Advanced Optical Communications
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Lecture No. #29

Integrated Optics – II

We have been discussing the integrated optical devices. We saw in the last lecture that there are certain materials, the refractive index of them can be changed by applying an electric field, and then we saw the basic device which is what is called the phase modulator, which is realized in the form of a channel waveguide made on this electro optic material. And then, we saw that by using this basic device which is the phase modulator, we can create a device which is what is called the amplitude modulator, and then the intensity of light can be changed in accordance with the data or the signal. Then we started looking in to another device which is what is called a directional coupler, and we saw the physical understanding of the directional coupler.

How the energy exchange takes place between two waveguides, when they are brought in the vicinity of each other? So, we saw that qualitatively when the two channel waveguides are brought close to each other, the evanescent field interacts and because of that, there is exchange of power from one waveguide to another waveguide. We also saw qualitatively that by using the even and odd modes, we can show that even if you excite one of the waveguides, after certain distance the entire power will get transferred to the second waveguide. So, we have now some qualitative or physical picture in our mind, how the energy exchange takes place between two waveguides. And now we are going to do the quantitative analysis of these phenomena of the evanescent coupling, which is the foundation of the directional coupler.

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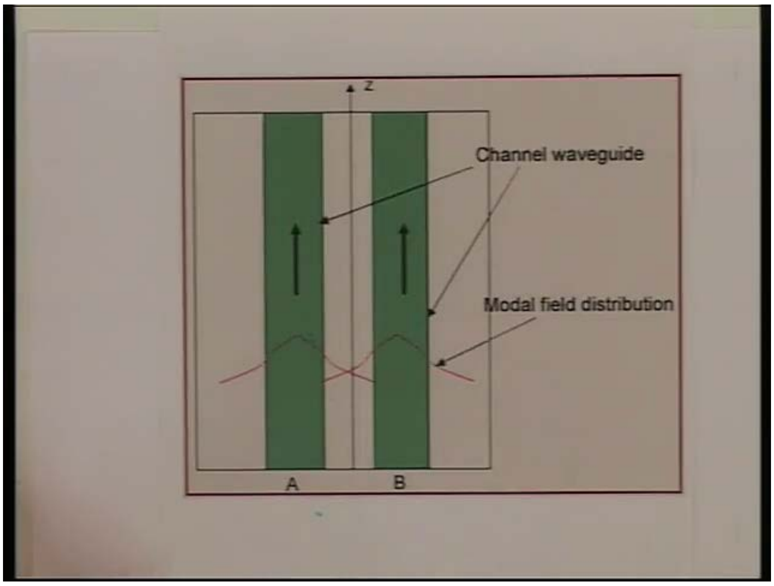

So, now we are discussing essentially a device, which is the directional coupler; in which we have two identical channel waveguides, and we excite one of the waveguide. And then through the evanescent field, we want to know how the power gets coupled to the second waveguide. So, without worrying about the variation of the field in the transverse direction, we simply say that whatever is the field distribution it is identical in both these waveguides. Because we are considering these two channel waveguides identical and that distribution is going to travel along the structure with certain phase constant. So, let us say this direction is z. So, we have now the phase constant in the direction z and we are going to excite one of the waveguides at z equal to 0; that is our definition of the problem. So, firstly let us write down analytically now that if we consider now the propagation of the wave in the z direction, the signal a travelling on this waveguide A will have a variation e to the power minus j beta z; this certain amplitude.

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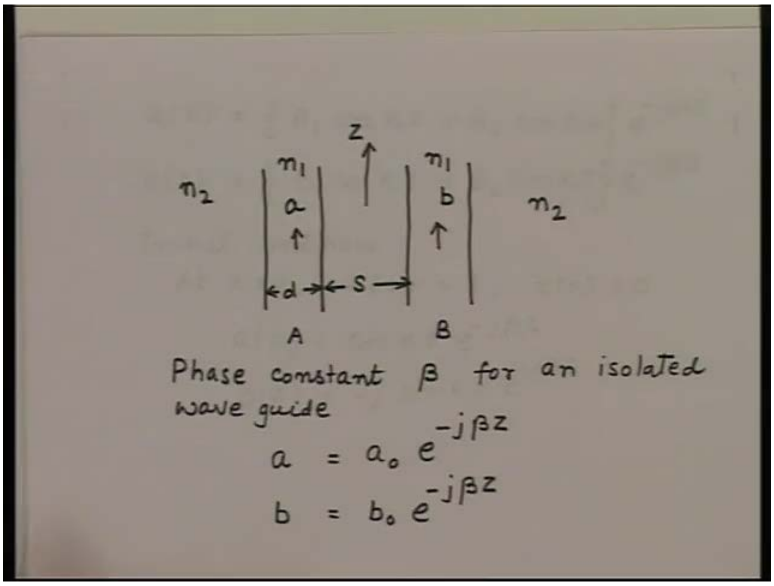

