Optical Fiber Sensors
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Lecture 37
Wavelength modulated sensors - 6

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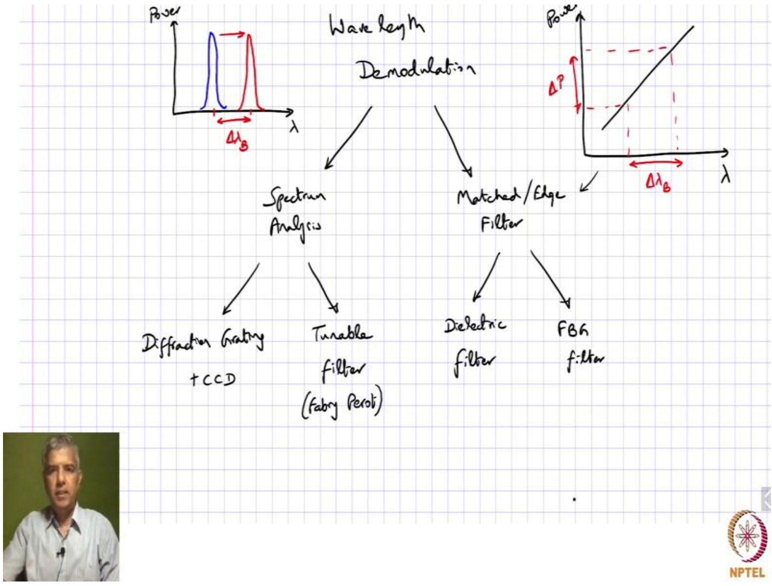

Now looking at wavelength demodulation techniques for fiber Bragg grating base sensors, and hope that we realized that one family of that is spectrum analysis and within that we were discussing this diffraction and CCD based interrogator.

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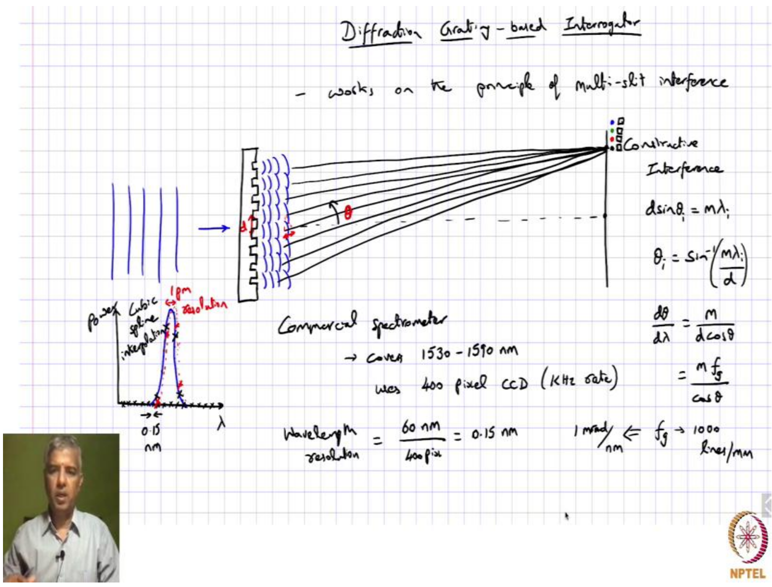

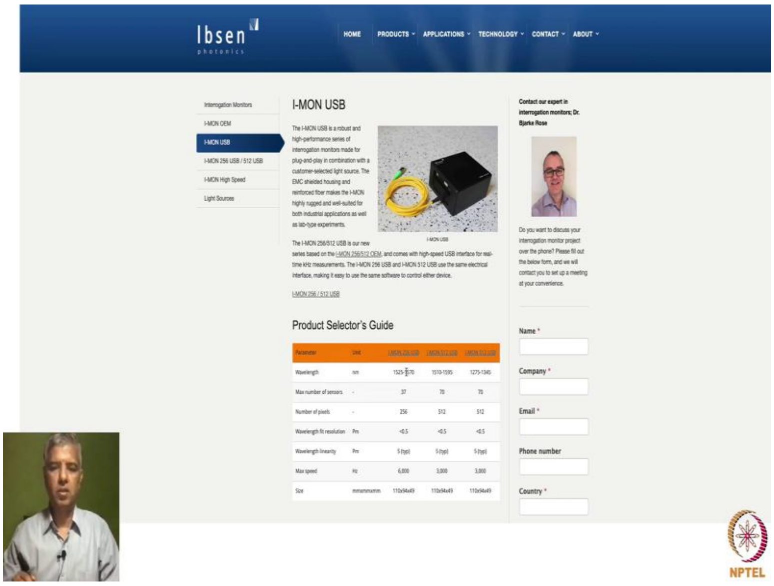

And we were looking at what are the possible, what is the basic concept behind that, and then what are the kind of performance issues that we can expect out of such interrogators. And we got to the point of defining like a typical commercial spectrometer, what the specifications are? One example for that is this interrogator that is offered by this company called Ibsen photonics, wherein you can see that they are giving two different models, one is from 1525 to 1570, about 45 nanometer, they are supporting 45 nanometers, and the other one from 1510 to 1595, so that is about 85 nanometers wide.

And of course, assuming that each of those gratings is going to occupy say, some 1.2 nanometer width then you can possibly accommodate 70 gratings and that, and they talked about how many pixels they have, in this case, it is 512 pixels. And this is the interesting part, although you say 512 pixels and covering 85 nanometers, you would say that each pixel is probably, 0.15 nanometers apart.

But the interesting part is that, like we discussed in the last lecture, the resolution could be, better than 0.5 Pico meter is what they are mentioning, provided you are able to fit the points that we have collected and just interpolate more points between the actual measured points. And of course, the maximum speed like we talked about this in the order of kilo hertz and that is because of the fact that your CCD element has to be scanned across in a sequential manner.

Of course, when you go from 512 to 256 here lesser number of CCD elements, then your speed can be, twice as much more, because you are half the number of pixels. So, you can go to twice as fast. And what do we give up typically, you might not actually have the actual optical resolution and well the range that you are looking at is smaller in this case. So, those are the typical issues, when we talk about this diffraction grating based interrogator. And like we discussed last time, it is very good for interrogating several grating sensors like what we talked about in the bridge monitoring type of situation, but only limited in terms of the rate at which they can be interrogated.

