Optical Fiber Sensors
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Lecture 33
Wavelength modulated sensors - 2

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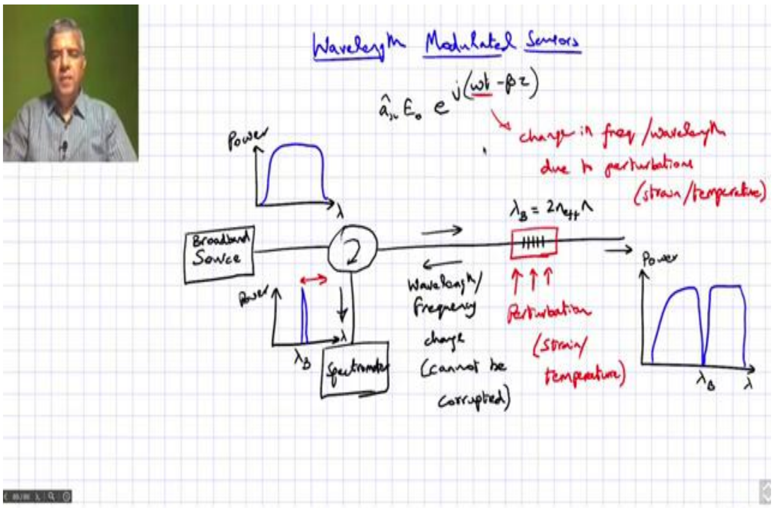

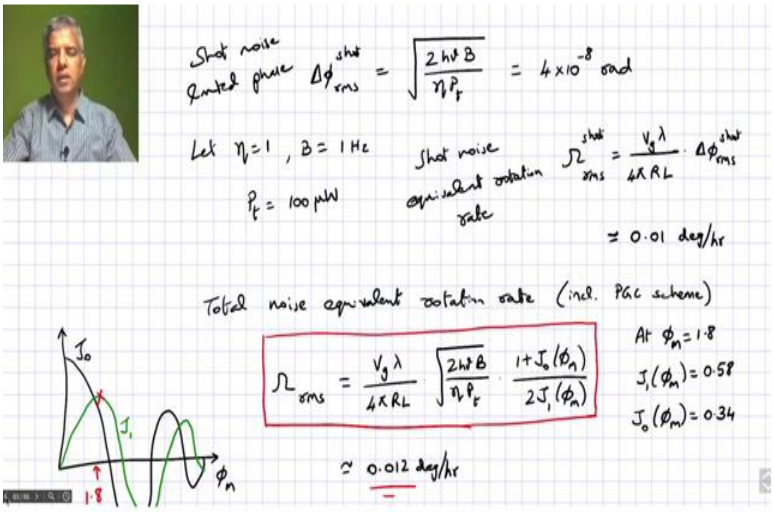

So, we have been talking about wavelength modulated sensors in our last lecture and before we go into specifics of wavelength modulated sensors, let me just go back and share you some information, which I had forgotten to do previously. So, when we were discussing phase modulated sensors, especially, when we were talking about fiber optic gyroscopes, we were deriving certain limits as far as fiber optic gyros are concerned due to environmentally induced phase noise as well as short noise and all that.

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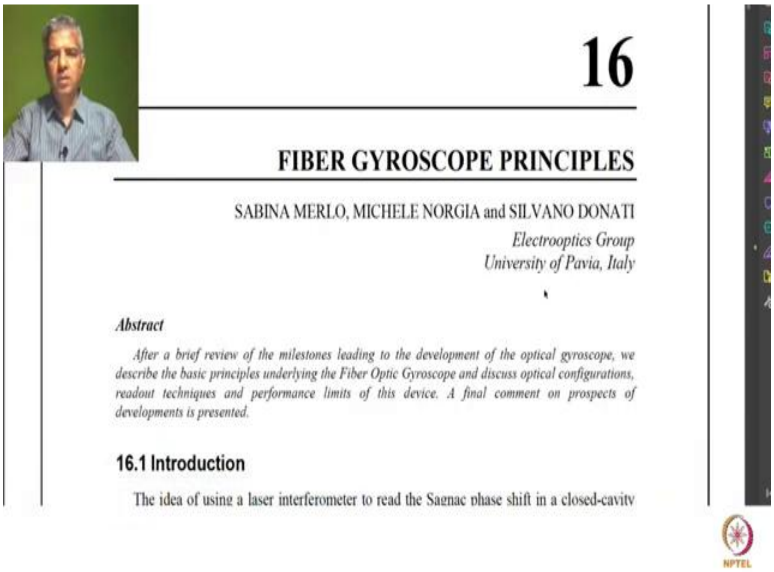

