in free space, you actually do this in an optical fiber.

Why because optical fiber light is confined to only 1 dimension, rather than, the propagation is confined to one direction that is along the axis of the fiber, rather than this you know 2 dimensional space that we have, in general, 3 dimensional space that we have otherwise. So, let us actually consider, this OTDR built for a fiber optic sensor. So in this case, what we have is, once again, we have the laser, let us say it is a fiber coupled laser.

So, it comes out in a fiber, and then you actually have a device typically like, like a circulator, you can use a circulator, or a coupler or whatever, you know that that is able to extract some part of the light and launch it onto this fiber. And, and then as it propagates down the fiber, it is going to keep backscattering. Because of a particular process called rally back scattering, that is one of the dominant scattering mechanisms in the fiber, that is one of the dominant loss mechanisms in the fiber itself.

But whatever is backscattered, now, the circulator, what it does is it takes it from port 1 to port 3, but whatever is backscattered, it comes down to port, port 1 to port 2, and whatever is backscattered, it actually comes to port 3, in directs to port 3. And that is where, let us say you connect your receiver. Now, to understand what it takes to build an OTDR, let us first understand this, what is happening around a particular region within this fiber. So, let us just zoom into that. And take a look. So, I am just going to show a zoomed version of this.

So, this is basically the core of the fiber, this is the cladding and this it is surrounded by cladding around. So, the core, of course, is higher refractive index than the cladding. And the light that is propagating the core, let us say is sort of like Gaussian shaped that there is the fundamental mode in the fiber. So, let us say this is actually a single mode fiber to make things easier for us. So, that is going to be confined to the core maybe a little bit of a text, spilling over to the cladding region.

And now, what we see is, as it propagates down the fiber there is going to be some scattering happening. So you say, that are density variations all along the length of the fiber, because the fiber is highly amorphous medium. So, it is, it is there are some in homogeneities and density variations all along the length or the fiber and that is actually going to create some scattering. Of course, like before, we see that scattering it can happen across all directions. But the and of course it is part of it is coming back here as well.

But this fiber has this problem property that it is able to support light scattered within a cone of angles. So, what we call that cone of angles as far as an optical fiber is concerned? Now, let us say this actually defines the cone of angles that not at that cone of angles that it supports, that is what we call as the numerical aperture of the fiber in other words is called the NA of fiber. So, it supports only a cone of angles that is scattered only that will be captured within this fiber and that is what is actually coming back here. And that is what is actually sent to your receiver. That collect at the receiver.

So now, let us actually get an estimate for how much power we are getting at the receiver? And what we want to look at is how much power are we getting over infinitesimally small region? So this, this extend, so we want to call this extent as dz. That is, that is what we are trying to show we are here. Over that dz what is the amount of power that we are scattering? So, if we look at that, we will say that the scattered power at a location L? So, let us say that this distance from your source that corresponds to L, so scattered power at location L due to scattering over distance delta z, rather, let us just call it dz.

So if we, if we look at that scattered power, what all is it going to depend on? Well, it is certainly going to depend on the power, of course, what we say this, actually, we are sending a pulse of light that is occupying a certain width W in the fiber. And, and it is got power P naught. So, let us say that the launch power into the fiber, so it is going to depend on that P naught. And then of course, it is going to go through attenuation in the fiber. So that attenuation, let us just call that as it is characterize by attenuation coefficient or attenuation equation, that is that we call us alpha.

So, it is it goes down as Beer’s law. So, it goes as e power minus alpha times L, that would be the power that you have over here. And let us say the fraction of light that is scattered, at this location, that corresponds to factor alpha s. So, that is, that is actually the scattering coefficient. Let us say that is the fraction of light that scattered. And but not all of that light is is actually collected by the fiber, so only a certain so what do you call, there is a scattering scatter scattering, I mean, the scatter capture coefficient, let us just call that as S.

So, that will be the fraction that is actually supported in the fiber and so, this is the scattered power at location L and the scattered power let us call it backscattered power and what you are interested in this received power due to this scattering and just say due to scattering at location L, and and of course, we are saying this is scattering happening over dz. So, that we will also have to figure so, this is actually before I write S, I will have to say this, this is actually alpha S per distance unit distance, that is the scattering and so, multiplied by dz that that corresponds to the extent that we are observing and then multiplied by S and this is the power that is starting to come off this place, but then by the time it goes back, it undergoes extra loss we know what that loss is that is going to be e power minus alpha S.