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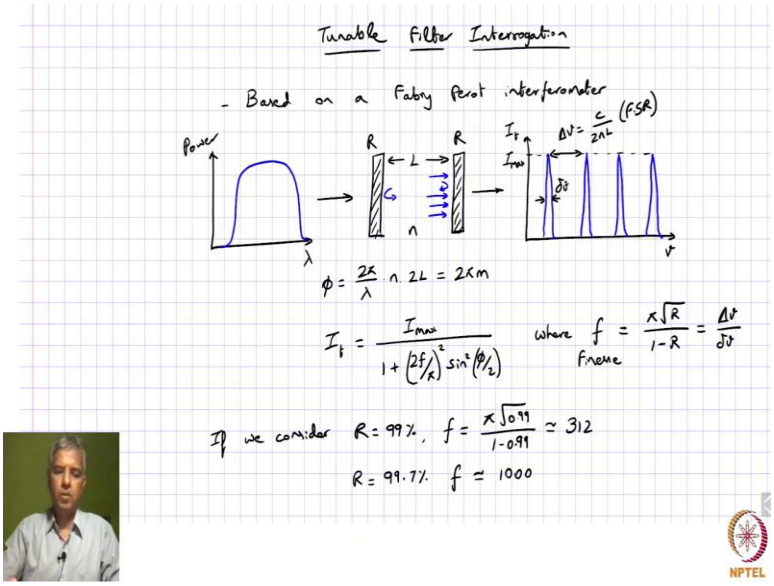

Now, let us move on to, let me just make some space here. So, let us move on to a different type of interrogation technique. So, what we would like to discuss a little more detail today is what is called this Tunable filter interrogation. So, so what are the, how does a tunable filter interrogation work and what are the pros and cons of a tunable filling interrogator?

First of all, we realize that this is typically based on Fabry Perot interferometer. And we are familiar with Fabry Perot interferometers. So, it consists of two basically mirrors that are playing parallel with respect to each other, let us say they are of reflectivity R each, and let us say the distance between them is L, and you have a medium with refractive index n between the two mirrors.

So, if you have a cavity like this, Fabry Perot etalon like this. If you come in with the say broadband light; we will just use a different color for that. So, let us say your input, so power as a function of wavelength, it is like this, it is a broadband light. We know that light goes in here, and then it gets back reflected, part of the light gets reflected. And then over this end, it gets reflected again, and then this component comes over here, and then it goes through another round trip, and that component comes here and then further round trips, they all come together here.

So, if they are all constructively interfering, that is a condition that you can say, is in their own true face, which is given by 2 Pi over lambda, multiplied by a refractive index multiplied by 2 times L, because it is going through a round trip. If that round trip face is integral multiple of 2 Pi, then they undergo constructive interference and those wavelengths will be transmitted.

So, if you are looking at the output, we see that the transmitted intensity as a function of wavelength is going to be a series of peaks. And these peaks are separated in, let me just represent this in terms of frequency instead of wavelength. So, these are separated in frequency, if you just work this out, you will see that, this is satisfied by specific wavelengths. And if you look at the corresponding frequency, and if you look at correspond two consecutive values of M for which this is satisfied, you will see that delta nu is given by C over 2 times n times L.

And, it can also be shown that when we look at the transmitted intensity, that is going to go through some maximum value that corresponds to these points over here, it goes to a maximum value, and then it is modulated by this function 2 f over Pi the whole square and then sine squared of Phi over 2, where phi is the round-trip face that is given by this, so that is Phi.

And the other thing that we have is the f, where f which is called the finesse of the cavity, is given by Pi times root R divided by 1 minus R. So, any of the standard optics textbooks like Sally (()) (10:05), other books like that you can find these expressions. So, what does this finesse mean? Well, the finesse, clearly what we are saying is, the finesse goes high as a function of R.

So, as you increase the reflectivity, this cavity supports more number of round trips, and then this interference condition becomes more constrained. And on other words, these peaks become more narrow as a function of finesse and that is denoted by, where this peak goes to half its value rather with this particular each of these features goes to half its maximum power and that is what is called the full width half maximum width.

And the finesse, such that this is also equal to delta nu over small delta nu, delta nu is the spacing between the different what are called the longitudinal modes of the cavity and that is corresponding to what is called the free spectral range. So, the free spectral range over this full width half max is what this finesse is. So, if we have, if we consider R equal to let us say 99 percent reflectivity.

If you find out what is the finesse corresponding to this is root, I mean Pi times root of 0.99 divided by 1 minus 0.99. And if you work that out, you will find that it is corresponding to both 312 value. And what that means is, your FSR is 312 times larger than delta nu or if you want for the same delta nu, if you want even narrower linewidth you can go to even higher reflectivity. For example, if you consider reflectivity of 99.7 percent, you will find that this corresponds to roughly about 1000.

So, what that also means is your full width half maximum is 1000th of this free spectral range. So, that is going to be an important aspect because as we will see these transmission peaks, this actually the transmitted light, so these transmission peaks would be used to interrogate a grating, and the width of this transmission peak, each of this longitudinal mode determines the resolution with which you can capture the individual Fiber Bragg Grating resonance. So, that is what we will look at next.

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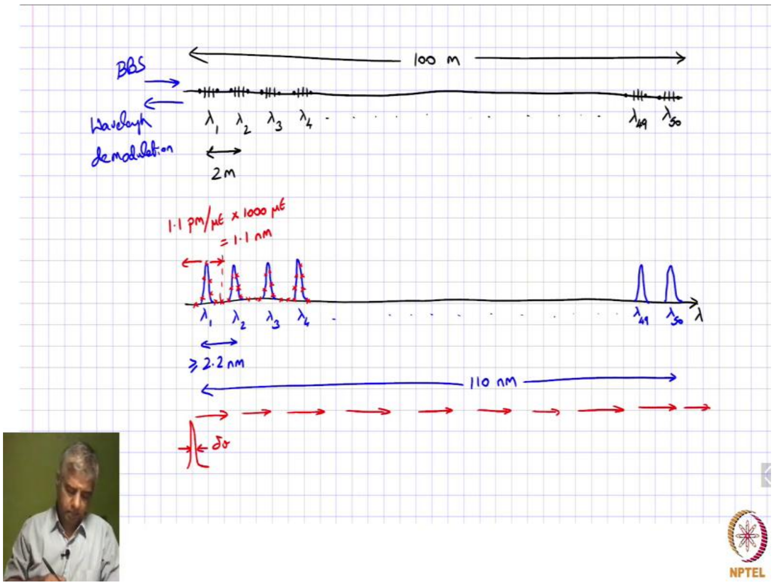

So, for example, if we consider the case that we had over here for bridge monitoring. So, we talked about requiring 110 nanometer spectral width. So, we need to be able to capture spectrum across this entire band, and how can you do that? Using a tunable filter, essentially, if this is the spectrum that is coming towards the receiver, you need to essentially have a tunable filter whose peak can be swept across all the spectrum.