So, now if we consider the two waveguides and let us say in waveguide A, the signal is given by a and we have waveguide B, on which the signal is given by b. So, this waveguide is A; this waveguide is B. And if these two waveguides are identical, then they have a phase constant for individual one which is given by beta. So, we say in the absence of this waveguide, the phase constant with which the wave will travel on this structure is what is called beta. So, we have the phase constant beta for an isolated waveguide. (No audio from 05:08 to 05:19) So, when the waveguides are not in the vicinity of each other, we can write these two a and b. So, a will be some amplitude a 0 e to the power minus j beta z and b will be some quantity b 0 e to the power minus j beta z. And in the absence of any coupling between these two waveguides, a essentially will be governed by differential equation that da by dz will be equal to minus j beta into a.

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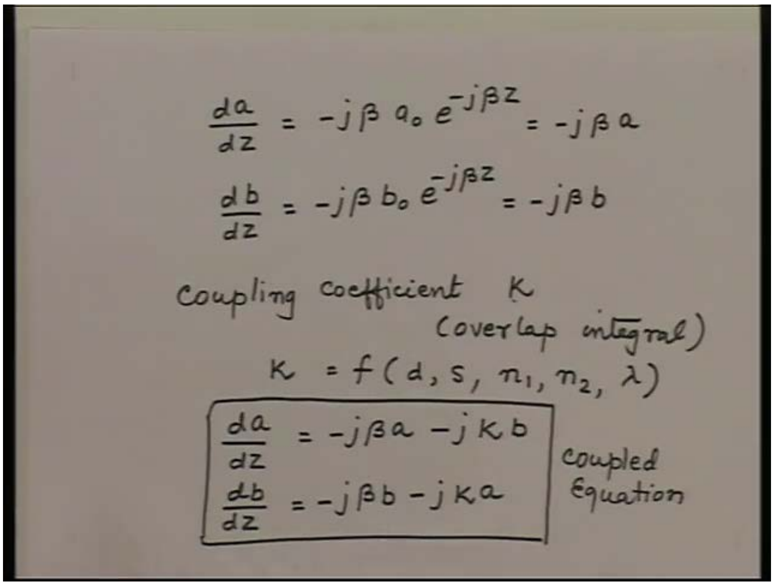

So, if I differentiate this with respect to z, this you can get the equation for a and b as da by dz that is equal to minus j beta into a 0 e to the power minus j beta z. But this quantity is nothing but a; so this is equal to minus j beta into a. Similarly, we can get db by dz that is equal to minus j beta b 0 e to the power minus j beta z; that is equal to minus j beta into b. So, these are the differential equations by which the signals propagating on waveguide A and B are governed, when they are not interacting with each other. But when they start interacting with each other (Refer Slide Time: 04:15) that means when they come in the vicinity of each other, then there is going to be some coupling of the field which will take place from this waveguide to this waveguide.

And since we are having a perfectly symmetric structure, if we have some fields here, they will get coupled to this waveguide by the same phenomena. Let us say we try to characterize that coupling phenomena by a quantity what is called the coupling coefficient. So, let us say we define a quantity coupling coefficient. Let us call that some k and k is a measure of how much field gets coupled from one waveguide to another waveguide. Or in other words, this k will depend upon how the overlap of the two fields modal field take place. See if I have a certain modal field from here, how much is the interception of that field by this waveguide; that will decide how much field is going to get coupled from this waveguide to this waveguide.

So, this parameter is essentially governed by what is called an overlap integral, which essentially tells you how the overlap of the two modal field take place, which essentially lead to the coupling of energy from one waveguide to another waveguide. Now, as we know from our analysis of optical fiber, then the field distribution which is going to be there in this region depends upon many parameters. It depends upon what is the width of this waveguide. It will depend upon what is the distance from this waveguide. Say, it will depend upon this size of this waveguide. It will also depend upon the spacing of the waveguide. It will also depend upon the refractive index of the two materials.

