Optical Fiber Sensors
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Lecture: Wavelength Modulated Sensors – 3

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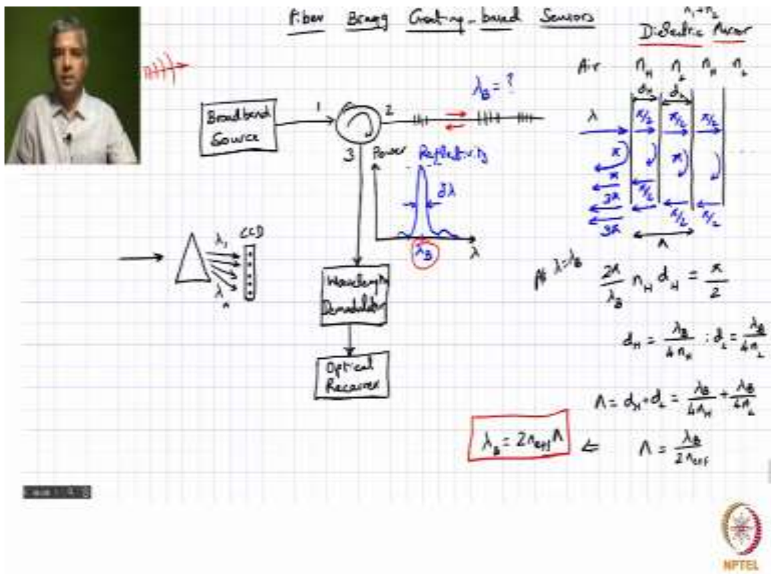

We have been looking at fiber Bragg grating based sensors as an example of wavelength modulated sensors and so far we have discussed how we can use this as a sensor in some loose terms we were saying that you can use a broadband source to integrate this fiber Bragg grating sensor in which case the fiber Bragg grating will reflect one particular wavelength or a narrow band of wavelengths and we needed a wavelength demodulator to convert any change in wavelength to intensity changes and then we are picking of the intensity changes using a traditional optical receiver.

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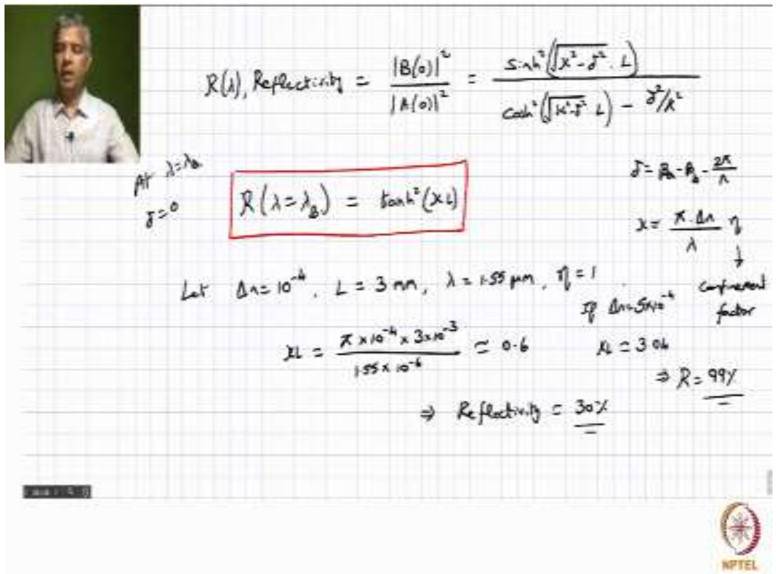

So we looked at how we get to this Bragg condition and then we looked at couple mode theory to quantify the reflectivity of a fiber Bragg grating and the reflection spectrum in general is given by this expression and if you look at specifically at the Bragg wavelength, we realized that all the waves are the forward propagating wave and the backward propagating wave is phase matched through this periodic refractive index perturbation and in that case the reflectivity was given by this expression.

And then we looked at one particular example where we said we can consider delta n is equal to 10 power minus 4, L equal to 3 millimeters and lambda equals to 1.55 micron and of course, we said eta which is the confinement factor we assumed it to be 1 in this case and for that case we said kappa L becomes 0.6 and then the reflectivity is roughly about 30 percent.

Now, of course, you can get much higher reflectivities for example, if you considered delta n of phi into 10 power minus 4 for the same parameters you would find that kappa L is approximately 3.04 and this would imply a reflectivity of close to 99 percent, so that is actually quite interesting because the refractive index perturbation that we are looking at is relatively small phi to 10 power minus 4 but we still manage to get reflectivity in the order of 99 percent.

