Optical Fiber Sensors
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Lecture No. 36
Wavelength Modulated Sensors - 5

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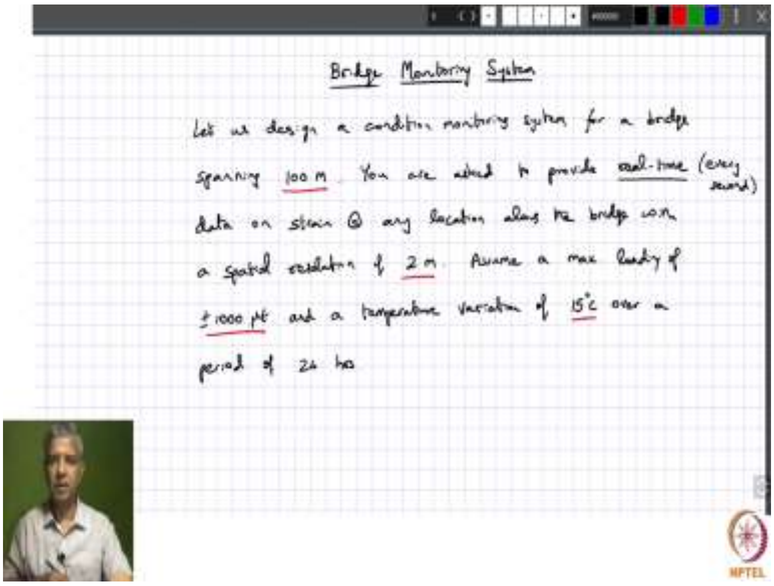
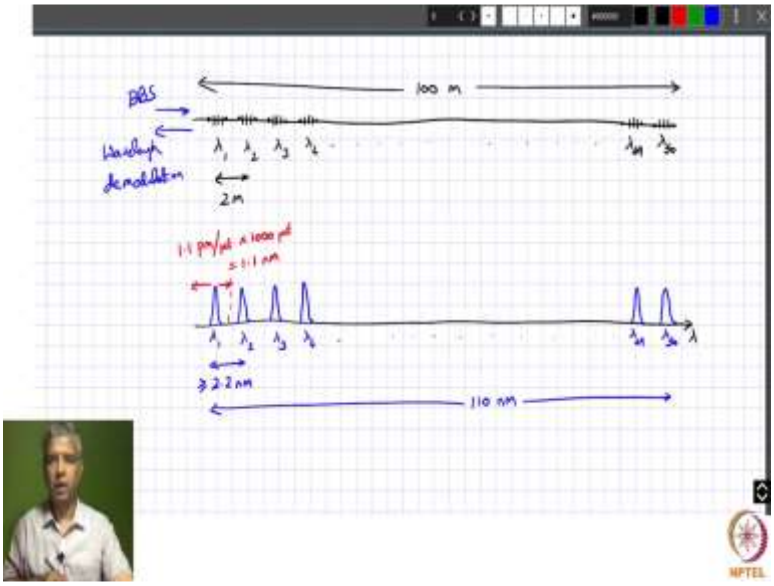


Bridge Monitoring System

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



We have been looking at Fiber Bragg Grating sensors as an example of wavelength modulated sensors and in the last lecture we looked at some practical examples. So, we were actually looking at the case of the Bridge Monitory System and then trying to figure out how we will design? And meet a particular requirement and we looked at what it means in terms of placing the Fiber Bragg Grating sensor and then also what it means in terms of planning the optimal use of the spectrum so that we can achieve this sensing.

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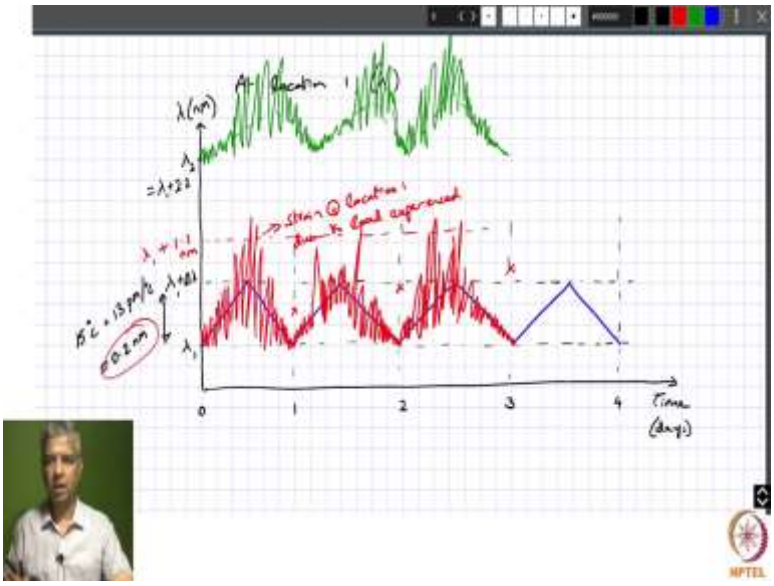

