Photonic Integrated Circuit
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Lecture 33
Light-chip coupling

Hello everyone, let us look at another important aspect in photonic integrated circuits, particularly it comes under the class of passive operation but very important one though. So, light coupling into the circuit or into the waveguide. So, we are talking about, so far in the whole discussion we assume that the light is there inside the waveguide and how we can manipulate it and all kind of discussion in depth sufficiently understood.

Now, the question is how are we going to get the light into that waveguide so like optical fiber you could have optical fiber that is hundreds of kilometers but unless you put the light at one end you are not getting it out of the other but you are not taking it outside anywhere in between. But you have to couple it from one end and take it to the other end, in between you can do all kind of interesting functions.

Similarly, in a photonic circuit you can do all kind of interesting optical functions once you have the light captured in the waveguide. Now, the question is how are we going to put the light into this waveguide? So, that is an intriguing question and very challenging at times as well. So, let us look at this a particular problem of coupling and how are we solving this coupling into the chip or coupling into the waveguide process, let us look at it.

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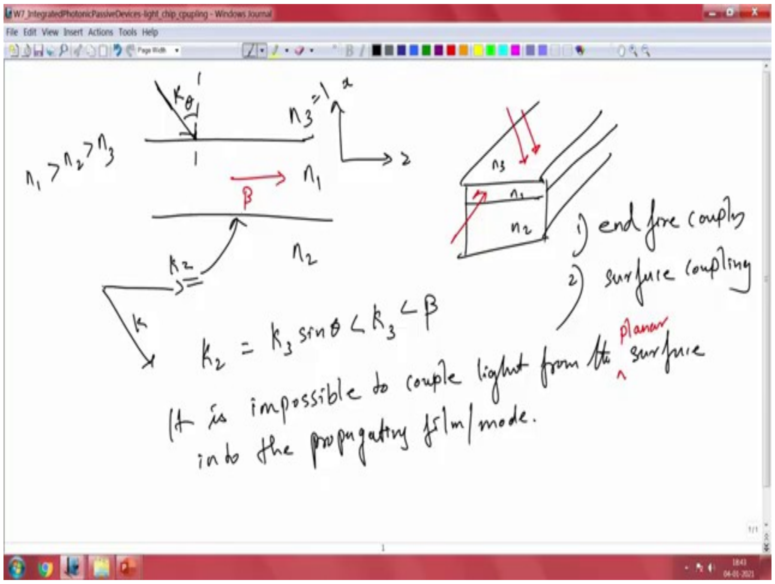

$k_2 = k_3 \sin\theta < k_3 < \beta$

It is impossible to couple light from the planar surface into the propagating film/mode.

$$k_2 = k_3 \sin(\theta) < k_3 < \beta$$

So, what we have as a system is rather straightforward, we take simple stack let us say of refractive index n1 this is cross section and you have n2 and n3 at the top. So, you want light to propagate through this medium n1 which has higher refractive index compared to other so that means n1 is greater than n2 which is greater than n3 let us say, so this is the condition we have.

So, when you take a very simple chip, so I am going to take a very simple optical chip that I have so this is your n2, this is n1 and n3 is on top. So, now there are two ways to couple the light into this, I have access in two ways. One is top access, the other one is side, so when I couple it from the side we call this as end fire coupling, so there is end fire coupling and when I try to couple it from the top it is called surface coupling so these are all two different ways of coupling light into the waveguide.

But then it is not that easy, so let us look at the real problem here or what is the problem here. So, I come in from here let us say, let us start with the top elimination, so I am coming it with some certain angle with the K, so it is theta here. So, I should be able to couple this light into the waveguide with some phase matching between this K and beta here, so that means the plane wave that I have outside this waveguide should be able to excite this beta here.

And this particular K it is not just K you have to couple it to K z, so if K is coming in so this is z and this is x, so I want to couple this to K z, so this is my K but I have to make this K z phase match with this beta. So, it is the longitudinal propagation constant that is the z component that should satisfy the phase matching condition. So, what is that?

So, Kz here should be equal to K3 sin theta which should be less than K3 and theta so it should be less than beta and at the same time it should be greater than K naught sin theta so where beta is your propagation constant in the waveguide. So, this is rather difficult to do, it is equally impossible to couple the field in a guided mode system without the waveguide having any kind of special arrangements, so without having some additional factors this is not going to happen because you can see here just by shining a light on top of this surface will not give you the required propagation constant here.

