Introduction to Photonics
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Non-linear optics-stimulated Brillouin scattering

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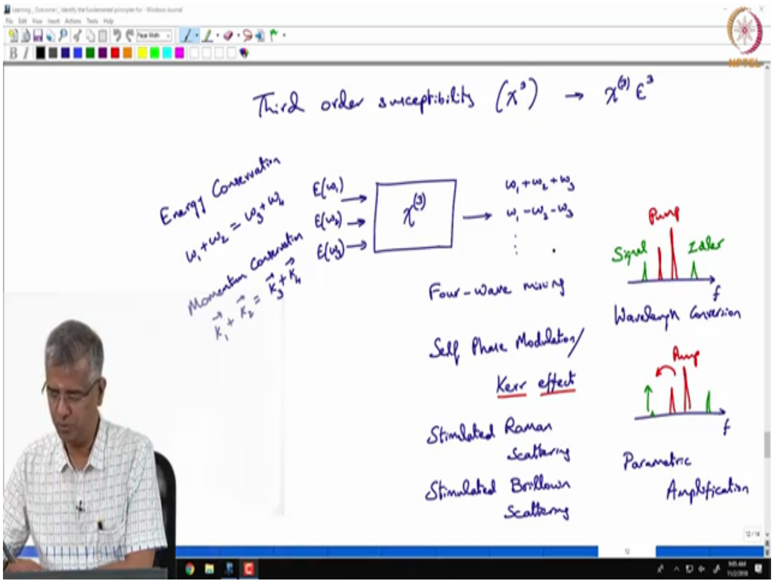

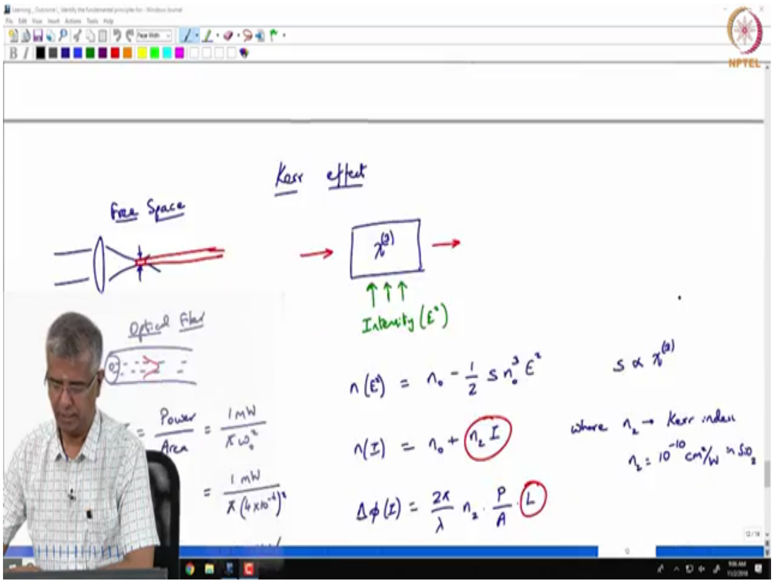

Okay, welcome to introduction to photonics, good morning. We had been discussing the non-linear response of materials to electromagnetic waves in this case the optical waves and in the previous lecture we were looking at the third order susceptibility, the one before that we were looking at second order susceptibility, but in the last lecture we were looking at third order susceptibility.

And we were discussing all the possible phenomena that can happen when you have a material with relatively high third order susceptibility, one question is to you know when do we see a Chi 2 related effects and when do we see Chi 3 related effects? Can both of those happen in the same medium? Yes, it can so (it) everything depends on the relative values of Chi 2 and Chi 3, but we do not have any control on the response itself that is the medium property, what the only thing that we can provide is the electric field the excitation.

So we were talking about four-wave mixing, we were talking about self-phase modulation through the non-linear Kerr effect.