So, we were looking at how the sensing could be achieved at different locations in the presence of temperature changes. We are primarily interested in picking up strain but then temperature also is changing and then we were seeing how we could still possibly do a measurement in that sort of a scenario. The primary thing that we are looking at is the temperature changes that are happening are typically at a much slower time scale compared to strain changes.

But in all of these we were assuming that we have something that can give us this spectrum of the Fiber Bragg Grating and give us actually some signal where if there is a small change in the wavelength you have a corresponding change in the intensity of light which is what we call as wavelength demodulation. So, we want to now look into for the next couple of lectures maybe we want to look into how we can achieve this wavelength demodulation or how we can integrate a Fiber Bragg Grating.

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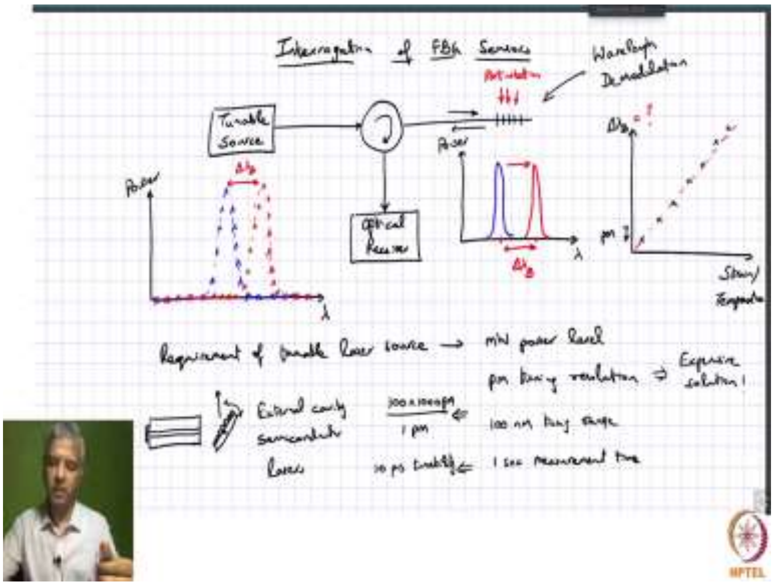


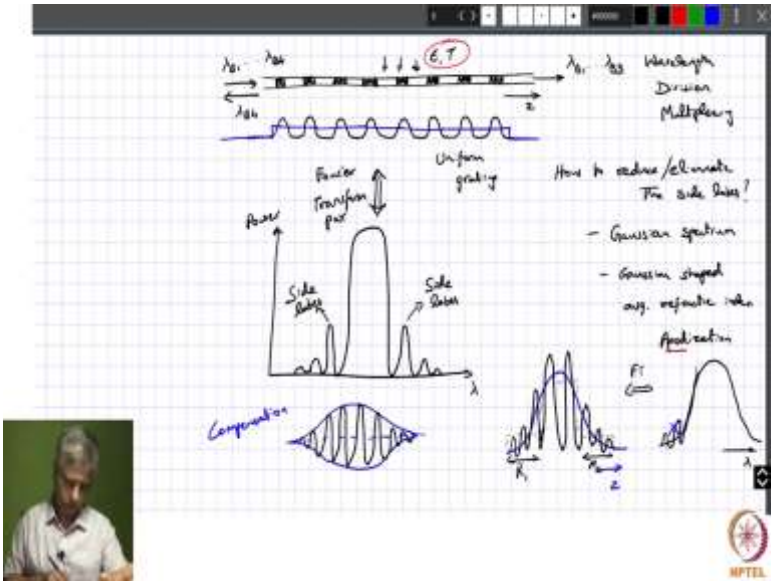
Interrogation of FBG Sensors

Requirement of tunable laser source → mW power level

pm tuning resolution ⇒ Expensive solution!