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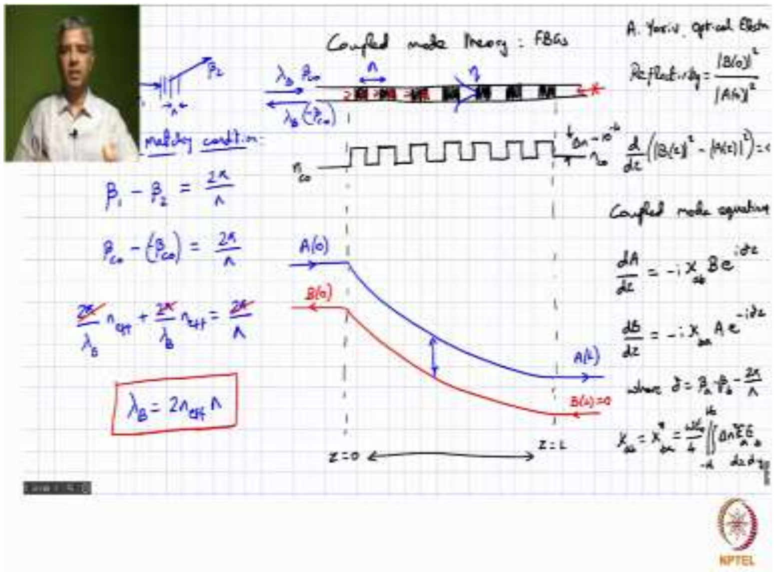

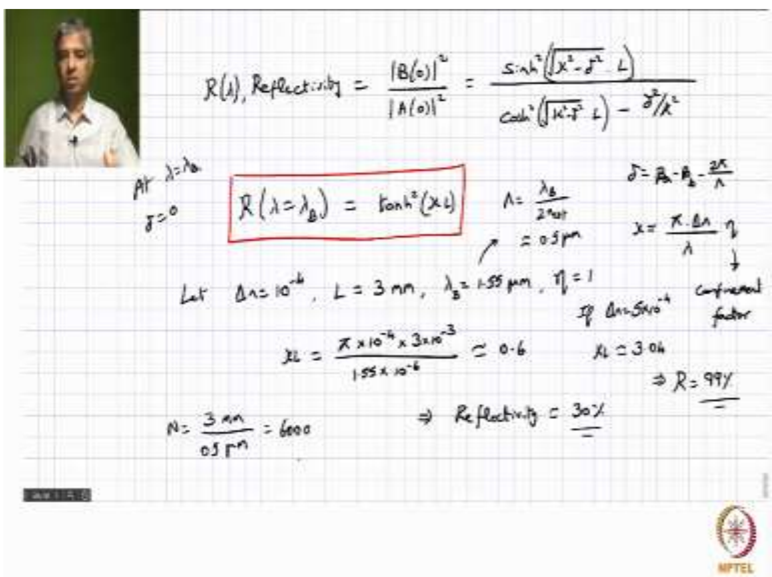

To put this in perspective if you are talking about a dielectric mirror, dielectric mirror when we are talking about nh and nL is typically like 2.32 and nL is like 1.38, so you have a fairly large change in the refractive index and compared to that this is much smaller delta n phi into 10 power minus 4 but still we are able to get reflectivity as good as 99 percent and that is because of the fact that when you think about it the period when you talk about a Bragg wavelength of, so this is basically the Bragg wavelength that you are trying to achieve of 1.55 micron, the corresponding period would be lambda b over 2 times ineffective.

So if you do the math it is 1.5 micron divided by 2 into n effective is let us say approximately 1.5, so that factor in the denominator becomes 3. So we are looking at something in the order of 0.5 micron, 0.5 micron period but then your length is actually 3 millimeter so what does that mean? It means the number of layers that you have, number of periods that you have is 3 millimeter divided by 0.5 micron, so that corresponds to 6000 periods, so 6000 alternate high and low refractive index regions over just 3 millimeters of length.

So that is what is actually contributing to this high reflectivity, so that is very different from how you look at from perspective of dielectric mirrors but then that picks up the question how can we get refractive index changes of phi into 10 power minus 4, so what is the physics behind getting such a refractive index change.

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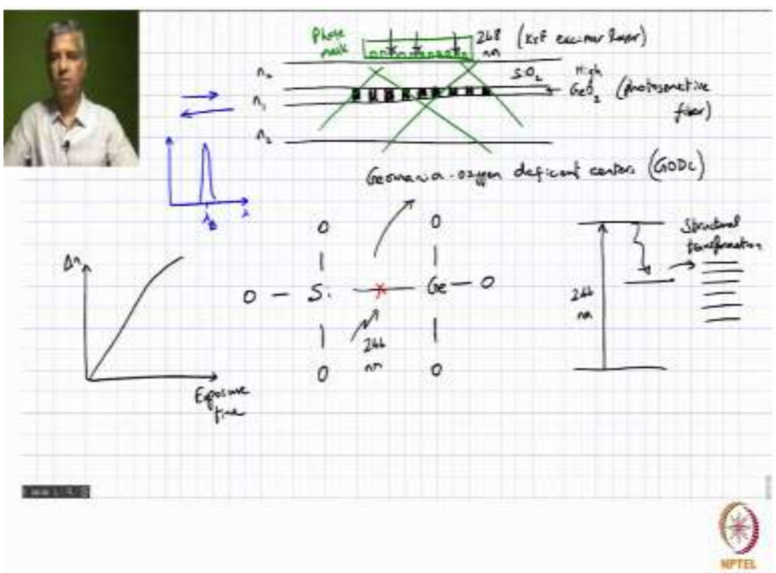

So let us actually look into that a little more detail. So we know that an optical fiber has a core surrounded by a cladding region and the core is having a higher refractive index compared to the surrounding cladding region. So the question is how do you get higher refractive index in this fiber, that is typically by doping this the germanium, when you dope Sio2 which is basically glass when you dope glass with germanium you actually get a increase in the refractive index within this region and within the core region compared to the cladding region which is just pure silica.

