Optical Fiber Sensors
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Lecture 35
Wavelength Modulated Sensors 4

Talking about wavelength modulated sensors lately, and we looked at the example of fiber Bragg gratings, how fiber Bragg grating can be formed and how can they be used for sensing applications.

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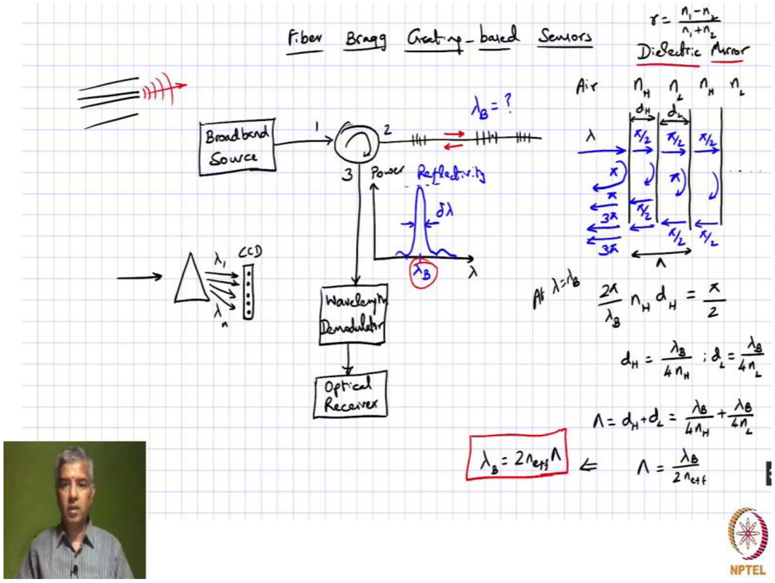
Fiber Bragg Grating-based Sensors

$r = \frac{n_1 - n_2}{n_1 + n_2}$

Dielectric Mirror

At $\lambda = \lambda_B$ $\quad \frac{2\pi}{\lambda_B} n_H d_H = \frac{\pi}{2}$

$d_H = \frac{\lambda_B}{4n_H}$; $d_L = \frac{\lambda_B}{4n_L}$

$\Lambda = d_H + d_L = \frac{\lambda_B}{4n_H} + \frac{\lambda_B}{4n_L}$

$\boxed{\lambda_B = 2n_{eff}\Lambda} \Leftarrow \quad \Lambda = \frac{\lambda_B}{2n_{eff}}$

And we just briefly said that when you want to use this fiber Bragg grating as a sensor you come in with a light at a particular well over a broad range of wavelengths, it can interrogate the grating over a broad range of wavelengths, and the grating will reflect around a particular Bragg wavelength which is given by this expression. And then we said if there is any perturbation that this Bragg grating is exposed to then there will be a corresponding change in the Bragg wavelength and that change is what we are trying to pick up to understand the magnitude of the perturbation.

So, we will go into this a little more detail in today's lecture. So, we will let us look at how we accomplish the sensing using fiber Bragg gratings and then we will look at case study. Let us go ahead and design bridge monitoring system using fiber Bragg gratings. That is what we are going to do in today's session.

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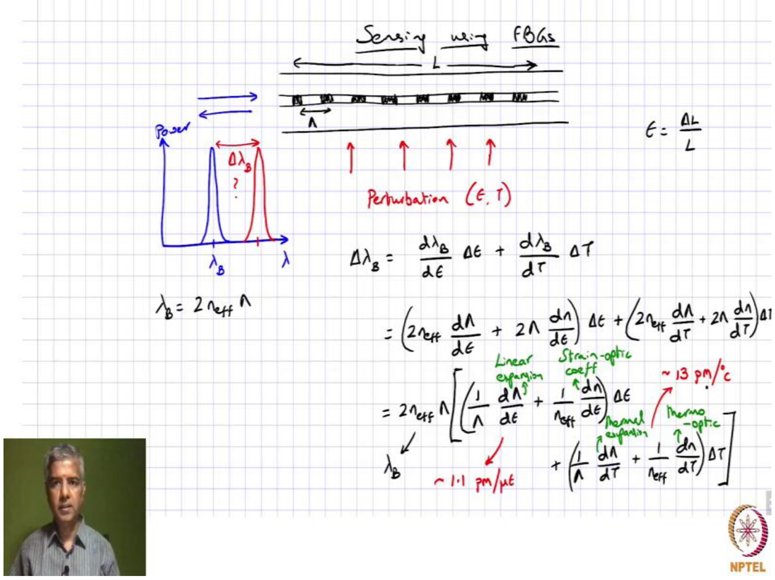