$\frac{100 \times 1000\,pm}{1\,pm}$ ⇐ 100 nm tuning range

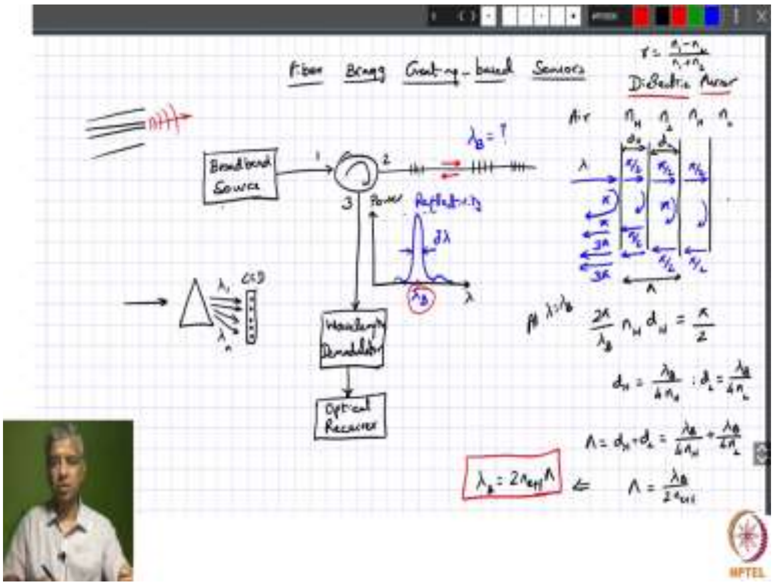
10 μs tunability ⇐ 1 sec measurement time



How to reduce/eliminate the side lobes?

- Gaussian spectrum
- Gaussian shaped avg. refractive index

Apodization



Fiber Bragg Grating-based Sensors

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

Dielectric Mirror

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

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

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

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

So, that is what we will now start talking about today. So, when we talk about integration of Fiber Bragg Grating sensors, typically it consists of a light source. So, you start with an optical source and that is connected to typically a circulator and then through the circulator we connect it to the Fiber Bragg Grating sensor that we want to integrate and we know that the Fiber Bragg Grating sensor exhibits a spectrum that looks like this when you look at power as a function of wavelength, it exhibits a spectrum like this and then if there is some perturbation that it is subjected to, then there will be a corresponding change in the spectrum.

So, essentially the lambda b which was over here now is changed to this. So, what we are typically interested in is this delta lambda b and what does that delta lambda b show? If you plot let us say delta lambda b as a function of strain or temperature, we expect a plot like this. Basically, this is what we were looking at in the past couple of lectures that the according to changes in strain or temperature we were seeing that there is going to be a corresponding change in the Bragg wavelength and that is what we are representing over here.

And the interesting thing about this is actually a fairly linear relationship. So, you get to see a very nice repeatable sort of relationship and that actually makes it a very good sensor because calibrating this is a matter of telling what the slope of this is going to be. You just work that out. So, when you do this measurement you are trying to pick up this delta lambda b. So, once you pick up the delta lambda b, then you can actually infer what is the corresponding strain or temperature value.

Of course you cannot discriminate between strain and temperature. So, we will have to make some arrangements based on the application that we are looking at. But the key question is how do you measure this delta lambda b? So, far we have been looking at cases where we typically, once again we are going back. But we are typically integrating the Fiber Bragg Grating with the broadband source.

If you integrate with a broadband source then Fiber Bragg Grating reflects part of that spectrum of the broadband source and then you need to actually figure out what is this spectral response power as a function of wavelength and that is typically not achieved directly using an optical receiver. So, you need to use a wavelength demodulator. So, this is the scenario that we have been seeing. So, that brings up the question when we talk about this optical source, does this have to be a broadband source? Can it be something else?

You can possibly consider one other light source. Basically you can use a tunable laser source. So, tunable laser source is where the center wavelength of the laser is actually changing with respect to some voltage or some current that you are providing. So, you could possibly use a tunable laser source and then if you do that, then you can integrate this Fiber Bragg Grating with that.

So, whatever is reflected back from the Fiber Bragg Grating, you can actually just directly put it to an optical receiver. So, how does this work? Well you are essentially tuning the laser and you are looking at what is the optical power that is received at this optical receiver as a function of the wavelength that you are tuning.

So, you can basically say I tune to this wavelength and I see very little power that is reflected by this grating and I tuned to this wavelength I still do not see much power. This wavelength, this wavelength I can keep going on until you start entering the or you getting close to the Bragg grating, Bragg wavelength of this Fiber Bragg Grating in which case you will see some reflected power. So, you can tune to one wavelength to another wavelength to another wavelength and you are looking at what is the power received.

So, you can sort of make up this spectrum through this sort of a measurement and of course when there is a perturbation all you know that these things do not change. You will have the same reading but then you start seeing changes over here and then maybe you will have this spectrum shift and these will remain the same. So, essentially we can see that the spectrum has shifted. So, you can basically figure out your delta lambda b by this manner.