So in the process of doping you actually get germanium oxygen deficient centers, germanium oxygen deficient centers, GODC in short, so what do I mean by that? Well, silica, the silica matrix is typically like this, it makes bonds with four oxygen atoms and when you dope it with germanium, the germanium atom actually replaces silicon atom in the matrix, so that is what germanium doping means.

Now when you do such doping there is a possibility that some of these oxygen atoms are not there and you form a bond directly between germanium and silicon or germanium and germanium and so on, so this is what we call as germanium oxygen deficient center, there should be an oxygen atom here but it is deficient of oxygen and so that is what we call as a GODC. The interesting part is this germanium oxygen deficient center has a absorption spectrum h like this, it is resonant at a wavelength of about 244 nanometers.

So if you come in with 244 nanometers, so you will end up breaking this bond, So if you illuminate this with 244 nanometers you end up breaking that bond and when you break that bond it rearranges itself, there is some structural transformation that is going on so the bond actually rearranges itself and there is some stress relaxation that is going on locally that stress relaxation is what is actually causing change in the refractive index in that medium.

So essentially, when we have this 244 nanometer absorption it goes to this higher energy level and then it comes to this metastable state and it is from this metastable state that it actually goes through some structural transformation and goes into one of these states. So, this is a structural transformation which causes stress relaxation at that particular point and then gives this change in refractive index.

Now the interesting, so you say, you basically illuminate this with ultraviolet radiation especially, some wavelength around 244 nanometers, let us say for example, 248 nanometers which you can obtain from what is called a krypton fluoride excimer laser that actually produced 248 nanometers, then you can essentially change the refractive index of this region.

Now of course, what you want to do is actually change the refractive index in only selected, in a periodic fashion so you want to achieve refractive index change like this, so how do you get a periodic refractive index change like this that is using a diffractive element which is called a phase mask, so you actually put this, you send this light through this diffractive element which is like a grating by itself that essentially creates two parts.

So you have a light beam that comes like this and then another light beam that goes like this and these two interfere and that interference pattern is where there are high intensity regions in these play locations and that actually causes a change in the refractive index at those points. So this is typically the way you make a fiber Bragg grating and longer the exposure, more will be this refractive index change.

So you basically, if you look at the refractive index change as a function of exposure time, it basically goes up like this and then it saturates because beyond a certain point there are no more germanium oxygen deficient centers and so you have already created all the refractive index change that you could possibly get from this fiber.

So such fibers with the high level of germanium doping is called a photosensitive fiber and so you take a photosensitive fiber and you expose it to ultraviolet radiation through this phase mask you can actually get a grating and you can monitor the grating basically by sending in broadband light and you can send in broadband light and you can look at what is reflected back, initially you would not see much light reflected back but as your grating starts forming you will start seeing a peak corresponding to lambda B the design wavelength. So that is how you fabricate a fiber Bragg gating.

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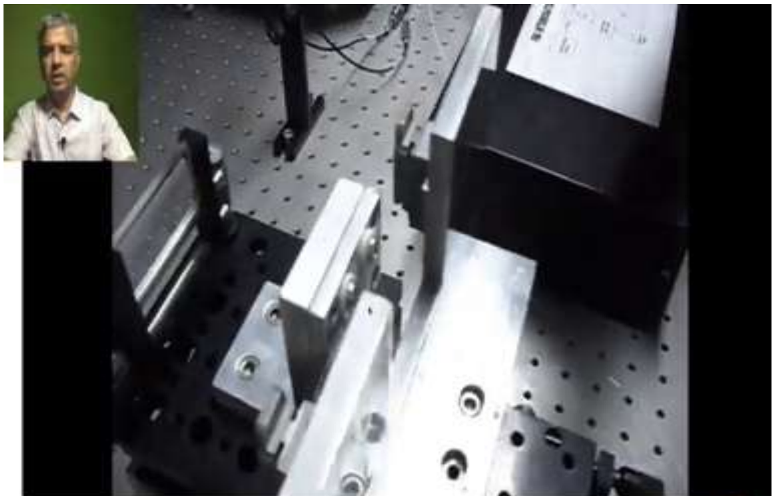

