Optical Fiber Sensors

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Lecture No. 03

Overview of Distributed Sensors

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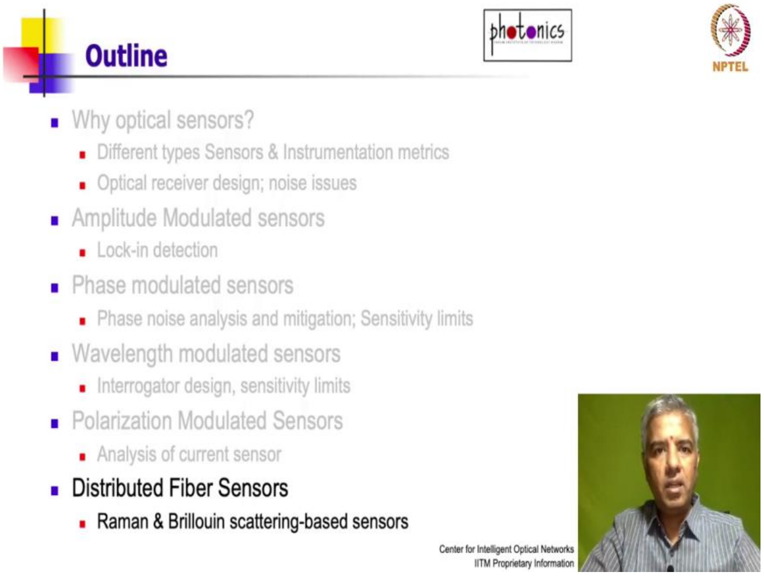

Outline

- Why optical sensors?
  - Different types Sensors & Instrumentation metrics
  - Optical receiver design; noise issues
- Amplitude Modulated sensors
  - Lock-in detection
- Phase modulated sensors
  - Phase noise analysis and mitigation; Sensitivity limits
- Wavelength modulated sensors
  - Interrogator design, sensitivity limits
- Polarization Modulated Sensors
  - Analysis of current sensor
- Distributed Fiber Sensors
  - Raman & Brillouin scattering-based sensors

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So far, we have been looking at different types of optical sensors, such as amplitude modulated sensors, phase modulated sensors, wavelength modulated sensors and polarization modulated sensors. Now it is time to look at a very unique type of optical sensor, which is distributed fiber sensor. So, I told you previously that one of the major advantages in an optical fiber is that we can send a pulse of light down the fiber over long distances because the fiber is relatively low loss as low as 0.2 dB per kilometer. So, you could possibly even go 100 kilometers and only lose 20 dB of the light or 2 orders of magnitude of the light.

So, we could you could send pulse down the fiber and you could possibly look at light that is backscattered. And from the backscattered light, you can possibly try to learn what is happening down the fiber. So, it is pretty much like when you send a pulse of light down the fiber, you are as if you are taking a flashlight and you are illuminating the optical fiber section by section and we get to see through the backscattered light, some information about whatever the physical environment is around that optical fiber. So, that is what distributed fiber sensors are about. And specifically, we will look at the examples of Raman scattered sensors and as well as Brillouin scattered, scattering based sensors.

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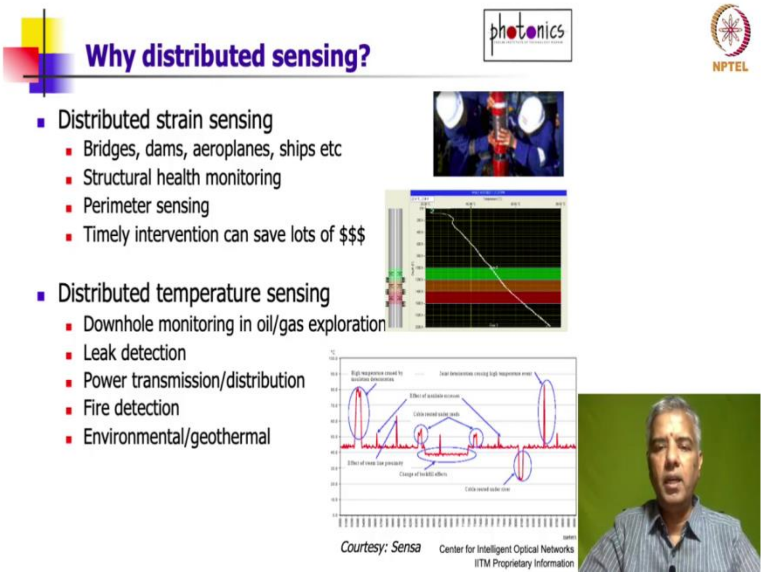

Why distributed sensing?

- Distributed strain sensing
  - Bridges, dams, aeroplanes, ships etc
  - Structural health monitoring
  - Perimeter sensing
  - Timely intervention can save lots of $$$
- Distributed temperature sensing
  - Downhole monitoring in oil/gas exploration
  - Leak detection
  - Power transmission/distribution
  - Fire detection
  - Environmental/geothermal

Courtesy: Sensa

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So, let us go back and look at the motivation for why distributed sensing we already talked about distributed strain sensing in which case, we said we may want to do structural health monitoring, perimeter sensing and so on. But, there is another class of sensors, which is based on measuring temperature along the length or the fiber and these are called distributed temperature sensing.

And one very nice example of that is oil and gas exploration. So, when you do oil and gas exploration, especially, when you when your drill pipe and you try to find out what is the level with which oil is present. Here, you are tracking the depth. So, this is actually the ground level, and then you are going deeper down the well and here you are tracking temperature. So, as you go further and further down, you will find that the temperature is increasing and then beyond a certain point, you will find that the temperature is going beyond a certain value and based on that temperature, you can actually figure out what is the level of oil present in that well. So, this is called down oil monitoring and that is very commonly used in oil and gas exploration.

Similar sort of information can be very useful for another application, which is power monitoring distribution. Remember, we talked about the example of a smart grid and we said it would be nice if we could monitor the transmission or distribution of power along those electrical lines and that is possible if along with a power cable you have an optical fiber embedded. So, what do you see in this case? This is actually temperature as a function of distance. And you know that whenever you are transmitting power through electrical cable, due to joule heating, you will end up having a rise in temperature.

So, you expect the temperature to rise to a certain level. But then you would you may see things like this see these spikes over here, which are indicating that there may be some faults in the power cable. So, by having a real time monitoring of the temperature as a function of distance, you can actually figure out if there is some damages in the insulation or some corona discharge that is happening. And, and, you know, faults like that. So, for real time power monitoring, distributed temperature sensing is very useful. And what we will see is, this is actually enabled by distributed fiber sensors.

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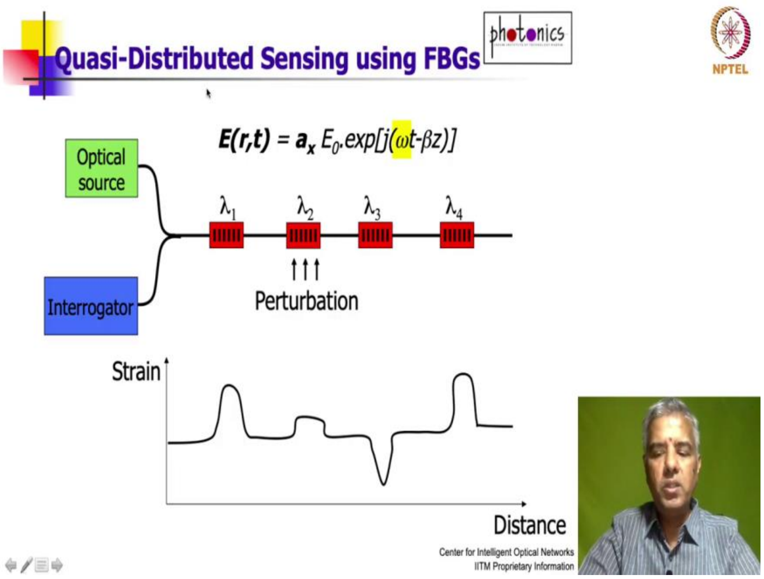

Quasi-Distributed Sensing using FBGs

$E(r,t) = a_x E_0 . exp[j(\omega t - \beta z)]$

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So, let us let us go on and look at the principle of distributed fiber sensors. Before I explain the specific principle of distributed fiber sensors, let us see what we can do for some of these applications that we talked about using known technology. We did talk about Fiber Bragg Gratings. And so why cannot we use Fiber Bragg Gratings. For such applications, sure enough, we talked about it.