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FIBER GYROSCOPE PRINCIPLES

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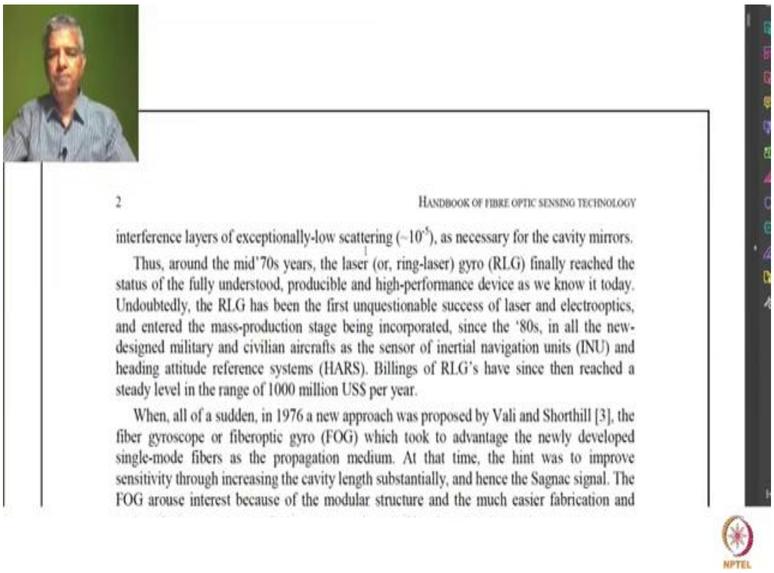
Abstract

After a brief review of the milestones leading to the development of the optical gyroscope, we describe the basic principles underlying the Fiber Optic Gyroscope and discuss optical configurations, readout techniques and performance limits of this device. A final comment on prospects of developments is presented.

16.1 Introduction

The idea of using a laser interferometer to read the Sagnac phase shift in a closed-cavity



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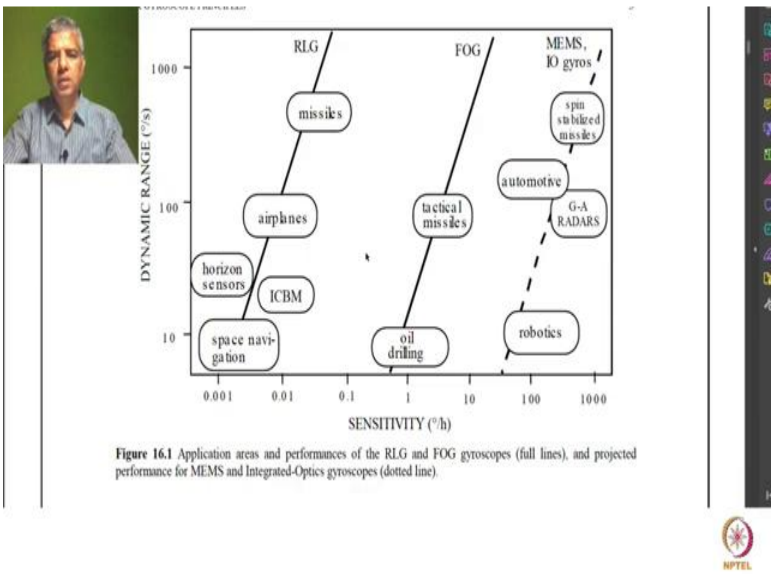
interference layers of exceptionally-low scattering (~10^{-5}), as necessary for the cavity mirrors.

Thus, around the mid'70s years, the laser (or, ring-laser) gyro (RLG) finally reached the status of the fully understood, producible and high-performance device as we know it today. Undoubtedly, the RLG has been the first unquestionable success of laser and electrooptics, and entered the mass-production stage being incorporated, since the '80s, in all the new-designed military and civilian aircrafts as the sensor of inertial navigation units (INU) and heading attitude reference systems (HARS). Billings of RLG's have since then reached a steady level in the range of 1000 million US$ per year.