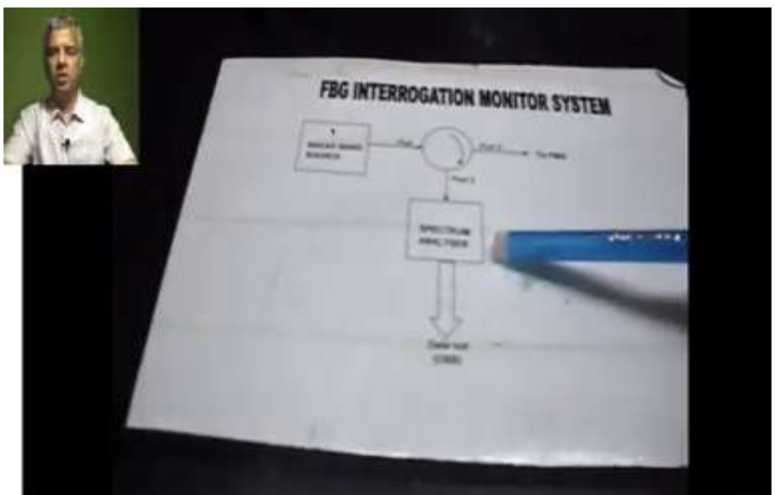
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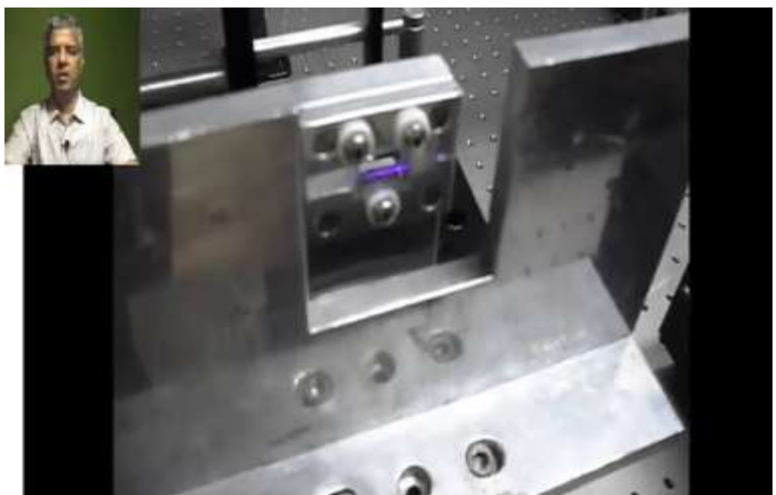

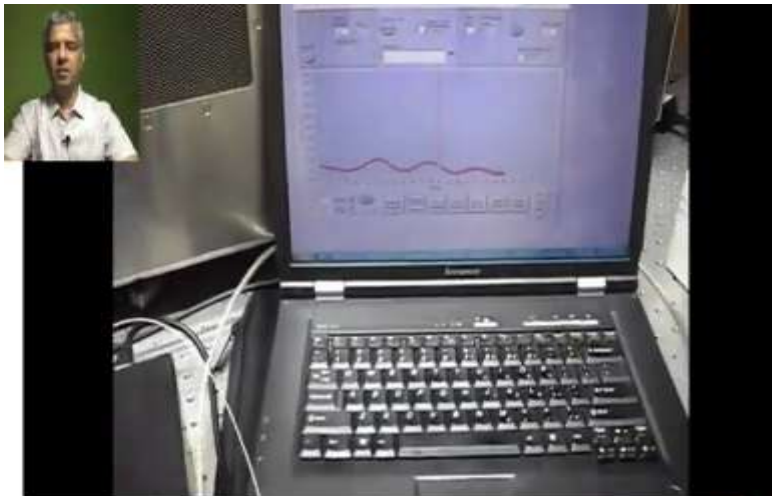

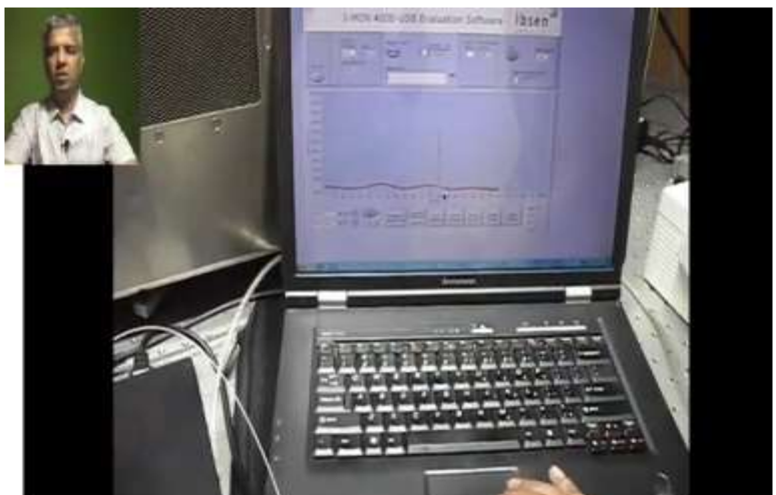
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So, I can demonstrate this, so we have basically made a video of this fabrication so we can actually play this video. So this is actually the excimer laser that we have and the excimer laser is going to emit a radiation at 248 nanometers that is going to come out of that aperture there and then that radiation is going to fall on this mirror, so the mirror will deflect that radiation in this direction and use a cylindrical lens to essentially collapse that beam into a narrow line over here and this is actually the face mask element and so light actually goes through the face mask element and it will be incident on this fiber which is held by these two fiber holders and that fiber will be connected to an integrator.

So essentially your integrator consists of a broadband source and sending light through a circulator into this fiber which is going to get exposed and the reflected light, back reflected light we are going to capture using a spectrometer, spectrometer output is like this is the reflected power as a function of wavelength.

So initially it is not showing much reflection coming from the grating but now we will turn on the excimer laser so it is going to basically shoot these ultraviolet radiation from this point and when it actually this incident on the fiber you can actually see a glow over here that is because ultraviolet radiation is absorbed and you have some fluorescence that is happening in some blue region as well as some pink wavelength region.