So, that seems to be a simple enough thing to do but then is it really that good? So, let us just examine that. Now first of all what do you need from the tunable laser source? You need a certain level of optical power. So, when we talk about the requirement of tunable laser source in terms of the specifications of the tunable laser source, so you need a certain optical power say milliwatt optical power level. So, that is not too bad.

So, I mean there are tunable laser sources like for example a semiconductor laser source where you have a semiconductor gain medium and one side of it is coated with high reflected but the other side of the gain medium is anti-reflection coated. So, you can extract the power and then you put an external grating element which reflect only one particular wavelength back and that actually forms the cavity of the semiconductor laser and when you tune the grating angle the wavelength that is reflected back into the semiconductor cavity that changes.

So, that is essentially what we call as an external cavity semiconductor laser. That is one example. So, this is actually the semiconductor laser and you have a high reflector over here but on this side you have an anti-reflection coating and then you go into basically a periodic grating element and by changing this grating angle you can change the wavelength of the light that you get out of this. So, you can basically look at the light that is coming out and that will essentially be of different wavelength according to this grating angle.

So, that is what a tunable laser source is. So, you can get milliwatts of power level. There is no problem with that but the real problem becomes when you or the finer details if you look at that you want to actually pick up Bragg wavelength changes in the order of picometer. Because if you want to pick up like say 1 microstrain of perturbation then you need to be able to resolve things with 1 picometer accuracy. So, you need basically picometer tuning resolution.

So, that is probably achievable with this what do they call this, external cavity semiconductor lasers. So, this external cavity semiconductor lasers picometer tuning resolution is not an issue. It is not as much of an issue. But then what else do you need?

Well if you want to have applications like these enabled. So, we are actually talking about tuning over 110 nanometers. So, something in the order of 100 nanometer tuning range you need if you want to integrate multiple sensors. I mean we are talking about only a single sensor here but we talked about this case where you can concatenate multiple sensors and if that is the case, then you need to achieve a 100 nanometer tuning range and this we want to achieve in a measurement speed typically what we looked at was 1 second measurement time.

Within 1 second you want to go across a 100 nanometer tuning range with a picometer tuning resolution. So, what does this imply? This implies that you need to have 100 into 1000 picometer with 1 picometer resolution. So, that is basically 100 1000 points and this you want to achieve in 1 second. So, you need to have 10 microsecond. Every 10 microsecond you need to go to different wavelength. So, 10 microsecond tunability you need and that actually makes this external cavity semiconductor laser.

It becomes a very expensive solution. So, all these requirements mean that it is a very expensive solution. So, you typically have these lasers that are sold for like tens and thousands of dollars and that may not actually justify the price that you could pay for a application like a bridge monitoring system. So, that is one issue with this technology but the other fundamental issue is the fact that what are we picking up? We are going in with a tunable laser and then we are looking at the back reflected power.

Now we are looking at power not the wavelength anymore because this way, wavelength information that is coming from this tunable source is converted to some back scattered power by the grating. So, essentially the wavelength demodulation is happening at the grating itself and that is a problem because when we are looking at the power it becomes like an intensity modulated sensor essentially. Now there is some modulation happening and that change in intensity, a change in power is what we are looking at in the receiver.

So, it becomes susceptible to all the noise sources that we talked about for intensity modulated sensors. So, we lose this advantage of actually going for a wavelength modulated sensor if you use this integration. Now nevertheless it is a relatively simple way of doing the integration if you have a tunable laser source but like I said it is not a preferred way of integration because of the fact that the wavelength demodulation happens at the location of the fiber Bragg grating and you essentially lose the inherent advantages of a wavelength modulated sensor. So, we need to now start looking at other ways of demodulation.

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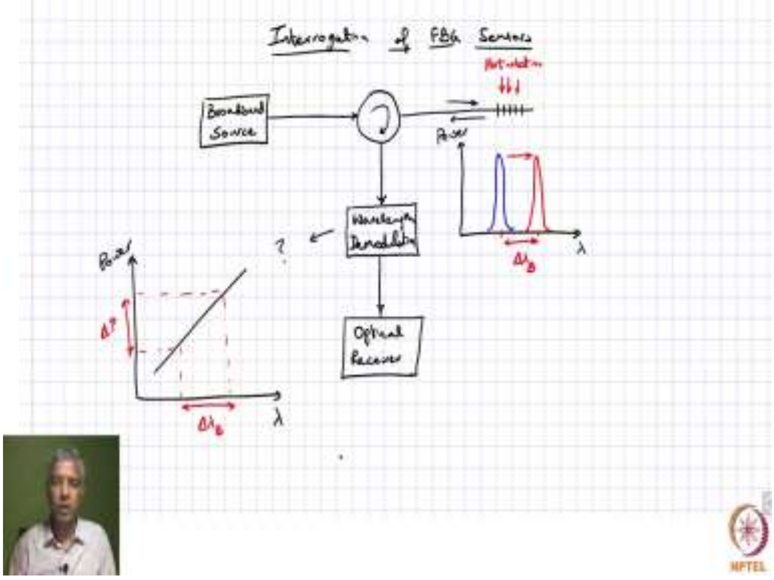