When, all of a sudden, in 1976 a new approach was proposed by Vali and Shorthill [3], the fiber gyroscope or fiberoptic gyro (FOG) which took to advantage the newly developed single-mode fibers as the propagation medium. At that time, the hint was to improve sensitivity through increasing the cavity length substantially, and hence the Sagnac signal. The FOG arouse interest because of the modular structure and the much easier fabrication and



And excellent reference for some of this is actually from it is this, I think it is probably a book chapter maybe, but Fiber Optic Gyroscope Principles by Merlo, Norgia and Donati, so this actually, so this is actually from the handbook of Fiber Optic Sensing Technology and they talk about lot of the basics of fiber optic gyros, where it is applied and then go going through the principles and all of that, so you may want to just go back and look at that as a reference.

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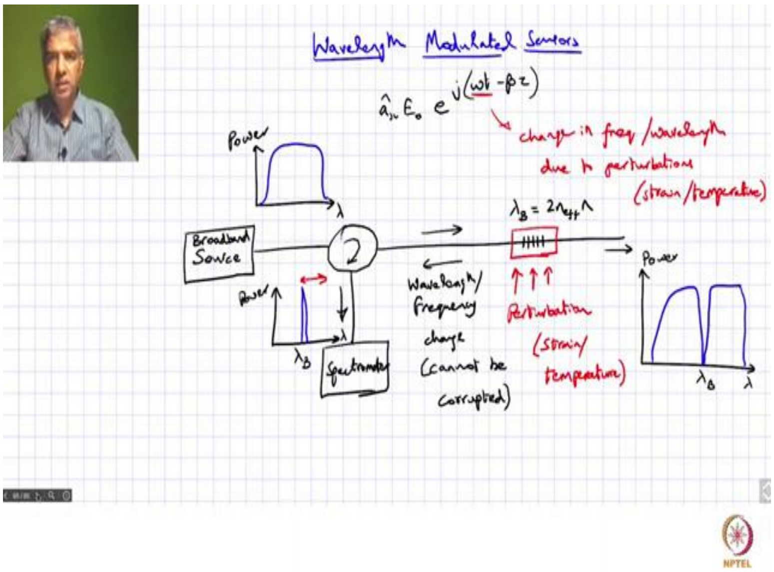

So, coming back to where we were, we were talking about wavelength modulated sensors and we recognize that what we are really interested in is encoding the perturbation in frequency or wavelength, so this is actually the perturbation information that we are interested in. And the reason why we want to do that is because of the fact that when it is encoded in wavelength of frequency it cannot be corrupted by all the traditional noise sources that we saw, for example, the environmentally induced noise.

It is not an issue as far as wavelength modulator sensors are concerned, because the, it cannot change the wavelength information. So that is actually a big advantage for these sensors and specifically we started talking about using these fiber Bragg grating. So, let us go into that a little more detail today.

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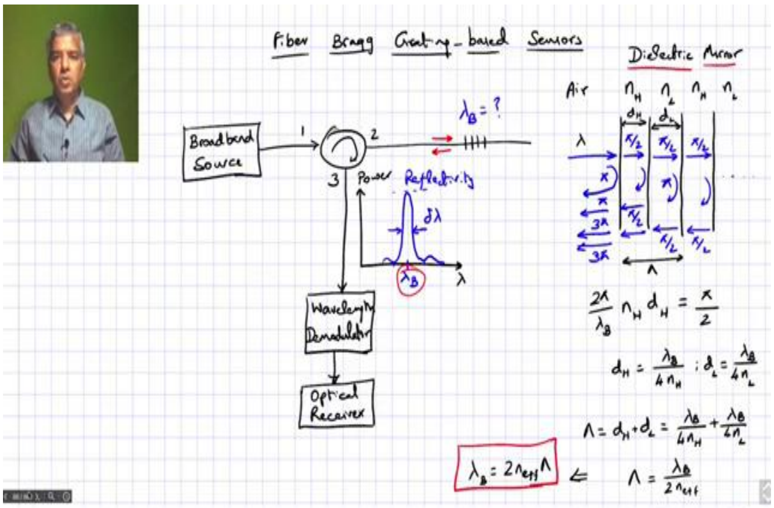

So, we are going to be talking about fiber Bragg grating based sensors. So, we will first look at what these fiber Bragg gratings are all about, but typical configuration is going to be something like this, you have a broadband source that is emitting radiation over a broad range of wavelengths and that is typically going into a circulator or a coupler so that it is it is sending light in one particular direction.