You can actually have different fiber, I mean, different gratings with different periods, and different sections, and then we will be able to pick up whatever perturbation in this case, you want to get temperature information along the length of a pipe, let us say or length of a cable, then you could put multiple gratings down the line, and you could possibly pick up the temperature information at these points.

The only problem with this is Fiber Bragg Grating is essentially a point sensor. So, it only provides information at that point, it does not tell you what is happening over here? What is happening over here? So, between gratings, you do not know what is actually happening. So this is not a true distributed sensing solution. So, we that is why we call this is a quasi distributed sensing solution. Now, what would a true distributed sensor look like?

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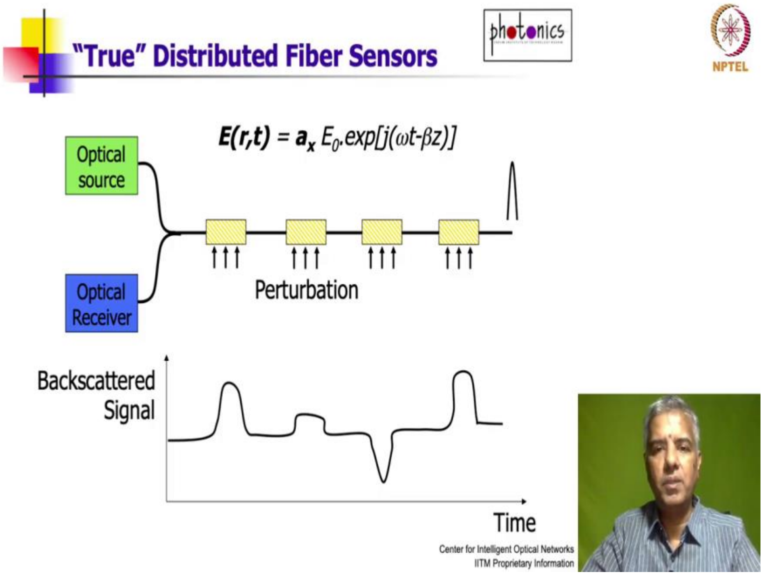

"True" Distributed Fiber Sensors

$E(r,t) = a_x E_0.exp[j(\omega t-\beta z)]$

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Well, a true distributed sensor would look like this, now you have an optical source, and you may want to send some light, and that as it propagates down the fiber is going to send some bracketed light all along the length of the fiber. So, you should not have to say, predetermine, this is where I am going to look at, like if you know exactly where you want to look at. And if there are, if you need only tens of sensors, then Fiber Bragg Gratings, are probably good enough. But if you want a true distributed sensor, that is, wherever the fiber is going all along the length of the fiber, you want to pick up physical parameters like strain and temperature, then you essentially need a solution like this. So, what do you do in this?

Well, you actually send a pulse of light. Instead of so far, we have been looking at the all the other cases where it is a continuous wave radiation that is sent into the fiber. But in this case, I am sending a pulse of light, that a pulse of light is having is extending over a certain time. And that actually, when it is propagating down, the fiber is occupying a certain section of the fiber? So, and it is going to propagate all along the length of the fiber.

So, this is what I was talking about. This is like illuminating section by section by section of the fiber and then you can look at the backscattered light. The backscattered light, you can actually look at it as a function of time. And so why would that? So, what would that give us? Well, we know that the light actually travels in this fiber at with a very specific velocity. The velocity is given by velocity of light in free space divided by the refractive index of the medium, or the refractive index that the light sees as it is traveling down the fiber. So, that would be the velocity of the light.

So, if you know the velocity of light, you can convert this time, this time, multiplied by the velocity of light will give you distance? Now, of course, you had to be careful about this. The light actually goes down the fiber and then it comes back. So, it is actually going through a round trip in terms of actually distance so you will have to, when you when you convert this signal as a function of distance, you would have to be taking care of that.

But, but nevertheless, if this pulse is going down the fiber as it is propagating down the fiber, it is going to send some backscatter signal, let us say the intensity of the scattered light is looking like this. And that might actually indicate that there are some perturbations happening at these locations. So, so, that is actually what we mean by a true distributed sensor, because in this case, the perturbation can be anywhere along the length of the fiber.

And because the pulse is actually traversing along the entire length of fiber, you get to find out what is the backscattered signal at any point along the fiber. And like I said, this can be converted, the x axis can be converted to distance, so you get a clear map of the perturbation that is happening in the fiber. So, let us actually look at how to make an instrument that can capture this backscatter signal precisely.

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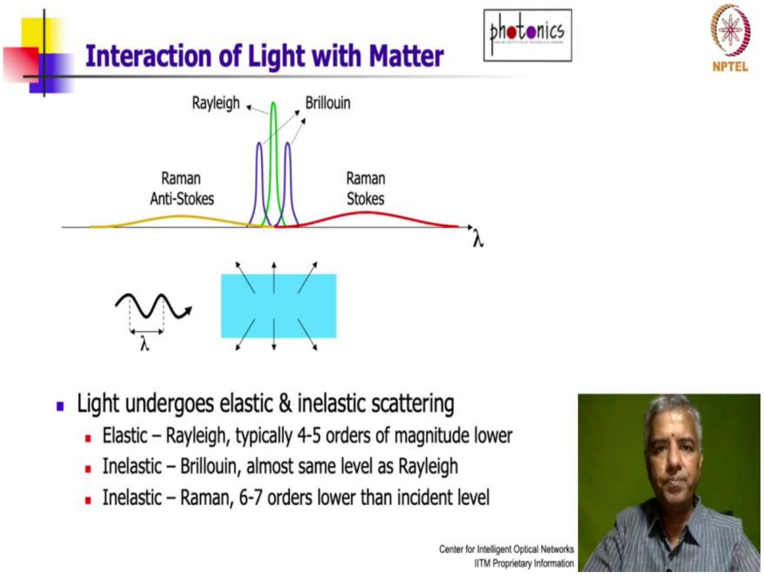

Interaction of Light with Matter

- Light undergoes elastic & inelastic scattering
  - Elastic – Rayleigh, typically 4-5 orders of magnitude lower
  - Inelastic – Brillouin, almost same level as Rayleigh
  - Inelastic – Raman, 6-7 orders lower than incident level

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And one aspect of light that helps in this process, is the fact that when light actually goes through any medium, let us say it is a reasonably transparent medium. Several things can happen, the light can actually, of course, propagate down the fiber get transmitted, but part and some part of the light may even get absorbed within that medium, but part of the light also gets scattered. So, why does it get scattered?