Sensing using FBGs

$\epsilon = \frac{\Delta L}{L}$

$\lambda_B = 2 n_{eff} \Lambda$

$$\Delta\lambda_B = \frac{d\lambda_B}{d\epsilon}\Delta\epsilon + \frac{d\lambda_B}{dT}\Delta T$$

$$= \left(2n_{eff}\frac{d\Lambda}{d\epsilon} + 2\Lambda\frac{dn}{d\epsilon}\right)\Delta\epsilon + \left(2n_{eff}\frac{d\Lambda}{dT} + 2\Lambda\frac{dn}{dT}\right)\Delta T$$

$$= \underset{\lambda_B}{2n_{eff}\Lambda}\left[\left(\frac{1}{\Lambda}\frac{d\Lambda}{d\epsilon} + \frac{1}{n_{eff}}\frac{dn}{d\epsilon}\right)\Delta\epsilon + \left(\frac{1}{\Lambda}\frac{d\Lambda}{dT} + \frac{1}{n_{eff}}\frac{dn}{dT}\right)\Delta T\right]$$

So, let us start with looking at fiber Bragg grating a little more closely, let us say this is the core of the optical fiber where you have refractive index modulation happening at a period of capital lambda. And, this is happening in the core of an optical fiber which is of course, surrounded by a cladding region and what we said was, we can interrogate this with broadband radiation and then when you interrogate with broadband radiation, what you get as the reflected spectrum is typically something like this as a function of wavelength let us say we have a single peak spectrum.

So, you have something like this you keep the power as a function of wavelength and this is happening at lambda B. Now, whenever we apply a certain perturbation of course, we also said lambda B is given by 2 times in effective capital lambda. Now, whenever we apply an external perturbation to this rating so, the perturbation maybe as strain or temperature where strain is basically defined as delta L over L the incremental change in the length of the grating over the length of the grating itself.

So, this is what we consider as the length of the grating itself. And let us say this is the length over which the fiber is attached to a structure. Now, the structure is expanding, then delta L will be a positive number. And if the structure is getting compressed, so delta L will correspond to a negative number and correspondingly there will be a negative strain perturbation. And of course, we know that you can apply temperature and that can also cause a change in the Bragg wavelength.

But whichever way you look at it, let us say we have this grating shift to a new wavelength from this point. So, let us say that wavelength shift we can call it as capital lambda. So, now the question is, how can we quantify capital lambda? So, what is, how do you quantify capital lambda and more importantly, we want to call that capital lambda B, because we are talking about changing the Bragg wavelength, from this wavelength to this wavelength.

So, now let us go ahead and try to see how to quantify that change in the Bragg wavelength. To do that, basically you can take this expression and then you can differentiate. So, you can say, delta lambda B would consist of some change in lambda B with respect to the rate of change of lambda B with respect to strain for an applied change in strain. And then similarly, you could also have a rate of change in the Bragg wavelength per unit change in temperature and that of course would have to be multiplied by the change in temperatures.

And that is actually one of the key things that we need to understand that the Bragg wavelength is sensitive to both strain and temperature changes. So, that is like we talked about earlier, that is one of the primary challenges when we talk about, doing sensing using fiber Bragg gratings. It is not easy to discriminate between changes in strain and temperature. But anyway, if we go ahead and try to expand this lambda B is given by this.

