Optical Fiber Sensors
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Lecture 39
Wavelength Modulated Sensors - 8

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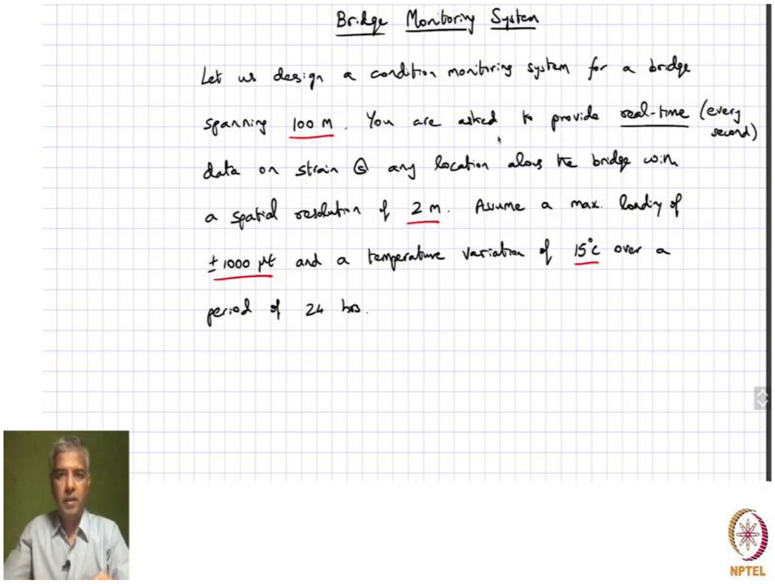

Bridge Monitoring System

Let us design a condition monitoring system for a bridge spanning 100 m. You are asked to provide real-time (every second) data on strain @ any location along the bridge w.in a spatial resolution of 2 m. Assume a max. loading of ± 1000 $\mu\epsilon$ and a temperature variation of 15°C over a period of 24 hrs.

Hello, we have been looking at sensing using wavelength modulated sensors. And we have been looking at the particular example of fiber Bragg gratings and we looked at potential example of using fiber Bragg gratings for strings sensing applications, and that is what we were looking at in a bridge monitoring system. And the real requirement is that the entire bridge has to be monitored for any defects or cracks in the bridge.

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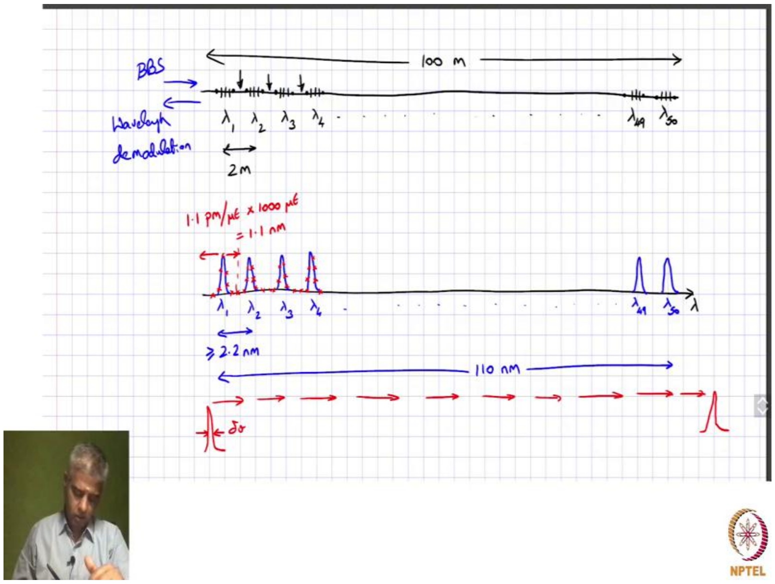

But what we ended up doing was actually putting fiber Bragg gratings at locations 2 meters away, and just picking up strain information in those locations. So, essentially this is not a true distributed solution. This is what you call us a quasi-distributed solution. Meaning, that the question is, what if the, defect happens in these locations, between two fiber Bragg gratings, those locations, you are not really monitoring.