Well, there is one reason where the optical fiber, you can look at it as having density fluctuations all along the length of the fiber, that is the way the fiber is made. It is a highly amorphous material. So, you have scattering all along the length of the fiber. And that scattering is what you call us Rayleigh scattering. It scatters at the same frequency or the same wavelength that it went into the fiber. So, it is called elastic scattering. And so, there is no transfer of energy light just goes in there and it gets scattered and we are looking at the backscattered light. Now, that happens all along the length of the fiber.

But it can also get scattered by what are called phonon modes, some vibrational modes, that are existing within this material or is called acoustic vibrational modes. And so, those are like the whole glass network is sort of agitating at room temperature and so that that causes some vibrational modes. And those will actually interact with the could possibly interact with the light and you can actually get scattering happening which is called Brillouin scattering.

Now, there is another process that can happen if you go at a mole and look at this material at a molecular level the molecule consists of 2 atoms attached with the bond and the atoms are moving around the mean position which means that there is some vibrational mode corresponding to the molecule itself corresponding the molecule itself and that vibrational mode can once again scatter this electromagnetic radiation, this this light radiation, and that scatter can produce what is called this Raman stokes or Raman anti stokes. I will go into more details in the in the following slides.

But the key thing to notice that this is not very high probability. Typically when you are talking about Rayleigh scattering, we are looking at 4 to 5 orders of magnitude lower compared to the light that you went in with and Brillouin scattering is almost within an order of magnitude compared to Rayleigh. But Raman scattering is much less probable. And correspondingly, when you look at the backscattered light that could be 6 to 7 orders of magnitude lower than the incident light. So these are very, very faint, scattered signals.

So this is why you know whenever light goes through any of these materials, you may be having Raman and Brillouin scattering but you are not normally seeing those because these are very, very faint sort of backscatter signals. So, unless you are looking for it specifically, you may not see it. So let us first look at Rayleigh scattering, and let us see how to make an instrument, which can characterize the loss of the fiber.

Let us say you have a long length of fiber with multiple bends and connectors and so on, how do you actually get information about that fiber by launching light into the fiber? That is, that is through a instrument, that is called optical time domain reflectometer. And I will talk about that in a minute.

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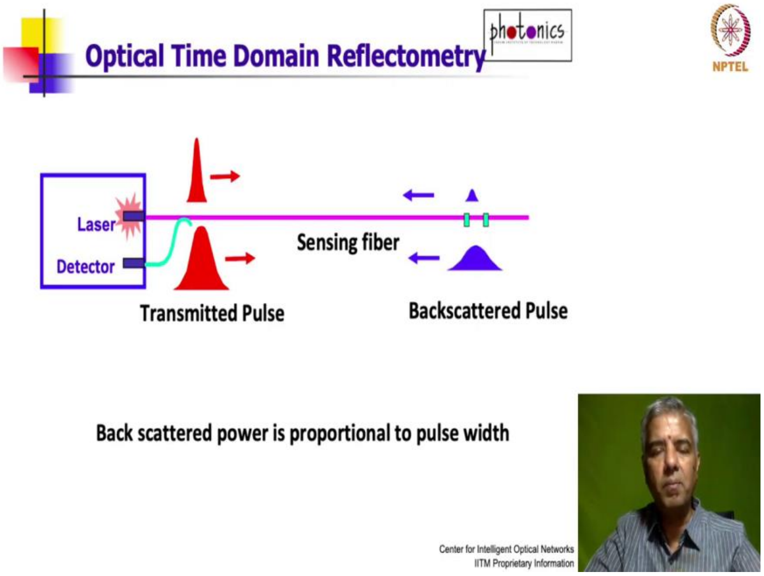

Optical Time Domain Reflectometry

Back scattered power is proportional to pulse width

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So, what is optical time domain reflectometry all about? Well, you could essentially take a laser and, and launch light into an optical fiber. And let us say you send it through a coupler device, which sends light from this port to this port, but whenever whatever backscattered light part of the backscattered light is actually coming through this port, and you can actually observe it using optical receiver.

So, if you send a pulse of light. That pulse is going to occupy a certain section of the fiber, right? And whatever, you know, scattering that could happen within that section of the fiber will actually come back towards the detector. So, this is actually an illustration of how light is scattered from this section of the fiber. So, it is going to take a certain time to go for this pulse to go here, and then the scattered light to go back to the detector. But it is all very well timed, meaning it is all highly deterministic, because you know the, what is the velocity of light and the fiber.

But the point is, if you send a relatively, large pulse, you get a relatively large backscatter signal. So, your signal to noise ratio could be fairly good when you send a pulse like this, but the downside of that is, if you have 2 perturbations, 2 events, as we call it, that are fairly close with each other, meaning they are, they are spaced a shorter distance compared to the section that the pulses occupying, then there is actually no way of telling that there are those 2 events.

So, the, you are not going to be able to resolve these 2 events. If you want to resolve those 2 events, what would you do? Well, you could actually go with shorter pulse. If you have a shorter pulse, that so that it is occupying a distance that is lesser than the smallest distance you want to resolve in the fiber, then you could potentially resolve these 2 events. But what is the disadvantage of that?

The disadvantage is that, because the fiber is occupying a smaller section, the amount of scattering that you that happens within that section is also lower. So, your the signal that you get back is going to be lower. And if you have a constant noise floor at your receiver, that means the signal to noise ratio is not going to be very good. And if the signal to noise ratio is not very good, then the accuracy with which you can actually detect these events may be compromised.

So, this is actually a classic trade off as far as optical time domain reflectometry is concerned. If you want to actually get signals from longer distances down the fiber, you want to actually go for a fat pulse, nice wide pulse. But you do not get very good spatial resolution, in that case. But if you want high spatial resolution, you need to send a thinner pulse, meaning a short pulse, and in that case, you are not going to be able to go very far down the fiber or the signal to noise ratio that you go that you get a farther part of the fiber is going to be quite low.

So, that is always a trade off between the signal to noise ratio and the spatial resolution that you can achieve. Using this optical time domain reflectometer, just keep that in mind, we will come back and look at that little more detail.

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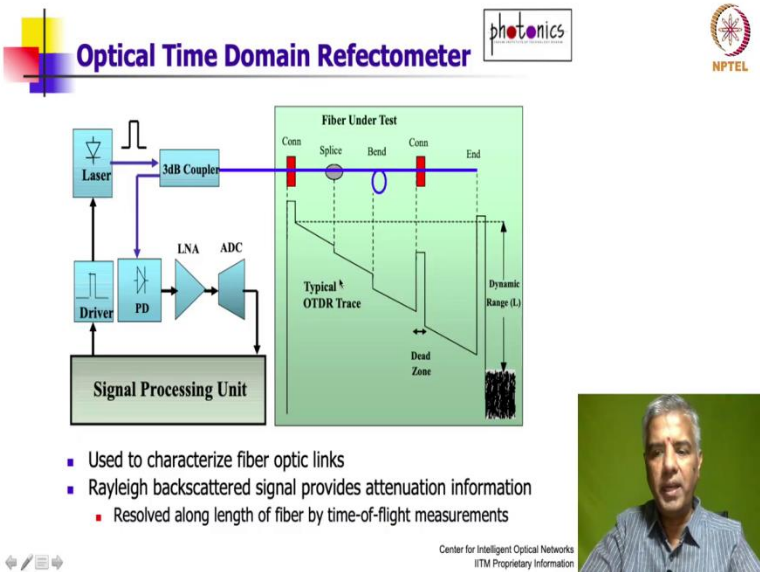

Optical Time Domain Refectometer

- Used to characterize fiber optic links
- Rayleigh backscattered signal provides attenuation information
  - Resolved along length of fiber by time-of-flight measurements

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So, how do you put together an instrument? Well, you start with the signal processing unit, something that triggers a pulse. And then that, this driver actually gives a current pulse, and the current actually drives the laser, so that you can get an optical pulse out of that, this optical pulse, you will send it through a coupler device, which sends 50 percent of the light down this fiber.