So, we understand that any change in strain can of course, change the period because physically you have say a stretching the fiber, there is a physical change in the capital lambda, but there is also a change in the effective refractive index and that is through an effect called strain optic effect. And similarly, when we talk about the change in lambda B with respect to temperature, you have one change, which is change in capital lambda the period which will correspond to what is called the thermal expansion coefficient.

That is more commonly known, but what is not as commonly known is the fact that the refractive index also changes and that is called the thermo optic effect. So, if we write this in terms of changes in refractive index and changes in period, we can just say you have one component which is two times n effective d capital lambda over d epsilon plus you have 2 times capital lambda d n over d epsilon, the change in refractive index with respect to strain and this is what we call as the strain optic coefficient.

So, the whole thing multiplied by delta epsilon now, and then of course, the other part where you can say is 2 times n effective you have the thermal expansion coefficient, which results in a change in the period with respect to change in temperature plus you have 2 times capital lambda d n over d t which is the thermo optic coefficient and the whole thing is multiplied by delta t.

Now, of course you can take out a common factor from all of this, let us say you take out 2 times n effective times capital lambda which of course corresponds to the Bragg wavelength itself. Then, you can just say this is, this first term will be 1 over capital lambda d capital lambda over d epsilon plus 1 over n effective d n over d epsilon multiplied by delta epsilon plus similarly, you have 1 over capital lambda d capital lambda over dt plus 1 over n effective d n over dt whole thing multiplied by delta t and this appears as a common term.

So, you have taken this term which is, which we know corresponds to lambda B. So, delta lambda is a fractional change around lambda B, because of all these factors. So, I can write all these factors, this is actually what is called the linear expansion due to strain and this is actually the strain optic coefficient. And similarly, this is your thermal expansion coefficient and this is your thermo optic effect.

So, you have all these contributing to possible change in the Bragg wavelength and of course, you can quantify this for the case of silica. And what you find is, for the sake of, for silica, this works out to be approximately 1.1 Pico meter per micro strain, so that is the value that is the coefficient if you plug in the coefficient for the linear expansion as well as the strain optic coefficient.

And similarly, if you calculate this factor within the parenthesis, that actually works out to be roughly about 13 Pico meter per degree centigrade. So, those are fairly small numbers, we are talking about Pico meter changes in the Bragg wavelength. So, that is one of the challenges as well as picking up these perturbations using this fiber Bragg gratings, how we can pick up even small changes like 1 Pico meter and mind you the wavelength that we are using, let us say it is 1550 nanometers.

So, we are talking about changes in the wavelength around 1550 nanometer to the level of one Pico meter per micro strain. But of course, if you are able to pick that up, you can say that it is due to perturbation at the grating location. And that is because of the fact that the, this wavelength information is not corrupted by all these traditional noise sources.

So, that is the advantage we have but nevertheless, it is a challenge to pick up such a small changes in the wavelength itself. So, let us now go ahead and try to design system. So, let us say we are going to go ahead and try to design what is called bridge monitoring system.

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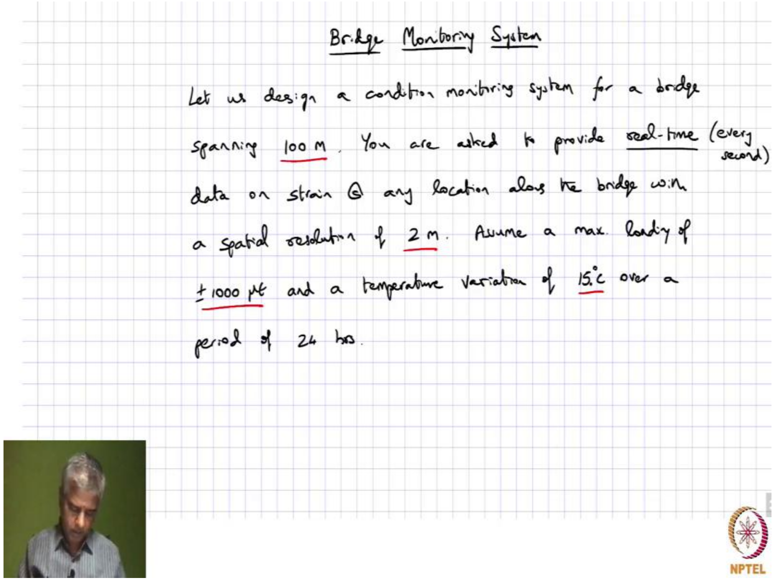