So, if there is a defect developing in those locations, then you are not going to be able to pick it. So, in other words, what you really need is a true distributed fiber sensor for such applications. And fiber Bragg gratings, excellent candidates for strain or temperature sensing, but they could work only in a quasi-distributed manner. So, what we are going to talk about today is a different type of wavelength modulated sensor, which is based on a nonlinear effect called stimulated Brillouin scattering.

I will talk about why it is a nonlinear effect and all that in a later on in the lecture. But if you use stimulator Brillouin scattering, and if you use possibly the optical time domain reflectometry techniques, we could possibly handle requirements like this in a truly distributed manner. So, that is what we are going to look at in today's lecture. So, first of all let us try to understand what stimulated Brillouin scattering is all about. And let us actually see how we can possibly use that for sensing applications.

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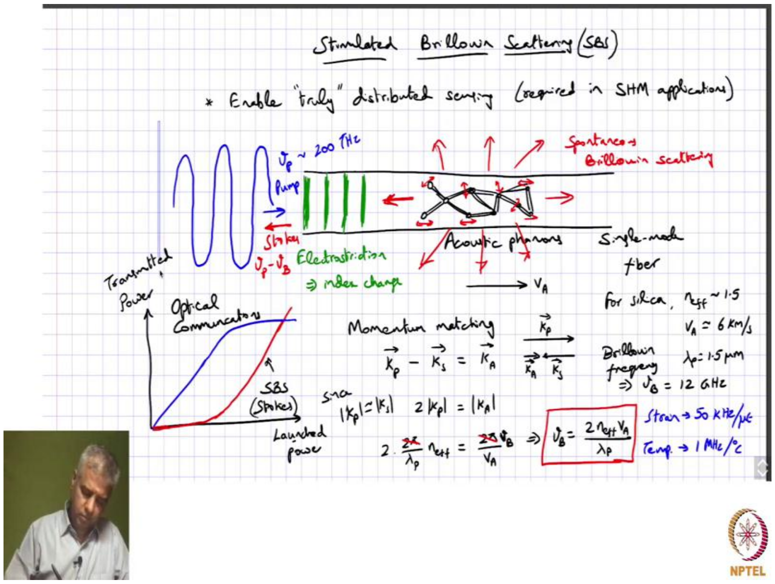
Stimulated Brillouin Scattering (SBS)

* Enable "truly" distributed sensing (required in SHM applications)

For silica, $n_{eff} \sim 1.5$

$v_A \simeq 6$ km/s

$\lambda_p = 1.5\ \mu m$

Brillouin frequency ⇒ $\nu_B = 12$ GHz

Momentum matching

$$\vec{k}_p - \vec{k}_s = \vec{k}_A$$

Since $|k_p| \simeq |k_s|$ $\quad 2|k_p| = |k_A|$

$$2 \cdot \frac{\cancel{2\pi}}{\lambda_p} n_{eff} = \frac{\cancel{2\pi}\nu_B}{v_A} \Rightarrow \boxed{\nu_B = \frac{2 n_{eff} v_A}{\lambda_p}}$$

Strain → 50 kHz/$\mu\epsilon$

Temp. → 1 MHz/°C

So, we are going to be talking about stimulated Brillouin scattering, Brillouin is the name of the person who observed this more than 100 years ago. So, that is the effect is named after him. But what we are really trying to do with this stimulated Brillouin scattering is to enable truly distributed sensing, which is a requirement for this is required in a lot of these structural health monitoring applications that we talked about previously.

So, what is stimulated Brillouin scattering is all about. So, let us actually limit this discussion to fiber because that is why we have been so far discussing, but of course stimulated Brillouin scattering can happen in any material. But if we talk about optical fiber, and let us just focus on what is happening in the core of the optical fiber. So, we can look at the core of the optical fiber.

Fiber, of course is made of few silica, so SiO2 and that means you have all these and it is a highly amorphous medium. So, you have all these atoms in located in different places, and they are all sort of networked. So, they form bonds with each other and so on. So, you have a sort of network of all these atoms and molecules. So, what happens at room temperature? At room temperature, each of these atoms are going to just bounce around their mean positions in some random manner.

And that means this entire network is now going to be agitated at room temperature. So, although when you look at a solid material, in this case, a glass material, it looks nice and static, inside that material at room temperature, there is a lot of activity happening. And one of those is actually these vibrational modes, which are called phonon modes that are happening inside this material.