So, you can, as you sweep it across, you are making up these points. So, you will get all these measurement points and then from that you can make up your spectrum. That is what you are doing as far as this tunable filter interrogation is concerned, you are sweeping this filter in front of the receiver. So, you are picking up information content at one point at a time. Now, in this scenario, it is very important that this delta nu has to be as small as possible, hopefully smaller than the width of the FPG itself, so that you can have multiple unique points measured as far as the spectrum is concerned.

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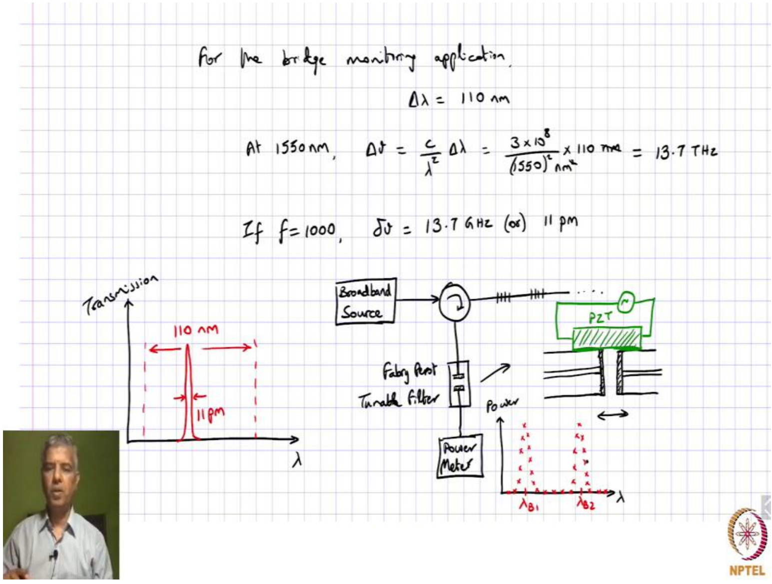

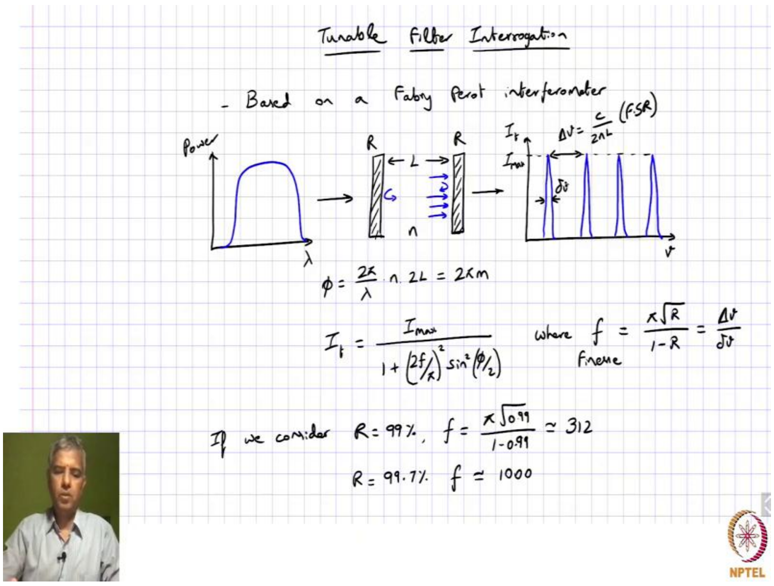

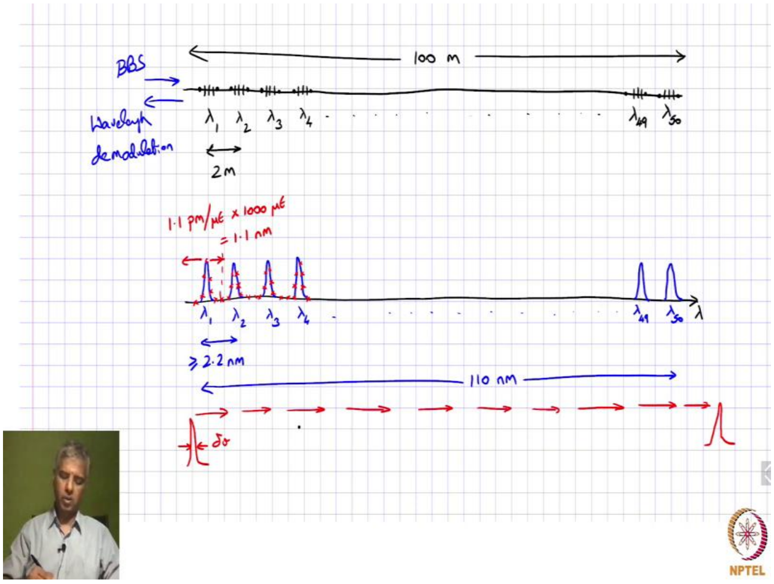

So, let us come back here and then try to capture all that information. So, for the bridge monitoring application delta lambda is equal to 110 nanometers. So, what does that mean as far as this filter function is concerned? You want to make sure that there is only one peak that is present within that 110 nanometers. So, going back to this picture again.

So, we are saying you have one peak here and the next peak should happen somewhere beyond this only. So, you should not have two peaks within this entire spectrum, because that will end up giving you some uncertainty as to what you are measuring, where you are measuring and so on. So, you need to have only one peak within that entire spectrum.