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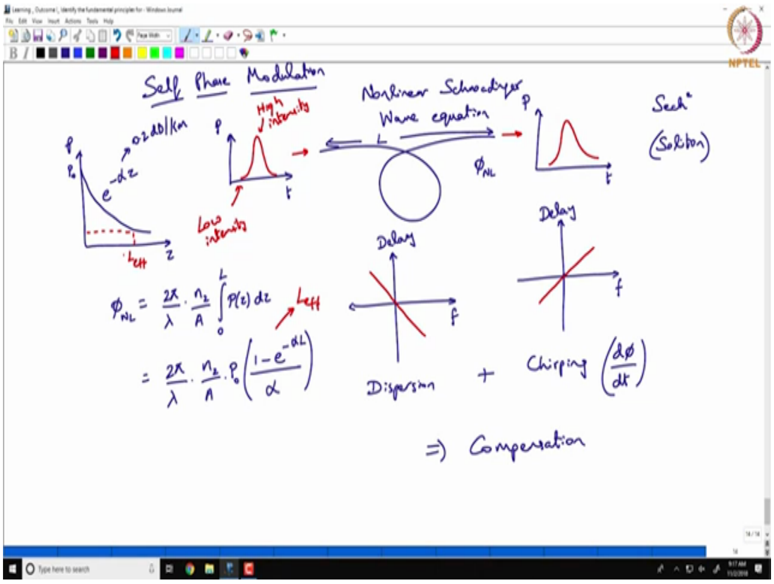

$$\phi_{NL} = \frac{2\pi}{\lambda} \cdot \frac{n_2}{A} \int_0^L P(z)\,dz \quad L_{eff}$$

$$= \frac{2\pi}{\lambda} \cdot \frac{n_2}{A} \cdot P_0 \left(\frac{1 - e^{-\alpha L}}{\alpha} \right)$$

$$\left(\frac{d\phi}{dt} \right)$$

And we stopped at this point where we were talking about self-phase modulation in long length of fiber, we were saying that depending upon the intensity of the light, the medium responds differently and so it essentially ends up delaying some part of the pulse with respect to others and that delay essentially is it produces new frequencies that were previously not present in the pulse spectrum.

So these new frequencies we essentially will call this as chirp, so what that chirp also does is that it that the delay it is a positive slope with respect to the frequency and we were discussing the aspect that this could actually be good in the sense that this could potentially compensate for the dispersion in a medium and so you could have you know the pulse retaining its shape as it propagates down the fiber which would be very good for optical communication systems because you do not encore this dispersion related penalties which is actually causing bit error rates in your communication system.

And I should mention that there is one particular shape of the pulse in which the self-phase modulation that it encores on the chirp that it encores automatically compensates for the dispersion that the pulse encores and you can remain that shape all along the length of the fiber. So effectively what we are saying is you know the propagation inside this medium is controlled by what is called the Non-linear Schrodinger Wave Equation, so it is just a Non-linear Schrodinger Wave Equation is just a modification of the regular wave equation that we have been looking at but it brings out the non-linear aspects clearly.

So if you take the Non-linear Schrodinger Wave Equation and you find the solution for the Non-linear Schrodinger Wave Equation, you find that a pulse which is actually a second square second hyperbolic square sort of shape is actually is the solution for this Schrodinger Wave Equation which means that that shape pulse if you send it down a regular single mode fiber, you will actually retain that shape and that sort of pulse is called a Soliton.

So a Soliton is essentially a solution for the Non-linear Schrodinger Wave Equation such that dispersion and this non-linear chirp it is automatically compensated so it retains its shape all along its the propagation. And in fact back in the 90's there was lot of research on Soliton pulses, so people figured if we use Soliton pulses you do not have any of these dispersion related penalties.

So they decide okay this is the way to do communication but of course there were other issues with the propagation of Solitons when you talk about practical things that happening in the field there were lot of issues with Solitons and people actually gave up on that idea after a while, but that is just for your information. So what we do now in communication systems and this is what you will learn if you take this fiber optic communication technology course is that you led dispersion to happen in the fiber upto say some 100 kilometers and then you have a dispersion compensation element which brings the shape back to original shape pulse shape and then it is allowed to go further down accumulate dispersion then dispersion compensation and so on. So that is what we call as a dispersion managed system that is what is practically implemented in modern day communication systems.