And we have a fiber grating that is connected to this circulator, so anything that is back reflected from the grating is going to come down this path. So, if you say port 1, port 2 and port 3, it is going to come to port 3. And, so port 3 typically has this information where, if you look at the power spectrum, power as a function of lambda, it is going to look something like like this and we are interested in picking up this center wavelength.

So, how do you measure that? Well, we know that our traditional receiver is not capable of picking up color, so you have to essentially go through what is called a wavelength demodulator that converts essentially the wavelength information into intensity information and then you can actually pick it up using an optical receiver. So that is typically the configuration that we are looking at.

Now there are several questions with this, first of all if we talk about this reflecting at lambda b, what defines lambda b, what is that Bragg wavelength dependent on and then you are interested in what is the width of this peak over here, what determines where it goes to 0, what determines the peak reflectivity level/ So, this peak actually corresponds to certain reflectivity, so what determines the reflectivity of a fiber Bragg grating and so on.

So, let us actually try to dwell into this a little more deeper as to what is the physics of fiber Bragg gratings before we go into how we can use fiber Bragg gratings as a sensor. So, how does the fiber Bragg grating work? A simple way of explaining this could be, this answer to this question of how does a wavelength, sorry, how does a dielectric mirror work?

We know that dielectric mirrors typically have refractive index, different layers with different refractive indexes, especially high refractive index layer followed by a low refractive index layer and then a high reflective index layer and so on. So, essentially it is, when you look at a dielectric mirror it is going to consist of multiple layers. So, one layer with high refractive index, another followed by another layer with low refractive index, another layer with high refractive index, another layer with lower refractive index and so on.

So when you have a wave coming in, it is going to undergo a reflection whenever there is a change in the refractive index, whenever there is an impedance mismatch and clearly when it is going from lower refractive index into a higher refractive index, from a rarer medium into a denser medium, it is going to undergo a phase change of pi, so in this case, for example, if you are looking at this reflected component, because it is going from air into this medium with higher refractive index, it is going to have a phase change of pi.

So, mirror is one, well-designed mirror with high reflectivity is one, where all these reflections from these different layers are going to add and phase. So, how can that happen? Well, that can happen if let us say this is designed so that you have a propagation phase of pi by 2 upon reflection here there is, because it is going from high refractive index into low refractive index there is no phase change upon reflection.

But let us say this is actually another pi by 2 because it is going through the same thickness. So, you have a cumulative phase change of pi. So, these two components are in phase with respect to each other, so they they add up, their fields add up essentially. And then you can do the same for the next layer also. So this is also pi by 2, but here you have a pi phase shift and because it is going from lower refractive index to higher refractive index, so you have a pi phase shift at that point and let us say this is pi by 2 this is also pi by 2.

And so what you get out here is pi by 2 plus pi by 2 is, pi plus pi is 2 pi, plus pi is 3 pi, so you have 3 pi, which is a different phase, but then it is 2 pi phase shifted with respect to the other component, so it is still going to add and same thing you can repeat and you you have 0 phase shift upon reflection but pi by 2 over here, so if you look at that component that will also have 3 pi and so on.

So, you can have multiple layers, alternating layers of low and high refractive index and you can essentially make a mirror, so this will be a highly reflecting mirror if you have more number of layers and so the reflectivity depends on the number of layers as well as the index contrast between high and lower refractive index. If there is a huge index contrast, then that would correspond to achieving say 99 percent reflectivity with less number of layers.

On the other hand if the refractive index contrast is low, you may need much many more layers to achieve the same reflectivity but that is the basic principle of a dielectric mirror and now let us just examine this condition, we have assumed that there is a pi by 2 phase shift while propagating through this thickness. So let us actually look at that, so when you look at the phase, that the light accumulates at, say a particular wavelength lambda, that phase is given by 2 pi over lambda multiplied by nh is the refractive index of the high index layer.

Let us say the thickness here corresponds to dh, similarly the thickness here corresponds to let us say dl, so 2 pi over lambda nh multiplied by dh is equal to pi by 2, if you work that out you basically say dh is going to be equal to lambda over, this 2 is going to come over here, so 4 times nh and similarly for the lower index layer you can also find dl will be equal to lambda over 4 times nl.