And then as it propagates down the fiber, you will typically have scattering all along the length of the fiber. But because of the fact that you are losing light, due to this scattering, the light is getting attenuated, the amount of light scattered from this region is going to be lesser compared to the amount of light that scattered from this region. And that is going to be still, the amount of light scattered from this region is going to be still lesser than this one, and so on.

So, what you expect to see in the backscattered intensity trace is, you know, you will have good reflection because of this connector, which is actually 2 fibers with an air gap. Whenever you have an air gap, that is like a impedance mismatch. So, you will have what is called a Fresnel reflection, so you get a reflection of the pulse. And then when you look at the backscattered signal.

This is the Rayleigh backscatter signal is going to keep going further and further down, because of the fact that it is getting attenuated as it propagates down the fiber, this is a 0.2 dB per kilometer attenuation that I talked about previously. So and of course, whenever there is, splice, or as a band or whatever, at that point, you are losing further light, so you will have a sudden change in the level. And then on the other side, once again, you have this, this Rayleigh scattering happening. So you have this attenuation and then further down, you have even more loss and so on.

And here at this connector, you have a back reflection, a Fresnel reflection, so that that is why you see like a pulse, and then further down, it goes down like this. And finally it reaches the noise floor, so you are not going to be able to see any signal once it gets to the noise floor. So, how do you see all this signal? Well, basically, whatever is backscatter, you extract that through this coupler, part of the light is coming over here. And that light, you make it incident on a photodiode, which can be PIN photodiode, or avalanche photodiode.

And the output of the photodiode is going to be photo current. And that photo current is converted to a voltage using a low noise amplifier, typically a transimpedance amplifier. And then the output of that is going to be digitized using analog to digital converter. And then it is going to go back to the signal processing unit. And this is where the signal processing unit is going to be important because you shoot 1 pulse, and then you start listening. You are listening for the backscattered light, and this case, you are detecting the backscattered light.

It is like what you do in, in a sonar, you send an acoustic pulse, and then you look for backscatter, like very much like what bats do. So, they navigate by sending sound waves and looking at how long it takes for the backscatter signal to come back. And based on that it actually says there is some obstacle close by and so on. So, it is the same principle, so you are actually looking at all the backscattered light. So, you wait until the light goes through the entire length of fiber and comes back.

For example, if you send a pulse of light over 100 kilometers, it will take roughly 1 millisecond to go and come back. So, you wait until then, and then you could send another pulse, because within 1 millisecond, none of this fiber characteristics have changed. So, you could potentially send another pulse and get signals once again and so on. And that might actually be helpful to improve the signal to noise ratio, and I will come back to that in a minute. But let us actually look at the level of light that is coming back.

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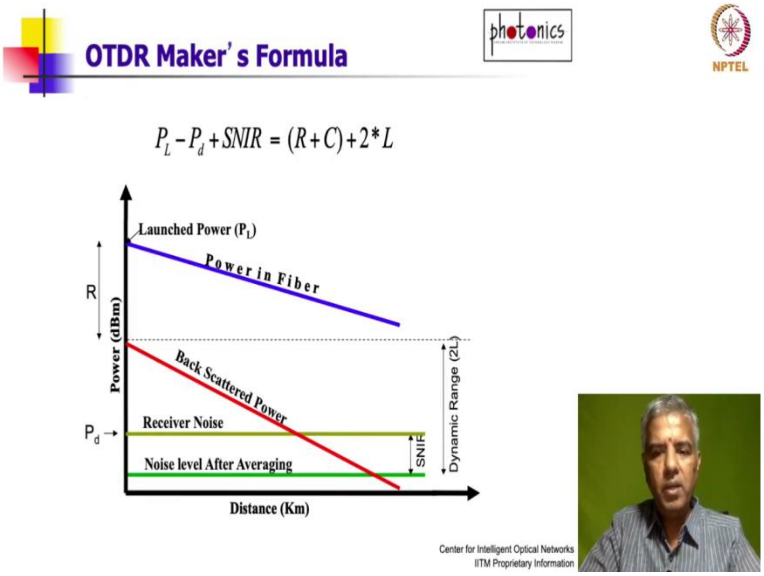

OTDR Maker's Formula

$$P_L - P_d + SNIR = (R+C)+2*L$$

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So, to really see what is the dynamic range of your instrument, that is, how much of the signal, can you get over what distance, you have to look at a map like this, this is actually power as a function of distance. So this is, let us say, is the launch power? Let us say 100 mill watts of power, you launch into the fiber, as it propagates down the fiber, it is going to lose, you know, some of the light because of the intrinsic attenuation in that fiber, that is, it says 0.2 dB per kilometer.

So, it is going to keep losing light as it is propagating down the fiber. Now, what we are interested in is the backscattered power, and this is actually defined by the Rayleigh backscattering coefficient R. So, it is going to be, say 30 dB or 40 dB lower compared to the launch power. So, you will have the backscatter power, you know, that is also decreasing because the incident power itself is decreasing.

But pay attention to this, the slope of this is higher than the slope of this, in fact, to be precise, the slope of this red line is going to be twice compared to the slope of the blue line, why? Well, this is just tracking the power that is going down the fiber, whereas this is tracking the power that is coming back also. So, while going down, it is it loses some light, but on the way back also, it is going to lose you know, light at the rate of 0.2 dB per kilometer. So, this actually will be twice the slope of this one.

And of course, what you can see coming back is going to be limited by the noise that your receiver. So, let us say this is the level of noise that we have for our receiver, then up to this point, I can see what is happening beyond this like my signal is submerged in the noise. So, I cannot I cannot see that. But on the other hand, as I mentioned in the previous graph. We have a possibility of you know, sending further pulses and improving the signal to noise ratio.

So how do you do that, you send another pulse and you get the backscatter signal then you add that to whatever you got for the first pulse and then you send another pulse and in the back get a signal add that and so on. So, when you add all these signals, the signals if you say n times, you have sent these pulses, n pulses you have sent and you have gotten signals back the signal amplitude goes as n.

Whereas the noise when you look at it, the noise variances add but when you talk about the RMS value of that, that is going to be root of n. So, the noise actually the noise floor increases, it also increases because every time you are accumulating noise it is also increases, but that increases only at root of n, whereas the signal increases as n. So, overall the signal to noise ratio improvement, you get this root of n, where n is the number of pulses that you have sent or in other words, the number of averages that you have done.

So, if you do that you can actually effectively reduce this noise level. And that means this backscatter power is meeting the noise floor at this point instead of this point. So, you have managed to unearth this much of the signal this much distance, so you are improved the overall distance or which you can get the signal. And this actually is called the dynamic range. From the point you start seeing the backscatter power to the point it disappears into the noise. That is called the dynamic range of the instrument. And that is actually a key parameter that we look at when we design this OTDR.