We saw why a tunable source based integration may not be ideal to achieve a wavelength modulated sensor. So, let us now just go back and replace this tunable source with a broadband source so that we can enable a true wavelength modulated sensor and of course when we replace with a broadband source we are getting a power spectrum like this reflected by the Bragg grating and that is not something that you can capture using your optical receiver directly. So, what you need now is a wavelength demodulation unit before you can take it to your optical receiver.

So, the question is what is this wavelength demodulation unit and what exactly are we trying to achieve using this wavelength demodulation unit? Well, what we are trying to achieve is this. So, ideally what we need is if there is any change in the Bragg wavelength we know we are trying to get this delta lambda b. So, if there is any change in the Bragg wavelength we want a corresponding change in the intensity of the light or the power that is the incident on this optical receiver.

So, and we would like this to be a linear response if possible. So, we want something like this where any change in your Bragg wavelength, let us say it is moved from here to here. So, this is your delta lambda b. For any change in Bragg wavelength you want a corresponding change in the amount of power that you can capture using your optical receiver. So, we want something that responds in a linear fashion with respect to the spectrum and also you want something that is as high a slope as possible.

So, even for very small changes in delta lambda you can get a large change in the power but of course, you also need to be vary about the fact that you may need to cover a large range of wavelengths. So, if you are talking about 1000 microstrains or if you want to go to even 5000 microstrains, then you are actually going to cover a larger range of spectral shift and it should be responsive un a linear fashion across that entire spectral shift also. So, that is actually the requirement as far as the wavelength demodulation is concerned. So let us see how we can achieve that.

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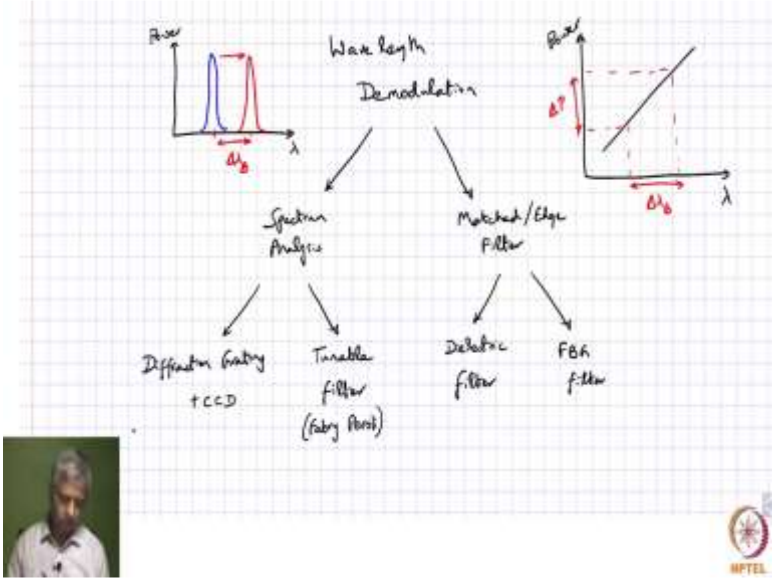

So, when we talk about wavelength demodulation, there are several schemes that can essentially do this function. So let me just copy this. So, let us keep that as a reference here. So this is what we want to achieve and let us see how we can do this. So, one possible way of looking at this is a complete spectral analysis. So, you capture the entire spectrum corresponding to this Bragg wavelength shift. So, maybe we can maybe capture this also.

So, let us keep this also in perspective. So, we want to achieve this. So, you can actually try to capture this entire spectrum or the other way of looking at this is you are not really interested in the entire spectrum. You are not interested in the shape of the spectrum and all that. What you are interested in is how this Bragg wavelength is changing.

So, that you may be able to pick up by what is called as a matched filter technique or match filter or you can also call it a edge filter technique which is essentially converting the change in spectrum to a change in power and then you can pick up the change. So, what exactly are we talking about? What are the kind of technologies we are talking about?

