Photonic Integrated Circuit
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Lecture 34
End Fire Coupling

Hello, everyone. Let us look at how do we couple light from the side. So, there are two ways to couple light. So, we looked at the vertical coupling. But now, let us look at lateral coupling. So, how light could be coupled the side, the edge of the chip? So, this is similar to any coupling problem, because if you want to transfer energy from one system to the another system, you would probably align face to face and energy should flow. So, you can do this even for transporting water.

For example, if you take two pipes and water is coming from one pipe, the other pipe with the same aperture, you can place it close to your inlet pipe and whatever water coming out can be coupled to the output. And of course, you need certain force or pressure in one of the fibres, one of the pipes in order to push the light or in this case push water to the other pipe. So, if the force or pressure on one of the pipe is lower, what you do? You have to make them really really close. And if there is a enough force, you can still do it with larger gap.

So, a similar kind of strategy is something that we are going to see now. So, in this case you have two slabs or two one is the source and another one is your chip and one has instead of water optical field. So, you have optical energy from one. So, is it possible to transfer this energy from one to the other? And what are all the implications in doing? Life would be very easy if it was like water or even electric current for example. So, electric current you just touch two conductors and there will be a current flow.

But in this case, we are talking about optical waves. So, optical waves are not easy to handle. So, they have their own characteristics, unless these two systems are identical, we cannot transfer energy one to the other. This is again takes us back to our couple mode theory. So, there we understood the face matching is is key to transferring energy from one mode to the other mode or one solution to the other solution.

Here we have two different systems. So, you want to transfer energy from one system to another system, then you have normal solutions for these two systems. So, we should look at what are those two solutions? How close are they? And what is the overlap integral? So, these are all the things that we should keep in mind when we talk about coupling light between two different systems.

In this particular case, we are interested in coupling light between an optical fibre and a photonic IC or this could be between an LED so or a laser diode and your photonic IC. So, let us look at how to visualise this thinking and also look at what are all the parameters we should look at in designing such coupling and arriving at the limiting parameter. So, what is limiting our coupling? So, let us look at that.

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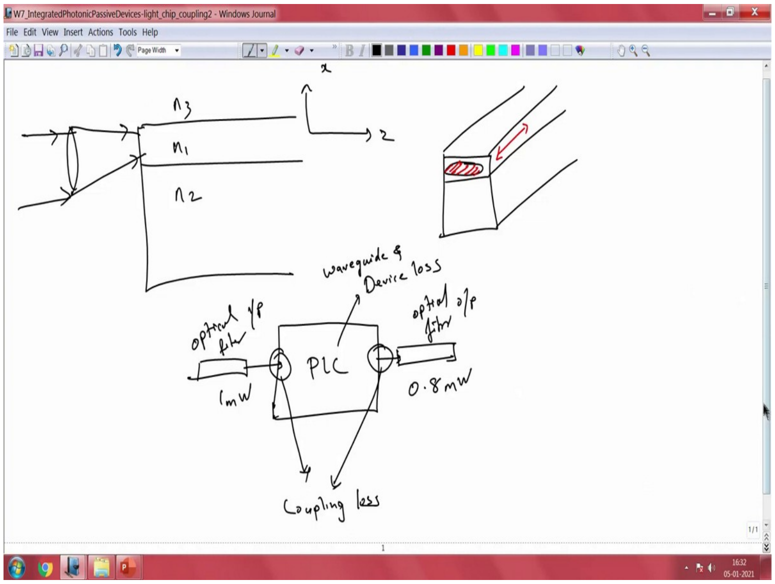

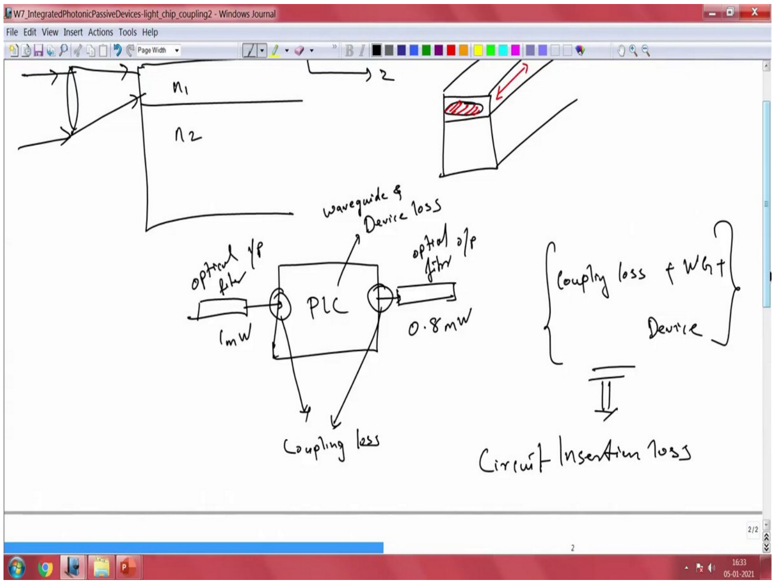

So, we shall start with a very simple structures that we would like to couple light into. So, you can think of a system like this. So, you have n1, n3 and n2, let us say and the light is propagating in this direction and this is x. So, I want to put the light into the system. So, I can put a lens here and I can focus the light into this particular thin firm. So, what I am essentially looking at is a system like this, so I want to couple light into this waveguide. So, this is the mode that I am going to excite and this would propagate through the system. So, this is essentially what I want.