So, you can quickly do the calculation you will see that this Kz that we have here this will be a radiating mode, so it will not be a propagating mode, I mean Kz will not be there to couple it, so you will not be able to attain the phase matching that is required in order to excite the beta here, it is simply impossible so I can say here it is impossible to couple light or couple we can say light from the surface into the propagating film or mode.

So, we should do a qualifier here from the surface or rather from the planar surface, so this is something that is very difficult to do because of the phase matching that is impossible to achieve, so you can just do the calculation here because we know the Kz is rather easy to calculate, let us say n3 is 1, so if you say n3 equal to 1 you would know that you do not have enough Kz in order to phase match it with beta it is simply impossible.

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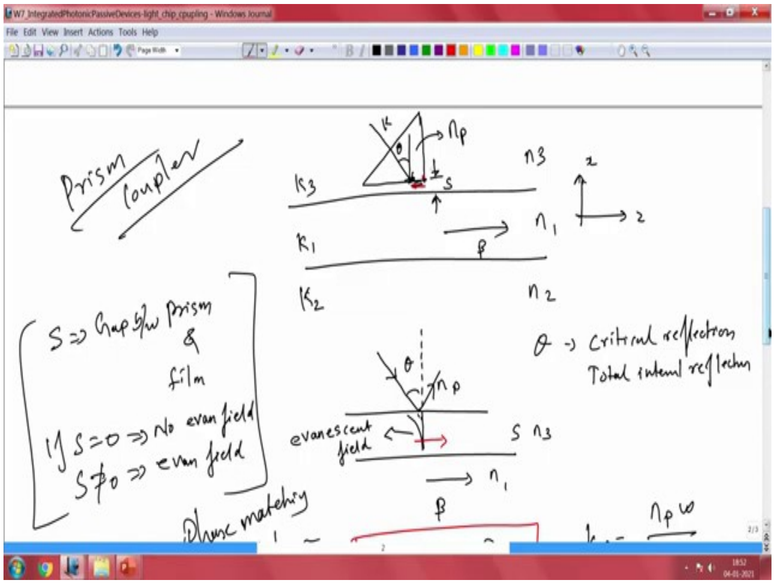

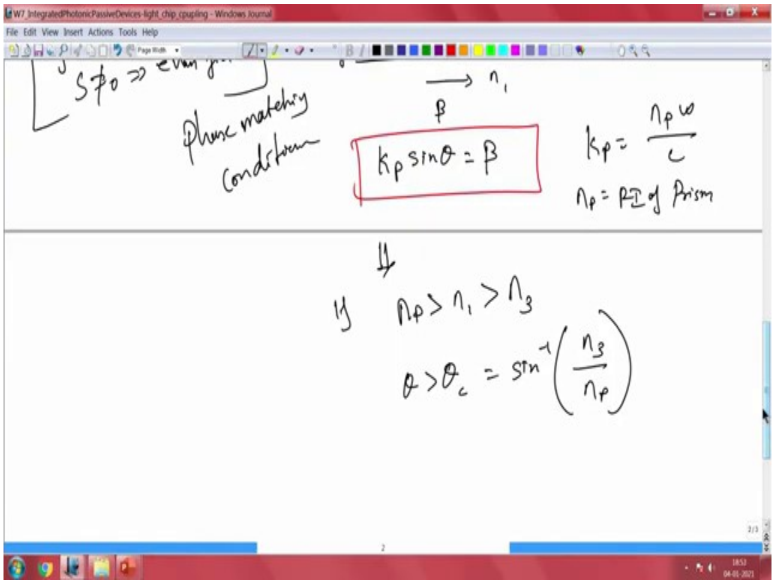

$$k_p \sin(\theta) = \beta$$

$$n_p > n_1 > n_3$$

$$\theta > \theta_c = \sin^{-1}(\frac{n_3}{n_p})$$

So, one approach is to attain this phase matching by using some arrangements, some arrangements is required, so some addition to this particular structure is required and we call that as a prism coupling strategy, there is a prism coupler. So, how does a prism coupler look like?