So, let us say if I take a refractive index n 1, n 1 and n 2 and the remaining medium, it will also depend upon the refractive indices n 1 and n 2 and it will also depend upon the frequency of operation or the wavelength of the signal, which is exciting the structure. So, in general we then have this quantity coupling coefficient k that is a function of many parameters; is a function of separation between two waveguides, size of the waveguides, separation between the waveguides, the refractive index of the waveguide and the surrounding medium and the wavelength of operation. And by changing any of these parameters, the coupling coefficient can be changed. We will see later the physical meaning for this coupling coefficient.

But at this point of time, here is a quantity which essentially is a measure of how much fields is going to get coupled from one waveguide to another waveguide. So, now what we are saying is that the da by dz is not only proportional to a; but there is certain thing which is related to b also; that is what is given by this coupling coefficient k. So, we can say that now in the presence of the coupling, we get da by dz; that is original term plus you are having something, which is coming because of coupling from second waveguide. So, we have minus let us say j k into b. So, you have a contribution to a or rate of change of a as a function of z; that is now related to the amplitude of the signal in the second waveguide which is b and their proportionality constant in this coupling coefficient.

Similarly, we can write down for b. So, we have db by dz that is equal to minus j beta b which is the original thing and the coupling term, which is j k into a. So, for the coupled waveguides, these are the differential equations which tell you the propagation of the signal. So, this analysis is called the coupled mode analysis. So, we have here coupled equations between a and b. And if we saw these two equations with appropriate boundary conditions, then we will have analytically the variation on the fields on the two waveguide which are interacting with each other. So, this we can analyze essentially by decoupling these equations and that is done by taking one more derivative of this and substituting from the second waveguide; second equation here.

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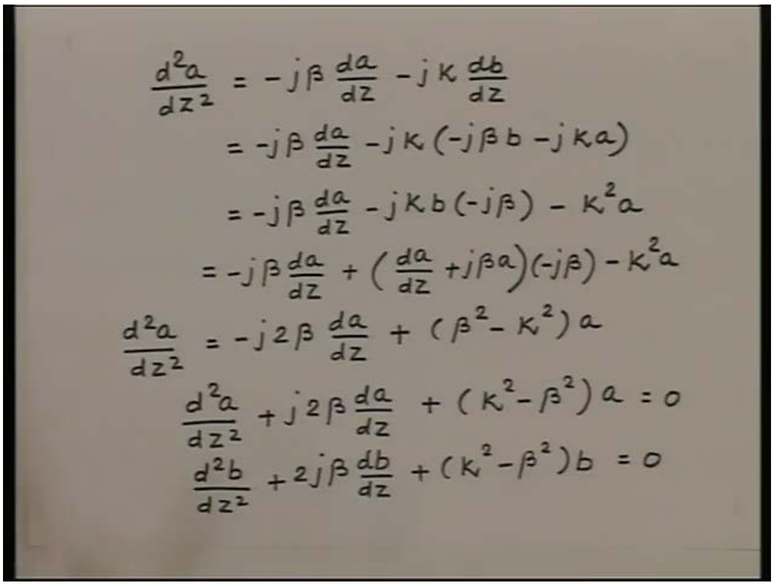

We can get d 2 a by dz square; that is I am differentiating this equation now with respect to z. So, you get minus j beta da by dz minus j k db by dz; beta and k are not function of z. So, we get here minus j beta da by dz minus j k db by dz. We can substitute for db by dz from this equation. So, this da by dz, this quantity d 2 a by dz square will become minus j beta da by dz minus j k minus j k into minus j beta b minus j k a. I can simplify this to write as minus j beta da by dz minus j k b into minus j beta this term minus k square into a and now I can substitute for minus j k b from same equation here. So, minus j k b will be equal to da by dz plus j beta a. So, I can substitute for that.

So, this will be equal to minus j beta da by dz plus this we can write now as da by dz plus j beta a; that is minus j k b from this equation multiplied by minus j beta minus k square a. Simplifying this this term here minus j beta da by dz can be combined with this. So, you get minus j 2 times beta da by dz plus this gives plus beta square. So, this is beta square minus k square a; that is d 2 a by dz square. Bringing all the terms on one side, essentially we get now the differential equation, which is for a. So, this is d 2 a by dz square plus j 2 beta da by dz plus bring on this side. So, this is k square minus beta square a; that is equal to 0 and the same equation essentially will be there for b also; because these two equations are exactly symmetrical equations.