Bridge Monitoring System

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 with a spatial resolution of 2 m. Assume a max. loading of ± 1000 με and a temperature variation of 15°C over a period of 24 hrs.

So, it is a fact, it is interesting fact that, India has 10s and 1000s of bridges that are built around the country and more than half of them are fairly old bridges, several of them actually built during the British era. So, see the these are bridges that have been standing there for more than 100 years in some of these cases.

So, it is really a very important requirement that we need to monitor the strength of those bridges. We need to monitor them for, if there are any cracks that are developing in these bridges, and if there are cracks developing them bridges, then you actually do some reinforcement so that it does not propagate, and we can prolong the life of the bridge as we go on.

So, that is to do that, you need to actually have a sensor which can monitor the health of the bridge across the entire span of the bridge. So, and one possible solution that a lot of people are considering is use of fiber Bragg gratings for this applications. So, this is the requirement so let us design condition monitoring system for bridge, let us say it is spanning, let us say 100 meters.

And let us say you are asked to provide real time data on the strain that it undergoes, on strain at any location along the bridge with spatial resolution of let us say, 2 meters, every 2 meters, you need to make a measurement of the load that you have on this bridge, and you need to do that in a real time manner. So, real time let us say we have to provide the data points, the load data on the bridge every second, once every second, so that is the kind of requirement you have.

And we need to assume a certain load, we need to classify that there is some of the work that needs to be done on the bridge. So, we need to define a threshold level in terms of the load at any particular point on the bridge. So, let us assume a maximum loading of plus or minus 1000 micro strain. So, if it goes beyond 1000 micro strain, then you are supposed to raise an alarm. But up to that point, you are supposed to just give a value at each point along this bridge.

And, of course when you are trying to measure strain, you are also having to contend with changes in temperature. So, we can assume that assume a max loading of 1000 micro strain plus or minus and a temperature variation of 15 degree centigrade over a period of 24 hours. So, that is the let us say that is the requirement.

So, you need to monitor over 100 meters with the 2 meter resolution. So, how many gratings do you need? So, how many measurement points do you need, you need a 50 measurement points across the bridge and let us say they are all uniformly located and you need to expect that the strain variation could be up to 1000, plus or minus 1000 micro strain. And we need to also contend with temperature change of 15 degrees centigrade.

So, let us ahead and try to visualize this problem, of course you find that when you visualize this problem, you are able to provide a solution you can have an intuition as to how the design should work out. So, let us go ahead and try to do that. Let me just go to a fresh page and do that.

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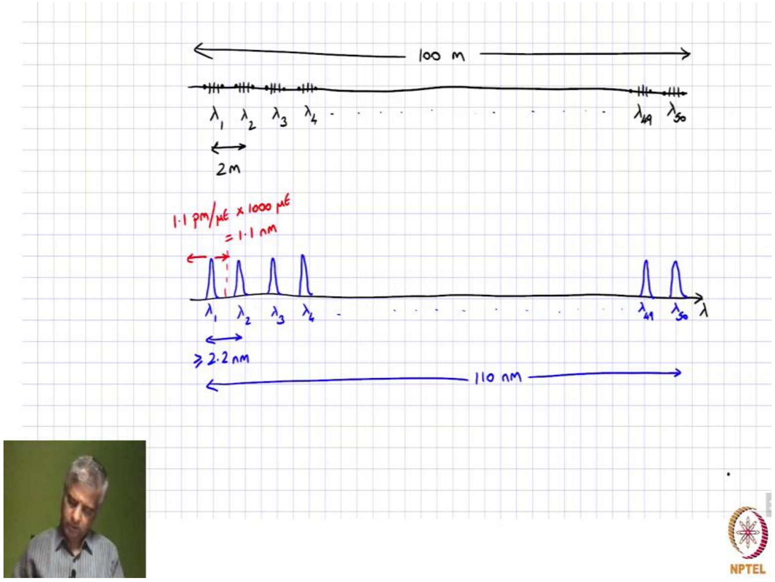