And you can also invert this problem. So, that means I am generating light here. So, I might be generating light inside this thin firm like a semiconductor laser and I want to take the light out. So, it is a similar kind of coupling problem we have. So, it could be from free space to our thin waveguide here or it could be from the waveguide to the free space that we have here. And later on, you might be able to couple it to a fibre on other systems as you will like.

So, when we are having such a system, one thing that we we should look at is when I, when I take a chip, so, let us say I have this is photonic IC, I have optical fibre input, optical fibre output. So, there is an input and there is output. So, when I put about 1 milliwatt of of optical power inside the system and then it goes through this and then I get let us say about 0.8 milliwatts.

So, there are three different loss that you can expect from the system. One is these two loss what we call coupling loss. And then we could also have what is called waveguide and device loss. So, this both to together, the coupling loss plus your waveguide plus device all these factors together is called insertion loss. This is general term we use. So, insertion loss or you say circuit insertion loss because it captures everything. So, input coupling, output coupling and also a loss on chip.

So, when you take a system where your waveguide loss and device loss is very low then your coupling loss is going to dominate. So, your coupling loss is very important. So, that is why we we try to make the coupling loss as small as possible, so, that we can get maximum light inside you want to get the maximum light inside this. So, the coupling efficiency is very important.

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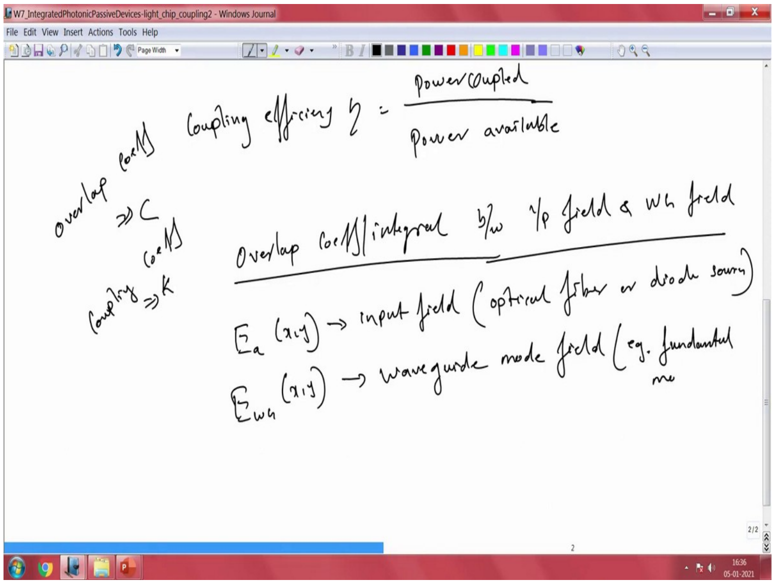

Coupling efficiency $\eta = \frac{\text{Power coupled}}{\text{Power available}}$

overlap coeff $\Rightarrow C$

coupling coeff $\Rightarrow K$

Overlap coeff/integral b/w i/p field & WG field

$E_a(x,y) \rightarrow$ input field (optical fiber or diode source)

$E_{WG}(x,y) \rightarrow$ waveguide mode field (eg. fundamental mo

So, coupling efficiency is nothing but the ratio between power coupled into the target power coupled to power available. So, this is our coupling efficiency. Similarly, on the output side as well because it will be a reciprocal device. So, how do we calculate or what are all the parameters that dictates this coupling efficiency? One thing that is, there are two things of course one thing that quickly comes to your mind is from our coupled mode theory.

So, there are two things we studied there, one is the overlap, overlap coefficient C and then the next thing is coupling coefficient, coupling coefficient, kappa. So, these two are the factors that we already know is important for coupling light. The same thing applies here as well. So, the overlap coefficient or another words overlap integral is between input field and waveguide field or waveguide mode field.

So, let us say Ea x comma y is our input field and this field could be from optical fibre or a diode source. And then we have our wave guide. So, field of the waveguide. So, this is waveguide mode field. So, let us say this is our fundamental mode. So, this could be for example, fundamental mode. So, in that case this could be approximated to a Gaussian. So, what is our coupling efficiency now? So, that means, you need to have the overlap integral. So, that is fair enough.