So, whatever equation we got for a, exactly identical equation we will get for b also. So, we will have the equation for b also, which is identical d 2 b by dz square plus 2 j beta db by dz plus k square minus beta square b; that is equal to 0. So, what we now find is that after decoupling these two equations the coupled equation which we had initially, we get a second order differential equation which governs a and b. We can write down the solution for this. This is just very simple differential equation; this quantity is constant; this quantity is constant. So, they are second order differential equation with constant coefficients.

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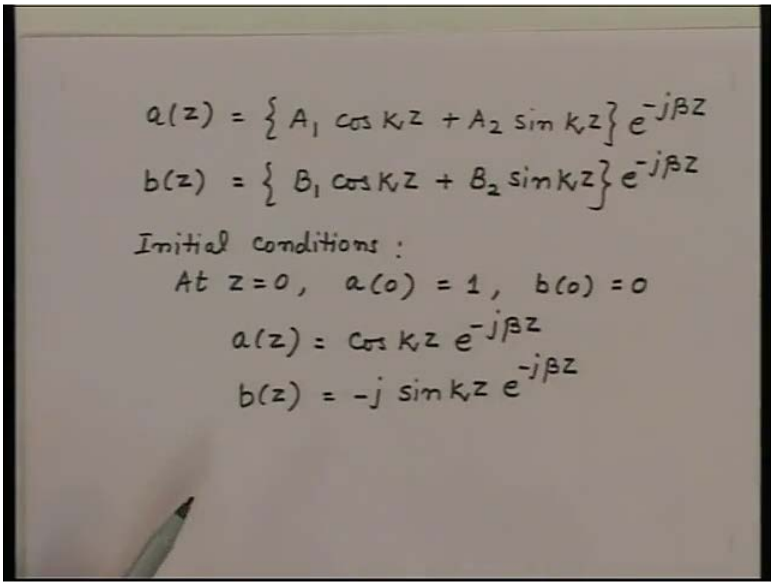

So, we can write down the solution to this equation for a and b. As a as a function of z that will be equal to some arbitrary constant A 1, which is to be evaluated; cos of k z plus A 2 sin of k z e to the power minus j beta z and b (z) will be identical with different arbitrary constant B 1 cos of k z plus B 2 sin of k z e to the power minus j beta z. So, up till now, the analysis has been very general what we have said is we have this two waveguide, which are interacting with each other. We write down the differential equation. We introduce a term what is called the coupling coefficient. Decouple the equations and then we get a general expression for the signal a and b on these two waveguides.

Now, we can apply the boundary conditions to this waveguide (Refer Slide Time: 04:15) and the boundary condition will be that initially we are exciting only one of the waveguides. So, what we are saying that let us say at z equal to 0, we have excited only this waveguide and nothing was excited inside this waveguide and this waveguide is simply brought in the vicinity of this waveguide. So, at z equal to 0, then we have excitation for this waveguide and without losing generality, we can say that it is excited with an amplitude unity; whereas, there is no excitation which is given to this waveguide. Now, we are having the initial conditions for this case that at z equal to 0, we are exciting waveguide a.

So, a of 0 that will be equal to 1 and no excitation is given to waveguide b; so b of 0 that will be equal to 0. If you apply these boundary conditions to this, we can essentially calculate this arbitrary constants and then from there, we get a (z) is equal to cos of k z e to the power minus j beta z and b of z will be minus j sin of k z e to the power minus j beta z. So, what do you see now is that if I consider one of the waveguide let us say waveguide a, as I move along this waveguide in the z direction and z direction is along this, which is z direction. We have a phase variation which is e to the power minus j beta z. So, the wave is travelling in this direction with phase constant beta.

But what we now find is that the amplitude of this wave is having a variation, which is cosine of k z. Similarly, variation on the second waveguide for the amplitude is sin of k z. So, earlier when the coupling was not there, we had a variation which is simply a 0 e to the power minus j beta z. So, the amplitude of the wave was remaining constant as they travelled. But now the amplitude of the wave is going to change along the length of this waveguide and along the length of this waveguide also. So, now when the interaction between the two waveguides starts taking place, essentially I have the variation in the amplitude of the signal and the phase which is essentially representing a travelling phenomenon. So, that is what is the variation essentially we get here; this thing essentially can be plotted now the amplitude.