And that means, when we look at this that the free spectral range has to be now 110 nanometers. Now, we know at let us say measurement wavelength of 1550 nanometer, if you want to find the corresponding delta nu, delta nu equal to C over lambda square delta lambda. And if you plug in the values, so this is 3 into 10 power 8 divided by 1550 the whole square in terms of nanometers and delta lambda is 110 nanometers.

So, you have something in the order of, so this is nanometer square and then this is nanometer, so that cancel so you have inverse nanometer. So, if you do the math, you will find that this corresponds to about 13.7 terahertz. So, you need to have a delta nu that is the free spectral range of 13.7 terahertz. And if we consider, you have a finesse of 1000 like we said, if the reflectivity is 99.7 percent, we can support a finesse of 1000.

That means your delta nu that is your FWHM of each of those longitudinal modes, now corresponds to 13.7 gigahertz this divided by 1000. And if you work this out in terms of pico meter, you will find that this corresponds to about 11 pico meters. You can plug this back in here and then you can find out the corresponding small delta lambda and that is 11 pico meters.

So, what are we talking about here? So, we are essentially looking at having a transmission peak for the tunable filter. So, if you are looking at the transmission as a function of wavelength let us say, then we have one peak, and that will have to tune across this range of 110 nanometers and this has a resolution of 11 pico meters.

So, that is essentially how we can use a tunable filter. So, the corresponding setup is going to look like this. So, if you can use a say broadband source and just like before you send it through a circulator into this string of gratings so on. But whatever is back reflected now, what we need to do is to send it through this Fabry Perot Cavity. So, essentially this fiber would have to come in here and then you would have a mirror here and mirror here and then whatever is transmitted from this cavity.

So, this is a Fabry Perot Tunable Filter, whose response essentially looks like this, and the output of that now is going to go into a Power Meter. So, you will essentially scan across and get the entire spectrum and you will identify the Bragg wavelength corresponding to each of these sensor gratings. And based on that you can tell what is the perturbation at each of these points.

So, then the question is, how can you build a fiber based Fabry Perot interferometer? Well, you can do that, provided you can have a fiber like this, let us say terminated over here. So, this is the core region and then the cladding region, and then in the facet of the fiber, let us say you are putting a coating mirror, coating on that, and then you can bring in another fiber make sure that these two are aligned with respect to each other and have another coating over here.

And so, this forms the Fabry Perot Cavity if it is perfectly aligned, and then if you are able to change the position of one fiber with respect to the other fiber, then what you are doing is, you are changing the free spectral range but if you are monitoring just one of these peaks, you will find that the peak is going to move around it is whatever its position is, original position is. So, that is essentially how we can tune that filter.

Now, how do we do this precisely? Well, what you can do is you can mount this on a piece of electric element. So, this is PZT and then apply a certain voltage to this PZT. In which case, PZT will expand and since it is bonded over here, that will essentially change the position between the mirrors. And that is what is going to make a tunable filter. So, as you tune this, like we talked about as far as the power meter is concerned, if you are looking at the power as a function of, what is the rate at which you are tuning, so you can calibrate that too certain wavelength change.

And like we looked at before, so, you are making this measurement and you are constructing this spectrum. So, clearly, give one of these gratings, so from that spectrum, you can figure out what is lambda B1, lambda B2 and all that and based on some perturbation, this lambda is going to change and corresponding Bragg wavelength change your if you are picking up, you can figure out how much is your perturbation. So, this is the principle of how to use a tunable filter for this interrogation and this is something that is now commercially available.

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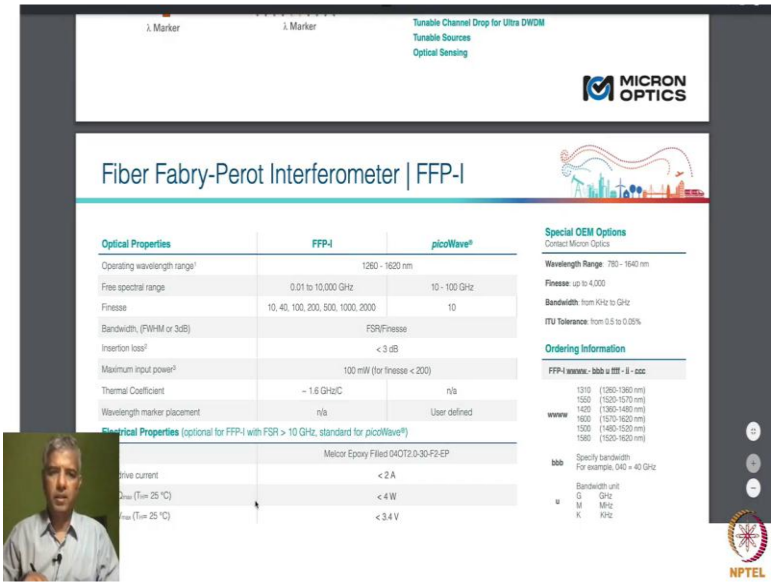