Well, as far as spectrum analysis goes, the most popular technique that we see is using a diffraction grating. So, you have diffraction grating. You know that a diffraction grating when you illuminate that with the broadband light, it actually separates out the different color components and diffracts them in different angles. So, by using a diffraction grating with the CCD element to pick up all these different spectral components you can actually get an entire power spectrum of optical source. So, that is what we call as a spectrometer in general.

So, you can achieve a spectrometer using what is called this diffraction grating and a CCD. We will go into some of those details in a minute. But the other way of achieving spectrum analysis is by using a tunable filter. So, if I have a band pass filter let us say that is able to transmit only a small part of the spectrum, so you tune the filter from here here here here, so all these points you do not have much of a throughput, but as you go into this part of the spectrum you will start getting more and more output and then you can actually trace out this entire peak. So, that is what we call as a tunable filter.

You, typically it is a Fabry Perot type filter. So, we will look into more details about this. Now, when we talk about match filter what we are essentially talking about is either a dielectric filter, so which is more like what you call as edge type of filter. It will typically have a say a transmittance, as a function of wavelength like this and so whatever if there is any change in wavelength, there will be a corresponding change in the transmittance.

So, that you can design a dielectric filter like that or you can use another fiber Bragg grating itself. You can even use a FBG as a filter and we will look into a little more detail in a few minutes. Now what we are talking about in all of these? In all these concepts the underlying commonality among all these different approaches is that they are all based on interference of light.

So, when you are talking about diffraction grating, we are talking about the multiple beam interference and here it is interference in a fabric or a cavity. Here, you are once again talking about multi, here in diffraction grating is this it is like a multi-slit interference and here it is like multiple reflection at multiple layers is what we are talking about here. This as well as the fiber Bragg grating. So, that is what is giving you this wavelength discrimination capability.

Essentially an interferometer, a typical interferometer would convert this wavelength to changes in intensity and that is what we are talking about as far as wavelength demodulation is concerned. So, let us go into a little more detail about each one of these principles and then try to understand what are the pros and cons of each of these approaches. So, let us just first look at how diffraction grating would work.

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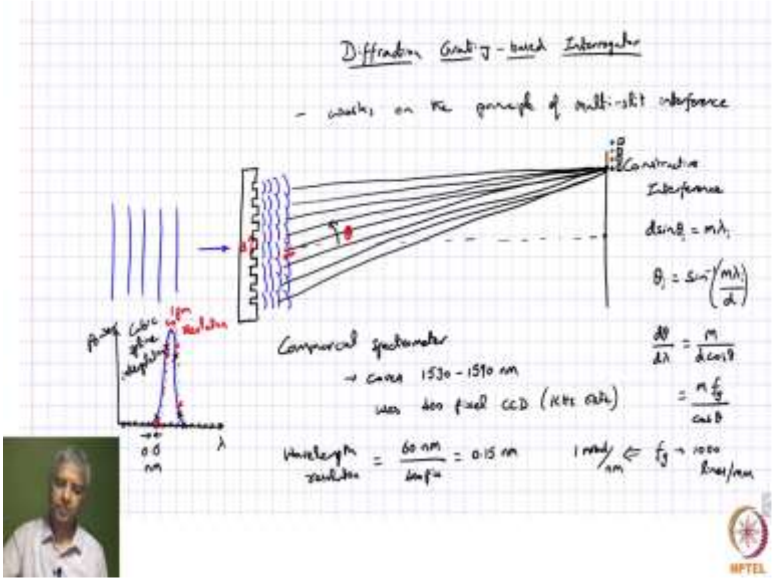

So, when we talk about a diffraction grating based interrogator, so what we essentially have as a diffraction grating, it can be explained through multiple slit interference. So, this works as the principle of multi-slit interference. So, what do we have in a multi-slit interference? Well, you have let us say a periodic arrangement of slits and each of these so if you illuminate the slit with say a plane wave radiation mind you what you get from an optical fiber if it is a single mode optical fiber. You know that is corresponding to close to a plane wave if you collinate that light from the single mode fiber.

So, let us say a plane wave is incident on this periodic arrangement of slits, then each one of this is going to now cause a secondary wavelength because the slit sizes are actually comparable to the wavelength of light itself. So, you will have all these wavelets that are generated from each of the slits and these wavelets when they propagate over space, they go to this. They strike this screen and when we look at the intensity pattern the screen what you get to see let us say this is our optical axis.

Of course, all of them will constructively interfere at this point because they will all have the same path and difference when they come over there. So, you have a constructive interference at the optical axis but if you go off the optical axis they will also have a constructive interference at one of these positions and that is because of the fact that each of these components the path length that they take.