And so, now, let us actually try to see what is the total power that will be scattered under this pulse width, that is what we are interested in. So, then this pulse would have to interact with this region and all the backscattery, scattered light is going to be integrated at the receiver and let us just say the receiver is such that it can pick up or integrate all this power under that pulse, the pulse width W. So, it has enough bandwidth to essentially integrate the power.

So, what we would say is the if you look at the total backscattered power at the receiver due to the scattering at location L over z, then you have to do some integration. So, integration over that pulse width. So, and of course, in doing that, you understand that P naught is a constant. So, we can take some of these factors out P naught, you have alpha S, S is actually also a constant because that is the same across this entire length and then you say you do an integral over that pulse width. We are denoting as W, dz.

Now, what comes within this well, you have basically e power minus let us say to alpha L plus z by 2 where z corresponds to, so let us say the pulses actually occupying this extent and so, within that you have z as the parameter, z as the distance which this scattering is happening. And I am actually putting z by 2, why am I putting z by 2? Because what we are looking at is the round trip quantity.

So, as we discussed over here, when we are actually looking at the round trip, right that that distance would have to be whatever is going or the single pass distance is basically the round trip distance divided by 2 and that is what we are denoting over here.

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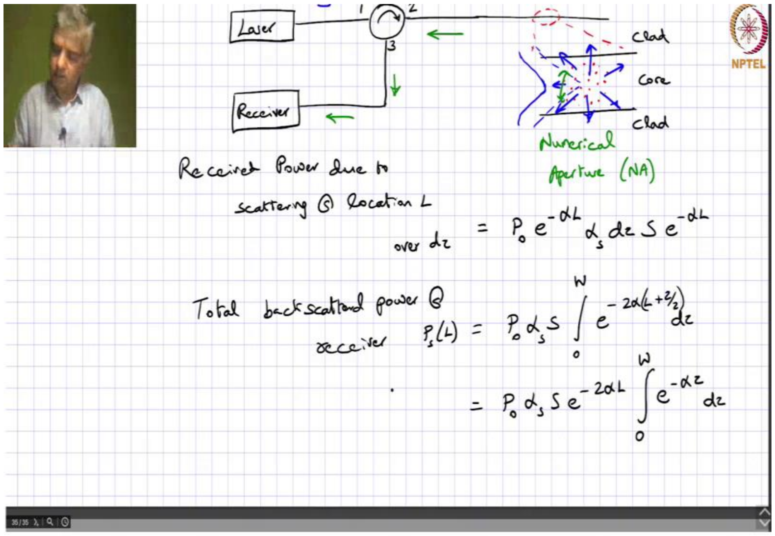

So, we are basically saying this is corresponding to z by 2 and of course, when we look at that we say e power minus 2 alpha L also you can take that out and so, you alpha S e power minus 2 alpha L 0 to 2 W, e power minus alpha z dz. So, that is the integration that you want to do. And of course, you would say that would if you do that integration, let us just take this over to the next page let us say this is the backscatter power Ps at of L due to scattering at a distance L.

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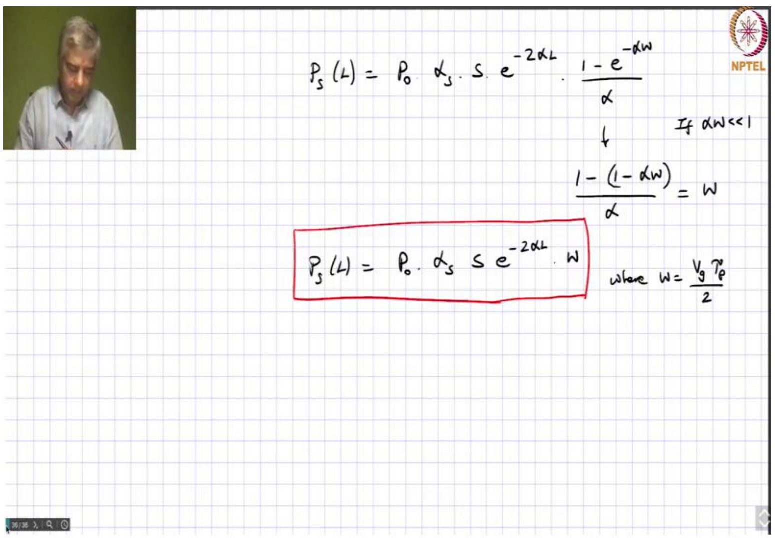

So, Ps of L what we saw was P naught multiplied by alpha S multiplied by S e power minus 2 alpha L and when you do that integration you get 1 minus e power minus alpha W divided by alpha. That is result and the result of this integration applying the limits. Now, if we consider the case of just look at this factor, if far far times W is alpha less than 1 or in other words you are sampling W is corresponding to the pulse width.