And, of course, these phonon modes you can say, are going to be more active as you increase the temperature, but we are not going there right now, we are just looking at room temperature itself that has some activity going on. Now, in this context, when we actually come in with an electromagnetic wave, a light wave in this case when you when you launch a light wave, inside this, inside this medium, that light wave, you can potentially interact with these phonons, which are essentially called acoustic phonons.

Because they actually travel with the velocity of sound in this medium. But when you have this electromagnetic wave coming in, that is going to actually scatter off all these phonons, and that scattering is going to happen in all possible directions. So, this is basically, what do you call as spontaneous Brillouin scattering. So, Brillouin scattering is about the interaction of light waves with acoustic waves, the acoustic phonons inside this material.

So, that is what we are talking about as Brillouin scattering. So, the key part is, there is one component, which is we are talking about this this fiber now is actually a single mode fiber. So, we are talking about, whenever we are looking at backscattered light, it is collected over a cone of angles corresponding to this numerical aperture of the fiber. But nevertheless, part of the fiber that scattered in the backward direction is collected I mean, it is basically going propagating along the fiber is supported by that fiber.

And that component now when it is interacting with this incoming wave, that is going to actually create a standing wave pattern. So, that standing wave pattern, you can say, it is going to be something like this in this fiber. Now, as you increase this, the amplitude of your incoming wave, as it becomes stronger, if you increase the amplitude of the incoming wave, if it becomes stronger, then the corresponding backscatter component is also going to be more.

And that makes this periodic the standing wave pattern which corresponds to periodic change in the electric field of this standing wave pattern that is going to be increased the strength of the electric field is going to be increased. And when that happens, you have a process called electrostriction. So, electrostriction, we know we have heard of it in possibly High School, it is basis of this piezoelectric effect as well, wherein if you have a high electric field existing across a medium, then the medium basically, that you are changing the density of the medium.

So, wherever there is actually high electric field in this medium, the medium density is increased, and whenever the medium density increases, there is a corresponding change in the refractive index of the medium. So, what we are essentially seeing is a periodic change in the refractive index. Now, does that ring a bell? Well, we know that a periodic change in refractive index through Bragg diffraction can actually backscatter light.

So, when we are talking about light that is backscatter, that is going to be enhanced by this process. So, essentially you have this incoming wave as it gets stronger, it is actually going to scatter more from these phonons. And then it is going to actually form the standing wave pattern through this electrostriction effect. So, this electrostriction is going to give you index change the refractive index change and that refractive index change will in turn make this component stronger.

To the point that this is something that we observe in communications when we look at the power as a function of our let us say, this is the in communication, you want to transmit a lot of power. So, the when we look at the transmitted power as a function of the power that you just call it launched power in a fiber. So, we expect this to be sort of linearly increasing. So, we expect this as you want to reach longer distances in a communication system, let us say, you launch more and more power.

So, it can essentially withstand whatever attenuation that is happening inside the fiber and then reach longer distances. However, the problem is that beyond a certain power level, we are saying that it is going to start saturating, why?

Because of the fact that as you increase your launch power, you are starting to build up this backscatter power, and that is going to make this through this electrostriction process make this grating stronger, and that is essentially going to reflect more power to the point that the reflected power may actually be I mean, the power that you are feeding in might actually go more into the reflected power than the transmitted power.

So, stimulated Brillouin scattering is really a big roadblock as far as communication over long distances is concerned. So, of course you can find ways to counter it which we will probably talk about a little later, but that is the problem as far as in optical communications. This is an issue this and this is due to stimulated Brillouin scattering SBS.

And this specific wave that backscatter is called the stokes wave, that is basically it feeds off certain energy to the optical phonons, sorry, the acoustic phonons and then is backscatters with lesser energy, essentially. So, that is why we call it as a stokes process. But how can we use this for a sensing application? Well, when we talk about this, this phonon altogether, this phonon is actually not static.

Because when you are talking about a wave that is going through, that wave is actually through this resonant interaction it is feeding into the phonons and the phonon and since the wave is moving in the forward direction, we expect the phonons to be moving in this direction also and that happens at a velocity vA. So, what is the effect of that? Well, if you look at, of course any of this energy transfer processes, you need to look at conservation of momentum.