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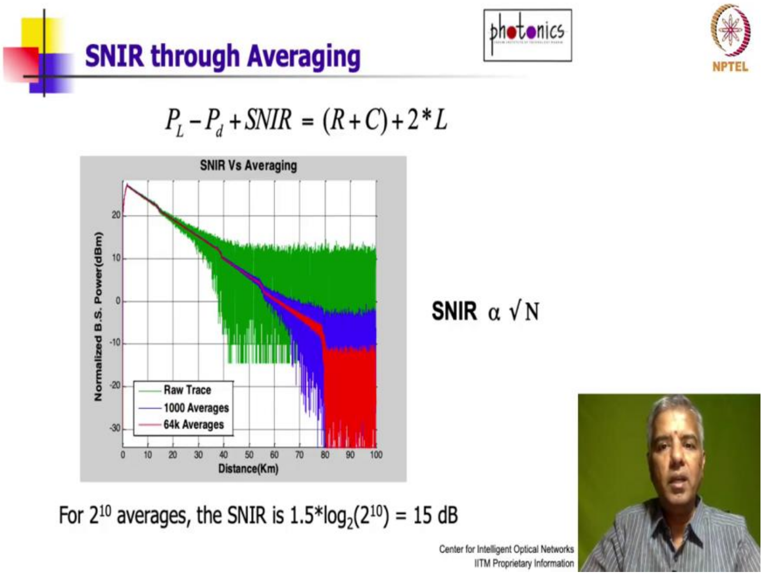

SNIR through Averaging

$$P_L - P_d + SNIR = (R+C)+2*L$$

SNIR $\alpha \sqrt{N}$

For 2^{10} averages, the SNIR is $1.5*\log_2(2^{10}) = 15$ dB

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So, let us quickly look at how to improve the signal to noise ratio, like I said, the signal to noise ratio goes as root of n, where n is the number of pulses that you have sent or the number of averages. So, to illustrate that, here is a typical OTDR trace, this is a backscatter power as a function of distance, what you see in the green is what you have got in after just one pulse. So, the signal is going into the noise, even at about 30 to 35 kilometers.

So, you cannot see the signal beyond this point. But you send further pulses, 1000 pulses, and then you keep accumulating the corresponding traces, this is where the signal processing unit is very important because it has to synchronize all these all these functions. And if you do that, that is what you get at the blue trace 1000 averages, you are able to improve the signal to noise ratio, which means that your noise floor effectively, yes, come down by 1000 average as you should see a noise floor improvement of roughly about 15 dB. So, that is that is almost what you what you see over here.

And correspondingly, you are able to see more of this, you know, you are able to see up to maybe 60 to 70 kilometers the signal, the backscatter signal. And then of course, you can keep doing this now I if I go to 64k averages, then you get even better signal to noise ratio improvement and noise floor goes even further down. And then I can see when longer length of fiber. So this is actually a very interesting trick that you use to improve the dynamic range of your OTDR. And this is made possible because to do the 64k average is guess how much time I have taken.

For 1 trace, I have taken 1 millisecond if I am going over 100 kilometers, right. And 1 millisecond, the light bulb goes to the end and whatever backscattered comes back within 1 millisecond. Now, if I do 1000 averages, that is 1000 milliseconds, that is 1 second. So, I managed to improve the signal to noise ratio in 1 second by this much. And then if I wanted to go 64k averages is 64 seconds. So, that is this 1 minute. So, what is happening within 1 minute, not much what if you are looking at what is happening in optical fiber over a minute, the environmental changes are not so great, the loss certainly does not change so rapidly.

So, you could easily take a minute or 2 to do this measurement. And in this process, you got a huge improvement in the signal to noise ratio and through that the overall dynamic range. So, so, this is actually a very, very powerful concept that is used in OTDR to improve the dynamic range.

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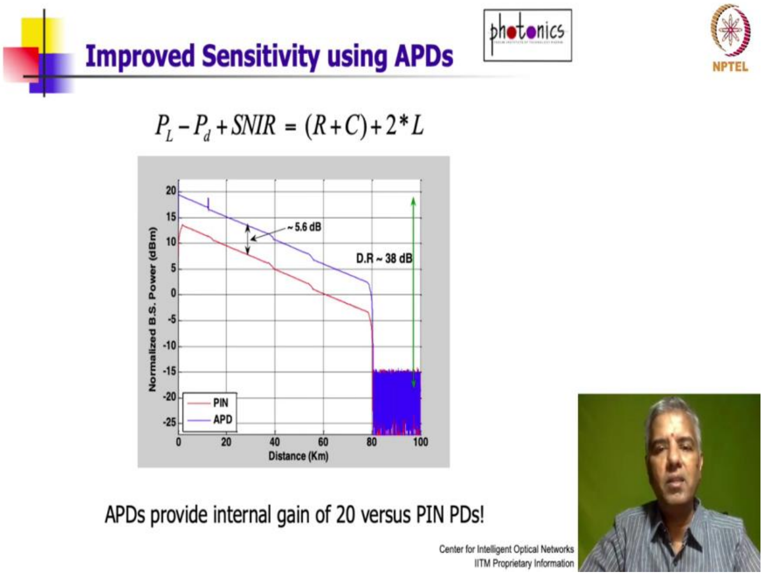

Improved Sensitivity using APDs

$$P_L - P_d + SNIR = (R+C) + 2*L$$

APDs provide internal gain of 20 versus PIN PDs!

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Now, the other thing you could do is also try to use an avalanche photodiode to improve your signal. So essentially, we know that something that we will look at in more detail is a PIN based receiver especially when you are considering for an OTDR application is typically limited by a noise called thermal noise that is happening in the receiver. Now, if you go to avalanche photodiode, you can you actually incur what is called a short noise. But because the short noise to start with is very low, you can actually keep getting an avalanche gain without significantly changing the noise floor.

So, in this case, we got an avalanche gain of about a factor of 20. And so that that corresponds to 13 dB, but then again, you get only half of that because of the fact that it is actually a round trip you know, backscattered signal transmission that you are getting, so, you have to account for that. But, I mean rather, this is actually 11.2 dB improvement divided by 2 is what you get as 5.6 dB. So, you could get better dynamic range by using photodiode which has an internal gain, that is what an avalanche photodiode is. So, you are able to improve the overall dynamic range.

So, that is what we have as far as the OTDR is concerned, but the OTDR right now, based on the Rayleigh scattering is only giving you information about loss in the fiber, what is the rate at which the signal is getting attenuated? And if there are any connectors or splices, what are the losses in those points, that is what it gets. Remember, what we started talking about is distributed temperature sensing.

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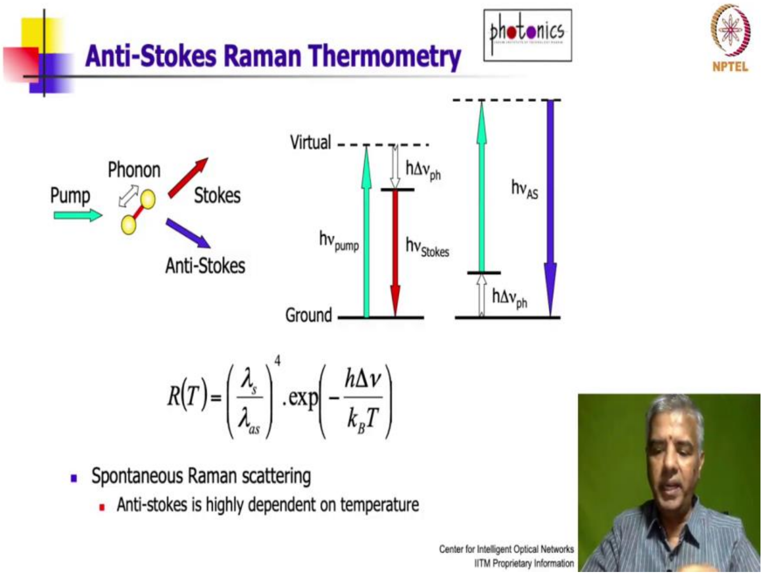

Anti-Stokes Raman Thermometry

$$R(T) = \left(\frac{\lambda_s}{\lambda_{as}}\right)^4 . \exp\left(-\frac{h\Delta\nu}{k_B T}\right)$$

- Spontaneous Raman scattering
  - Anti-stokes is highly dependent on temperature

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So, let us see actually, how to implement distributed temperature sensing using this OTDR concept. So, essentially, we need to marry the OTDR concept with something else, what is that something else? That is what we are talking about is Raman scatteringk. So, what is Raman scattering as I mentioned briefly before, when you have an incoming electromagnetic radiation interacting with the vibrational modes of the medium, which are called the optical phonon modes.