So, the path length difference if it corresponds to an integral value of lambda they will all have constructive interference. And what is the criteria for this constructive interference? Well, if you say that each of these are having or rather the average angle that it subtends if we say it is corresponding to theta, then and let us say the spacing between 2 consecutive slits if that period corresponds to d and this is data, then you can basically look at the path length difference between 2 consecutive paths.

So, you can basically define a triangle. You can drop a perpendicular from here and then you say that this corresponds to that path length difference. That path length difference you can actually see. It would correspond. If this is theta, this is theta so then the path length difference will correspond to d times sine theta and d times sine theta is actually an integral multiple of lambda.

For example, the first constructive interference the point from the 0 interference point that we can call as order equal to 1 m equal to 1 and then if it repeats again at a later point that will correspond to m equal to 2 and so on. So, this is actually the constructive interference criteria. So, I will just write this here, d sine theta equal to m times lambda. Now this criteria now is actually works very well for one particular wavelength. So, this is actually, it is wavelength dependent. So, I can write it as d sine theta equal to m lambda i. So, for each wavelength you will have a unique theta i.

I can rewrite this and say theta i is sine inverse of m lambda i divided by t. So, for each wavelength you have a unique value of data i. So, what that means is if your incoming light, let us say has a spectrum like this, talking about wavelength power if it has a spectrum like this it has a multiple spectral components and each of those components, each of those wavelengths will have a different angle. So, it will be such that at this point this one color and at this point it will be some other color and at this point it will be some other color and at this point it will be some other color.

So, all the different colors now will undergo constructive interference at slightly different points along this axis and then of course if you want to construct the spectrum, all you do is, I will put 1 CCD element here, 1 CCD element, 1 CCD element. So, if I have array of CCD elements, each of those points in that array, each pixel in that array would correspond to a slightly different wavelength. So, all these pixels now are actually picking up a different wavelength. So, they will actually pick up information at different wavelengths.

So, essentially what we have done is, we have done a wavelength demodulation wherein you can come in with light over multiple wavelengths and they will get sorted out as different angles, different values of data through this constructive interference criteria and then if you actually position a CCD element over there, then you will be able to capture all these different wavelengths separately. Now of course you can say, can you do that in the zeroth order itself? Well you cannot because when m equal to 0, then theta equals to 0.

So, all the colors actually combine at the same point over here but if you go to m equal to 1, you get this separation. When you go to m equal to 2, you get even wider separation because the angle scales as value of m. So, higher the value of m, more will be the separation and more will be the resolution with which you can pick up changes in wavelength. However, the problem is as you go to higher orders the diffraction efficiency goes down because now you are having to support a larger path and difference and so your incoming source is not absolutely temporarily coherent.

So, because of that the diffraction efficiency will be lower as you go to larger values of m. So, you are typically dealing with m equal to 1 or m equal to 2 type of orders. So, that is typically how a diffraction grating based integrator would work. And it is important to understand that in all of this the key is that you have a broadband source that eliminates the entire possible spectrum that you are expecting as far as the sensor is concerned.

Because for example the sensor maybe multiple concatenated gratings and even in that sort of a scenario you have a very large spectral content, very wide spectral content that is coming to the wavelength demodulator. In this case we are talking about a diffraction grating based element and it should be able to pick up that information using a CCD element which in this case is acting like a optical receiver. So, it actually has that intensity information captured in each CCD pixel.

Of course, we are projecting this for only 1 wavelength here, 1 fiber Bragg grating, but when you multiply several fiber Bragg gratings this sort of function should repeat itself for each of those Bragg gratings. So, you need to make sure you are able to do that. So, this is actually, this sort of dependence is more relevant for this than this because in the spectrum analysis you are actually trying to pick up the power at individual wavelengths. So, you get the actual complete spectrum here as far as these approaches are concerned.

But what are the finer points about such diffraction grating based integrator? We will just look at this now. So, the question is what is the minimum spectral or what is the best spectral resolution that it can support? What is the smallest change in wavelength that we can pick up? So, that is dependent on a parameter that is called the angular dispersion of your grating. So, the angular dispersion we can basically find out by differentiating this expression in which case you get d theta over d lambda, that is going to be m over d times.

When you differentiate sine theta will become a cos theta. So, that is corresponding to m over d times cos theta. The significant point here is that it is inversely proportional to d. So, that means smaller the spacing between these slits then that would correspond to a higher angular dispersion. So, this is typically expressed in terms of number of, so this transmission grating will be something like this corresponding to this slits you have all these surface relief structures. So, the gratings are typically defined in terms of number of lines per millimeter.