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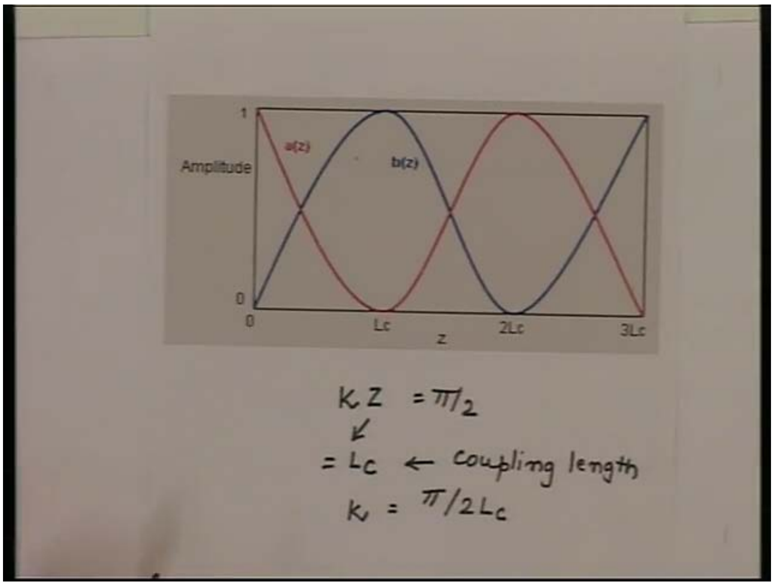

See, if I take the thing and plot the amplitude for these, we get a amplitude which will look like that. So, here is the variation this red color; that is the variation for a and here is the variation blue, which is for the signal b. So, at z equal to 0, the whole signal was on waveguide a. So, we had amplitude 1. Slowly as the z increases, this quantity becomes smaller and smaller and when this quantity is equal to pi by 2, that time this will become 0 and at that time, this will become equal to 1. So, what we see that is what we have seen qualitatively that as the signal starts propagating other after certain distance, the entire power has been shifted to the second waveguide and that is what is shown here.

That if I go to a distance such that (Refer Slide Time: 18:22) the k z is equal to pi by 2, then this quantity has become 0 and this quantity has become 1. So, this is the distance when k in to z becomes equal to pi by 2. So, that is the distance at which essentially the entire power which was in waveguide a has been shifted to waveguide b. So, this condition will be satisfied for z equal to we call a length what is called the coupling length. So, we have this characteristic parameter now and now we can give some meaning physical meaning to this quantity coupling coefficient which we defined. That from here, then we can write the coupling coefficient k that will be equal to pi divided by 2 L c.

So, for this device, firstly we see there is a length characteristic length over which the entire power is shifted from the first waveguide which was originally excited to the second waveguide. This length we call as the coupling length and the coupling length is now related to this coupling coefficient; they are inverse of each other. So, larger the coupling coefficient; that means stronger is the coupling between the two waveguides, over a shorter distance this exchange will take place. But the important thing to note here now is that no matter how small the coupling coefficient is. If the waveguides are permitted to interact with each other, there will always be a length over which entire power will get shifted to the second waveguide.

So, the characteristic parameter for the directional coupler is the coupling length and that is the length, where the power completely shifts from one waveguide to second waveguide. Now, if I let the interaction continue on this waveguides, then whatever was the situation originally (Refer Slide Time: 04:15) with this waveguide after a coupling length, entire power is here now and there is no power here. So, the situation is exactly reversed. As if the waveguide is excited here with unity and there is no excitation here, so slowly the power starts travelling back. And after two coupling lengths, again the entire power will come back to this and no power will remain here; that is what is shown in to this.

That if I go to one more coupling length, then the power in waveguide b would be 0 and whole power would again come back to waveguide 1. So, what we are now finding is (Refer Slide Time: 02:54) that if we consider a couple structure like this and you excite one of the structures, slowly the power will get shifted to this. After same distance, the power will get shifted back to this; again the power will get shifted back to this; again back to this; back to this and again so on. So, that means if I take the length which is equal to one coupling length, the power effectively has gone from here to here. Whereas, if I take the length which is equal to two coupling lengths, then the power would go here and come back as if nothing has happened.