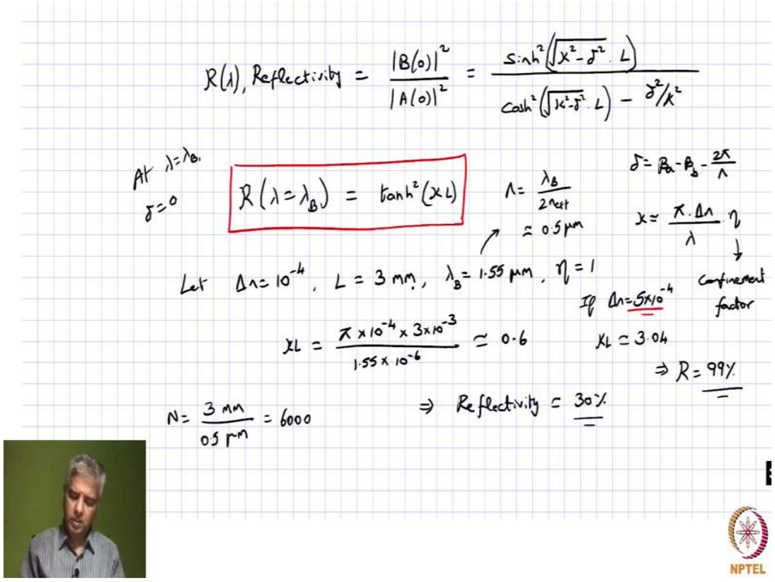

$$R(\lambda), \text{Reflectivity} = \frac{|B(0)|^2}{|A(0)|^2} = \frac{\sinh^2\left(\sqrt{\kappa^2-\delta^2}\cdot L\right)}{\cosh^2\left(\sqrt{\kappa^2-\delta^2}\cdot L\right) - \delta^2/\kappa^2}$$

At $\lambda = \lambda_B$,
$\delta = 0$

$$\boxed{R(\lambda = \lambda_B) = \tanh^2(\kappa L)}$$

$$\Lambda = \frac{\lambda_B}{2n_{eff}} \simeq 0.5\,\mu m$$

$$\delta = \beta_a - \beta_b - \frac{2\pi}{\Lambda}$$

$$\kappa = \frac{\pi \cdot \Delta n}{\lambda} \cdot \eta$$

$\eta \downarrow$ Confinement factor

Let $\Delta n = 10^{-4}$, $L = 3$ mm, $\lambda_B = 1.55\,\mu m$, $\eta = 1$

$$\kappa L = \frac{\pi \times 10^{-4} \times 3 \times 10^{-3}}{1.55 \times 10^{-6}} \simeq 0.6$$

$\Rightarrow$ Reflectivity $\simeq \underline{30\%}$

If $\Delta n = \underline{5 \times 10^{-4}}$

$\kappa L \simeq 3.04$

$\Rightarrow \underline{R = 99\%}$

$$N = \frac{3\text{ mm}}{0.5\,\mu m} = 6000$$

So, we are talking about having long length of fiber. So, this is spanning 100 meters. So, we know that in fiber Bragg grating based sensing system, you can concatenate gratings, you can concatenate gratings with different periods. So, that you can actually, use one broadband source and interrogate the entire length of fiber, which consists of gratings at different wavelengths.

So, and where should all these gratings be? Well, basically, they need to be 2 meters apart and so on, and so we need to have 50 of this grating. So, this one should be let us say, lambda 1, lambda 2, lambda 3, lambda 4 and all that and lambda 49, lambda 50. So, one possible solution is that you have 50 different gratings that are reflecting, that are with different periods.