Okay, so let us actually take a look at this in a slightly deeper manner, let us actually try to quantify what is the non-linear phase that you accumulate while propagating down the fiber. So to look at that what we have to consider is that non-linear phase you have one value if you consider the power to be uniform along the length of the fiber, but we know that is not possible because the fiber does have loss, so the power is actually exponentially decaying along the length of the fiber. (So the) if you look at the power that is propagating through the fiber we know that it is going to be exponentially decaying.

Of course it is not probably you know very strong exponential decaying because alpha tends to be very small, alpha is 0.2 dB per kilometer typically for a communication grid single mode fiber. Nevertheless we do have to when we are talking about the non-linear phase that is accumulated, we do have to consider the fact that the phase that you have at any particular section along the fiber is dependent on the power at that particular point.

So if you want to look at the accumulation of phase, you have to integrate over all those power levels. So this is going to be 2 Pi over lambda multiplied by n 2 divided by A and then we were just previously considering the power but now we are talking about phase accumulation along the entire length of fiber, so you say P of z dz with your limit going from 0 to L, where L is the total length of this fiber, so that is the total phase that is accumulated.

Now of course you say P of z is P not multiplied by E power minus alpha z, so you can write this as 2 Pi over lambda multiplied by n 2 divided by A and if you do the integral you get P not multiplied by this factor e power minus alpha L divided by alpha that is what you get when you integrate e power minus alpha z. So previously when we were looking at the phase we were saying 2 Pi over lambda n 2 over A power multiplied by length.

Now instead of length we are actually having this thing in the parentheses, so this is actually denoting an effective length. So what does that effective length mean? Well, physically what that means is that the power is going down over a certain length, so beyond a certain length the power is so small that the medium starts behaving linearly beyond this length the power is so small that the medium is starting to behave linearly.

So even if you have length longer than that, there is no extra non-linear phase that is accumulated, do you understand this? So the non-linear phase actually depends on the intensity that is what the Kerr effect is, and for a given effective area for the mode it depends on the power if we are talking about the single mode fiber. So and the power is decreasing along the length of the fiber.

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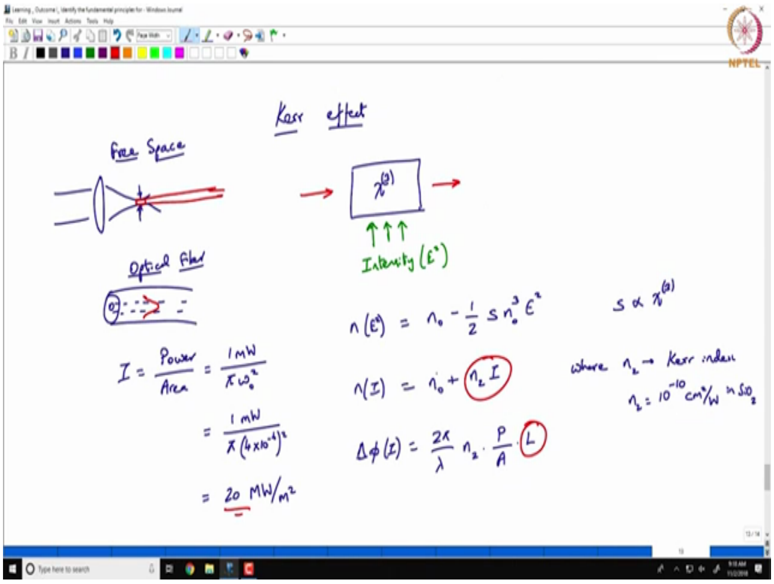

So if you go to such a length that the power is decreased to let us say you know something the order to 100 microwatts or lesser than that, then you do not accumulate any non-linear phase the intensity is so low that you do not accumulate any non-linear phase, you accumulate only the phase due to this n not term, you do not have this n 2 I term come into the picture because that is negligible compared to n not, do you understand this?

Student is questioning: Power (())(13:30).