Because I will connect the power here, you receive the power here. So, you will see that internally power is removed this way. But if I see externally, this is a module essentially power has connected to this waveguide and appears at this waveguide; say as if this waveguide has not done anything. So, now one having understood these phenomena now, that power keeps moving from one waveguide to another. One can now develop various devices based on the directional coupler. See you will see that directional coupler is a extremely powerful device which you have developed. Because now we can build now the device is around this. So, that the power can be tapped or can be connected from one port to another. And we can develop complex switching kind of devices by using this basic module of directional coupler.

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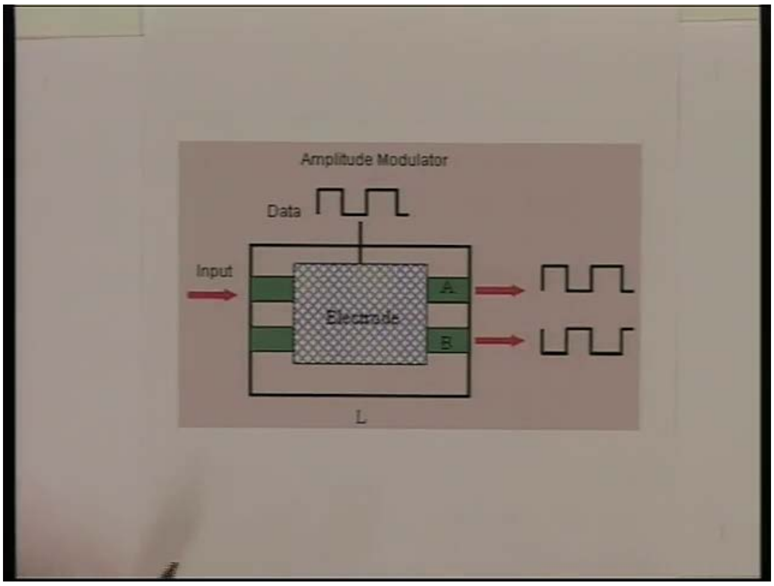

So, let us say the first thing which can come to our mind; we started the whole discussion from the amplitude modulation that we have this Mach-Zehnder interferometer and we wanted to see do we have any other possibility of creating amplitude modulation.

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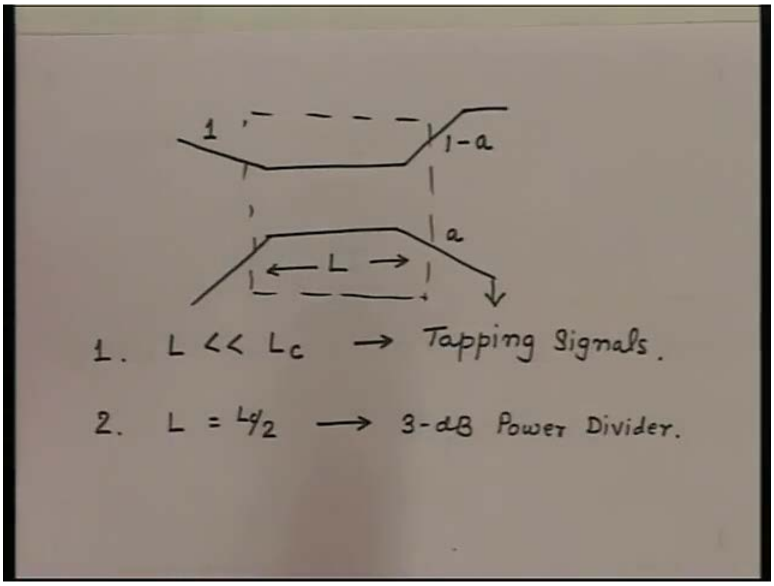

So, firstly without getting in to this, let us first see that I have now the coupling device which is like this. The waveguide comes from here; from here and they are made to couple with each other. So, since they are every close to each other, the interaction will take place. Then if you separate them out, the separation between them is very large; so no interaction will take place between them. Now, if you take this length L which is the actual length of the device; if L is much much smaller compared to L c, let us say situation 1 that the actual length over which the interaction takes place is much smaller compared to the coupling length corresponding to these dimensions and separation.