So, when we look at momentum matching condition, we can write it as let us say the wave vector corresponding to the, so you call this as the pump and this as your stokes. So, this minus the stokes that is actually whatever change in momentum between the pump and stokes is because of the fact that you have these acoustic phonons. So, that has to be matched by the wave vector corresponding to the acoustic phonon.

Now, we know that the wave vector the wave number corresponding to acoustic because it is much lower frequency the wave number corresponding to acoustic phonon is actually relatively small compared to the optical wave. So, we can represent this picture like you have this Kp and then that is scattering of KA, the acoustic phonon and that is producing Ks in the opposite direction.

And since Ks is almost equal to Kp. So, since we can say that they the magnitude of Ks is almost equal to Kp you can rewrite this expression as, and it is actually happening in the opposite direction. So, you can rewrite this as 2 times Kp equals to the magnitude of KA and 2 times Kp the wave number is given by 2 Pi over lambda p times n effective, the effective refractive index of the fiber.

This is going to be given by 2 Pi over lambda a, but lambda a you can write it as VA multiplied, I mean divided by nu B. So, you have a 2 pi nu B over VA term where nu B corresponds to the frequency of these acoustic phonons. So, this you can simplify and you can say that you can get expression for nu B, which is, you can basically cancel this and so you get 2 times n effective to VA divided by lambda p.

So, that is actually the frequency shift that you get because of the scattering of the acoustic phonon. So, what we are saying is if your pump is having a frequency nu P, your stokes is now going to have a frequency nu P minus nu B it is going to be downshifted in frequency corresponding to this scattering from the acoustic phonon you can actually look at it in a different way as well because the scattering is happening from acoustic phonon traveling in from left to right.

It is constituting a sort of shift in the backscattered frequency through the Doppler effect, we know that when a wave is actually incident on an object that is moving away, that takes us essentially ends up elongating the wave and that means whatever is backscattered is going to be of lesser frequencies, downshifted in frequency and that downshift what we are saying is dependent on this acoustic velocity.

And that actually gives us some idea, why? Because, the acoustic velocity is actually sensitive to changes in the density of the material. So, that is how we can use it as a sensor. Because whenever you have this material, this optical fiber exposed to strain or temperature, that change in strain or temperature will constitute a change in the density of the material. And if that if the density of the material is changing, the local acoustic velocity is now going to change.

And that means the backscatter frequency from that region is now going to be different. So, a nu B is going to be different, depending upon strain or temperature. So, let us just try to, put all this into perspective. Let us start putting some numbers. So, for let us say, for silica, you have n effective, let us assume it, it is around 1.5, it is actually less than 1.5 1.46, or something, but let us say it is 1.5.

When we look at the acoustic velocity that is roughly about 6 kilometers per second, that is the speed of sound in glass. So, that is, about 6 kilometers per second. And, let us consider lambda p as 1.5 micron. So, if lambda p is 1.5 micron, then this implies that if you plug all these numbers here, so 2 into 1.5, multiplied by 6, that is about 18 divided by 1.5. So, that will correspond to a nu B the Brillouin frequency.

So, nu B is actually, what is called the Brillouin frequency is corresponding to about 12 gigahertz. So, we know that nu P, nu P is in the order of 200 terahertz if you look at wavelength of about 1.5 micron at somewhere around, close to 200 terahertz. So, we are essentially looking at backscattered frequency, which is 200 terahertz minus 12 gigahertz. So, it is a very small change with respect to the incident frequency.

So, that is one aspect. But the other aspect is that this nu B is changing. It is not the same across the fiber it changes in response to any change in strain or temperature. And that means, if you look at for example for with respect to strain, we see that it actually shifts by 50 kilo hertz over per micro strain and with respect to temperature it changes by 1 megahertz per degree centigrade.

So, that is actually a very, very small shift. And that is actually poses a major issue as far as picking up that frequency that small frequency is concerned, but nevertheless what we have hopefully established through this discussion is that, this SBS this stimulated Brillouin scattering is actually a good way of actually picking up changes in strain and temperature and it is essentially wavelength modulated sensor or you can call it as a frequency modulated sensor.