And if that is the case then we are talking about this entire thing corresponding to one high and low index pair. So, let us have that overall thickness as a capital lambda, that corresponds to the period of this structure. So, if you look at capital lambda, which is dh plus dl is going to be lambda over 4 times nh plus lambda, sorry, lambda over 4 times nl.

So, if you consider that nh is approximately equal to nl if the index contrast is on the lower side, then you can effectively replace nh and nl by say n effective and if we do that, then we get this expression capital lambda equals to lambda over 2 times n effective, which implies that you can write this lambda, which we now can call as a center wavelength in instead of just calling this lambda, if you have that center wavelength is called lambda b, then you can just say lambda b equal to 2 times ineffective capital lambda.

So that, so it works nothing, I mean, it is not any different from how a dielectric mirror works upon normal incidence. Why normal incidence? Because we are talking about light coming in here in an optical fiber, it is typically a single mode optical fiber and it is incident normally on this grating and and the grating is actually reflecting light in this case. So, the fiber Bragg grating behaves in a similar way as as a dielectric mirror.

So, that is one way of explaining, of course, the other way of explaining is actually through couple mode theory. So, we can look into the little more detail, but before we do that, I mean, this just gives you the condition for getting this lambda b, but it does not actually give us any information about what is going to be the reflectivity and what is the width of the reflection peak and so on. So, let us look at that, so in order to actually determine those you would have to use Coupled mode theory. So, let us actually go into that and check that out.

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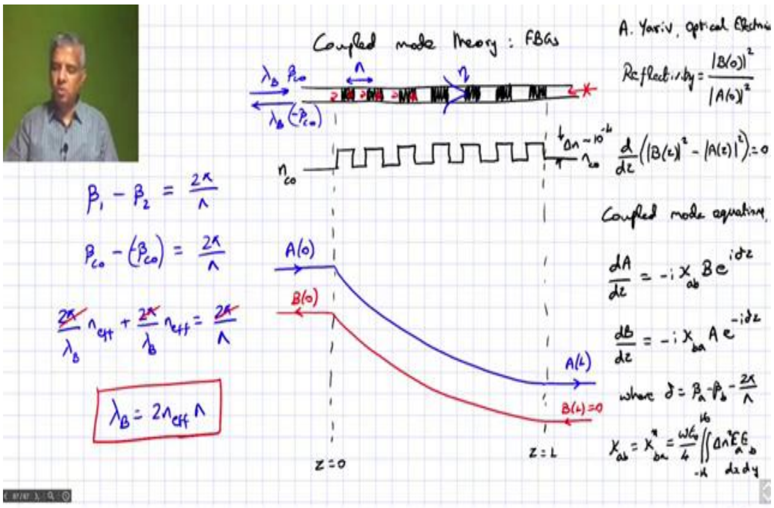

So, essentially if you look at coupled mode theory corresponding to fiber Bragg gratings FBGs in short, what we are looking at is you have essentially an index perturbation corresponding to the fiber Bragg grating, so essentially you have some change in refractive index like this, so you have a change, a periodic change in the refractive index.

So, if you express in terms of the refractive index, what we have is, let us say this is actually corresponding to the core refractive index NCO and these regions you have a higher refractive index corresponding to the, I mean, compared to the core refractive index and it goes back to the core refractive index here. And this refractive index change, let us call that delta n. This could be a fairly small number.

But what it is doing is essentially you have light at a certain wavelength, so let us just say this is, if you are looking at the Bragg wavelength, then it is coupling a forward propagating mode to backward propagating mode with the same wavelength. So, that is what this is doing and that is done through this grating structure, which has a period of capital lambda. So what we learn in coupled more theory is the fact that if you want to couple from one wave to another wave, then you have to essentially satisfy a phase matching condition.

So, what is this phase matching condition? Well, you consider essentially the phase constant beta 1 which is loosely called as a propagation constant as well. So, you have two waves with different propagation constants and they need to be compensated by or one wave may need to be slowed down with respect to the other wave by this grating structure. So this grating structure is having a component, say you can call that as a wave vector corresponding to 2 pi over capital lambda.

So, if you, essentially, if you want to couple from one mode to another mode, from one wave vector to another wave vector you can do that by a periodic structure, so this is what Bragg diffraction is all about as well. So, in this case we are talking about coupling a core mode beta c naught that is what this mode has, into a mode that is going in the opposite direction, so that is actually represented by minus beta c naught.