So, you can just rewrite this as mfg over cos theta where fg is actually corresponding to the spatial frequency of these slits or the lines and fg is typically in the order of 1000 lines per millimeter or rather if you want to talk about in terms of d, that will correspond to d of 1 micron spacing and for this you typically have a resolution that is about 1 milliradian. That is the angular dispersion that corresponds to about 1 milliradian per nanometer and that is actually a fairly small value if you think about it is just 1 milliradian over a nanometer and we want to achieve something in the order of picometer resolution.

So, that means you have only 1 microradian difference between subsequent pixels that are 1 picometer away. So, to realize that in a compact setup is going to be extremely difficult. So that is one of the major challenges. For example, let me just make some space here. If I consider the spectrometer and this is some of the commercial. So, you want the spectrometer to be compact. So, you should not have potentially fit in the palm of your hand.

So, you do not have a lot of space over which you can observe this. Obviously, if you have 1 microradian that you want to resolve, if this is over in the order of several meters then you can imagine that the spacing will be in the order of micrometers over here and then you can actually pick up using CCD pixels. Commercial CCD pixels are typically about 5 micrometer apart. So, you can resolve them if you have very large spacing as far as the integrator is concerned. But then that becomes very bulky.

So, it cannot handle, you cannot afford to use such a bulky spectrometer in the field. So, what you want typically is a spectrometer that you can support the palm of your hand or even if it is smaller, the better. So, commercial spectrometers for example, if you consider a commercial spectrometer, a compact spectrometer, suppose it covers 1530 to 1590 nanometers over a spectral width of say 60 nanometers and it uses something like let us say 400 pixel CCD, then the wavelength resolution that you can expect using such a spectrometer is given by the 60 nanometer divided by 400 pixels and so that corresponds to 0.15 nanometer spacing between pixels.

So, our requirement is, so what we are talking about is this spacing is 0.15 nanometer. So, what it means is when you are trying to pick up this grating, you have all these pixels that are about 0.15 nanometer away. So, you might have a pixel here. You might have a pixel here. You might have a pixel here and a pixel here. So, based on this you should that essentially defines your grating because you think about the grating width that we typically get. We looked at it before that is in the order of a fraction of a nanometer by itself.

So, that means you may have only a few pixels that are representing your spectrum. Now is this good enough to support changes in the order of 1 picometer? Well, when you look at this, it says no it is very difficult but if you are able to do some clever interpolation techniques, so even though you might have only a few samples but if you do, let us say one typical interpolation technique is what is called a cubic spline interpolation. Then you can start actually with your interpolation. You can start putting more points.

You can create more points within that and then you would actually be able to pick up potentially with a picometer resolution. So, even if you have say slightly different Bragg wavelength, even though for that different Bragg wavelength you are picking only these pixels. You are picking only few pixels but if you are doing your interpolation correctly like if you use this cubic spline interpolation even if this is only 1 picometer, you can resolve that and the key to resolve that is the fact that your signal to noise ratio has to be very very good.

That means if these points are by themselves, if they are having a lot of noise, if they are collecting a lot of noise then this 1 picometer resolution is not possible. But on the other hand if you have highly sensitive CCD array, especially let us say you are using a 14 bit CCD array. So, you have 2 power 14 levels for each pixel, then you could keep the at least the noise due to your ADC. That noise you can keep it low and if you have done other things right, you can potentially keep. You can maintain a relatively high signal to noise ratio.

Then this interpolation might work fine and to support this 1 picometer resolution. But this is typically the issue in terms of the optical resolution that you have, that is actually only 0.15 nanometer but with some clever post processing you can still possibly pick up perturbation with 1 picometer resolution as far as this technique is concerned.

However, before we move on I should also mention that, if you are looking at perturbations that are changing over a period of time, the other thing that matters, the other parameter that matters is how fast can you pick up this information, pick up the spectrum information. And that is limited by the fact that your CCD array when it is reading all these it is able to do only in a sequential manner.

So, if you have 400 pixels it has to read 1 pixel at a time and then has to come back and read the next image and so on. So, to read 400 pixels, typically the rate at which you can read this is in the order of tens or hundreds of kilohertz at the best case. So, we are talking about the rate at which it can read spectrum is typically limited to about kilohertz rate. So, to get 1 snapshot of the spectrum it takes about a millisecond. So, to get the next snapshot you can only do that after the millisecond. So, that represents kilohertz rate.

So, what that means is, if the perturbation is changing at a rate faster than a millisecond, you are not able to pick it up. But typical things like static strain values or static changes in temperature or even if there are somewhat quasi static cases like you have vibration measurements which are in the order of 100 hertz and so on. This type of an integrator is actually fairly good for that. So, we will go on to talking about some of the other techniques in the next lecture.