Because we are actually looking at changes in this frequency nu B as a function of strain or temperature. So, it gets encoded and what did we talk about previously as far as wavelength modulators sensors concerned, once you generate this frequency, that frequency is not going to be corrupted by just the propagation of that light. So, you preserve that frequency very well with so you not it is robust against any conventional noise processes during that the optical wave may encounter during propagation.

So, this is one more example of a wavelength modulated sensor. Now, that actually brings up the point. So, what if, I mean, how do you eventually pick up these changes in this, such small changes in the frequency? For that, let us actually look at this maybe in the next slide. So, let me just copy this and take it to the next slide.

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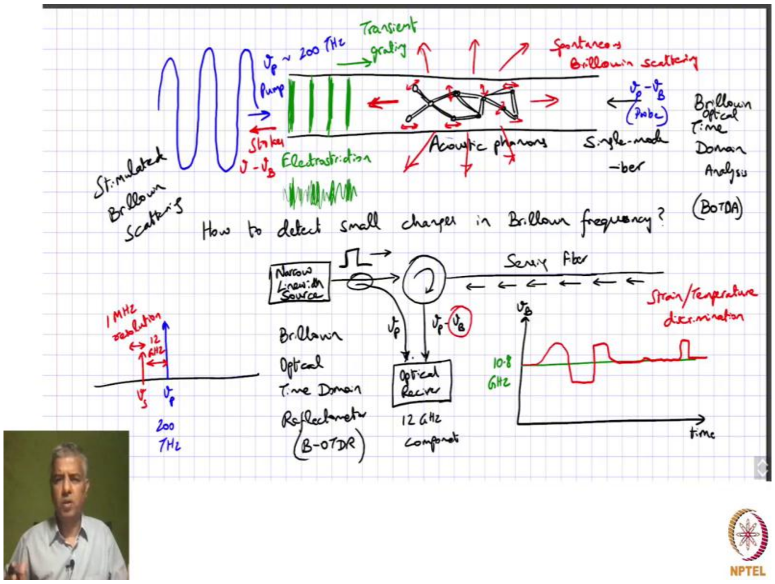
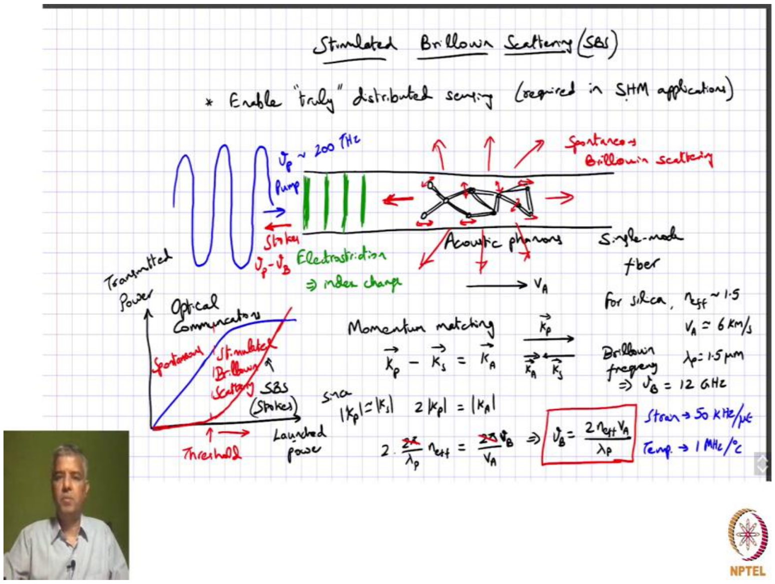


How to detect small changes in Brillouin frequency?


Stimulated Brillouin Scattering (SBS)

* Enable "truly" distributed sensing (required in SHM applications)

Momentum matching

$$\vec{K_p} - \vec{K_s} = \vec{K_A}$$

Since $|K_p| \simeq |K_s|$ $\quad 2|K_p| = |K_A|$

$$2 \cdot \frac{\cancel{2\pi}}{\lambda_p} n_{eff} = \frac{\cancel{2\pi}\nu_B}{V_A} \Rightarrow \boxed{\nu_B = \frac{2 n_{eff} V_A}{\lambda_p}}$$