So, you have minus of minus beta c naught, this is equal to 2 pi over lambda and when you talk about the phase constant corresponding to the core mode you can write it as 2 pi over lambda for this particular wavelength lambda b times n effective plus you have 2 pi over lambda b times n effective is equal to 2 pi over capital lambda and so in this case basically the 2 pi cancels, so you have 2 times n effective over here in the numerator.

And then you interchange the terms and of course, what you get is lambda b times, lambda b equals to 2 times n effective multiplied by capital lambda, which is of course, consistent with this other picture where we were just looking at the phase changes upon reflection. So, you can essentially use either of those pictures and you can show that this lambda b, the Bragg wavelength is determined by 2 times n effective capital lambda.

So, if you come in with broadband light you are able to pick up one particular wavelength or rather it is actually a small spread of wavelengths around lambda b. Why do I say it is a small spread? Well, even if you are off lambda b, if you are slightly off from d tuned from lambda b this this reflection still happens, all these points the reflection still happens, it is just that they are not exactly in phase.

So, because of that they do not add up as much as it does in lambda b, but that does not mean that there is no reflectivity, so the reflectivity is a finite value around lambda b. It just sets a value less than the value at lambda b. So, we want to actually find out how this reflection spectrum is going to look like. So, that is what we will do next. And to do that like I said we need to probably go into a little more details as far as coupled mode theory is concerned.

So, the basis for which we can actually write out here, so we are basically saying that, let us say this is along the z direction, so you are going from z equal to 0, z equal to l is where this perturbation is present and what this perturbation does is you have a incident wave, let us say with a field whose amplitude is given by A, so you say the field over here is A of 0, but as it propagates down the grating, it is getting depleted.

Why is it getting depleted? Because at each of these interphase it is getting reflected, so the original amplitude is now going to go down. So, it it basically goes down, let us say like this and then finally it goes out with this value, which you can write as a of l. Now what about, what can you say about the reflected field component? Well, the reflected field component is going to, let me just represent this in red.

So the reflected field component is going to have start with the value of b of l, but it is going to actually increase as it is actually propagating because it is coherently adding up with other field components, so it is going to run parallel to this line and it is going to come out with b of 0. So, now, what is reflectivity? Well, reflectivity, if we were to define, so this is what we are trying to find out, reflectivity is a value that is defined with respect to the power, it is reflected power over the incident power.

So, this is basically b of 0, so the the power is proportional to the magnitude of the field square, so this is what we want to find out. And this we want to find out at different wavelengths essentially. And of course, there are some generic in the conclusions that we can make or observations we can make, based on this we can say that the rate at which it is getting depleted depends on the index contrast between the high and lower regions.

So, larger the index contrast more will be the depletion, and of course, vice versa if it is, if the index contrast is relatively small as in the case of a fiber Bragg grating that delta n is typically in the order of 10 power minus 4, if relatively low index contrast, then you may need the depletion, the rate at which it depletes is not as much, but on the other hand if you have a longer length, it will actually end up depleting more and that actually means that you have more reflectivity. So, you can make some observations like that.

Now, the other observation you can make is essentially the boundary condition, the boundary condition at this side, you can actually say this b of l should correspond to 0, let us assume that there is no other light coming from the other direction, so the only light that we are considering is actually incident from this direction.

So, if you consider that and if you also, you can also consider that the, when we look at the reflection or the reflected power it is not going to change with respect to, the total reflected power is not going to change with respect to this direction. So, you can write that d of z, the differential with respect to the z direction of b of z whole square that corresponds to the, actually the intensity, but we can we can consider that is proportional to the power.

So minus a of z, that is going to be equal to 0. So, essentially we are saying that whatever reflected component you have is going to be because of the incident field components, presence of the incident field component at that particular point. So, you can, that is another observation you can make and that can help solve this particular set of equations. Well, what we have is actually these coupled mode equations.

So, we can write the evolution of the incident component, incident field component as well as the reflected b field component, it is going to be dependent on each other like the incident field component evolution is going to be dependent on the reflected component because of the fact that even as it is reflected, part of it is going to be reflected back and that is going to add to the incident field, so it is it is going to happen in a continuous manner.