If the pulse width is you make it short enough that there is very negligible absorption happening over there this can be approximated as 1 minus 1 minus alpha W e power minus alpha W when alpha W is far far less than 1 can be approximate as 1 minus alpha W divided by alpha and then of course, that is going to give you just W. So, you can write Ps of L go to P naught multiplied by alpha is multiplied by yes e power minus 2 L multiplied by W.

Where W if we see that that corresponds to a certain pulse width and then the velocity of light in this medium previously we looked at the velocity of light in free space, but now, we are going through this glass medium. So, you will have a certain velocity Vg that is the group velocity multiplied by tau P is the pulse width, but divided by 2 because now, we are W corresponds to the single pass distance. So, we since we are looking at round trip configuration, we would say that will correspond to this factor of 2 in the denominator.

So, this is what characterizes the amount of power that you get at at the receiver due to scattering at a location L. Of course, with what we note from here is that this is proportional to W. So, if you want more scattered power, what you need to do is increase your W. How do you increase your W? Basically by choosing larger pulse width? We will see what is the downside of that in a few minutes.

Of course, when you say larger pulse width, then you you what you are compromising is the spatial resolution the ability to look at scattering between 2 points within this region. So, scattering at this point was is this point you know the what is the minimum distance that you can actually distinguish this scattering events.

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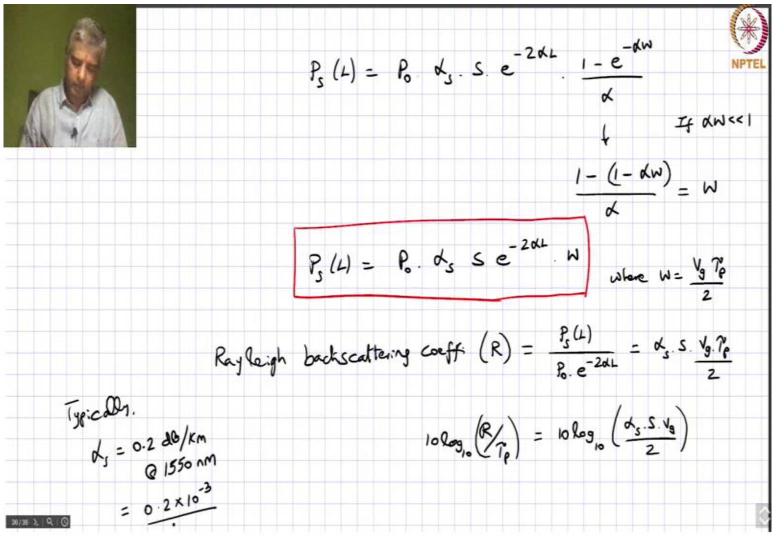

So, if your pulse width is too large, then you compromise on that, we will look into that little more detail shortly. But let us just, let us just try to see what this corresponds to in terms of real numbers. And before we do that, so there is actually a convenient way of representing all of this. That is, that is basically what do you call as? A Ray Leigh backscattering scattering coefficient that that typically call as represent as R. So, R is actually given by Ps of L, divided by P naught, which is, now we have a background loss. So, we need to make sure that we account for that.

So, normally without the scattering, you would have still encountered this background loss. So, that is e power minus 2, alpha l. So, B naught multiplied by e power minus alpha 2 alpha L is the power that is available at that point at L. And then, with respect to that you have a certain power that this backscatter now it is (())(41:59) for all other losses. So that, that is, that is why we call this backscattering coefficient point. So, so that is what it is typically referred to. And if we do that, then you can basically it corresponds to alpha S multiplied by S, multiplied by W, where W is given by Vg, tau P over 2.

So, that is what that that character is the backscattered coefficient. Now, in practical sense, what you are interested in is what is the backscattering coefficient in in a dB scale. And also, you want to make sure that you normalize with respect to the pulse width, because the pulse width is a parameter that you want to be changing and not these other things, you can change it, it is actually characteristic of the fiber that you are chosen. But the pulse width is actually a parameter that you can change.

So, you want to normalize this with respect to the pulse width. So, so what you are interested in is you are interested in dB scale, so 10 log base 10 of R over tau P, is what you are interested in. And so we can, so that is basically 10 log base 10 of alpha S, S multiplied by Vg divided by 2. That is a useful parameter to have. Why do we want to do it a log scale, because we know that everything is actually exponentially decaying in the fiber, so it is much easier to represent everything in log scale.