Then there are 2 different events that are possible, one is it can give energy to this vibrational mode, in which case it scatters off with lower energy. So, this is what you have indicated here, this is the incoming photon energy, but part of it is given to this vibrational mode. And it scatters off with a lower energy photon and lower energy corresponds to longer wavelength. So, that is why I have indicated incoming as green and the scattered as red. Just to keep track of the wavelength.

But there is also another event that is possible that event is it can suck the energy from this phonon mole and scatter off with a higher energy photon. And that is what we call as anti stokes process. Now, that is what is indicated here. If you already have a vibrational mode, with a certain photon energy, you can suck this energy with the incoming photon and you can scatter off with the higher energy photon.

So, you want to ask the question, under what circumstances is this more probable? Well, one reason why you might actually have this vibrational mode or lots of these vibrational modes, these phonons, phonon modes is because of the ambient temperature that the material is experiencing. If you heat up the material, then all the atoms are going to bounce around their mean positions.

And so you are going to have lots of vibrational modes. And in that scenario, the probability of this process happening is is higher. So, as you increase the temperature, you can expect more and more of this anti stokes you know scattering happening. So, the, if you take the ratio of the anti stokes scattered light, light intensity to the stokes scattered light intensity that actually comes through a Bose Einstein distribution, but it falls out as having this exponential dependence on temperature.

Here, delta nu corresponds to the delta nu of the phonon the phonon h times nu corresponds to the phonon energy of the, of the material. But the key point is it is got an exponential dependence on temperature. So, by observing the backscattered light intensity for the stokes as well as the anti stokes, I take the ratio of these 2 intensities, you can get a very good idea of what is the temperature at any point along the length of the fiber. So, now you marry this concept with your OTDR concept, and what you get is a Raman OTDR.

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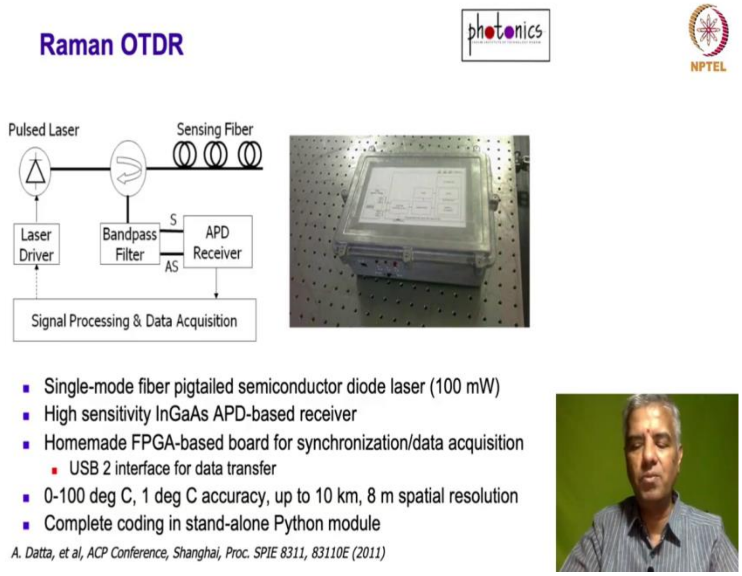

Raman OTDR

Pulsed Laser
Sensing Fiber
Laser Driver
Bandpass Filter
S
AS
APD Receiver
Signal Processing & Data Acquisition

- Single-mode fiber pigtailed semiconductor diode laser (100 mW)
- High sensitivity InGaAs APD-based receiver
- Homemade FPGA-based board for synchronization/data acquisition
    - USB 2 interface for data transfer
- 0-100 deg C, 1 deg C accuracy, up to 10 km, 8 m spatial resolution
- Complete coding in stand-alone Python module

A. Datta, et al, ACP Conference, Shanghai, Proc. SPIE 8311, 83110E (2011)

So, how does the Raman OTDR look like? The typical setup is like this, just as before we are a signal processing unit, which triggers a pulse, laser driver gives a current pulse and the laser actually gives an optical pulse that goes through a circulator, circulator is a device, which takes light from this port and gives it to this port, and whatever comes back is actually directed to this direction into this port.

So, it launches the pulse of light down the sensing fiber, just like we saw previously, the OTDR concept, it goes all along the length of the fiber and gets back scattered you have Rayleigh backscattering also, but in addition, you have stokes and anti stokes generated all along the length of the fiber, was it available in the previous case also? Certainly, it was available, but we were not looking at that we were looking at one leader Rayleigh scattered signal.

Because that is much higher intensity than the stokes or anti stokes. So, we were neglecting that information. But if you put a bandpass filter, which actually separates out the Rayleigh from the stokes and anti stokes, then you can actually extract the stokes and anti stokes and then you can send it through corresponding photodiodes. This is actually a 2 channel receiver. So, it keeps that information, and then it digitizes all of that, and gives it to the data acquisition system, which is typically like FPGA based mode.

That is what we have actually developed this an instrument that we developed in our lab. And, and this FPGA board is able to do this entire synchronization as well as the data question. And it will also help us capture the stokes and anti stokes time traces, average time traces, and it gives it out and you can take a ratio of that to get the temperature. So, for example, you know, we have demonstrated that we could pick up to 0 to 100 degrees in.

You know, over 10 kilometer length of fiber, you know, that is a fairly long length of fiber with one degree accuracy. And in this case, because the receiver bandwidth was limited, we could achieve only 8 meter spatial resolution, but other people have demonstrated that they could do 1 meter spatial resolution. So imagine this, this is like 10 kilometers with 1 meter spatial resolution.

Once again, it is almost like putting 10,000 thermistors you concatenate all of them and whatever information you can get with them, that information you get with a single strand of fiber, and that fiber is just connected to a small box like this, each of these holes is like, inch wide and, distance between them. So, you are looking at a fairly compact box with which you can get all this information. So, that is a fairly powerful technology.

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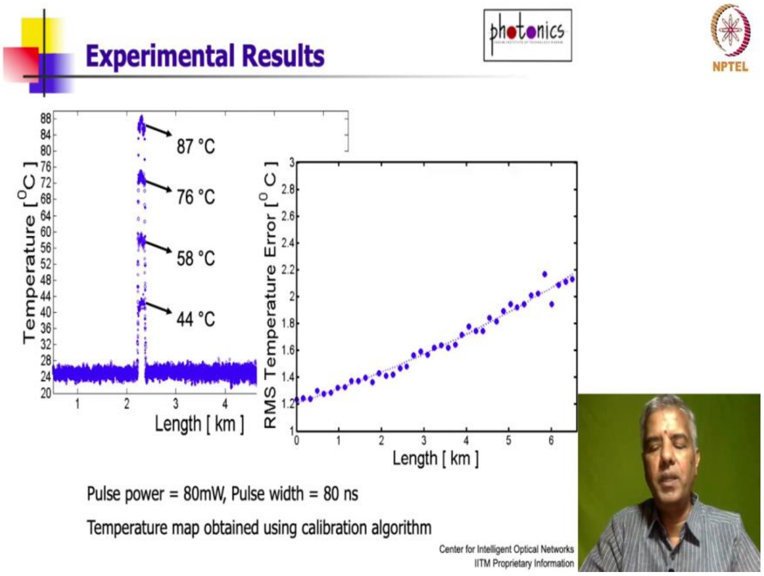

Experimental Results

Pulse power = 80mW, Pulse width = 80 ns

Temperature map obtained using calibration algorithm

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So, this is the kind of map that you get after some processing basically temperature as a function of length. And we basically put a test fiber inside an oven and we cranked up the heat of the oven, and the instrument is able to beautifully bring out the temperature of the fiber, different settings of the oven. One thing to note here is that is certain noise at the baseline. So, that is corresponding to the noise that you have at your receiver itself.