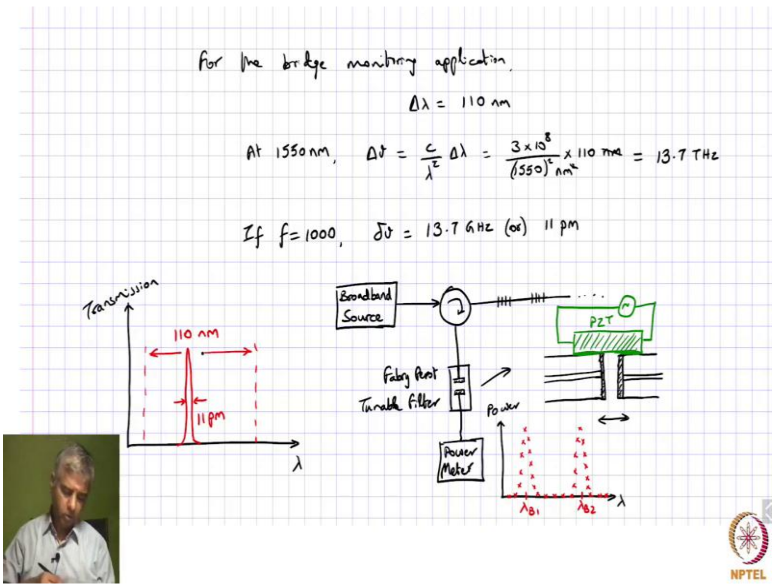

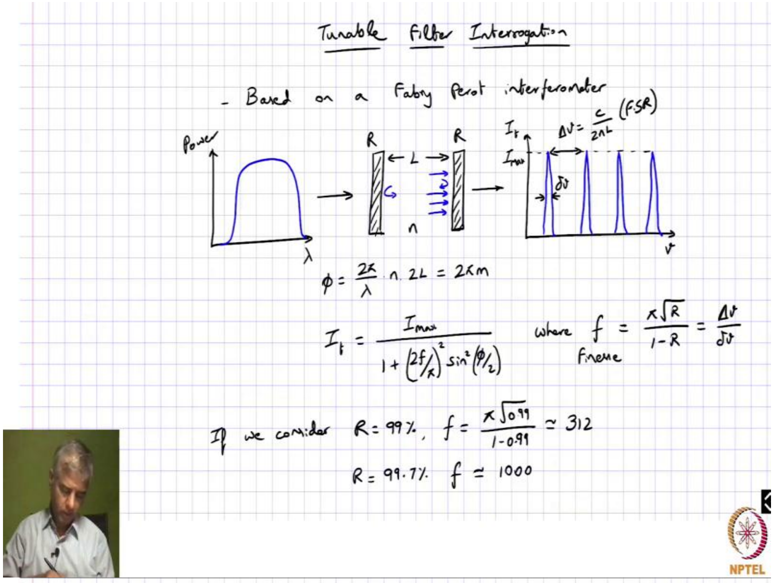

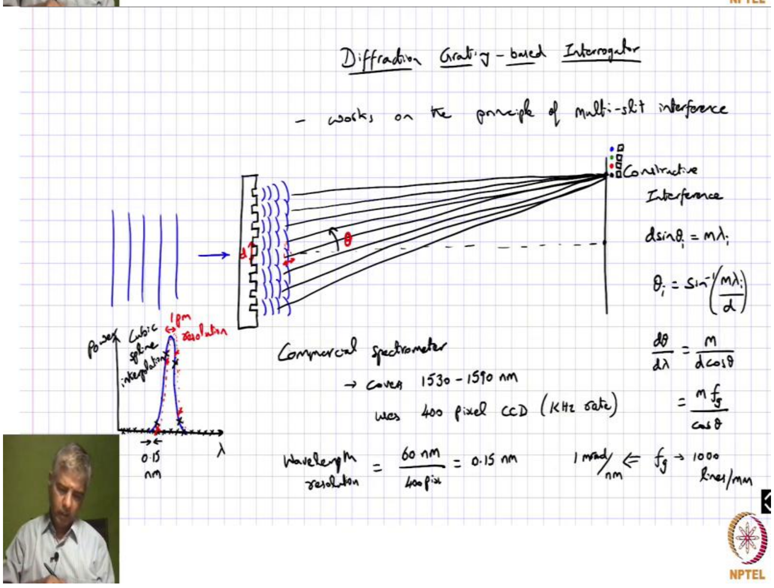

So, one example of that is this fiber Fabry Perot interferometer that is made by Micron Optics. Essentially, like we showed, two fibers whose ends are coated, and they could, depending upon the mirror coating, they could support wavelengths in this range. But the key thing that we want to look at is what is the free spectral range that you are interested in for your sensor system and what is the finesse you are interested at.

Clearly, you need to have higher finesse so that you can achieve better resolution, but higher finesse will probably cost you a little more. So, those are the kind of typical specifications that we look at, when you are getting this tunable filter. Now, once again, we go back to this, one of the things that we are interested in is how fast can we tune across this 110-nanometer thing and how quickly can you interrogate all the gratings?

And if you can look at one grating separately, you can just keep monitoring, one grating and then switch to another grating and all of that. That is not going to be easy, because now you apply a PZT, it is going to sweep across all the gratings and get to that point.

So, it is essentially like a sequential tuning is what you are getting. But the tuning speed, typically these PZTs have resonances in the order of 10s of kilo hertz. So, if you want to get a linear response, you want to keep it to 10 kilo hertz or even lesser than that. So, those are the kind of tuning speeds that you can get. So, you can achieve, the bridge monitoring application, we were looking at, we wanted this entire scan done within one second.

So, if you are doing it in 10 kilo hertz let us say then you can do 10000 points within a second and so, you can do that to the resolution of possibly 11 Pico meters in this case. So, both of these techniques are fairly good to measure the entire spectrum, both this tunable filter interrogation and the diffraction grating based interrogation. They are very good to measure a wide spectrum with large number of grating sensors. Now if you want to do this for only a few numbers of grating sensors and if you wanted to do true dynamic sensing, then this is not going to work out very well.

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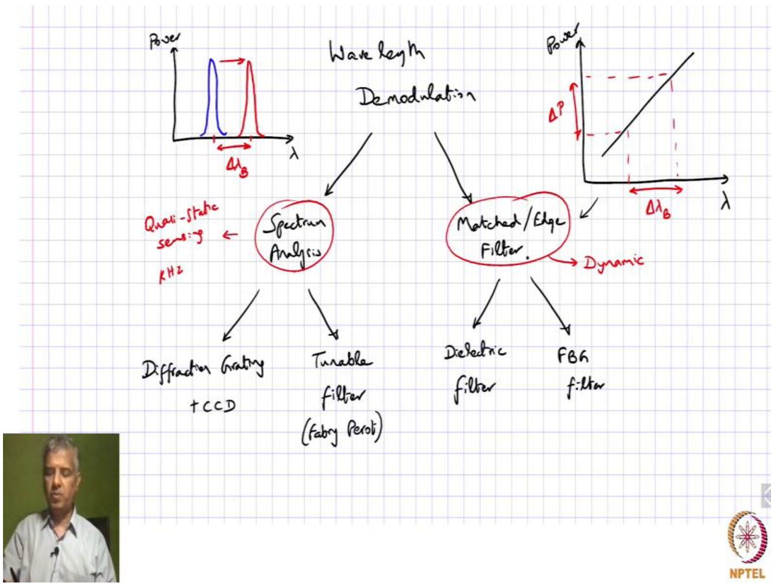

So, the spectrum analysis is typically for Quasi-Static Sensing. So, that is over kilo hertz, but it can handle really large number of sensors at a time. But if you want it to go to true dynamic sensing and if you do not have that many numbers of gratings to interrogate, because if you have only a few gratings, the cost that you incur in doing the spectrum analysis it is not something that you can justify very easily.