So typically that is showing that there is some absorption happening in the fiber and then there is some structural transformation happening and all that, so you can see that a little more clearly over here. So while it is actually getting exposed it is actually going to start changing the refractive index in a periodic fashion. Of course, you do not see a periodic change in the intensity there because that period is extremely small you cannot resolve that but nevertheless when you look at the output spectrum now, previously remember it was all noise over here but now we can clearly see a peak that has formed.

So this is actually a live demonstration, so the exposure is going on and even as exposure is going on you can see a grating which has come up in less than a minute, so all you need is just like 60 or 120 seconds of exposure and you see a grating that is developed over here. So that is actually the typical procedure, so you look at the growth of the grating and beyond a certain point that peak is not changing or get saturates and at that point you will stop the laser, so you would you would basically say the grating is already fabricated.

So that is actually how these fiber Bragg gratings are actually fabricated in a real environment and like I said basically longer the exposure time more will be the delta n but it will saturate typically in the order of a minute or a couple of minutes, the delta n will saturate and correspondingly the reflectivity that you can get from the grating will saturate at that point. So we understood how we obtain a certain reflection spectrum from a fiber Bragg grating, how we get a certain reflectivity and now that.

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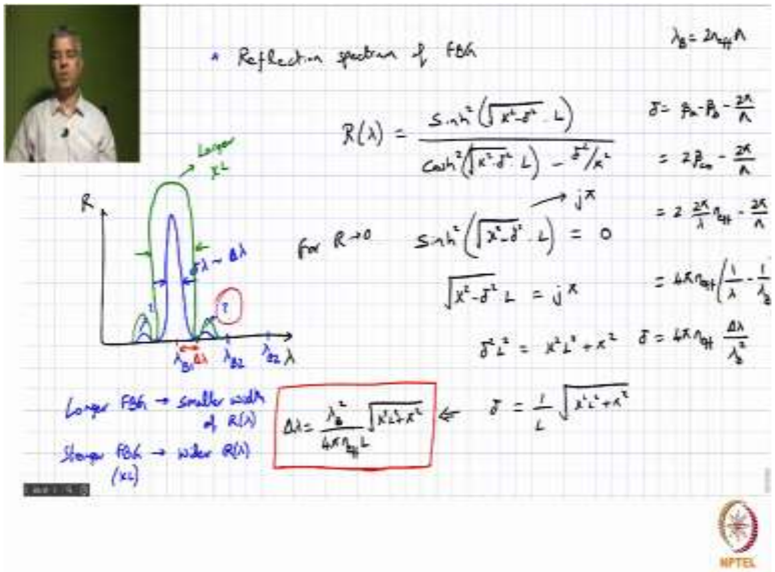

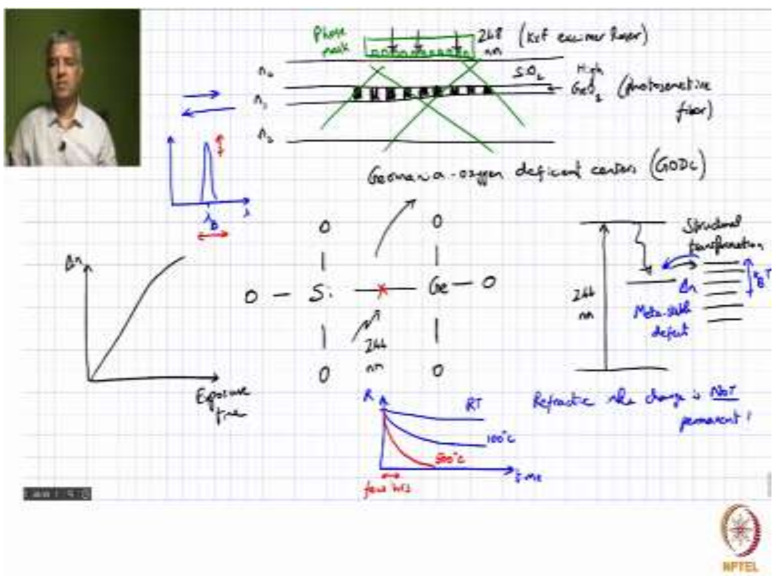

Now, let us dwell a little deeper into the reflection spectrum of an FBG. So what is the shape of that reflection spectrum and what does that mean in terms of the performance of fiber Bragg grating as a sensor. So let us look into that little more detail, of course, we previously saw that the reflection spectrum is given by sine square root of kappa square minus delta square multiplied by L divided by cos x square root of kappa square minus delta square multiplied by L minus delta square kappa square.

So if we plot that the reflectivity as a function of lambda we typically see something like this sort of a spectrum, so where the center is certainly we know it corresponds to lambda B, but then the question is what about the width of the peak delta lambda and what can we do about these side lobes. So can we possibly get rid of those side lobes, so those are the kind of things that we want to look at next.

First of all let us get an estimate of what is this width and to understand that let us actually figure out where it goes to 0, at what wavelength does it go to 0. So if the reflection spectrum is going to 0, then that corresponds to a fact where this sine h square this function would have to go to 0. So for R if it has to go to 0 then sine h square root of kappa square minus delta square multiplied by L, this has to go to 0, where does this go to 0? This goes to 0 when this argument here that becomes j times pi, so sine h square of j times pi is what is going to give you 0.