So, we talked about this thin layer where you had n1, there is n3 and you had n2, so this is the propagating direction z and this is x.

So, now instead of directly eliminating it we are going to eliminate light by using a prism, so I keep a prism and then I am going to come in to this elimination at a certain angle theta and this will have refractive index np, so you have K1, K3 and K2 let us say, so these are all different K vectors here.

So, now I am putting a prism on top of my thin film and I am giving a certain space between these two and eliminating this prism from free space here. So, when I do this, this is going to create some sort of interesting reflection, so you can zoom in to this particular region, so if you zoom in what you will see is a layer here, there are two layers and light is coming here and at a certain angle theta and this is n1 and there is a space here, this is n3 and you have here np.

So, now we have to eliminate this at a critical angle, so the eliminating angle theta is critical reflection angle or in other words total internal reflection angle. So, when the total internal reflection happens what do we know, it creates an evanescent field, so this will create an evanescent field along this direction, so this creates an evanescent field so this will create because of total internal reflection.

I think this is something that you might remember from our earlier discussion on the total internal reflection in optical fibers. So, you will have oscillating solutions inside the fiber, then you will have decaying solution outside, the same thing happens with this prism as well. So, when the light is illuminated at total internal reflection angle in the surface between np and n3.

So, your total internal reflection angle is not from the angle that you are eliminating outside the prism, the angle is inside the prism. So, when you do that, then it creates an evanescent field and we all know that evanescent field will have a tail and this evanescent field would try to couple the light to your beta, so the your beta is here.

So, now the question is what is the propagation constant of this evanescent field? So, that evanescent field is given by the following. So, K p is my propagation constant in my prism sin theta should be equal to beta, so this is our phase matching condition, this is the between an optical, sorry, between a prism here and my waveguide that is sitting underneath. And this is the phase matching condition your Kp is nothing but np omega over C, so np is the refractive index of the prism, so np is refractive index of prism.

So, now this can be achieved, so there is a condition to this, so this can be achieved if np is greater than n1 and it should also be greater than n3, so this is some qualifier here and theta should be greater than theta C which is nothing but sin inverse of n3 over np. So, by knowing the refractive index or choosing the right refractive index of prism we should be able to couple the light into this thin slab waveguide that you have by using this simple prism coupler approach.

So, you can see here it is rather straightforward, so you can just put a prism close to this but it should have a gap there, if there is no gap you will not be able to create that evanescent field. So, S is the gap between prism and film. So, if S equals to 0 then you will not have the evanescent field, so this, so S should not be equal to 0, so this, when you have this then you create evanescent field.

So, just keep that in mind, you do not, you should have a certain gap that will be taken care by your coupling so that should be fine, you need to have that evanescent field and that condition for creating this particular propagation constant that matches your beta is given by this Kp sin theta equals beta. So, let us keep that in mind for vertical coupling or surface coupling we should be able to easily do this by using a simple prism.

And now the question is what if I do not have a prism of light refractive index? So, an important point here is the refractive index of the prism should be greater than or nearly equal or greater than the refractive index of the thin film itself. So, if you are using glass waveguide you can use glass prism but then if you are going to use really high density material like 3 5 compound semiconductors or germanium or silicon where the refractive index is very large, where refractive index is three and a half, but then we should have also prism that are made out of germanium or silicon if you want to do that.

The problem in doing that is aligning your light beam into the prism here because it has to have this distance between the corner that you have, that I am marking here in red here, so there should be some distance between these two, if there is no distance then you will not have that beta propagating so you want this particular evanescent mode to actually propagate. So, then only you can match the beta between these two, but if you get it at the edge here you will not have that matching at all, so it should have certain length there. But aligning it will become difficult if you cannot have a material of interest.