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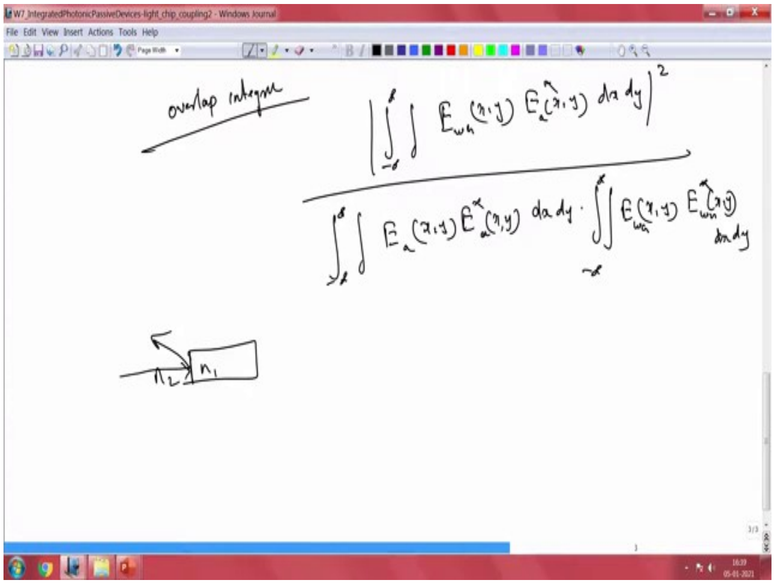

$$\frac{\left|\iint_{-\infty}^{\infty} E_{wg}(x,y)E_a{}^*(x,y)dxdy\right|^2}{\iint_{-\infty}^{\infty} E_a(x,y)E_a{}^*(x,y)dxdy \iint_{-\infty}^{\infty} E_{wg}(x,y)E_{wg}{}^*(x,y)dxdy}$$

So, let us look at what is that overlap integral? So, so, that is power coupled to the total power available here. So, that is all about the two fields that you have. So, that would be given by so, this is integral across this E waveguide x comma y to Ea x comma y dx dy divided by Ea x comma y. So, this is basically our overlap integral. So, how much of the field overlap that you have between the waveguide field and also the input field that you have. So, that Ea x comma y could be from multiple sources.

So, now, this is there and then another important factor that we should get here is also the reflection. How much of power is going through? So, if I take two different or we know this for a fact that if there is a refractive index difference n1 and n2, when light is impinging on this, you or light is going to do two things, one is refraction and other one is reflection.

So, the reflected power is lost. So, we are not going to get it. So, we should know what is the reflected power? So, how much will be the reflectance of this? So, for that we can look at the two sources here, that is the source Ea and source Ewg. So, these two are the two modes that we have.

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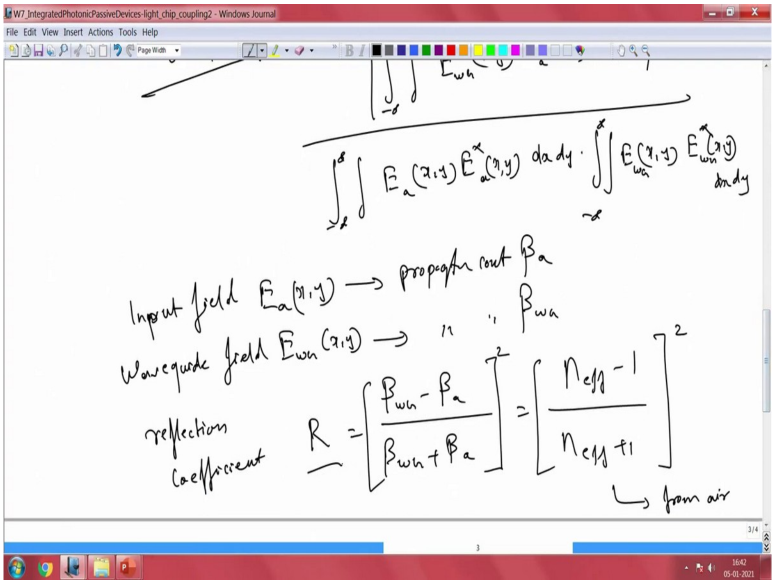

$$\int\int_{-\infty}^{\infty} E_a(x,y)\, E_a^*(x,y)\, dx\, dy \cdot \int\int_{-\infty}^{\infty} E_{wg}(x,y)\, E_{wg}^*(x,y)\, dx\, dy$$

Input field $E_a(x,y) \longrightarrow$ propagation const β_a

Waveguide field $E_{wg}(x,y) \longrightarrow$ " " β_{wg}

reflection coefficient $\underline{R} = \left[\frac{\beta_{wg} - \beta_a}{\beta_{wg} + \beta_a}\right]^2 = \left[\frac{n_{eff} - 1}{n_{eff} + 1}\right]^2$

↳ from air

$$R = (\frac{\beta_{wg} - \beta_a}{\beta_{wg} + \beta_a})^2 = (\frac{n_{eff} - 1}{n_{eff} + 1})^2$$

So, we can characterise this by using a very simple propagation constant of this. So, the propagation constant so, you have the so input field we talked about Ea x comma y. So, this has a propagation let us say beta a and now the waveguide field. So, this will have propagation constant beta wg let us say.

So, now how to calculate the reflection now? So, we know both the betas, if you want to calculate the reflection here, so, the reflection coefficient is given as so, this is our reflection coefficient or in other terms you could call this as effective index if you are coming from between air. So effective index minus 1 n effective plus 1 the whole square sorry I missed the square here. So, there should be square here.