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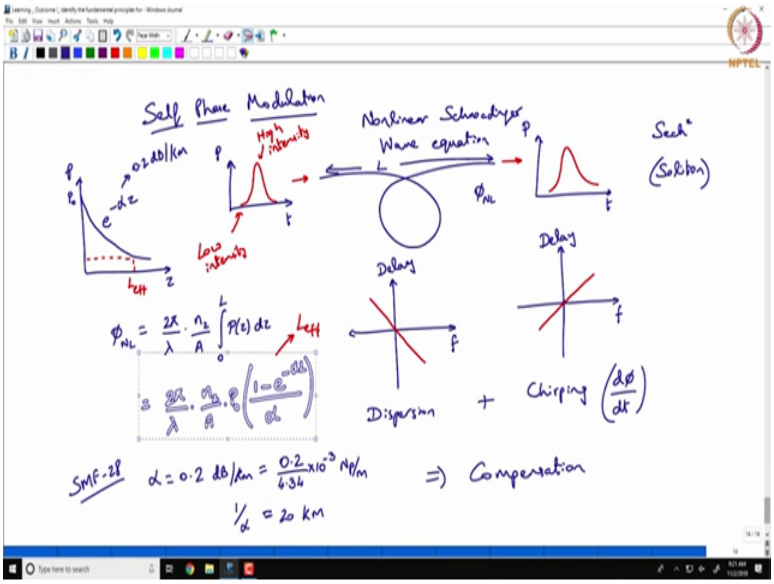

Professor: That is right you are gone to such a long distance so if you want to compute what is L effective for a given fiber. Let us take the case of your regular single mode fiber SMF-28 is regular telecom grade single mode fiber. For SMF-28, alpha is 0.2 dB per kilometre. So that is actually if you want to convert it to nepers per meter, how do you do that? So that is 0.2 into 10 power minus 3 dB per meter and if you want to convert to nepers from dB to nepers you divide by 4.34, so you can say this is 0.2 divided by 4.34 multiplied by 10 power minus 3 nepers per meter.

So that is such a small value that if you consider 1 over alpha that is the term that you have over here, if you have 1 over if you consider 1 over alpha that would work out to be roughly about 20 kilometers 21.7 kilometers or something like that. So what we are saying is it is accumulating this non-linear phase over 20 kilometers, but beyond that the power level is so low that it does not you know have any non-linear phase that is accumulated, do you understand this?

So that is what we mean by the effective length, the physical length can be greater than 20 kilometers, but as far as figuring out the effect of figuring out the Kerr effect, the non-linear phase that is accumulated due to the Kerr effect you have to take only the L effective NL effective (so let me grab this and).

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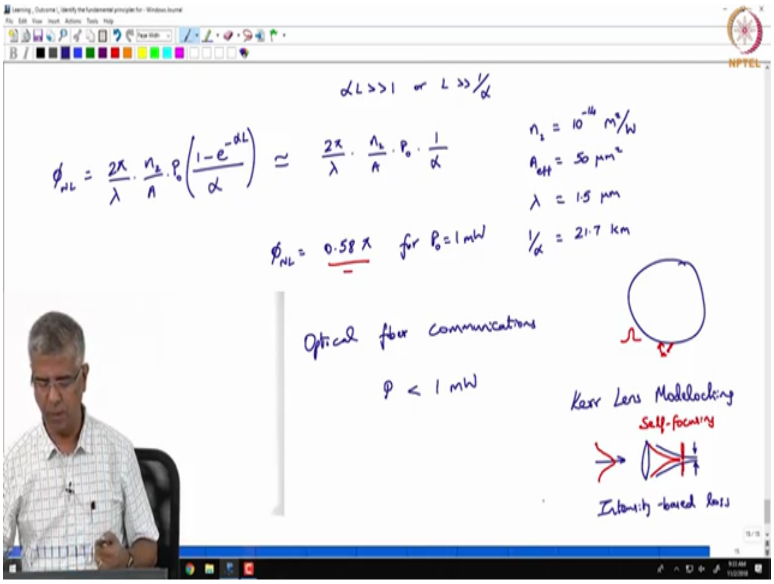