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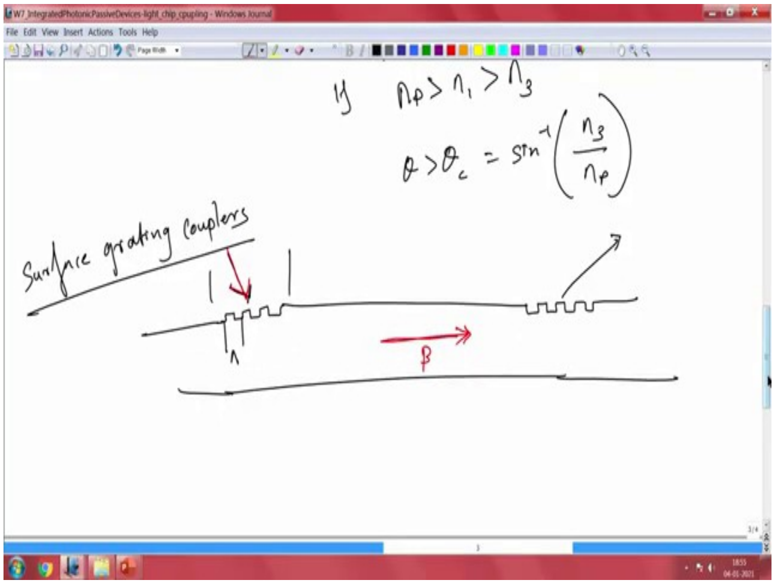

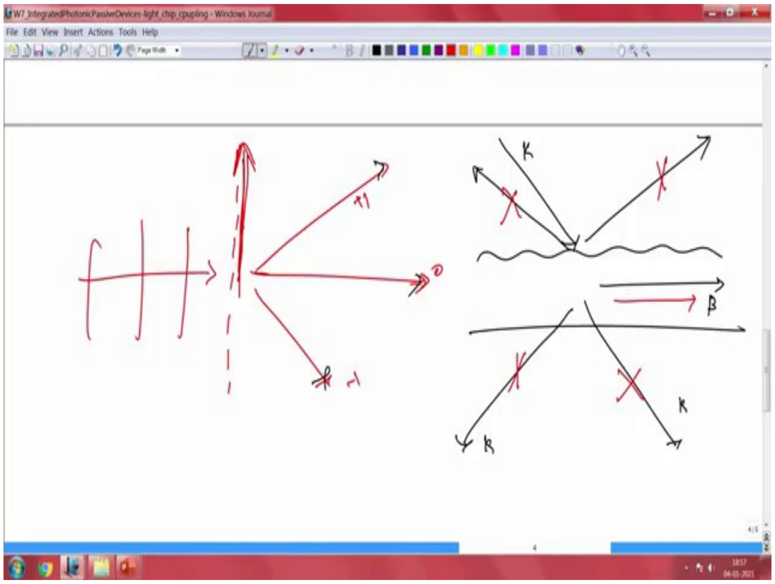

But still if you want to do a vertical coupling, the other way to do that is by using grating couplers, recall surface grating couplers. So, here what we can do is we can put gratings onto the surface. So, the way to look at it is you take a thin slab and we will make corrugations here, it is rather smooth here but I do not want smooth, so we will make gratings here for coupling the lights from the surface and then we can also take the light out.

And this grating will have a certain period lambda and it will also have a certain distance, the certain length and so on which is not very important right now, but let us look at how this structure is going to help. This is not something new, so we have seen this in a different context, so you are going to couple this into this propagating mode beta.

For some of you who have still remember a simple diffraction so this is basically a grating so if you take a grating and then if you come in with a plane wave, what would happen? You will get zeroth order, you will get first order and then you will get higher orders as you move through. But what we are trying to do here is this plane wave that we have here instead of going through this we want to make it excite the particular mode or diffraction order that is perpendicular to the incoming direction or in other words it should be parallel to the grating itself.

So, the line space grating that we have we want the diffraction order to be parallel to that. So, this is the whole idea as we can see here, I want to come in with the input light. I have this grating given here and I want this to be in line with the grating plane, so I want the grating plane and the diffraction plane to be identical.

So, how do I do this? So, the way to look at this is by using K space diagram, so when the light is illuminated into a simple grating, what are all the things that could happen? It will just diffract and it will radiate. So, whatever we have seen here so these are all nothing but radiating modes, so same thing would happen if you take a very simple grating.

So, let us say I have a grating and the light comes through the grating, so let us say the light is going to fall this way, so you will couple let us say this is one possibility where it is coupled to beta, but you will also have diffraction ordered this way, you will also have diffraction this way and also diffraction this way. So, this is all possible, these are all the possible diffraction that you will see, the other possibility is this as well, so back reflection, these are all the different orders of diffraction that you will see.