So, by knowing the the effective index of the the the mode that we have, we should be able to calculate how much reflection one could expect. So, this is a very simple argument when you, when you have from air, let us say, so, this is coupling through air then this is much easier to understand now, it is just n effective minus 1 divided by n effective plus 1.

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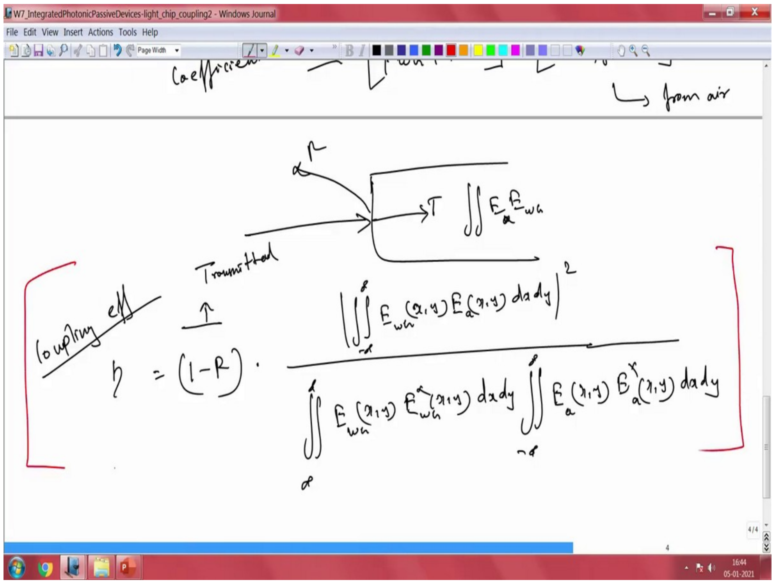

$$\eta = (1 - R).\frac{\left|\iint_{-\infty}^{\infty} E_{wg}(x,y)E_a{}^*(x,y)dxdy\right|^2}{\iint_{-\infty}^{\infty} E_a(x,y)E_a{}^*(x,y)dxdy\iint_{-\infty}^{\infty} E_{wg}(x,y)E_{wg}{}^*(x,y)dxdy}$$

So, now, based on this we know the reflection. So, as I mentioned, when you have a system, you will have reflection and then you will have transmission and once this transmission is known, then we should know what, how the overlap integral looks between the two fields. So, between the two fields, we should know what is the overlap integral? So, we already know these two elements, we just have to put it together.

So, if this this R is the reflection coefficient, then we know what is the transmission and that is 1 minus R. So, now, we can put both this together to find the coupling efficiency. So, now, so now the coupling efficiency eta is given by the transmission coefficient. So, we know the reflection here, so, 1 minus R is nothing but the transmission. So, this is nothing but how much is transmitted. So, this is the transmission coefficient times our overlap integral here. So, we can just write this whole overlap integral here and that should give us the total so dx dy modular less square and then we have the two fields here, so, your waveguide field and your input field. So, this will give us our field overlap.

So, this whole equation that we have is a characteristic of our coupling. So, this from the here we should be able to find what the coupling should be. So, there are two important things that is important here the spatial profile that means, how the the wave looks like, the field look like and also the propagation constant which is captured by the reflection coefficient that we just saw. So, the reflection coefficient depends on the the propagation constant that you have. So that those two are the two important factors that we have.

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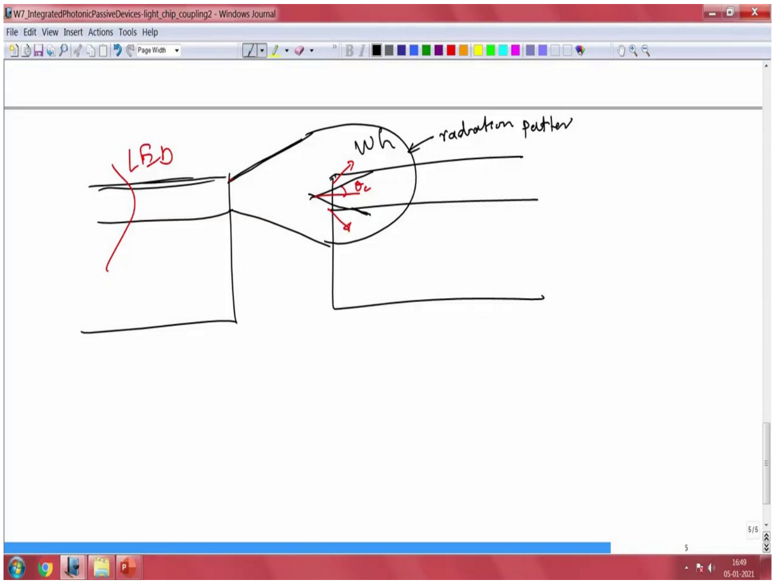

So, now, if you want to look at a system where we have let us say an LED put in front of the waveguide here. So, instead of having an optical fibre, if we put an LED, let us say, how will the coupling look like? So, that is something that we should know. So, for that, let us look at a very simple system where I put an LED. So, we take again simple slab and I am going to put a very small, let us say, an LED structure here.