$\alpha L >> 1$ or $L >> 1/\alpha$

$$\phi_{NL} = \frac{2\pi}{\lambda} \cdot \frac{n_2}{A} \cdot P_0 \left(\frac{1-e^{-\alpha L}}{\alpha}\right) \simeq \frac{2\pi}{\lambda} \cdot \frac{n_2}{A} \cdot P_0 \cdot \frac{1}{\alpha}$$

$n_2 = 10^{-14}\ m^2/W$

$A_{eff} = 50\ \mu m^2$

$\lambda = 1.5\ \mu m$

$1/\alpha = 21.7\ km$

$\phi_{NL} = \underline{0.58\pi}$ for $P_0 = 1\ mW$

Optical fiber communications

$P < 1\ mW$

So what we are saying now is Phi NL is given by this, now this can be approximated if alpha L is far far greater than 1, if alpha L is far far greater than 1, or L is far far greater than 1 over alpha then what we find is e power minus alpha L is a negligible number then you can just represent this as 2 Pi over lambda n 2 over A P not multiplied by 1 over alpha, where n 2 is 10 power minus 10 centimeter square divided per watt, so we can basically write as 10 power minus 14 meter square per watt, A corresponds to basically A effective is the effective mode area in the fiber which we said is 50 micron square, let us consider a lambda of 1.5 micron and 1 over alpha is given by it is actually 21.7 kilometers if you do the math.

So the question is if you have 1 mill watt of power, how much non-linear phase do you accumulate? So if you substitute all these values what you will find is the non-linear phase that is accumulated is 0.585 Pi.

Student is questioning: (())(18:36).

Professor: Yes, so L is far far greater than 1 over alpha is that?

Student is questioning: (())(18:47).

Professor: That is right, so beyond that it will not remain non-linear so you can cap it at 1 over alpha, if the physical length is greater than 21 kilometers you can, or even if it comparable to (20) 20 kilometers you can just approximate that as 1 over alpha. So we say that is the phase that is accumulated and is that a problem may be because what this phase means is that you are expecting your pulse to come at a particular slot, which slot? In your digital communication system, because of this phase the pulse is actually moved over here, the pulse is moved over here so part of the energy that is in this slot is actually showing up in the next slot.

So if you are trying to make a decision whether this is a 0 or a 1, you will end up actually making an error in that. So there is only so much phase that you can tolerate in fact in communications they say okay we can tolerate only upto 0.1 Pi, so fraction of a Pi is all the phase that you can tolerate and you can work backwards and say what should be P not, what should be the power level that we transmit so that you get only 0.58 Pi, by the way this is for P not of 1 milliwatt.

So you have to be careful about the so in communications so in optical fiber communications the power level in the fiber P is typically less than 1 milliwatt so you do not try to go beyond milliwatt in communications because this is one of those nonlinearities that can affect your communications. But there is one more thing which is also quite important to consider, there is one more non-linear effect that can affect that can limit your power that you use for optical fiber communications, so let us move on to that, any other question related to this?

Oh! By the way so I am talking about this being a deleterious effect as far as communications is concerned, but it could be used as a beneficial effect, it could be used to our advantage in certain other applications, one example of that is in mode locking of a laser there is actually what is known as Kerr Lens Mode locking that you can do, remember what we want to do in mode locking is that we want to lock all the longitudinal modes in phase that is what we talked about several weeks ago.

And to lock all the longitudinal modes in phase one of the things that you will have to do is you have to essentially limit the time over which the cavity is open, so we talked about the case in mode locking like if you have a let us say a ring cavity you essentially have a switch that opens or closes, what is the rate at which it should open or close to achieve mode locking? We talked about opening or closing at the rate of the cavity round trip frequency, so you open and close at the cavity round trip frequency so that you form a pulse and that pulse is actually you know circulating within this cavity that is what we talked about when we were discussing mode locking.