And so hence, they are reflecting at different wavelengths, then you can possibly interrogate them, with one broadband source, and what we are talking about here is the physical location of these gratings, let us say, these are attached to the structure, attached to the bridge at these locations. And these physical locations are separated by 2 meters, the center to center spacing, it is 2 meters.

And like we looked at previously, each of these gratings, as we considered in one of these examples over here, each of these gratings is typically like in the order of millimeters. So, you can paste that and then at that particular location, you can actually figure out what is the strain that is developing. So, in terms of the spectrum, how does that look? If we look at the spectrum, along this entire length.

So, if you look at this, if you interrogate the grating, without any perturbation, what we are going to see is you will have 1 grating at let us say, lambda 1, it is centered around lambda 1 and another grating is centered at lambda 2, then another greeting is centered at lambda 3, lambda 4 and so on and something corresponding to lambda 49, something corresponding to lambda 50. So, you will have a lot of these grating peaks.

So, if you send in broadband light and you look at the reflected spectrum, you will see all these peaks. And then the question is, what should be the spacing between the peaks. So, that is something that we need to decide and how do we decide that? Well, we need to consider the fact that each of these gratings can be undergoing a perturbation of 1000 micro strain. So, it could be negative strain or positive strain. So, it but it could be 1000 micro strain.

So, what is 1000 micro strain correspond to, we know that these gratings have a typical strain coefficient of 1.1 pico meter per degrees centigrade. So, you have 1.1 pico meter per degree centigrade multiplied by 1000, sorry, it is not degrees centigrade, in this case, we are talking about micro strain with respect to strain. So, 1.1 Pico meter per micro strain and that is over 1000 micro strain.

So, that corresponds to on one side, just this side itself, it corresponds to 1.1 nanometer. So, this is 1.1 nanometer, this is 1.1 nanometer on the other side as well. So, the spacing between the two Bragg gratings has to be now 2.2 nanometer at least, I mean larger the better because that way you will make sure that the peak that you see corresponding to strain at one point is not overlapping with the peak corresponding strain at another point.

So, you want to be at least so it is actually greater than equal to 2.2 nanometer spacing, that you are going to have to do. And, of course, you are doing this over 50 gratings. So, the entire spectral width from here to there, so that will correspond to 110 nanometers. So, you need to be able to interrogate over 110 nanometers. So, that is nice, but what is the kind of let us go ahead and try to see, what is the kind of signals that we expect at any of these grating points?

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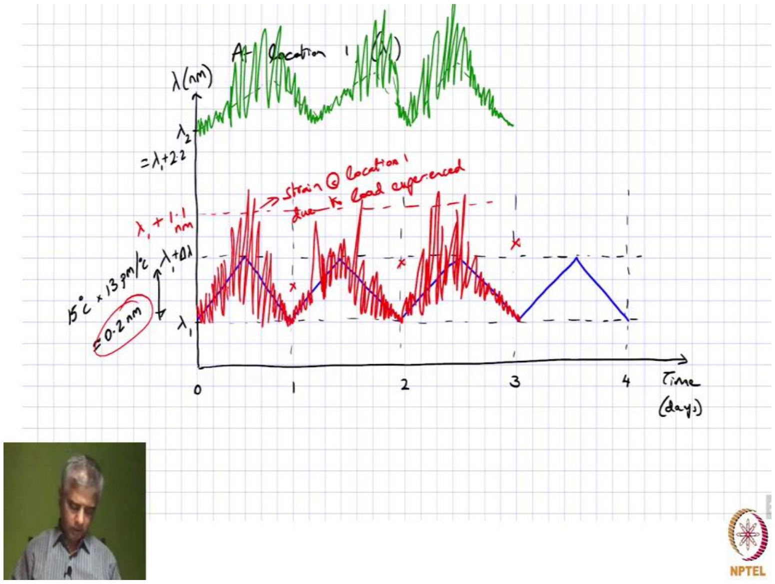