So we can write that condition separately, so we can just say basically kappa square minus delta square root of that multiplied by del equals to j pi or you can rearrange terms, you can take that square root to the other side, so it is going to give you a minus pi square. So you can write this such that delta square L equals to kappa square L square plus pi square. So you can basically this minus pi square you can take it to the other side and you get this expression and then this should be delta square L square.

Now we can further rearrange this and we can say that delta is going to be equal to 1 over L root of kappa square L square plus pi square, but then the question is what is delta? Well delta we said previously corresponds to beta A minus beta B minus 2 pi over capital lambda, so that is what we defined delta S over here in this couple mode theory.

So that for the case of fiber Bragg grating beta B corresponds to the reflected wave, so that is going to have beta B is equal to minus of beta A and both of beta A corresponds to the propagation constant of the mode in the core of the fiber, so you can write this as 2 times beta core minus 2 pi over capital lambda and this 2 times beta core can be written as 2 multiplied by 2 pi over lambda times ineffective minus 2 pi over capital lambda.

So and of course, capital lambda since we know lambda B equals to 2 times ineffective capital lambda, capital lambda itself can be written as lambda B over 2 times ineffective, so you essentially have 4, you take this common terms 4 pi ineffective 1 over, multiplied by 1 over lambda minus 1 over lambda B.

So you can you can write this like that and so this you can 4 pi times ineffective, so you get, if you simplify this you get lambda into lambda B in the denominator and lambda B minus lambda in the numerator, so lambda B minus lambda you can write as delta lambda and lambda into lambda B, since lambda is very close to lambda B you can approximate it as lambda B square.

So delta is given by this, so you can substitute this over here and if you do that what this will imply is you get a expression for delta lambda which is given by lambda B square over 4 times pi times ineffective and you have in the denominator you have a L also, root of kappa square L square plus pi square.

So what is this delta lambda correspond to? Delta lambda corresponds to this over here the shift in wavelength that you have to go to from lambda B, so that you are going to 0 on either side, and that can in some ways be approximated as this delta lambda itself. So you can say this delta lambda is approximately equal to capital delta lambda under some very specific criteria but nevertheless that is actually giving you some idea as to what is the width of that spectrum is, so and what does it depend on.

Well one thing we can clearly say is that depends on, it is inversely dependent on L, so that means longer FBG, maybe I can just write it here, so longer FBG that is actually typically giving rise to smaller width of that reflection spectrum. So smaller width of R of lambda, so longer the FBG, basically you can also understand it from this perspective longer the FBG is more number of alternating high and low refractive index layers and that means more number of sources of interference and we know from our theory on interference that more the number of sources more constrained is the interference condition.

So that actually corresponds to a narrower spectral width, but that has to be looked upon with respect to this kappa L term also, so what this tells you is delta lambda is actually proportional to kappa L, that means if you have a stronger grating then your width is actually going to increase. So, if you have a stronger FBG, that is you have a large value of kappa L that means wider reflection spectrum.

So effectively it is going to show up as if you try to enhance the reflectivity by going to larger kappa L, what you will most likely see is this is going to look something like this. So it is going to basically look fatter, this is for larger value of kappa L, so in that case the width is actually going to be larger as well.

So those are some of the trade-offs that you have to deal with, you want as small a delta L as possible because what you are interested in as a sensor is the position of lambda B, you are not interested in the width of delta lambda and if you have a narrower width that means that you can actually concatenate gratings which are essentially if you have a narrow or width so this can be looked upon as lambda B1 and then you can actually have lambda B2 right next to it and then lambda B3 next to it and so on.

So you can actually have multiple sensors that are concatenated and they are placed close to each other if you have a narrower line width, spectra width for your, whereas if you have a fatter grating then your ability to actually pack more gratings, the reflection spectrum of those gratings if they are packed closer then they will interfere with each other and they will also limit the range over which you can do this, you can do this sensing.

So that is one important criteria, so you do not necessarily need to get the highest reflectivity possible, you want to get to as higher reflectivity without significantly increasing the spectral width of the grating. So that is one important point, now having said that I should also mention this part, now when we look at the physics of how the grating was formed we talked about the structural transformation happening and then because of that you are getting this change in refractive index, so this is what this structural transformation is what is giving rise to this change in refractive index at any particular location.

But all said and done this actually corresponds to what is called a metastable defect, meaning it cannot stay there forever, it will have to stay there for some time and if it actually finds enough energy it can revert back to its original state from this modified state it can revert back to its original state, what that means is your refractive index change is not permanent.

So you have a fiber Bragg grating say it is a reflectivity of 99 percent today, if you look at the same grating, if it is kept at room temperature then you know it may not be 99 percent after a year, it might actually be 97 percent and after another couple of years it might come down to 90 percent and so on and that is when it is kept at room temperature, when it is under field conditions especially when there is an application where you are having to use this grating in a high temperature environment, we talk about high temperature you are talking about going deeper, this energy can correspond to KBT, so you are talking about reverting some of these defects to the original state, some of these deeper defects in the original state.

So essentially what we are talking about is when you look at the reflectivity of the grating as a function of time, if it is kept at room temperature the reflectivity may be something like this initially and then it might decay slowly over a period of time, this is at room temperature but when you go to higher temperatures let us say about 100 degree centigrade, then it goes like this.