And, and interestingly, we see that the noise is actually increasing as you go to larger distances. That is essentially because of the fact that from this longer distances, the stokes and anti stokes scattered signal are going to be so much lower in intensity from this point compared to this point. Because the fiber inherently is attenuating light as the pulses propagating so because of that you have very low level of light and because of the signal to noise ratio is poor and there because of that you do have higher uncertainty in the temperature measurement over here compared to here.

So, this is actually a plot of the RMS temperature error as a function of distance and what you can see is clearly as you go to longer lens, you will actually have higher errors with respect to your temperature measurement. So, that is actually what we call us Raman OTDR, or distributed anti stokes Raman thermometry, which is useful for distributed temperature sensing and I already talked to you about what are the different applications of that.

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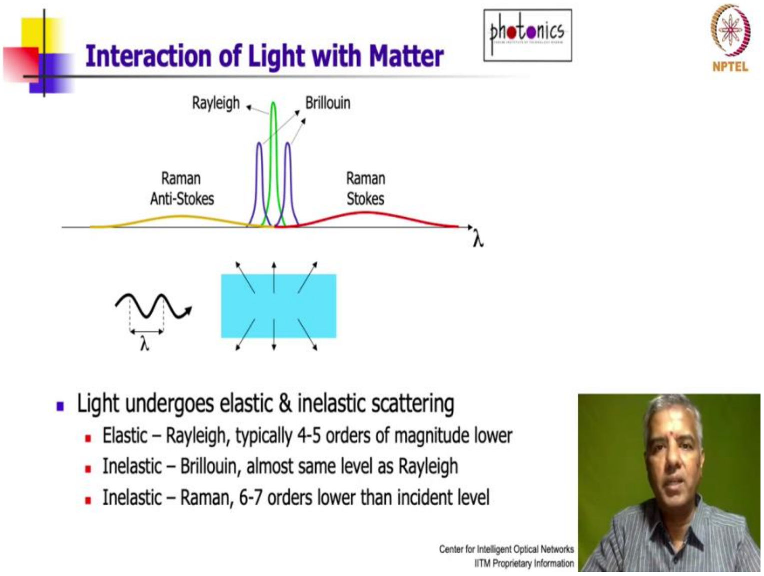

Interaction of Light with Matter

- Light undergoes elastic & inelastic scattering
  - Elastic – Rayleigh, typically 4-5 orders of magnitude lower
  - Inelastic – Brillouin, almost same level as Rayleigh
  - Inelastic – Raman, 6-7 orders lower than incident level

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Now, let us move on to another aspect of distributed sensing, I told you about Brillouin scattering. The Brillouin scattering is essentially interaction of light with these bulk phonon modes inside the material, which are called acoustic phonon modes. That just to differentiate that from the optical phonon modes. That is contributing to Raman scattering, which is basically moleculer vibration, here, the entire glass matrix is vibrating. So, that is what we call acoustic phonons. So, what is how is this interaction working out? And what do we what can we learn by observing this Brillouin scattered light, that is what we are going to look at next.

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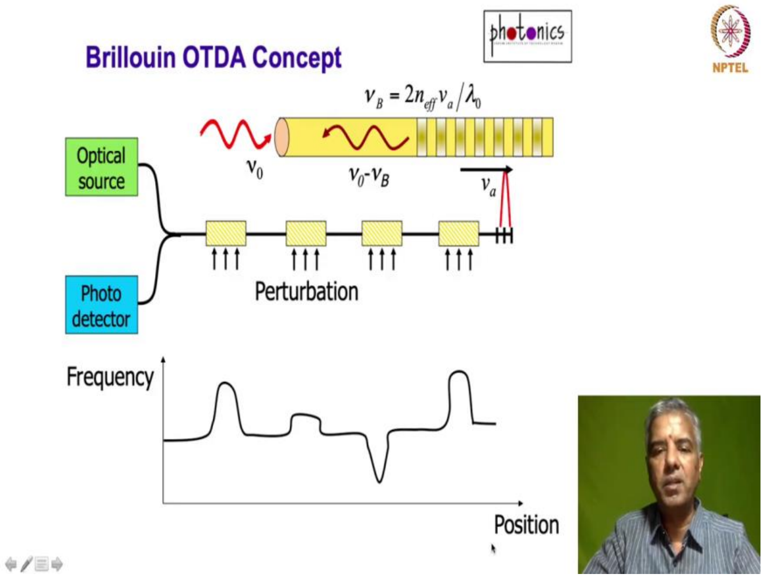

Brillouin OTDA Concept

$\nu_B = 2n_{eff}v_a/\lambda_0$

So, let us actually look at a cross section of a fiber, let us say this is the core of the optical fiber, I have an electromagnetic wave that is coming in. That wave as it propagates down the fiber is going to interact with these acoustic phonons these are these vibrational modes that are bouncing around in all random directions, and part of that light is actually backscattered towards the, towards the source itself. Because this, this is a waveguide it captures light within a narrow cone of angle that is backscatter.

So, some of the other light that scattered is going to just escape of the fiber, but a little bit of the light is actually directed back towards the source itself. And this light can interact can essentially the field corresponding to the incoming radiation and the field corresponding to the backscattered wave, they can actually add, and they can add constructively or destructively and they might actually generate a standing wave pattern over here.

Now, if you increase this intensity, then that standing wave pattern now is going to become you know, with higher amplitude, you have a higher amplitude in terms of the field and there is a process of what is called electrostriction basically, if you have a high electric field across a material, it acts it makes the it compresses the material, right, it makes the material more dense.

And correspondingly, you will have change in the refractive index corresponding to, the constructive interference of these, these oppositely traveling waves. So, does that resemble something? Well, this is what we looked at previously as Fiber Bragg Gratings, those are actually permanent changes in the refractive index that are inscribed in the fiber. But in this case, it is not a permanent, you know, changing the refractive index, it happens when only when the pulse of light is there, it is covering this region.

And as the pulse goes away the this, this grating is going to vanish from this location, but it is going to form in some other location and so on. But, like I said, if there is enough intensity coming in, you could actually have a strong interaction with the backscattered light and, through that is mediated by this, this grating that is formed. And so you will have a stronger backscattered signal that you get from this and this backscattered signal is going to be downshifted in frequency, why is it downshifted?

Because this grating is going to move in the direction of your optical wave, but it will move only at a slower speed corresponds to the acoustic velocity in this material, that is what we VA is. So, it is like having some sort of a Doppler effect like a wave is going towards a moving mirror, the mirror is moving away from the wave, then it ends up like stretching the wave and the backscattered light is going to have lower frequency a longer wavelength essentially.