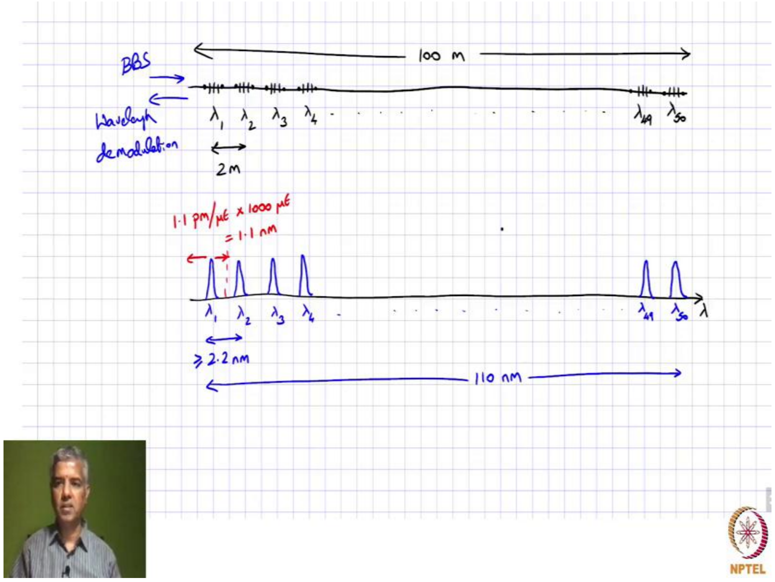

So, let us say at location 1 which corresponds to Bragg wavelength of lambda 1. So, how does this, the change in Bragg wavelength, look in terms of with respect to time. So, in this axis, let us say we are looking at time in, let us say, days. So, talking about starting from 0 here, 1 here, 2, 3, 4, and so on. So, what do we expect in terms of this axis? It is in lambda, so you are measuring so let us say you have some way of measuring lambda.

So, of course, if we, if you look at lambda 1, at location 1, it is going to be, let us say at minimum temperature at ambient temperature or minimum ambient temperature at any particular day, it is actually at lambda 1. But of course, we know that it is going to change over this 24 hour cycle. So, and the rate at which it changes 13 pico meter per degree centigrade and we know that the temperature change can fluctuate over 15 degrees.

Let us say this is the lambda 1 that you measure in early morning hours, during the course of the day the temperature is going to increase and correspondingly you will have change in the Bragg wavelength. So, and let us say we look at this on a daily basis section by section, 24 hour sections. So, it is going to now increase during the day, go to a particular point and then of course, decrease as you, as the sunsets and you go towards the night.

And then of course, the next day similarly, you will going to have an increase and then decrease and increase and decrease and so on. So, this is what we expect and it goes up so, what wavelength does it go up to? So, this is let us say this is the maximum temperature it reaches on any particular day.

So, this wavelength is going to be lambda 1 plus some delta lambda and that delta lambda you can actually figure out we are expecting you know 15 degree change in temperature multiplied by the rate at which the Bragg wavelength changes with respect to temperature let us say it is 13 pico meters per degree centigrade. Mind you that is actually a rough number, in reality the, it depends on the constituents of the fiber or what the actual fiber is made of and then what are the type of doping that you have incorporated to increase the photosensitive of the fiber.

So, all those things actually come into the picture, but nevertheless, if you assume it is 13 pico meter per degree centigrade, then that works out to be roughly about 0.2 nanometer. So, you have a 0.2 nanometer shift in Bragg wavelength because of this. Now, of course, due to strain, you do expect a lot of changes that are happening and to put that in perspective, we are expecting up to 1000 milli strain sort of changes over the period of the day.

And of course, what is important is that this temperature change does not affect the measurement at some other wavelengths. So, in this case, we are considering lambda 2, where is lambda 2 with respect to lambda 1 that is going to be, lambda 2 is given by lambda 1 plus what we decided here it has to be 2.2 nanometers. So, if lambda is a nanometer so, that is actually 2.2 nanometers away.