So, in this case, the LED is also a chip let us say it is a, it is an edge emitting LED. So, now, this is how my LED is. So, this is my light emitting diode and this is my waveguide (()) (20:39) waveguide now. So, when the light is coming out of this, so you cross section wise, it might look something like this, but then you should remember that this is again a flat thin semiconductor wave.

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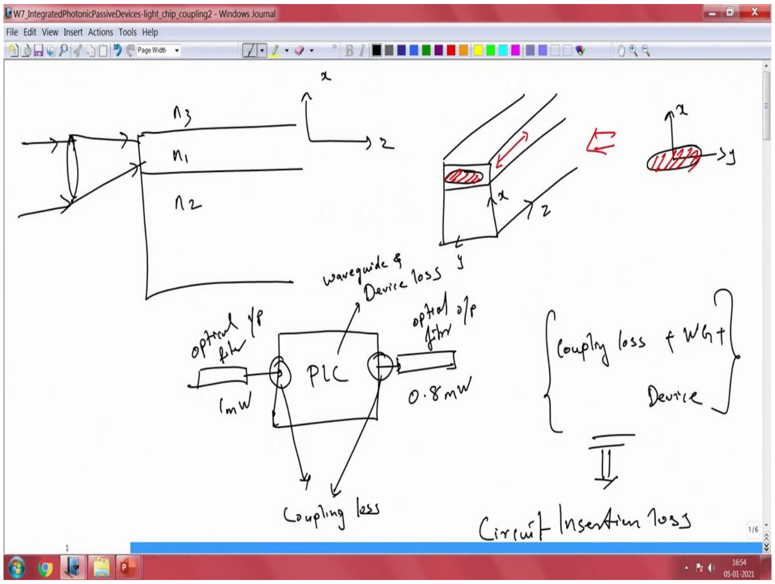

So, it looks something like this. So, if this is the case, the way that I have drawn is nearly the way that you would expect it to be between x and y. So, if we were to put the axis so this is z and this is x and this is y. So, if you look at the cross section of this, so, you will get a mode that is elliptical in nature. So, you have elliptical light out coming from here it will not be a Gaussian like distribution, it will be elliptical.

But then that also suits our waveguide. So the our waveguide is also flat. But then the question here is, what is the overlap between these two? So, that we will anyway capture with our overlap integral. But then before that, the light that is coming out of an LED will also diverge. So, you have a lot of divergence that comes out. So, this is probably the radiation pattern, radiation pattern of our LED.

So, now you can see here the light is emitted at various angles here. And similarly, when it, when it, when it approaches our waveguide, it is also going to excite different angles. So, it is going to launch light at various angles. This is something that we know from our very basic thin firm waveguide understanding that not all the angles are going to be propagating here. So, you have a critical angle only light within that critical angle will be transmitting.

So, the way to to look at that is you have an accepted angle, acceptance angle here. So, there is a a cone here. So, there is a acceptance cone only within this cone, you are going to get all the light propagate through the system, otherwise, the rest of the angles are going to be radiated. So, all this is all radiating outside. So, you should have this particular angle here for it to propagate. So, again, whatever total light available from the LED here may not couple into the waveguide here. So only a subset of that is going to couple.

And that the brightness of our LED that is from from on the left side can be given as the angle, the exit angle that we have from this light emitting diode. So, it is normally follows Lambertian source format, and that is, that is what is shown here, it will be three dimensional in nature. So, now, we can write the power to this coupled into the system, very very simple system by using what is the pattern, the output pattern of the LED along with our waveguide dimension we have.

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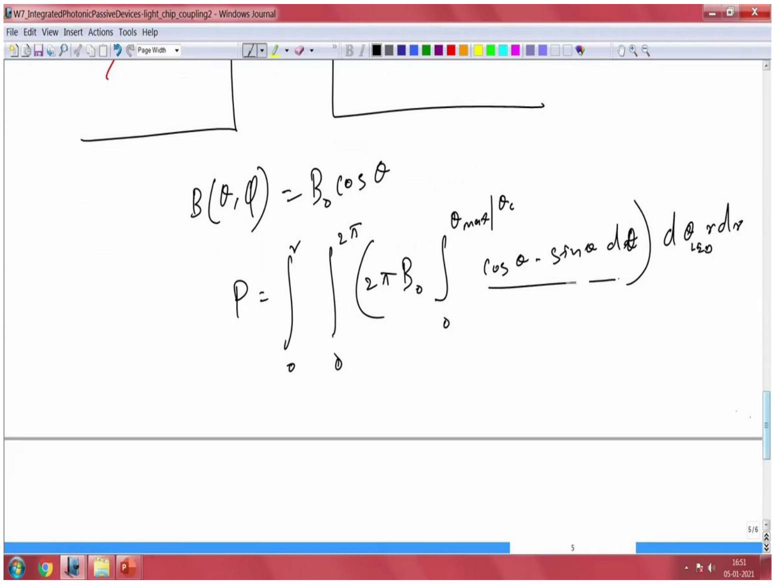

$$B(\theta,\phi) = B_0\cos(\theta)$$

$$P = \iint_{00}^{r2\pi} (2\pi B_0 \int_0^{\theta_{max}/\theta_c} \cos(\theta)\sin(\theta))\, d\theta_{wg} r dr$$