So, this might actually, the reflectivity would go down as a function of time and probably stabilize at a certain point because after a certain time all the defects corresponding to this shallow energy levels they would have reverted back to the original state leaving behind the deeper defects and that is constituting the change, that is giving the reflectivity.

And if you talk about really high temperature applications you might actually have something like this, you might end up completely erasing the grating if you are using this for example, at 500 degree centigrade. The reflectivity will come down rapidly within about a few hours, within a few hours it might actually come down, it might completely erase and of course, if you go to thousand degree centigrade it will in a matter of few seconds it might actually erase uh itself.

So what that tells you is that this fiber Bragg grating, the reflectivity of the fiber Bragg grating is something that is not to be taken for granted, it has to be monitored every now and then to see whether the reflectivity has actually decreased from the original value. Now the magnitude of the reflectivity itself is not as much of an issue because what we are interested in once again is how this Bragg wavelength is shifting, we are not interest even if this actually is changing we are not bothered by that but the Bragg wavelength if it is shifting that is what is actually of more concern for us.

But having said that if your index contrast is reducing that also corresponds to an average refractive index change across the grating and that actually means that lambda B also shifts a little bit, so you do have to calibrate your grating every now and then to account for that shift due to decay of this grating reflectivity, due to the fact that the refractive index change that you have is not permanent in nature. So those are some practical issues that you have to deal with when you are using these fiber Bragg gratings.

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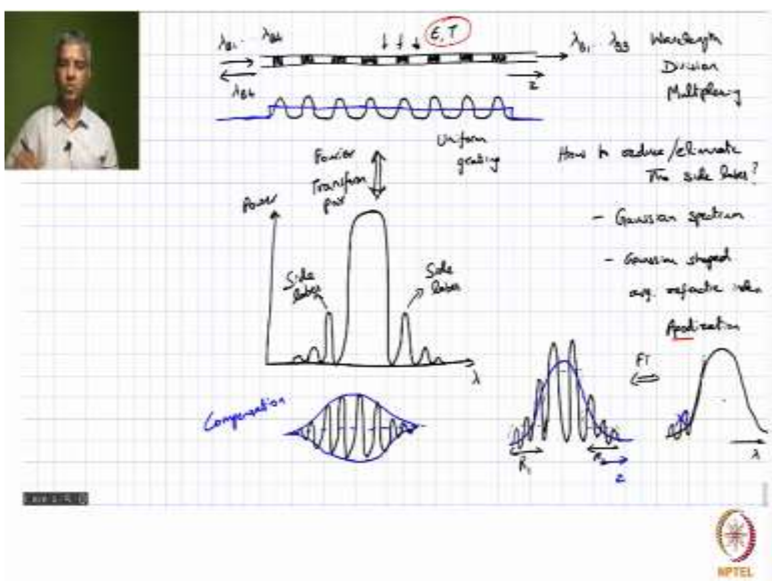

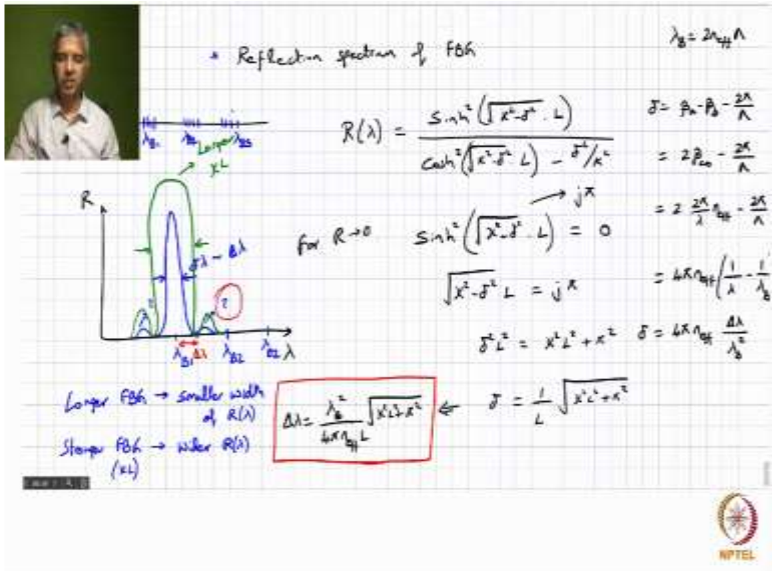

But the other issue is it is a question of these what are these side peaks and what is that due to? So let us actually examine that in a little more detail, so when we are making a grating, so we are saying we are making a grating in the fiber, in the core of the optical fiber, in a periodic manner.

Let us say something like this and if you look at the refractive index change, previously we denoted the refractive index change as something like a squarish change in refractive index, but in reality it is not like a squarish it will be more like a gradual change in the refractive index.

Something like this it is not squarish, of course, what we talked about here is as you expose it longer and longer it will tend to saturate this grating, so it will start looking a little more squarish shape but in terms of the reflection characteristics what we are actually seeing is if you look at the average refractive index across this grating structure, so the average refractive index is like this and then across the grating structure the average refractive index goes like this.