So, whatever you see here that marked in red are all undesirable, so this is all loss, so this is all radiative coupling, so you are coupling to this diffraction unintentionally because that is what happens in a grating. But all we worry about is coupling to this beta. How do we achieve this? So, this is where we need to look at the phase matching condition here, so the grating phase matching condition is something that we have looked at earlier as well, but let us look at recap it.

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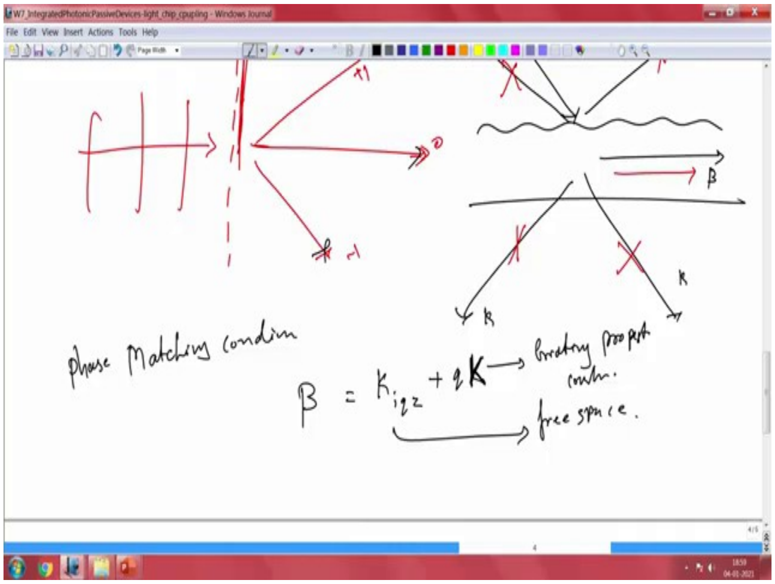

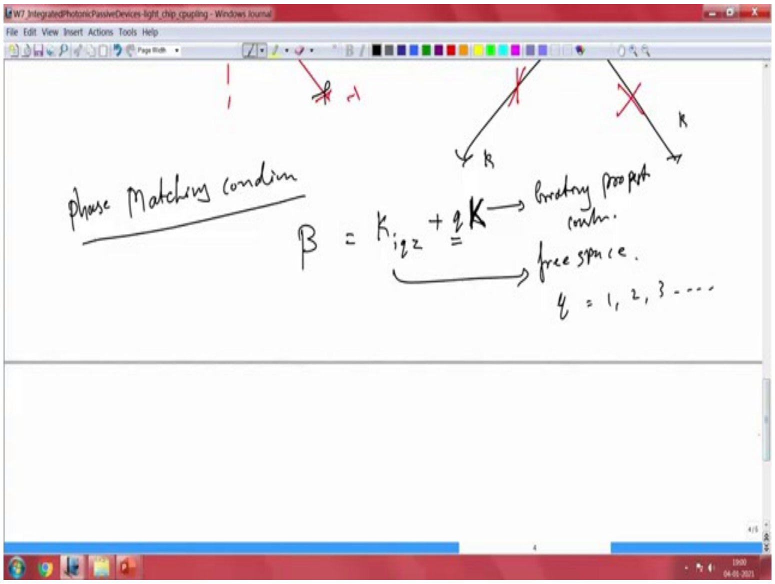

$$\beta = k_{iqz} + qK$$

So, here the phase matching condition is nothing but beta should be equal to Ki times qz, so q is nothing but your order so this plus q times K, so this is from your free space, so this is your free space eliminating K that is coming in and you should be able to couple this through your structure, sorry, this the K here this is the K that you have and this K is your grating propagation constant.

So, the dark K here is our propagation constant coming from our grating while the small k here is the incoming light beam from the surface illumination. So, once we match this we should be able to make sure that we have coupling. So, you can choose your order of your gating based on q, so we know q can be anywhere between 1, 2, 3 so these are all integral numbers that you can pick so they will be able to design these gratings appropriately and find the right order that you could couple the light into.

So, we cannot completely avoid the radiation modes but we should be able to handle these different radiation modes by choosing your coupling here between your beta and your incoming waves appropriately. So, let us quickly look at the phase matching diagram for a simple first order grating, so where your q is 1.