So, you can write dA over dz as minus i kappa a to b that is actually what is called the coupling coefficient multiplied by B times e power i delta z, I will come back and define what delta is, that is clearly a phase term, phase modulation term that we have, and similarly when we write, you can write the evolution of the reflected field, which is denoted by B as minus A kappa BA and that is actually dependent clearly on the incident field amplitude.

A e power minus i delta times z, minus i because it is actually going in the opposite direction. So, by the way all these are discussion from this book by Amnan Yariv, it is a book that is titled Optical Electronics write by Amna Nyarev, so you can you can find this discussion here. Where you need to, we need to define two terms, where you have delta, where delta is actually the detuning constant.

Remember we talked about beta 1, beta 2 and and 2 pi over lambda, so that is what this is representing, so you have beta A that corresponds to the propagation constant of the incident field minus beta B that is the propagation constant of the reflected field minus 2 pi over capital lambda. So, what can we say about delta at wavelength lambda b, at lambda b we know beta a minus beta b equals to 2 pi over lambda, so delta would be equal to 0.

So that is actually a special condition that we will look at. And we will also say that kappa ab is nothing but conjugate of kappa ba, so in terms of magnitude it is the same and because it is all happening in the same structure and that is actually going to be given by the overlap of, it is going to correspond to coupling due to some perturbation to the field. What is causing this perturbation? What, here the perturbation is caused by this refractive index change.

So, when we talk about quantifying kappa, so this will correspond to omega times epsilon naught over 4 in double integral of delta n square, the refractive index perturbation that we have, multiplied by the field corresponding to the incident wave, field corresponding to the reflected wave, Ea Eb dx dy, so that is actually integrated over all this dimension in the transverse plane, so that you can write it as minus infinity to plus infinity.

But most of the action is happening around this core region, so even if you go a few microns from the core region there is not going to be a significant field. But essentially this Ea Eb dx dy what it is denoting is actually the overlap integral, so it is basically the overlap of the two fields. And that overlap as far as the structure is concerned, we can say is going to be fairly strong because the, both of these waves have to satisfy Maxwell's equations for this waveguide.

So, essentially, we can say that if your incident field has a distribution like this that looks somewhat Gaussian because it is a fundamental mode, the reflected field also is going to look somewhat similar, except that the overlap of the fields with respect to the perturbation is limited to only the fields within the core region, so that is where the delta n comes into the picture, it is limited only within the core region, the cladding, the fields in the cladding is actually not seeing this index difference.

So, you need to actually account for that in terms of a confinement factor, let us say you have a confinement factor eta, which talks about how much of the energy is actually present in the core of the optical fiber. So, we will go, we will come back and look into that. Now, we need to solve this with these boundary conditions, b of l equal to 0 and then you have to basically conserve energy in this structure and that is what this is reflecting.

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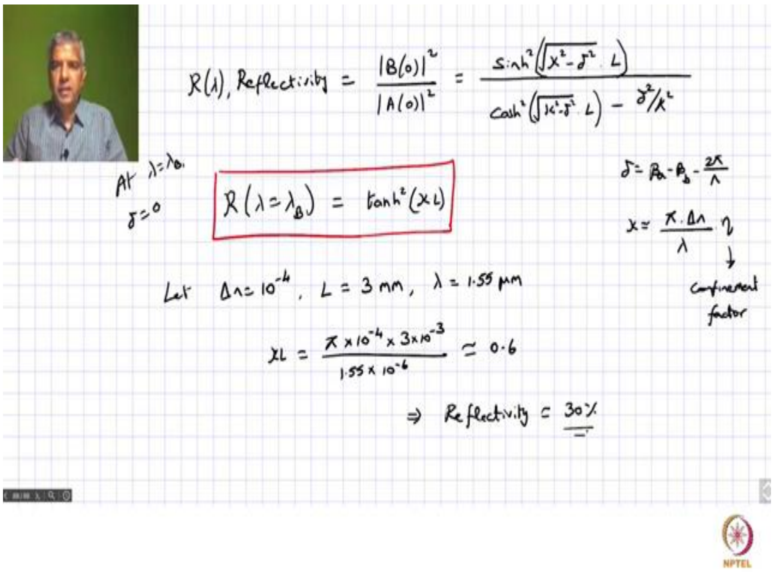