So, the temperature change by itself is not actually causing a huge problem, but nevertheless it can cause a problem at this other wavelength because now, this 0.2 nanometers is not something that we have accounted for here. So, do we have to worry about it? Well, let us actually look at the real time changes in the Bragg wavelength as a function of time. So, what we typically have a case where the Bragg wavelength is changing because of loading conditions during the day.

So, it will tend to fluctuate around this value depending upon for example, the traffic that the bridge is seeing. So, during the early days, the traffic is not as much but during the middle of the day and during maybe peak hours you will see a lot of traffic and then it comes down during the night and then it is like this. So, you might have the depending upon the traffic all these changes that we are expecting.

So, you have all these. So, these are due to strain at location 1 due to the load experience. So, that is one thing to note here. And of course, we are saying, when does this go beyond, say 1000 so we say the threshold level for this perturbation is somewhere in the middle. So, this is actually at 1.1 nanometer, lambda 1 plus 1.1 nanometer that is where the threshold is, so we are trying to see if it actually reaches that threshold during the day. That is what we want to find out.

And, of course, if there is a pattern like this, where it goes up and comes back, you are not too worried about it that you say it is the dynamic load on the structure. What you are worried about is, if it does not, when it comes back, it does not come back to the same point. If we end up actually, after day 1, it ends here, after day 2, let us say it ends here, after day 3, it ends here and so on.

It is, actually having some incremental change in the loading on a day to day basis, then you can clearly say that this is actually at location 1, there is a crack that is developing, and it is getting wider and wider by the day. So, then you will clearly see a signature, where it is not coming back to this point, it is actually going up and then coming back here, going up and coming back here going up and coming back here and so on.

So, then you know there is actually some, some intervention that is required, you need to go back and do some reinforcement work. But this is the interesting part, the question is, should be account for this 0.2 nanometer change in temperature? And it turns out, you do not have to, because this is at lambda 1, but let us say what is happening at lambda 2, if you look at it, lambda 2 would also have a similar sort of fluctuation it is going up, and then it is, it is coming down.

So, over the day, and then it is going up and then coming and down, as the day progresses towards the night and similarly and so on. So, you will have these traffic and towards the night it comes down. So, it is going to be like this, but the key point is whatever temperature that change that lambda 1 is experiencing the grating with the center wavelength that lambda 1 is experiencing, that almost the same temperature profile, the grating at lambda 2 is also experiencing.

So, in this sort of a scenario, if you understand that, that there is no differential in the temperature across a bridge you know, there may be some momentary changes in temperature, but over a period of 24 hours, there is hardly any change in temperature. So then, in that sort of a scenario, you do not necessarily need to compensate for this 0.2 nanometers.

But if you have an industrial process, where the temperature that you see at lambda 1 can be very different from the temperature that you can see at lambda 2 and so on. In those sort of cases, you want to actually make sure that you can account for that and correspondingly design your next lambda to be at a slightly longer wavelength. The spacing between the different Bragg gratings in terms of the spectrum is actually more accounting for that change in temperature as well.

So, this is the kind of measurement design challenges that you will be posed with and then of course by looking at it systematically by looking at the bigger picture understanding the requirement first in terms of placement of the gratings that is very important. And then you go into, what should be the, for a given requirement, what should be the spacing in terms of the spectrum between the different gratings.

And then you go on to actually do some simulations as to what sort of load profiles that you expect, and then make sure that there is very little source of uncertainty in terms of measuring these loads. And, that is basically what constitutes the design of the system. Now, of course, so far we have assumed that we have something. So, this is actually, you are sending in some light and you are interrogating the backscattered light or the light that scattered from these Bragg gratings.

So, this we assume it is a broadband source, but then how do you actually pick up the spectrum of all these gratings. So, you need wavelength demodulation. So, far we have assumed that the wavelength demodulation is available to us, but what we want to understand is what are the common ways of actually doing the wavelength demodulation, how do you do this integration of these Bragg grating sensors. And that is what we will look at in the next lecture.