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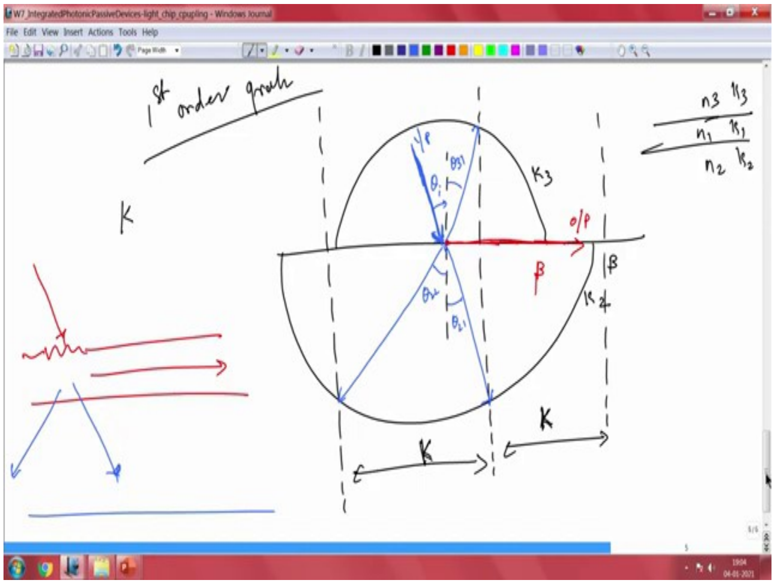

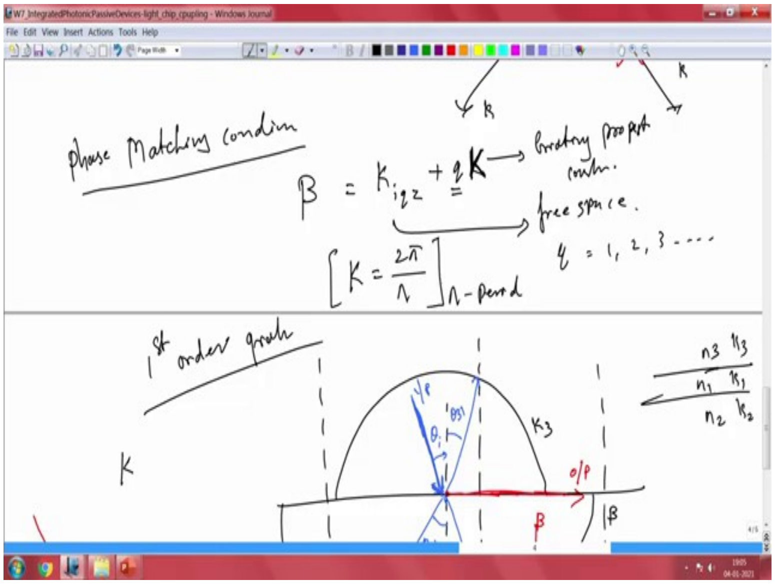

$$K = \frac{2\pi}{\Lambda}$$

$$\beta = k_3 \sin(\theta) + qK$$

So, this is first order grating, so we will just draw the K space, so this is our beta, so this is the beta, we will have two semicircles one is K3 so n1 n2 and n3 so that means K1 K2 and K3, so because K3 is lower index, you will have smaller circle so this is K3 and your substrate will be much bigger so this is K2.

And now we need to look at how to incorporate our K that is our grating, so K is our grating propagation constant here. So, K should be represented here, so we represent K which is periodic in nature here, so these are all the lines that will be represented by this is our K, so this is from the grating.

So, now we have K, we have these things then we need to match our beta so we start at the center here so this is the center of the circle let us say, so this is our beta and now the incoming light so let us look at, this is just for the guidance there is nothing more to this, so there is a incoming light, so the incoming light is at certain incident angle theta i and this will actually propagates diffract out here with an angle theta 21 and there will be a backward order theta 22 and then there will be a reflection as well from here that will be theta 31.