For silica, $n_{eff} \sim 1.5$

$V_A \simeq 6$ km/s

$\lambda_p = 1.5\,\mu m$

Brillouin frequency $\Rightarrow \nu_B = 12$ GHz

Strain → 50 kHz/$\mu\epsilon$

Temp. → 1 MHz/°C

So, the question is how to detect small changes in the Brillouin frequency? So, what are we talking about we are talking about in terms of the frequency spectrum, this nu P is somewhere over here, but and that corresponds to about 200 terahertz but you have newest component which is downshifted by 12 gigahertz. And now comes the important point so, it to use it as a sensor. Now, we are looking at some changes in this in that frequency and the change that we want to get is something or 1 megahertz resolution. I mean smaller the better but you will be happy if you can get if you can pick up changes with 1 megahertz resolution.

So, how can you possibly do that? Well, one of the things you can do for sure is whatever pump frequency you are sending, let us say you have your narrow linewidth source. So, and by the way, it has to be a narrow linewidth source. In fact, if you see this I have actually drawn a monochromatic wave. So, for a monochromatic wave you have a fairly well defined grating here, I say grating, but of course, you have to understand that this is a transient grating, it is not like a fiber Bragg grating, where it is permanently etched in the fiber.

This transient grating is actually moving, because, as the excitation wave is moving, let us say, if you are sending a pulse of this light, as the pulses moving, this grating is actually getting dragged along. So, this grating is also moving, because only where the stokes, I mean only where the pump is present, that is where this backscattering is happening. And that is where this grating is formed. So, this is actually what you call as a transient grating, which is moving along the fiber.

And it is moving continuously along the fiber that is the key part. In a Bragg grating, you have only stick fixed positions where the grating is present and then of course, you can have multiple gratings along the length of the fiber, but those are all in discrete positions. But in this case this grating is swept all along the length of the fiber. And, so, you can essentially realize a true distributed sensor, because of that.

But the point is, what is talking about is with respect to these narrow linewidth source is only when you have close to a monochromatic wave, you can get this very nice sort of grating, which enhances the backscattered signal, that is when you can actually really go up in terms of the power that you have. But, if you do not have a narrow linewidth source, if it is actually a polychromatic source, it is multiple frequencies over here, then each of those frequencies is going to have a standing wave pattern.

And the effect of that is that this grating would not be so strong anymore, that grating will now be more like, it is a weak grating, maybe it will be slightly stronger in these certain regions, but it is actually relatively, if the refractive index change the contrast that you get is small, and that means the amount of stokes backscattered signal will be very small. So, one thing maybe I did not mention explicitly is only when you have a strong enough power, you get into this domain, which you can say is stimulated Brillouin scattering.

And below this power level, all you have is only spontaneous scattering and spontaneous scattering is actually not really very useful because the amount of power that you get is very small. So, you have lots of signal to noise ratios, if you try to use spontaneous scattering scattered light for your sensing application. So, for all sensing applications, it is imperative that you operate at a power level that is greater than the what is called this threshold for SBS process.

But nevertheless, so, I mean, I talked about communication applications and needing to actually be able to push more power into the fiber, the way you can possibly do that is, instead of going in with an arrow, it is a monochromatic source like this, you slightly chop that frequency, you make it slightly broader so that this threshold can actually move out to higher power levels. And, and if that is the case, then you launch power can go up even further.

So, you can chop that, you can broaden the spectrum of your optical source to essentially move the threshold to higher power levels, that is what you want to do in optical communications. But as far as sensing applications are concerned, you are fine with the lower threshold itself. Because you really want to encourage simulated Brillouin scattering, you want to be able to pick up more light in this stokes wavelength.

So, from that perspective, you really want to use a narrow linewidth the source for these applications. So, we are talking about sending this narrow linewidth source in through a circulator into this test fiber the this is basically your sensing fiber, which for the bridge monitoring application, you might want to actually have this fiber implemented all across the length of the bridge.

And then you are looking at the backscattered stokes wave. However, what you are interested in is not the amplitude of the stokes wave you are interested in the frequency of the stokes wave. So, you want to go into a optical receiver which actually consists of so, you basically tap a part of that and feed that also into this. So, this is nu P minus nu B is the frequency that is coming back and this is actually nu P.