So, that backscattered frequency the frequency shift that you get is proportional to the acoustic velocity. So, that is actually a very important aspect; why? Because the acoustic velocity depends on the density of the inherent material density itself and the density of the material this class medium here is going to change or is going to respond to changes in strain or temperature. So, whenever there is a change in strain or temperature, the density of the medium changes in the density of the medium changes the acoustic velocity changes and if the acoustic velocity changes, then the corresponding backscattered frequency that is changing.

So, contrary to what we were doing with Rayleigh backscattered signal and your Raman backscattered signal where we will essentially making an intensity measurement in this case, what I want to do is to make a frequency measurement. Specifically I want to extract this frequency nu B. So, if I look at the backscatter frequency as a function of time, and that time can be converted to position just knowing the velocity of light in this medium, then I can actually get a perturbation map along the length of the fiber. So, this is what happens.

So, you have basically once again you send a pulse of light, but the pulse of light is essentially because of this Brillouin scattering is creating a temporary grating and that grating is going to back reflector this this is called is going to create this Brillouin backscatter radiation which. which actually carries this frequency information. So, the frequency will now be whatever the local is going to be depend on the local acoustic velocity which is dependent on the density of the medium and that is dependent on the strain and temperature at that particular point along that medium. So, this is what we are looking at. Now, by looking at frequency as a function of time you are looking at strain or temperature as a function of position in this fiber.

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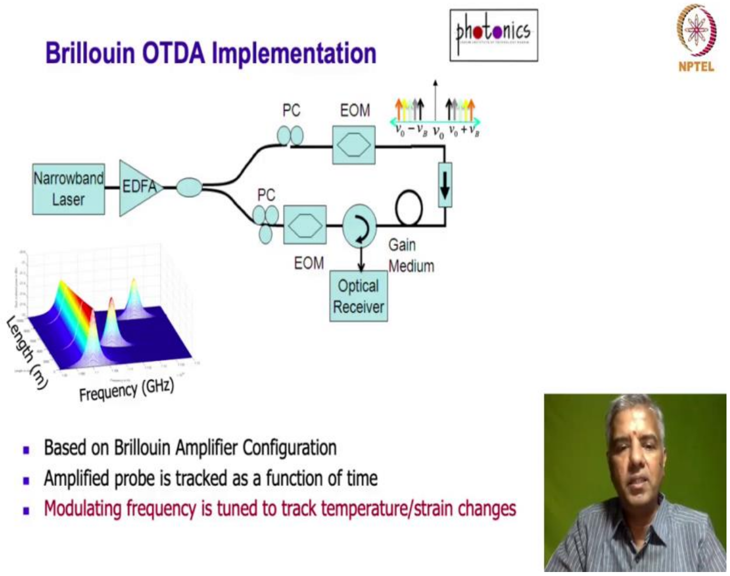

Brillouin OTDA Implementation

- Based on Brillouin Amplifier Configuration
- Amplified probe is tracked as a function of time
- Modulating frequency is tuned to track temperature/strain changes

So, this is how the final map is going to look like this is actually intensity axis here, this is the length of the fiber, this is the start of the fiber and end of the fiber. And this is actually looked upon at different frequencies, the backscatter signal frequencies, I will not go into the detail of how we extract this frequencies that can wait but you essentially get a map like this, where this is a Brillouin frequency corresponding to an unperturbed fiber. So, all the all of the length of the fiber all these regions, there is no perturbation.

But there is one section where there is actually maybe an event maybe the fiber is getting strained or maybe the fiber is exposed to some hotspot along let us say a power cable, there may be a hotspot and that will constitute a change in the backscattered the Brillouin frequency. So, by looking at the shift in the frequency, you actually figure out what is the magnitude of the perturbation that the fiber is experiencing. So, this is the concept of Brillouin based distributed fiber sensors. And this is useful for both in strain as well as temperature sensing.

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Implementation Challenges

- Quasi-distributed point sensors vs distributed sensor
- Need to know apriori where to place the sensors
- How to discriminate between strain & temperature?

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I have talked about a bunch of, different solutions as far as fiber sensors are concerned. But there are some you know, having the technology is just the beginning now, use when you want to implement it for a real situation, there are a lot of challenges. For example, let us say this is a bridge, and you need to look at the strength of this bridge, if there are any cracks that are developing in this bridge?

If you want to do that, then you need to incorporate sensors all along the length of the bridge, then the question is, do you want to use a quasi distributed point sensor like a Fiber Bragg Grating sensor? Or would you want to go for a distributed sensor? Would you want to go to a phase modulated sensor like what we talked about with the hydrophone and all that. So, you have a bunch of solutions available, then you need to decide which one is the best suited for that you need?

And for that, you also need to know where should you incorporate these sensors, where are the specific points, you may say that, all these points which are well supported are less likely to develop cracks. Whereas, the middle region between these two supports, that may be a region where there is more probability of having a crack. So you may want to put a sensor there. Or if you cannot decide where to put the sensor, just do a distributed solution, just just, you know, have a fiber all across.

And then you can get the entire map the strain map along the length of the fiber. And of course, some of the things that we talked about. For the Brillouin sensor, for example. It is sensitive to both strain as well as temperature. So, how do you discriminate between strain and temperature? How do you know it is one? If you see a shift in the frequency? How do you know it is only because of strain?

How do you know it is not because of temperature. So, you have to come up with some ingenuous methods to do that discrimination. And those are the kinds of challenges that we will look at as far as this course is concerned and see how to address them.

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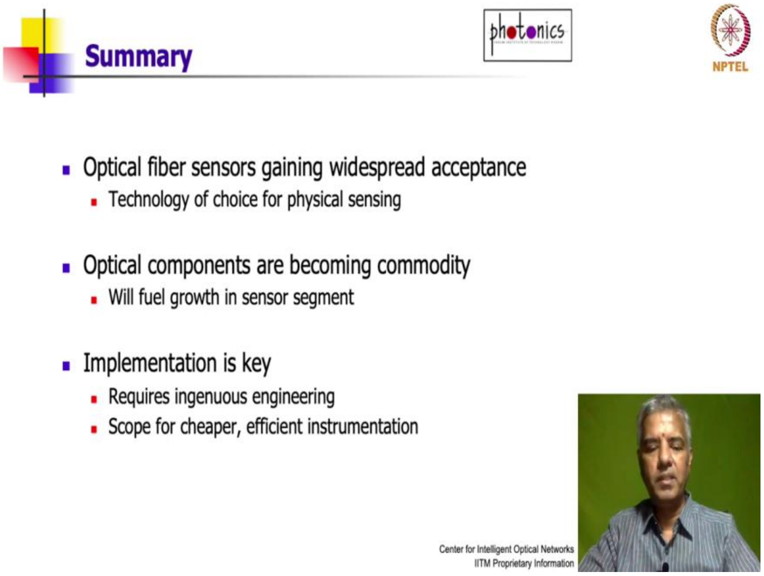

Summary

- Optical fiber sensors gaining widespread acceptance
  - Technology of choice for physical sensing
- Optical components are becoming commodity
  - Will fuel growth in sensor segment
- Implementation is key
  - Requires ingenuous engineering
  - Scope for cheaper, efficient instrumentation

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So, let me just summarize what we talked about. We talked about optical fiber sensors, gaining widespread acceptance. And it is really rapidly becoming the technology of choice for physical sensing. And that is because of the fact that optical components are becoming a commodity thanks to all the excellent developments in optical communications. But all said and done, we have a variety of solutions.

But finally, the implementation is going to be the key. And that requires engineers engineering and that is exactly what we are going to do in the course, we are going to try to develop you as a better engineers that could make better decisions and you could come up with good solutions that are useful for a lot of practical applications. So, we will meet further to go into details about a lot of these things in the subsequent weeks. Thank you!