So you need a mechanism that can open and close at the cavity round trip frequency and that mechanism could be this Kerr lens, so what do we mean by Kerr lens? Normally let us say you have a light wave coming in, it is going through a lens and then it is focusing at a certain point, at a certain location it is coming to a focus at a certain location. Now if this medium, if the power level that is incident on this medium, the intensity of light incident on that medium is very high, the refractive index that it actually exhibits is different.

So if I have a light wave which has an intensity pattern like this that is incident on the medium, then what it does is, it the medium responds differently and so your instead of this being focusing over here it might actually focus here itself. So this is actually what is called self-focusing effect and because of that self-focusing you know you essentially if I put an aperture over here, low intensity pulses will focus over here and high intensity will focus over here, so that aperture prefers to send high intensity pulses, whereas it will block low intensity pulses, do you understand that? If I put an aperture over here such that it allows only the self-focused light, self-focusing happens only for high intensity, so if I have a low intensity pulses that pulse would have actually would be focusing over there and there when it is trying to get there this aperture is blocking it, so it is actually providing a loss for low intensity pulses.

So you have what is called this intensity based loss mechanism and this intensity based loss mechanism is through the Kerr effect so that is why we call it as a Kerr lens effect and you can use this to do mode locking that is you can use that to shape pulses within the cavity and so that is actually very good mechanism for mode locking a laser, it is a very popular mechanism for mode locking a laser.

So I am not doing justice to that, just trying to give you some general idea but there is lot more detail in that that you may not understand but that is okay, I just wanted to give you a picture that it could be used for a beneficial purpose also.

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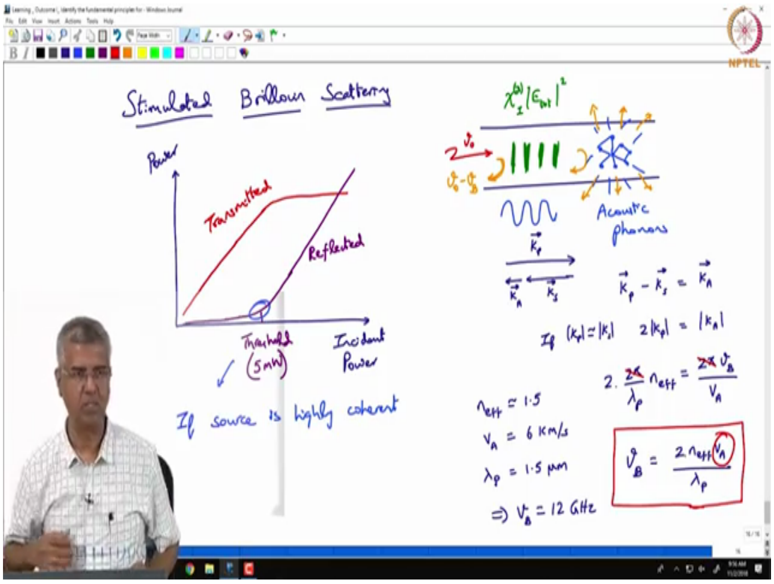

Okay, so we said the power is limited to milliwatt levels, the other mechanism that limits the optical power that can be sent through an optical fiber is this effect which is called stimulated Brillouin scattering, Brillouin is actually name of scientist who obviously did some very nice experiments to demonstrate this effect. So what really happens in this? Let us take once again the example of an optical fiber communication system, I say I want to I am communicating between point A to point B let us say over a distance of 100 kilometers, now I have a new locality that is developed beyond point B, I want to stretch my communication system to reach that location, I want to put extra fiber and reach that location, what would you do if you want to do that?

If you want to use the same fiber link but I have that extra length that I want to support, so I need to at the extra that new location I will put a receiver and I need to be able to detect a minimum amount of power, so what would you do to reach that location? If you are sitting at the transmitter you can increase the transmitter power, so you say okay I mean this is the same as your antenna problem you were supporting a certain cell with certain amount of power, now there is a requirement to expand the cells, so you increase the transmit power that is the natural thing you would do in a communication system.