So, if you beat with respect to nu P, then you can extract a nu B. But mind you, that frequency is still 12 gigahertz away. So, effectively, you get 12 gigahertz component over here in this receiver, and then you need to look for small changes in frequency around that. So, that is what you typically try to do, as far as using this Brillouin sensing is concerned, but essentially, you are trying to work in the regime where you are encouraging stimulate Brillouin scattering.

So, the typical power levels, the threshold power levels, for a silica, a single mode silica fiber is in the order of 10 milli watts. So, if you are working in the order of 100 milli watts of power, then you can actually, it can be sure that you are able to generate stimulated Brillouin scattering over a long length of fiber. And of course, you want to localize the strain and temperature information, which means that you are going to be sending a pulse of light.

So, that is actually like your OTDR technique. So, you generate a pulse the source, you can directly modulate the laser, or do external modulation and generate this pulse over here and that pulse can move all along the length of the fiber. And even as it moves down the fiber, it is going to cause stimulated Brillouin scattering, and it is going to cause scattering from these different regions.

And that scattered light, you are picking up as a function of time and specifically you are picking up the scattered frequency. What you are interested in is picking up this nu B and then you can actually, once you pick up nu B, you can actually look for changes in nu B as a function of time. So, finally, you are plotting nu B as a function of time, you are not plotting the intensity of the light that you are picking up, but rather the frequency of the light that backscattered light.

And nu B as a function of time, if there is no perturbation in the fiber, it will look just like this, it will be constant across time. In silica fibers in standard single mode, silica fibers, this actually works out to be about 10.8 gigahertz, we calculated for 12 gigahertz. But that is actually a just a rough number, if you go to standard single mode fiber refractive index is about 1.46.

So, this value will be lower because of that, and also, this pump wavelength is typically around 1550 nanometers. So, if you look around there, it would be about 10.8 gigahertz and essentially what we are looking for is perturbation around that so, so we are looking for things like, if there is any perturbation in these regions, that is actually increasing the frequency which may be because of higher strain, in these regions has actually decrease in the frequency because of some compressive.

So, this is because of tensile strain and this is because of compressive strain and so on. So, you can actually pick that up. But again, the key point here is, you are not able to distinguish the difference between strain changes and temperature changes here. So, you do really have an issue in terms of strain, temperature discrimination and that is similar to what you have, as far as a fiber Bragg grating is concerned.

So, whatever techniques that you are using, they are to discriminate between strain and temperature, you may want to use it here as well. So, that can, there is, you got to come up with some ingenuous engineering to do this discrimination. But the other point is, in a backscattered configuration, as you go deeper into the fiber, the amount of light that you are going to get is going to be very weak. And so, if you want to actually get say stronger signal at the receiver you could possibly go for this technique called BOTDA.

This is basically what you call as Brillouin Time Domain; Optical Time Domain Analysis, in short it is called BOTDA. So, the key principle of BOTDA is that you are feeding light from this direction at a frequency of nu naught, rather nu P minus nu B. If you feed in nu P minus nu B, from the other direction that can actually stimulate this interaction and that can actually enhance this stokes.

So, instead of going to higher and higher power if you inject something from this side, this actually called the, this side it is the pump, this side is called the probe and you can inject the probe and you can enhance the interaction and that, through that you can increase the signal to noise ratio but that of course requires more components and it is a more sophisticated technique compare to this technique where we call this is actually the Brillouin Optical Time Domain Reflectometer, in short it is called BOTDR.

So, BOTDR is good for shorter distances, say few kilometers where you can still get a reasonable signal but if you really want to go to long distances like 100 kilometers and above you need to go towards a BOTDA type of solution which we are not be discussing in much detail right now. But the key point is SBS base sensors are another example of wavelength modulated sensor and what it enables is actually a truly distributed sensing which is preferred in lot of structural health monitoring applications.

So, what is the tradeoff between SBS and FBGs? FBGs are good when you know where you want to look for your strain temperature changes exactly which points, which locations you want to look at and it is relatively cheaper compared to this SBS based sensing because right from starting with an arrow and the laser to actually incorporating this optical receiver and signal processing in all of that it tends to be much more expensive solution compare to roughly by an order of magnitude compared to a fiber Bragg grating based quasi-distributed sensing solution. So, those are the typical tradeoffs.