So, these are all the various components that you will have when there is an incident light here, so I am making it dark so this is our input and this is our output but then you will also have these orders that are leaky. So it is reasonably difficult to completely get rid of these radiating modes so we need to live with these radiating modes because it is an order that diffraction order that you get when you are using a grating.

But there are ways to handle this when you are having a grating and you are eliminating this so you will have light that is propagating through this and the blue ones are this way so there is a blue here and you could also have something like this, so the light is going through this. What you could do is you can use a reflector in order to reflect the light back, that is a possibility and this is all by engineering our structure it is not intrinsic to the device but we can engineer these structures. So, this is something that we will look at when we talk about the case studies and real life example of these kind of structures.

So, by using this particular phase matching first of all we will find out what K is required and based on that so based on that K we all know that K is nothing but 2 pi over (())(30:33), so this is again an important relation so this is nothing but period. So, you can choose your period appropriately in order to get the kind of phase matching and that is one thing and you can also work with your angle of incidence.

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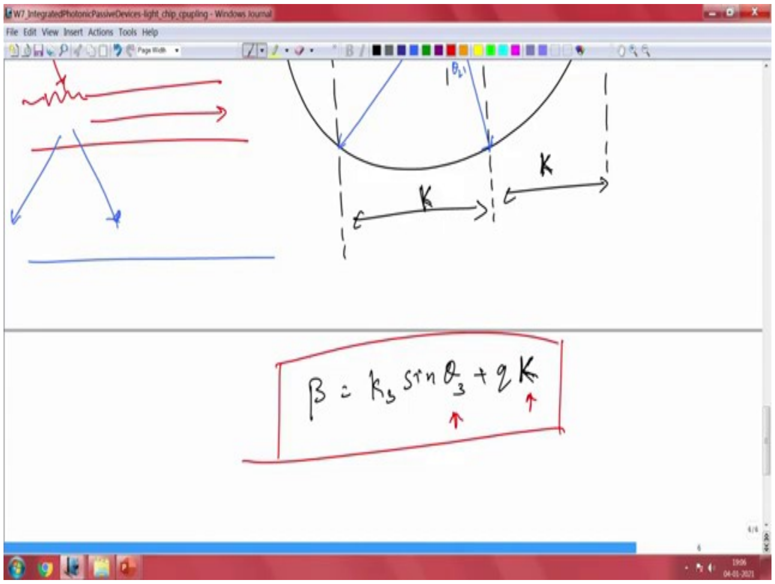
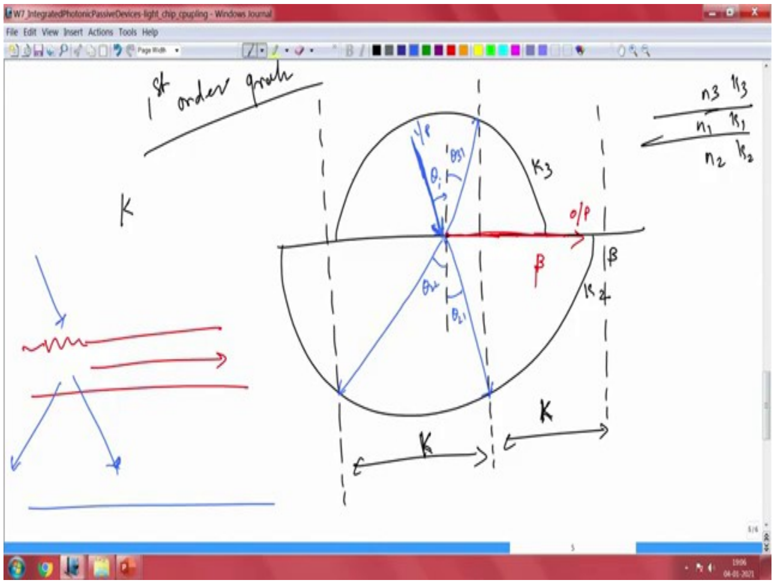


$$\boxed{\beta = k_3 \sin\theta_3 + qK}$$

$$K = \frac{2\pi}{\Lambda}$$

$$\beta = k_3 \sin(\theta) + qK$$



So, when you change the angle of incidence K we should also be able to change the coupling here, so this Ki qz could be written as, so let us say beta here, could be written as K3 sin theta 3 so that is your input plus qK so where K is your input. So, this is the relation that you may want to use.