So, you would want to go to a technique where you can deal with fewer number of gratings. And it can be possibly more cost effective. And that is what we are looking at when we are discussing this matched or edge filter technique. So, let us see what this is about.

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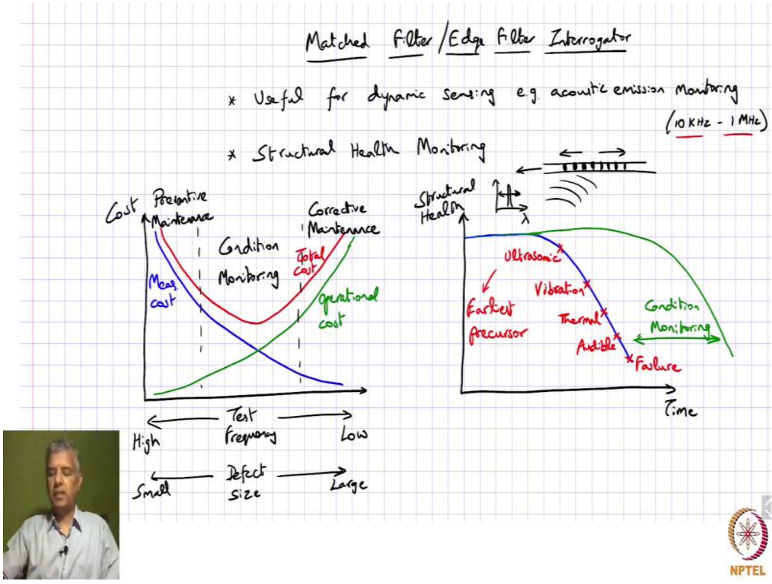

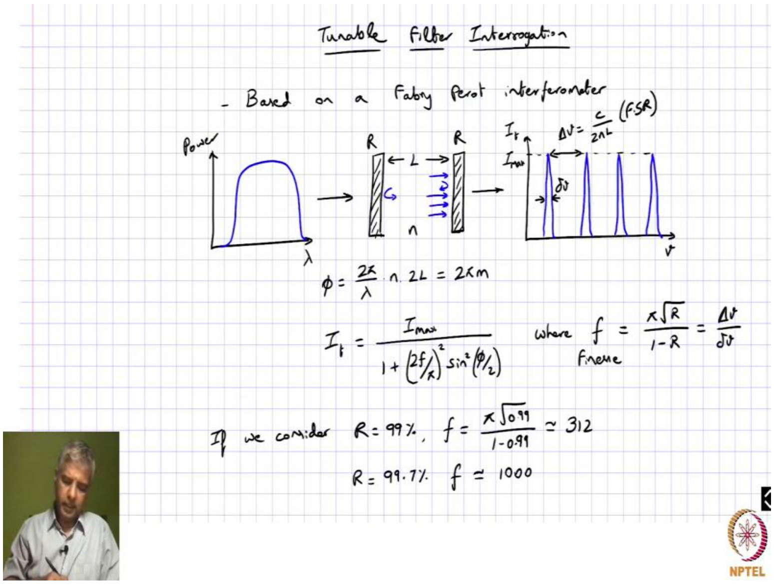

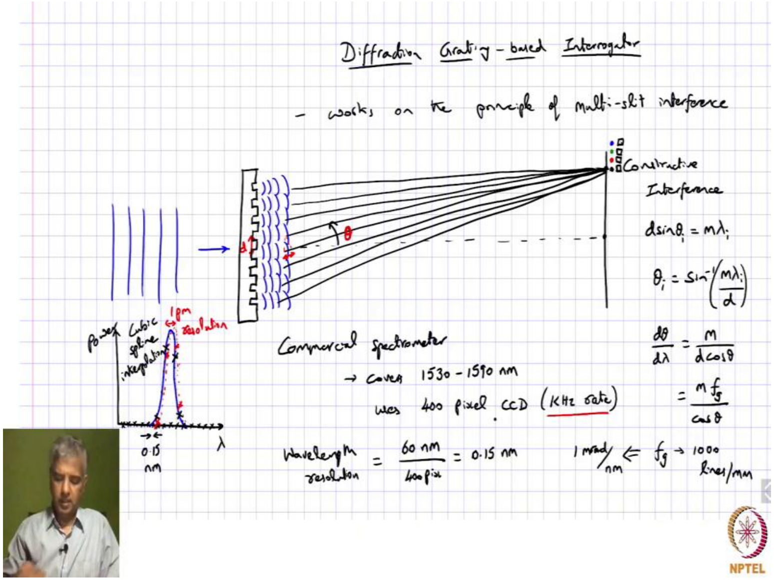

So, if we look at Matched Filter or Edge Filter Interrogator. So, we just quickly looked at why we need such interrogators. So, these are useful for dynamic sensing, as in the case of, one example is acoustic emission monitoring, where you are trying to pick up strange changes in the order of 10 kilo hertz to one megahertz. So, these are ultrasonic waves that you are trying to pick up.

So, why do we need such sensing? Well, one of the key applications for this is structural health monitoring. And so, let me take a couple of minutes to tell you a little more about what structural health monitoring is about. Now, whenever you have a capital-intensive structure, like an aircraft, for example, then you want to make sure that you can keep the aircraft free from defects or maintain it such that you can, have it free of defects.

And then if you do regular maintenance, you can draw possibly increase the lifetime of that sort of structure. So, when we talk about structural health monitoring, what we see typically, is when you look at the cost of maintaining structure as a function of, let us say, test frequency. So, if you are looking at test frequency, you can go to two extremes; one is, you test frequency is high that you are doing tests very frequently or it is low, almost never do any testing.