But in this case in optical fiber communication system let us say this is the incident power that is the power that is launched into the fiber as you increase your incident power the transmitter power is also going to increase linearly and beyond a certain point it will just saturate. So there is you know it basically says that I cannot go beyond a certain power level, even if I put more power it is not going through it is like hitting a wall, I am not able to increase the transmitted power, why is this happening?

Well this is happening because if you look at so this is on the transmitted power, but if you look at the back reflected power, the back reflected power would be like this so this is my reflected power. So whatever I throw into the fiber beyond a certain power level it is just coming back to me, it is all back reflected and that obviously does not help in a communication system, you are trying to send information from one end to another, but beyond a certain power level that information is just coming back to you, it is not going through to the other end.

So what is happening in this sort of case? What actually provides this threshold and I would say that just give you a feel for this, this threshold is in the order of about 5 milliwatts around about 5 milliwatts in a regular single mode fiber, so what exactly is happening? Well to understand this you need to look at what is happening when light actually propagates through a medium, in this case let us say it is few silica glass medium in that corresponds to an optical fiber.

You are sending an electromagnetic wave into this medium let us say at a frequency Nu not, okay now within this medium you would actually find that it is consisting of atoms and molecules and if it is a few silica medium it is highly amorphous in nature, so you have all these atoms that are sitting around and then there are bonds between them, so it is a network, it is a glass network and that network is not at room temperature, it is not static, I mean you look at a fiber and it says a piece of solid and that is all static, but if you look at the microscopic picture all these atoms are all moving around their mean positions.

So there are some vibrations, there are that entire network is getting agitated and these vibrations are referred to as acoustic phonons, this is like even at room temperature there is some there are some sound waves that are generated within that optical fiber, if so happens that this these sound waves are now backscattering part of the light, your light is getting scattered by these acoustic phonons and so now part of that light I mean it is scattered in all directions, but part of that light is captured by the fiber and it is going back and that part of that light will now interact with the incoming light so if the fields of the incident light and the field of the back reflected light they interact with each other and they actually generate a periodic change in the reflective index, so that periodic change is corresponding to so your that is through your Chi 3 that is actually through the imaginary part of your Chi 3 E total square that E total is the incident electric field and the scattered electric field corresponding to that there will be total electric field.

And that electric field will essentially cause a change in the response of the medium change in the refractive index of the medium and it will give you this periodic thing, that periodic grating now will reflect this even more strongly so that you go back with a frequency that is given by Nu not minus Nu B, Nu B is referred to as your Brillouin frequency and then this entire effect is essentially called Brillouin scattering, so what are we talking about? We are talking about light getting scattered by sound waves inside this medium, naturally occurring sound waves inside this medium and because of that you have a down shift in the frequency, why is it down shift in the frequency?

Well you can say that since your light wave is propagating from left to right, your sound waves or you know also you know growing in that direction but it cannot move at the speed of light, it can move only at the speed of sound. So you can say that if you are sending a pulse of light that pulse actually travels from left to right and correspondingly there is a scattering happening and there is a interference pattern that interference pattern also moves from left to right in the same direction as your light wave.

So what happens when you reflect of a moving object, so you have a sound wave let us say well we are talking about light wave but I am just giving you an analogy, if you have a sound wave echoing from a moving object, what happens? Doppler shift and if it is a object that is moving away it is a downshift in frequency if it is coming towards you it is upshift in frequency, so that is the kind of frequency shift we get because this entire interaction is moving from left to right it is actually corresponding to a downshift in the frequency.

And that downshift can be quantified by considering you know what is happening in terms of the K vectors, so we have an incident K vector like this let us call this the pump K vector, pump is basically the incident K vector and then what you have is K S coming in the reverse direction, this is actually what is called that is the Brillouin scattered wave and it is also you know the difference between the two is given by the acoustic wave vector.

So I can write an equation saying that K P minus K S is given by K A, so I have a scattered wave due to this acoustic wave that is in that propagating the material. Now if I say that the magnitude of K P is approximately equal to the magnitude of K S and since it is actually K S is in the opposite direction so you can write this as 2 times magnitude of K P is equal to the magnitude of K A because what we are saying is this both of these the incident wave as well as the scattered wave correspond to the wavelength of light, whereas K A corresponds to the wavelength of sound waves, sound waves have much longer wavelength compared to light wavelength and because of that K which is 2 Pi over lambda K S is much greater than K A.