So when we look at the envelope of the average refractive index, that is actually sort of like a rectangular shape, this is as a function of distance z, it is actually rectangular in shape. So this type of grating when you take a Fourier transform of that, you would actually see in the power spectrum density as a function of frequency or I can look at it as a function of wavelength also, that will tend to have these side lobes, it will have all these side lobes.

So where the index contrast is uniform across the grating this is called a uniform grating, so for a uniform grating you will find that when you look at the reflection spectrum it will look like a sine square, essentially what we are saying is that the average refractive index distribution across the grating and the power spectral density are Fourier transform pairs.

So if it is rectangular shape this will correspond to a sine square function and from that perspective you can understand why we are getting these side lobes, these side lobes are just because of the fact that this there is a sudden transition over here and a sudden transition over here and that is what is creating all those side lobes.

Of course, there is a question, there may be a question as to you are looking this as more sinusoidal what if it is squarish? Well if it is squarish then that corresponds to harmonics of this reflection spectrum at longer wavelengths that we are not too worried about at longer frequencies essentially and shorter wavelengths, but that we are not too worried about, but what is actually important is that these side lobes they can actually cause problems for us because, like we talked about previously we want to concatenate multiple gratings with different Bragg wavelengths and look at possibly sensing this in a distributed manner.

So you take a fiber and you have lambda B1 and then another grating at lambda B2 and another grating at lambda B3 and so on. So you want to have multiple gratings in a length of fiber and you can look at perturbation multiple locations but that ability is going to be constrained by having all these side lobes.

So then the question is how can you reduce those side lobes, how to reduce or if possible eliminate the side lobes that is not at all desirable for a sensing application and this is actually a question that has been discussed early on when fiber Bragg gratings came into the picture back in the 90s itself, because in the 90s these gratings are looked upon as elements which can help in doing wavelength division multiplexing.

Basically you can come in with in communications, you can come in with different wavelengths, so lambda B1 to lambda B4 let us say and this can reflect lambda B4, the information contained in lambda B4 and lambda B1 to lambda B3 can be transmitted, so this is actually a very nice application it is called wavelength division multiplexing.

So that was actually a very popular application for fiber Bragg gratings back in the 90s, only problem and of course, in those applications you needed to make sure these side lobes are as low as possible, because these can interfere with the neighboring channels, corresponding to this different lambdas.

Only problem in that application, people found out was that this grating was not very stable, meaning if there was any strain or temperature changes, if there are any environmental changes through which the strain or temperature is changing and there are any perturbations the Bragg wavelength was shifting.

In communications all these wavelengths are corresponding to a grid and they have to remain fixed in that grid, if one of them is shifting around, then that will be a big problem as far as communication applications concerned. So eventually fiber Bragg gratings were not found to be very suitable for communication applications for this wavelength multiplexing applications.

But that is when scientists actually figured out if it is very sensitive to perturbations it is might work very well as a sensor, so what was a problem for communications became an opportunity as far as sensors were concerned, so of course, that is where we see that most of our applications we find this fiber Bragg gratings as a very good strain and temperature sensors.

But nevertheless coming back to the point how to remove these side lobes? Well we know, if you look at it at the Fourier plane, if you want something without these side lobes what sort of function would you use, so that the Fourier transform pair itself would work out that way. One example is if you use a Gaussian spectrum, we know that a Gaussian spectrum does not have side lobes and more importantly when you take the inverse Fourier transform of a Gaussian spectrum that will correspond to a Gaussian shaped average refractive index.

So instead of having a rectangular index shape, if you have a envelope that looks Gaussian in nature, so then what we are talking about is the average refractive index along this z direction, it looks like this, so your index variation basically goes like, index variation goes like this, so it is not uniform, it is actually sort of Gaussian shaped change in the refractive index and this you can accomplish by changing the intensity of the light coming from the excimer laser.

So the shape of this of this beam if this is corresponding to Gaussian intensity pattern, then correspondingly you will have Gaussian change in the refractive index like this. So this would actually if you take a Fourier transform of this, that would correspond to in spectrum it will be once again a Gaussian, so this is actually with respect to wavelength and then of course, you are talking about something without these side lobes.

And this process is called Apodization, I think pod in Greek corresponds to feet, so these are considered like feet and so if you do not have those feet that is what Apodization is all about. Of course, very subtle aspect of this is the fact that you have, essentially you can model this as something like having a average refractive index like this and then it is going to a higher average refractive index and then lower average and refractive index like this.

So these regions are essentially like two mirrors which are having a different average index compared to this region and so this one we consider as R1 and R2 and that actually it looks like a Fabry Perot cavity. So in reality what we will have is these small peaks over here in the lower wavelength side, because these correspond to lower average refractive index compared to these regions.

So, the apodization typically produces these spectral features on the lower wavelength side which you can of course, remove by going to refractive index change that looks more like this. So if your refractive index change is like this, then that means the average refractive index across this entire structure is the same and in that sort of a scenario you can get rid of these side lobes as well.

So this is actually called a compensation step which can remove these ripples on the lower wavelength side and then you get nice one single peak which is very good for a sensing application. So, we looked at how to make a grating, how to essentially characterize the grating, what gives the width of the grating and what gives the spectrum of the grating and how to essentially get a grating with a single nicely shaped Gaussian shaped peak. So with that information now we are ready to go on to understand how this can be used as a sensor and that is what we will look at in the next lecture.