So, clearly the cost of doing such testing, it is going to change according to this. So, if you are doing high frequency of testing then the cost is going to be very large. But of course, when you do not do much testing at all then the measurement cost, so this is the measurement cost is going to be quite low. On the other hand, there is something called Operation costs and that is how much do you pay for maintaining the structure and also taking care of repairs and all of that.

So, if you do high frequency of testing, you make sure that things are not, there are not many faults or even if there are any faults, you can take care of them when they are relatively small minor in nature. So, you do not incur a lot of costs when you do minor repairs. But on the other hand, if you do not do much testing, then you may not know that there is a fault that is developing until it becomes really large fault.

So, in which case you will have to incur a lot of costs. So, if you are looking at the operational costs, operation costs tend to go like this. So, this is the operational cost. So, overall, when you look at these combined costs, the combined cost is going to be something like this and we can clearly define three different regions of operation. So, one is what we what we are calling as, in this case, it is corrective maintenance.

So, only when a fault happens, you do the maintenance because you are not testing very frequently. So, you might end up doing the maintenance only when you have a large fault. And the other side is what you can call us preventive maintenance. So, you are not waiting for a fault to happen. So, you are being very proactive, you keep testing very frequently and you can take care of faults when they are relatively minor in nature.

So, those are the two extremes, but we clearly see that if it comes to the total cost neither of these are optimum. So, what you really need is what is called condition monitoring. So, if you are monitoring the health of a structure frequently and you are keeping track of whatever, there are any faults developing you keep attending those faults, you can work at this optimum point. Right test frequency and you can also look at it in terms of the magnitude of the defect.

So, the magnitude of defect is likely to be small over here, it is likely to be large over here. So, that you can say, you can also look at this in terms of the defect size. So, the defect size is likely to be small over here and large over here, you may not pick it up before it becomes very large. So, you want to make sure that if you are doing some condition monitoring, when you are working in this regime, you are working in this optimum sort of regime.

So that is what structural health monitoring is all about, you can a subset of structural health monitoring is what is called this condition monitoring. And when it comes to condition monitoring, there is something else that you want to keep in mind. So, when you look at the structural health as a function of time, we know that the structure is going to maintain its health when it is relatively new, but then it is only a matter of time before it starts going down.

Which, of course, you can, what you are trying to do with condition monitoring is if it is condition monitoring is done properly, then you can possibly extend the lifetime of the structure. So, this is enabled by condition monitoring. So, the question is, what do you monitor, what sort of signatures do you monitor to understand the health of the structure? So, let us take example of a motor.

If a motor, you monitor the structure health to the point where, it fails at some point, after some time of operation, it completely fails. But before it fails, it would have given you some indication and that is some audible noise, some audible acoustics it would have given. And even before that, you could get some thermal signatures, if some moving part is developing a fault or maybe it will heat up a little more compared to other parts.

And so, if you are measuring temperature, you can say that this part is going to fail if it is going to be operated like for further time. And even before that, you can get some signatures in terms of its vibration. So, if there is a fault developing, if you look at the vibrational modes or the structure, you will probably see some changes in that and based on that, you can say something is abnormal about this structure.

But even before the vibrations it is in, you typically have these acoustic emissions or rather, you can say these are ultrasonic waves that are emitted. So, these are the waves that we are talking about, 10 kilo hertz to megahertz type of frequencies. So, if you have an ultrasonic sensor, you have an early warning to an impending failure, you can pick up the defects early and then take some action related to that and then you can possibly go on the curve.

If we can pick up defects that add early enough. So, this ultrasonics is the earliest precursor of any abnormality which can possibly lead to failure. So, for a lot of applications you want to be able to pick up ultrasonic waves. Now, just look at this for a second and are you able to pick up some audible sounds? Yeah, possibly, sound waves are nothing but pressure waves. So, they are going to if you have a fiber Bragg grating exposed to those pressure waves, the fiber Bragg grating is going to get stretched.

So, if it is put on a substrate then as the pressure waves are hitting that substrate, it is going to stretch the fiber Bragg grating and then you can pick up those audible sounds. Is it capable of picking up temperature? Yes, certainly, if you put that on different parts of the motor, you can tell what is the temperature at those local points. Can you pick up vibration? Yes, you can do that also, that is that is quasi-static type of strain signatures, which you can certainly pick up as well.

And above all, what we want to see is can we pick up ultrasonic waves using this. Now, clearly, when we talk about ultrasonic waves, the fiber Bragg grating itself, we are subjecting it to, so this is just the periodic structure and we are subjecting it to some let us say some ultrasonic waves that are hitting this and based on that it will stretch and compress.

So, according to the frequency of the waves, you were going to have back reflected wavelength, which is going to just move back and forth in wavelength corresponding to this waves that are incident on that wave that the grating is exposed to. So, you can certainly the grating itself is sensitive to that, but how can you pick that up using an interrogator?

Clearly, if you are using an interrogator like this tunable filter interrogator or the diffraction rating-based interrogator these are limited to kilo hertz rates. So, they are not going to be very good for this type of application. So, you need something else. So, what is that something else? Well, you can go for what is called Edge filter interrogator.

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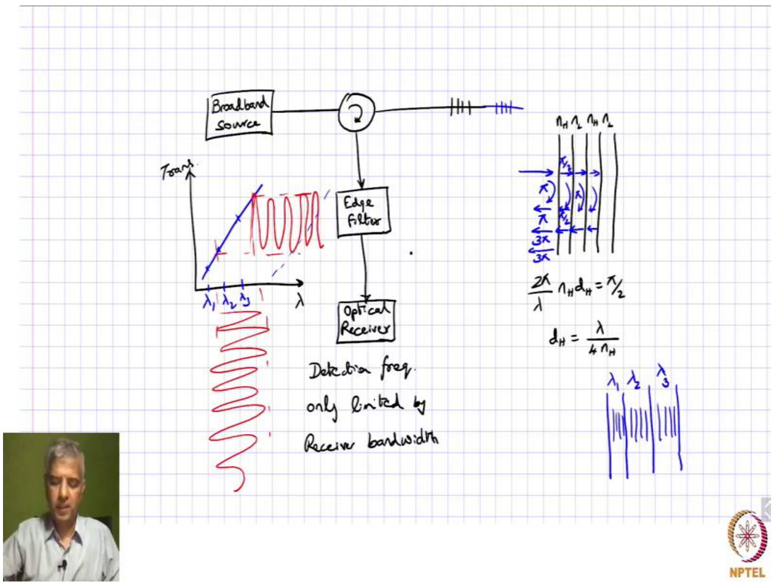