So you can write this as K S is almost equal to K P in which case you can say 2 times K P equals to K A and 2 times K P is nothing but 2 Pi over lambda P, lambda P is the wavelength corresponding to the incident wave multiplied by n effective is the effective refractive index that the wave is seeing in the fiber, this equals your angular frequency which is 2 Pi Nu B that Nu B is the frequency of the acoustic wave divided by V A, the V A is the velocity.

So you can write this as 2 Pi over lambda, where lambda corresponds to the wavelength of acoustic wave and that wavelength is V A divided by Nu B. So ofcourse you can say in this 2 Pi 2 Pi cancels and so what you have is Nu B is given by 2 times n effective multiplied by V A divided by lambda P. So this is essentially the downshift in the frequency that you get to see. So if we put some numbers to this n effective let us say is approximately 1.5 and V A is the sound of I mean it is the velocity of sound in fuse silica which is about 6 kilometers per second and lambda P let us consider that to be 1.5 microns, if you substitute all of this you just get Nu B is 12 Gigahertz.

So your scattered frequency is 12 Gigahertz downshifted from the light frequency, this is what you see in silica fibers (but) so that is the level of detail that may not be so interesting to some people, what is important to understand is that you have this effect where beyond a certain power level that you put into the fiber you start having this Brillouin scattering which means that light is actually getting backscattered, it is not going forward.

Now so that is actually very bad for communications, it is really bad for communications, but there is actually a finer point which may be gives us some hope that finer detail is that this is the threshold if your source is highly coherent, what do I mean by that? If my source is highly coherent that means it is a monochromatic source it has only one colour, if it has one colour then I have a very specific wave pattern like this and if you have a very specific wave pattern then my interference fringes are very strong.

If you do not have that coherence, if you say my light wave is relatively incoherent it has got multiple frequencies to it, then you do not have a very specific wave pattern, the wave is sort of like spread out and correspondingly when you are doing that interference, what do you get as interference for incoherent light? The fringes just wash out, you cannot you do not have this high visibility fringes.

So for incoherent light stimulated scattering this Brillouin scattering is not a problem and why I am calling it is stimulated Brillouin scattering? Because Brillouin scattering happens at any power level, when light actually goes through the medium it gets scattered by these acoustic phonons in the medium, but only beyond a certain power level the scattered light is actually interacting with the incoming light and creating a grating which really enhances the backscattered light.

So only beyond you know this sort of power level you have that backscattering happening in a very strong manner and in that case it is actually stimulated that backscattering is stimulated by your regular spontaneous scattering, so that is why it is called Stimulated Brillouin Scattering but nevertheless it is this is a threshold if it is highly coherent if but you need coherence in communications, why? Narrower the line width less will be the dispersion that you incur in your optical fiber communication system.

So that is why you try to go for a highly coherent laser like a distributed feedback laser, but if you use distributed feedback laser you better not go you know beyond milliwatt of power level because beyond that you start seeing effect of Stimulated Brillouin Scattering, it does not help to keep increasing the power because you will end up having this issue of Stimulated Brillouin Scattering, but I teach this other course optical senses in parallel I am going to go to a lecture in an hour from now on and I am going to tell them Stimulated Brillouin Scattering is great, why?

Because for sensing it is actually a wonderful opportunity primarily because of the fact that when you look at this V A this velocity of acoustic wave that velocity is dependent on the density of the medium and that density changes whenever you are subjecting the fiber to strain or temperature, so what does that mean? In a long section of fiber if I have particular section where I have strain or temperature, in that section the velocity of the acoustic wave is changing which means that the frequency that is backscattered from that particular section is changing.

So if I am tracking this frequency around 12 Gigahertz, I can tell how much is the strain or temperature at that particular point, so it is bad for communication, but it could be very good for sensing applications, okay let me stop here.