So, let us actually look at some typical values. So, if you start with alpha S, so typically for single mode fiber alpha S is 0.2 dB per kilometer at a wavelength of 1550 nanometer. So, now, we want to actually see if we can show this in in terms of linear units. So, you say, So, 0.2 dB per kilometers, 0.2 into 10 power minus 3 that is in dB per meter and that divided by 4.343.

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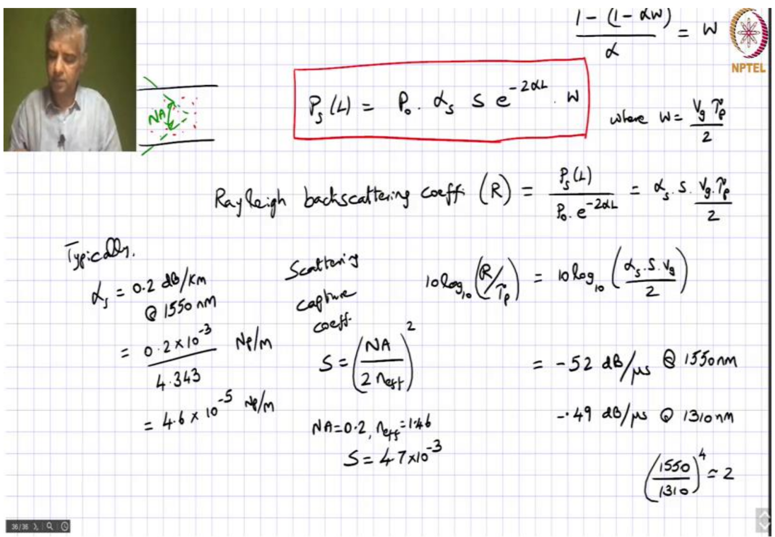

If you want to actually convert to neper per meter. So, if you do that calculation, that would correspond to roughly about 4.6 multiplied by 10 power minus 5 nipers per meter. So that is alpha S. Now what about the scattering the capture coefficient? So, you have the scattering capture coefficient that is given by S. So, what we are looking at is as far as S is concerned like we denoted previously there is all this scattering happens because of the oldest inhomogeneities.

And we said it was only over a certain cone of angles we are picking up and that cone is defined by the numerical aperture.

So, so it is actually in 3 dimensions, so the total area, you will have to see the angular extent in 3 dimensions. So, that would roughly correspond to the numerical aperture over 2 times ineffective that is actually the angle over one axis, let us say in elevation and azimuth, there will be a similar angle. So, you basically say that that corresponds to square of that. So that is, that is actually a rough expression of this. Now, if you put in a typical numbers for the NA is for a single mode fiber around 0.2 and effective will be around 1.46.

So, if you calculate S based on these numbers, that will correspond to about 4.7 into 10 power minus 3. And that is unitless because it is just a fraction. So, if you plug that back in, so what you get is you will get a number with respect to the pulse width, let us say typically, the pulse width that is looked at is in the order of microseconds. So, what you will find is this is about 52 dB per microsecond.

What is 52 dB, well minus 52 dB. So that is corresponding to 5 orders of magnitude lesser amount of light compared to the incident light. So, that is, that is the level of light that is backscattered and, and captured within the fiber and that is with respect to if you are sending a 1 microsecond pulse, so if you send and so, once again, if you take 1 microsecond and put it in this and try to look at W, W you will find is for 1 microsecond it corresponds to a distance of about 100 meters.

So, 1 meter would correspond to about 10 nanosecond if you do that conversion. So, if you if you wanted to, so, this is actually 1 microsecond is covering 100 meters, if you wanted to see what it is for 1 meter, then you would like to go down 2 orders of magnitude lesser, so if it is then be 10 nanosecond, so, within 10 nanoseconds, you will find that the backscatter coefficient is minus 72 dB. So, you will have much 2 orders of magnitude lesser amount of light.

And mind you all this we are calculating at 1550 nanometer. Now, the other wavelength that is typically used for example, in telecommunication applications is 1310 nanometer. So, if you want to find out what is the backscattering coefficient 1310 nanometer knowing what it is at 1550 nanometer, all you have to consider is that your backscatter coefficient is inversely proportional to the fourth power of lambda.

So, you would basically say this is if you want to look at this, this will be 1550 divided by 1310 to the power of 4. Which will roughly work out to be approximately a factor of 2. So, you can say that this will correspond to minus 49 dB per microsecond at 1310 nanometers. So, this is typically, so shorter the wavelength, more will be the scattering. So, because of that you will have a smaller negative number so, that that that is what it will correspond.