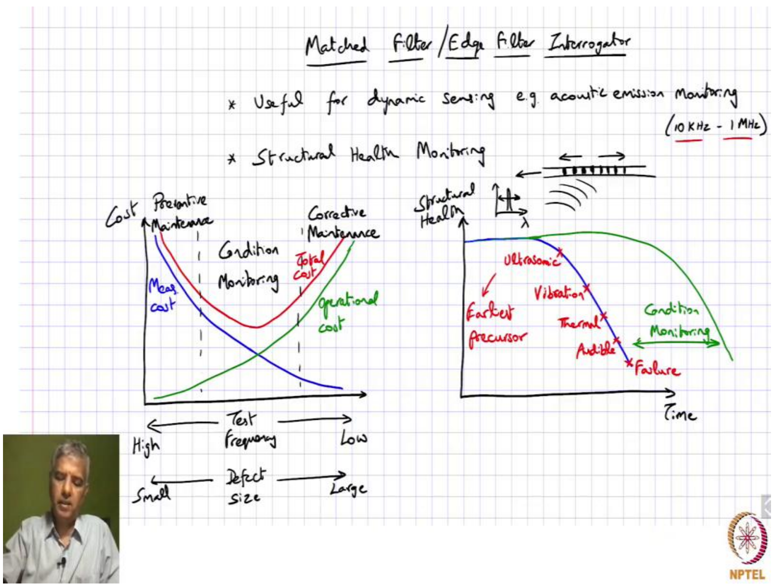

So, essentially, you have a broadband source once again, let us say it is going through a circulator. And then it is incident on this grating and the back reflected light now, let us say you are putting it through an edge filter. Well, what is an edge filter? The edge filter will have a transmission as a function of wavelength that is going to look like this. So, the transmission changes as a function of wavelength.

So, if you have something like this, then if there are any perturbations at the acoustic that these ultrasonic frequencies. So, you have all these perturbations here, so correspondingly it is going to change the transmission of this filter. And correspondingly you will have all these the transmitted intensity is going to change as a function of time.

So, what you can do now is from the edge filter you can put a power meter or a regular optical, let me just instead of calling it a power meter, I will just say it is optical receiver. So, once you have made this demodulation, then it is directly picked up by this optical receiver and the frequency at which you can pick up these oscillations, these can be very slow oscillations or very fast oscillations, irrespective of that you are going to have the corresponding change over here.

So, it is only going to be limited, so the detection frequency only limited by the receiver bandwidth. So, you can pick up frequencies even up to megahertz reasonably easily. So, how are you able to do it? So, what is this edge filter? Well, that edge filter is nothing but dielectric filter stack. Now, you must have seen this in some other introductory photonics course, where if you have alternate layers of high and low refractive index, so you say nH, nL, nH, nL.

And if you come in with the wave, it is going to anytime there is a change in the reflectivity, it is going to go through reflection, part of the light is going to go through a reflection. And whenever it is going from rarer to denser medium, there is going to be a Pi phase shift. And if you make the thickness such that there is a Pi by 2 phase shift that is incurred while going through this, and that you can ensure by making 2 Pi over lambda n H multiplied by d H equal to that you are making it Pi by 2, which means that d H equal to lambda over 4 times n H.

So, if you make it this thickness, then it can give a Pi by 2 phase shift. But it is going to once again undergo reflection here, but it is going from high to low. So, the reflection that you undergo here is not going to incur any phase, it is because it is going from denser to rarer medium. And then of course, when you look at what is coming here, this is once again Pi by 2, so what is coming here is going to have a Pi phase shift.

Similarly, if you have another Pi by 2 phase shift over here, in this layer, there is going to be a Pi phase shift. And there is Pi by 2, another Pi by 2 here and when you look at this, this is going to be 3 Pi. So similarly, you can say another Pi by 2 here reflection here, Pi by 2 here, and that is also going to be 3 Pi.

So, all of these are, either 0 or 2 Pi or integral multiples of 2 Pi phase shifted, so they are all going to constructively interfere and we know that so we can make dielectric mirror. Wherein more number of these high low pairs you have, more will be the reflectivity that you get. So that reflectivity depends on the index contrast and the number of pairs that you have.

So, imagine that you are going to have a, to make an edge filter like this, you say okay, at lambda 1 you have a certain transmission, at lambda 2 you have certain transmission, lambda 3 you have certain transmit and so on. You can define all these things. So, essentially, you make, this one structure for lambda 1 and then you have another structure for lambda 2, and then you have another structure for lambda 3 and so on.

So, effectively lambda 1 is low transmission, so this should have high reflectivity. So, you have more layers that are reflecting, that are crossing a reflection at lambda 1 and then for lambda 2, it has higher transmission, so lesser reflectivity. So, that means, that this is going to have lesser number of layers and lambda 3 is going to be still lesser and so on. So, you can concatenate multiple dielectric stacks and through that you can achieve this edge filter response.

So, this is a very simple way of doing the wavelength demodulation, so it could be quite cost effective as well, once you are able to make this filter coating, you make it on a large substrate. So, I mean, you can dice it up and get several filters like this. So, the cost of this could be relatively small compared to some of the other things that we looked at previously.

However, it does have a limitation. The limitation is if you want it to interrogate multiple gratings, then you need to have, so if you want to put one more grating over here, then you need to have for that grating, you need to have a separate filter and all of that. And that is going to, it is not impossible, but then it is going to make this design quite complicated. So, this edge filter design is not very scalable from that perspective. So, that would be the drawback of something like this.

And that could possibly be addressed by this other technique called Matched filter technique, the idea is like this, you are trying to interrogate Bragg grating, the response of a Bragg grating. Why cannot you use another Bragg grating to do that interrogation? So, that is essentially the key thought as far as Matched filter Interrogator is concerned, which we will look into more detail in the next lecture.