So, in that case, we can write the brightness of our LED as a function of theta and phi. So, this is, this is how the light is distributed. And that is given by very simple theta. So, theta is the angle the divergence angle that we have and this can excite different spatial modes that we have, different theta's we have. So, let us look at what is that overlap integral is going to look like? So, we have kept your LED very close to this and we want to understand how much power will be carried out through this.

So, we can since this is associated with a three-dimensional solid angle here, we we can use cylindrical coordinate system here. So, the power coupled could be written as if if you consider the circular symmetry here, you could have a radius along the radius and along the the angle here will be given as some theta max or theta critical is what you have cos theta sin theta d theta into. So, this is this LED part. So, what is the LED angle of illumination that you have. So, this gives you the capture or the power that that is coming out of the system.

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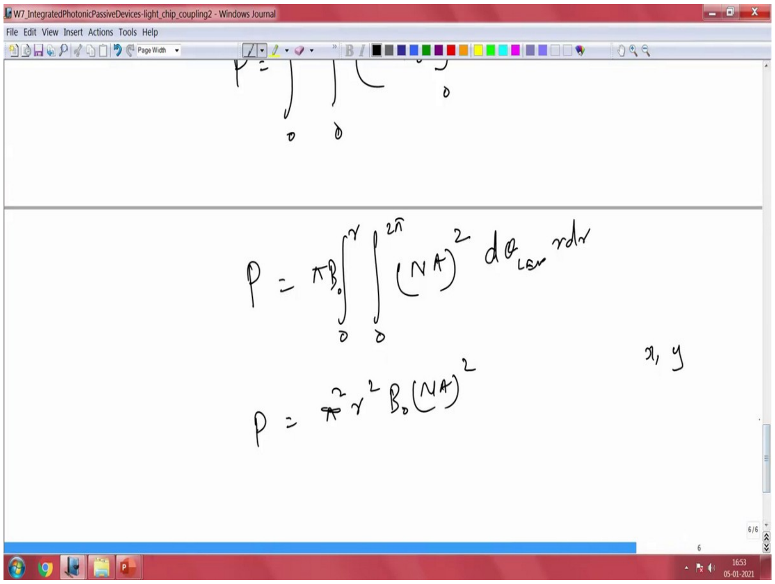

$$P = \pi B_0 \iint_{00}^{r2\pi} (NA)^2 \, d\theta_{wg} r dr$$

$$P = \pi^2 r^2 B_0 (NA)^2$$

So, now, though you have this power coming out we should understand that it all depends on the numerical aperture of this. So, basically what you you end up with is though you have all the power that is required you only get the power that is within the numerical aperture of your waveguide. So, your numerical aperture here becomes very important here. So, you can simplify this and the power coupling will be pi square r square times b naught into NA the whole square.

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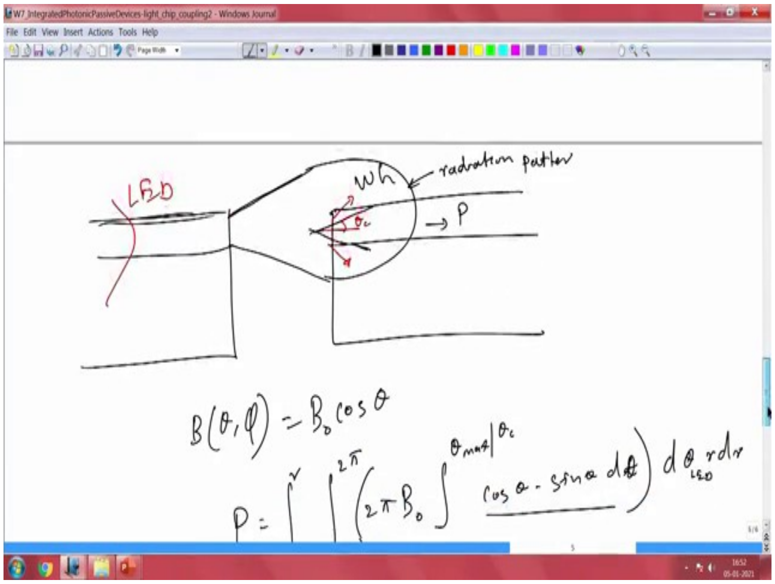

$$B(\theta,\phi) = B_0 \cos\theta$$

$$P = \int^{r} \int^{2\pi} \left(2\pi B_0 \int^{\theta_{max}|\theta_c} \underline{\cos\theta \cdot \sin\theta \, d\theta} \right) d\theta_{LED} \, r dr$$

So, there is a disclaimer here. So, we are considering a circular symmetry for this particular waveguide. So, you have a power coupling where you you it is almost like a fibre. So, in this case, it is it is like a fibre, but then you can instead of R the reason why I am doing this as a for a circular is it is rather easy to do the math for this. If you want to do it for a rectangular waveguide then then you have to do for both x and y. So, everything remains the same, but the integral will be along dx and dy. So, that is the only difference that you will see from this.