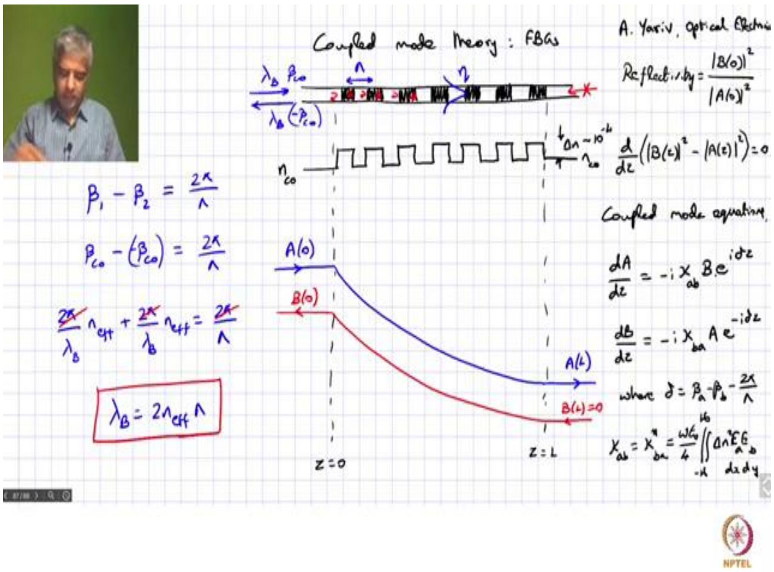

So, if you do all of that, I am not going to actually go through the steps in the interest of time, but if you do all of that you get an expression for the reflectivity of this grating and that expression, so in terms of reflectivity, which we defined as the magnitude of the reflected field square divided by the magnitude of the incident field square, the solution for this is going to be in the in terms of hyperbolic sin and hyperbolic cosine.

So, essentially, the expression for reflectability will also be in that sort of manner, so this is going to be given by sin x square kappa ab and kappa ba, let us just represent that with a common kappa, kappa square minus delta square, the whole root multiplied by l, where l corresponds to the length of this fiber Bragg grating divided by cos h square root of kappa square minus delta square multiplied by l minus delta square over kappa square.

Where delta as as we talked about corresponds to beta a minus beta b minus 2 pi over capital lambda, which is equal to 0 at lambda equal to lambda b, but it is some other finite value for any wavelength away from lambda. Where does lambda come into the picture here? Because beta a is given by 2 pi over lambda multiplied by n effective. So, that is where the lambda dependence comes from.

And kappa, if you evaluate for this structure, this can be approximated as pi times delta n divided by lambda multiplied by eta that is essentially something that you get by evaluating this integral for this particular structure and once again I am not going to the details of how that is done but, so that is how it works out as far as the coupling coefficient is concerned. And eta is actually your confinement factor, which we can assume to be a relatively large number as far as a well-guided fundamental mode is concerned.

But if you go to a long wavelength much longer than the design wavelength, which is around the cut-off wavelength, if we go to much longer wavelength, then we know the fields are going to extend much farther into the cladding and in that case eta is going to be a number that is much smaller than 1, and if that is the case then the coupling coefficient also is going to be relatively weak.

So, how does this all work out? Now, this is actually the reflectivity, we can say reflectivity as a function of wavelength is like this, but if you are interested in the reflectivity at lambda equals to lambda b, at the center wavelength, then we know at lambda equal to lambda b, your delta equals to 0, so if you drop delta then this term the denominator goes away and these terms would go away as well, so you just get a kappa times l.

So, this actually works out to be tan n square kappa multiplied by l, so that is one important result and of course, if you want to evaluate this, if you want to get a feel for how this works out, if you say, for example, let delta n equals to 10 power minus 4 and let us say the length is typically 3 millimeter and let us say lambda.

We are considering as 1.55 micron, if we use this, then if you evaluate kappa times l that is going to be pi times 10 power minus 4 multiplied by 3 into 10 power minus 3 divided by lambda which is 1.55 into 10 power minus 6 and this will work out to be a number approximately equal to 0.6 and if, what that means is the reflectivity is work out to be something in the order of 30 percent.

So, how can you increase the reflectivity? So, why is the reflectivity important? Because you are picking up this Bragg wavelength from any other background noise at the receiver, so higher the reflectivity the better, but you cannot ensure high reflectivity over an extended period of time, so you should be able to work with even lower reflective gratings. But anyway reflectivity, if you want to increase the reflectivity what can you do, you can possibly go for higher index contrast or you can increase the length of the grating. So, we will look into some of those details in the next.