So, input angle is something that you can change, so this is your grating period and you can choose the order as well, it is a first order or second order based on this we can create the phase matching and couple the light into the waveguide. So, now by eliminating it from the top we should be able to couple the light into the waveguide. So, we will see how these structures could be evaluated when we see the real life examples here.

And final light coupling is by using end fire, so end fire coupling is relatively straightforward where you need to really find the overlap integral so that is all you have to do when it comes to coupling light between the input wave and the waveguide mode. So, that is something that is relatively straightforward to do.

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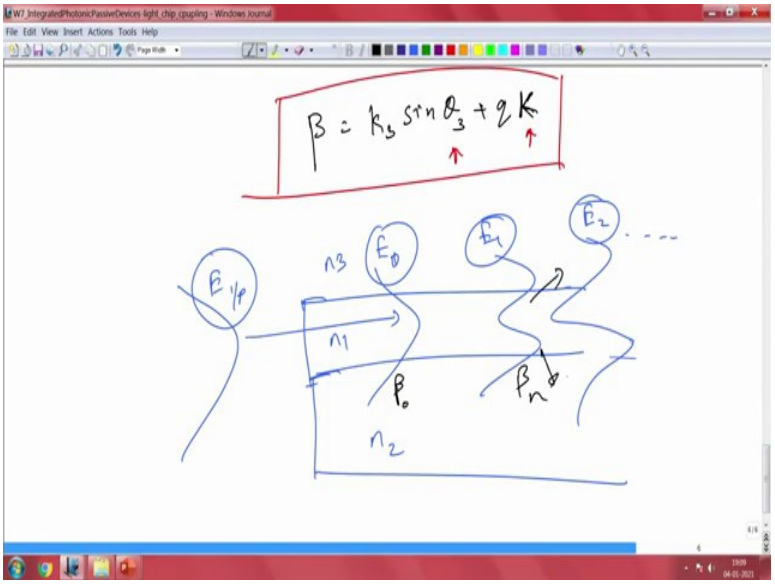

So, you have the waveguide here and we have an input wave here but then we know there is input propagating mode here and you will also have lot of higher order modes as well, so these kind of modes will try to get excited as you are eliminating the waveguide here. So, let us say this is n2, this is n1 and this is n3, so when you are doing this particular illumination we all know that it is just a overlap integral between your E input and then E naught, E1, E2 and so on so you need to look at what is the overlap that you have between these individual components and based on that your energy will be distributed in this.

As we have seen in many coupled equation or coupled light coupling problems when you have a non-zero overlaps you have potential coupling, so that means exciting one particular mode is not straightforward. So, if you can couple to zeroth order mode here you may also be coupling to the first order, sorry, second order mode here because they are even, so the mode overlap will result in non-zero overlap integral, so it is impossible to avoid those.

So, that is the reason why using a surface grating is a much better solution because your beta is now matched, so you know the propagating beta, so there is no confusion here. So, you know the beta and you can choose your illumination parameters and also grating appropriately in order to get the right beta excited. But in this case we have various beta coming in so you will not know which one you are exciting but these could be radiating as well, if it is radiating you will lose the light, but in this case you will not when you use targeted excitation.

So, with that we have understood the light coupling problem which is very, very important and also challenging as well. So, by engineering our surface, you can use surface gratings and appropriate design would give you a good phase matching and reduces loss. And the other way to do it is by using prism but there are limitations in using prism because the prism refractive index should be greater than the thin film refractive index that you have, the waveguide refractive index that you have.

Sometimes you may not be able to get the right kind of prism and also the elimination could be much difficult because you have to allow certain propagation distance inside the prism which may not be easily available with this alignment. And the other challenge that we have is the size itself, the prisms are very large but the gratings can be made very small, so you can make grating as small as your spot size itself, it can be few microns.

But then if you make a prism of few micron it is going to be very hard to handle and also integration would be difficult, but nonetheless you can use this prism couplers when your thin film refractive index is low. For example, silicon nitride you can use to some extent, polymer waveguides, silica waveguides, titania, so there are material platform that you can use with this prism coupler setup for exciting slab modes, so you can you can clearly do that and large area coupling could also be established. So, with that thank you very much for listening, I will join you in another lecture.