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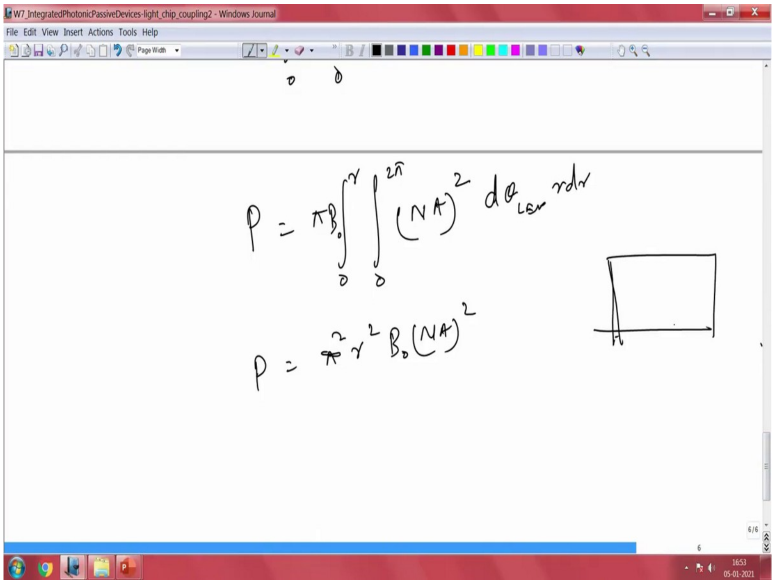

$$P = \pi B_0 \int_0^{r} \int_0^{2\pi} (NA)^2 \, d\theta_{LED} \, r dr$$

$$P = \pi^2 r^2 B_0 (NA)^2$$

$$P = \pi B_0 \int_0^r \int_0^{2\pi} (NA)^2 \, d\theta_{wg} r dr$$

$$P = \pi^2 r^2 B_0 (NA)^2$$

And you can approximate this if your x and y are are identical that means if they are square, then you can use this approximation as well. But nonetheless, this is something you should keep in mind that this assumes that there is a radial symmetry here, that means it is all circular in nature. So, this is how you can arrive at the power that you that you can couple between a very simple LED and a fibre for all practical purpose here, so which has a circular symmetry here.

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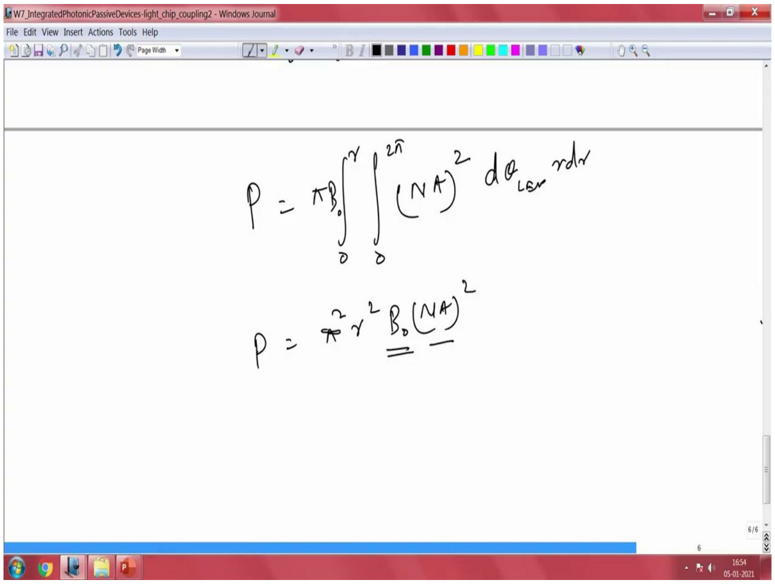

$$P = \pi B_0 \int_0^r \int_0^{2\pi} (NA)^2 \, d\theta_{Lsr} \, r\,dr$$

$$P = \pi^2 r^2 \underline{\underline{B_0}} \underline{(NA)^2}$$

So, and then, if you want to couple light between two different waveguides as I mentioned, you need to look at the propagation constant and find their reflectivity and so on. In this case, it is all taken care because this brightness is is given by the source, what is the source that we have and also the NA tells you about the receiving end. So, the power coupling is taken care with this very simple relation.

You can also elaborate this discussion and continue it when you have a lens-based coupling for example, that is a first drawing that I had, you could have this lens base coupling. What happens in that case? When you take a lens then you should know what is the size of the spot that you are going to take, the spot size should be approximated based on that spot size, you should be able to find whether it is overlapping with the mode here.

So, you will have a Gaussian mode at the end and you will have you will follow the same discussion here. So, we will have a Gaussian mode along with your input field that is your mode that you want to excite this could be fundamental mode. So, you find the overlap between the fundamental mode and your the spot that you have the Gaussian spot you have.

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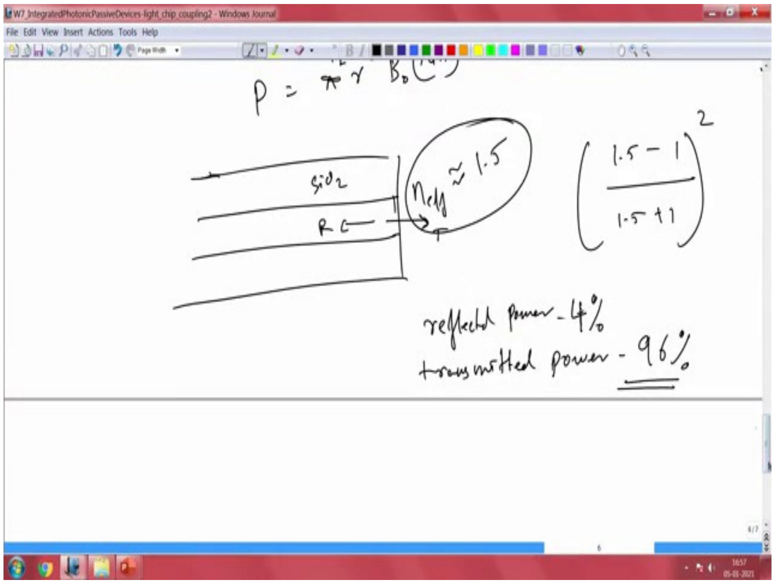

Just to give you an example, how much the reflection will be in a simple system for example. So, if you take a simple fibre so, I have an input fibre. So, the fibre has a silica this is all sio2 and n effective is approximately equal to 1.45 or 5 let us say. So, I want to know how much of power could be transmitted? And how much will be reflected? So, here you can easily calculate this by calculating this factor and it will turn out that you know the power, the reflected power will be, will be about 4 percentage coming from this reflection and the transmitted power will be 96 percentage.

So, even when you have a fibre it is not 100 percentage of the power is available. So, you will only have 96 percentage of the power available when it comes to coupling between the fibre and some other system, let us say. But now, if you are going to increase the refractive index, if you going to increase the refractive index from 1.5 to let us say 3, then you can quickly do the calculation and then see it is not going to be 96 anymore it will be much lower.

So, the higher the refractive index contrast between the systems then your reflection is going to increase and your transmission will reduce and this is a challenge that we have when you take high coupling between high refractive index platforms for example, coupling light into silicon or silicon nitride is is challenging compared to coupling light into a circuit with silicon dioxide.

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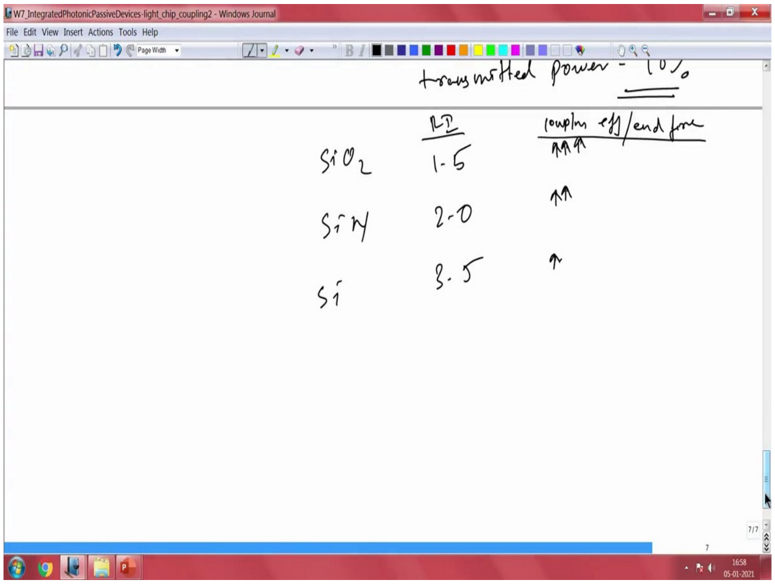

transmitted power - 10%

	RI	coupling eff/end fire
SiO_2	1.5	↑↑↑
SiN	2.0	↑↑
Si	3.5	↑

So, if you there are silicon dioxide, there is silicon nitride and there is silicon. So, silicon refractive in silicon dioxide refractive index is 1.5 and this could be 2 and this is 3.5. And the coupling efficiency this is for end fire the edge coupling without doing any fancy you you will have the highest coupling here and you will have a bit lower here but here the lowest. So, the coupling efficiency reduces based on the refractive index that you have between silicon and also with the environment.

So, that is something we should keep in mind when we are designing for coupling. So, with that we have understood coupling between coupling light into the waveguide from a lateral side. So, you can couple the light from lateral or you can couple from the side in this discussion we saw what are all the implications and design criteria we should take when you are coupling the light from the side. So, with that, we conclude this section on coupling light into the chip. Thank you very much for listening.