In that case, the small amount of power will get connected here and most of the power will still remain with this. So, we will be operating somewhere (Refer Slide Time: 23:21) somewhere here very close to this. L is much much smaller than L c. Most of the power will still remain with waveguide a and the small amount of power has been transferred to second waveguide. So, when I get here if I start with 1 input here, a small fraction of power a will appear here and here I will get a power 1 minus a. So, essentially now this configuration can be used for tapping the optical signal. So, you can use this for tapping device.

So, whenever we are having let us say optical highway which is running and we want to tap the small light output from that without disturbing the flow, essentially we can introduce this device in between. The signal will keep flowing practically unaffected on this and the small amount of thing can be tapped from this. So, you can get a small output from this device. If you make the L substantially large in the second case, let us say I make L is equal to L by 2 L c by 2. So, if this length is half of the coupling length, then half the power would have come to this point and beyond the point is separate these waveguides. Now, the power cannot go back; it will remain with this.

So, in this situation essentially half power appears here and half power remains with the original waveguide. So, in this case essentially we got a device what is called the power divider; because whatever power is coming here, half the power is connected to this pole and half the power is connected to this pole. So, we can treat it like a closed box which has 4 ports and I connect the power to this. At this output ports, I get the power which is half, which is 3 dB down compared to this. So, essentially we got 3 dB power divider. So, in this case we get 3 dB power divider. So, a simple passive coupled structure can be used for tapping the optical signals in the optical network or it can be used for distribution of the power.

So, we can have a 3 dB division here; then we can put one more here, which will give 3 B 3 dB down. So, we can have divided into 4 parts and so on. So, essentially by using combination of these, we can build the structures from 1 to n dB distribution of power. So, instead of huge coupler, we can now use this device for dividing the power in to different poles. So, these two are the possibilities when we are using the directional coupler more like a passive device. So, once the directional coupler is made, we know its length relative to the coupling length. So, it will function in a certain way; either it can tap a small amount of power or if L is equal to L c by 2, then power be divided equally into 2 ports.

Or if I take L equal to L c the third possibility, then essentially the power will get transferred to this and you will get a signal getting connected from here to here. But when the signal is getting connected from here to here for L equal to L c, if you connect the signal at this point, that will also have connected getting here; because now L is equal to L c. So, if I consider the two signals which are in the same wavelength, one connected here; one connected here. This signal will get connected to this and this signal will get connected to this. So, if you wanted to exchange let us say the signal between the two optical communication systems, we can simply pass through this device and essentially I have transferred the signal from this to this and from this to this.

So, I have created what is called a cross-over of the signal, if the length is equal to coupling length. So, these are the three primary things you can get by a passive operation of the directional coupler. Now, let us say we make this directional coupler on an electro optic material like Lithium Niobate and if we do that, then we can change the refractive index of the material by application of the electric field. If the refractive index of the material is change, then as we saw earlier the coupling coefficient which is the function of the refractive index of the channel waveguide and the surrounding medium that will change. If the refractive index changes, the coupling coefficient changes; the coupling length would change.

So, for a physical length given, if we apply the electric field to this and if this device was made on a electro optic material, then L c will change and consequently, this relationship will change. So, I may have a situation when the field was not applied, this thing is there; but when the field is applied suppose L c reduces significantly, so that L c becomes equal to L c by 2. Now, the half power can be connected to this. So, essentially now by applying the electric field to this device, I can dynamically change the characteristics of directional coupler and that now introduces the whole new dimension of devices; because now we can change the characteristics of this power coupling from one to another in the dynamic sense.

Because we can apply the electric field, which can vary as a function of time and therefore, this coupling characteristics would change as a function of time. And in that case, then the first application which would come to your mind would be the amplitude modulator. (Refer Slide Time: 29:38) So, here is the directional coupler. These are the two channel waveguides A and B. We are exciting this waveguide with optical signal here and we have electrode. This is a electro optical material now and let us say, we apply some voltage data to the electrode and this electrode would change the refractive index of the material.

And if we choose the dimension of the waveguide in such a way that when the voltage is applied, you get the length is equal to coupling length; whereas when the voltage is not applied, that is equal to two coupling lengths or vice versa. Then when this 1 is applied, you will see that the signal will get connected to this. The whole power will get transferred to second waveguide or vice versa depending upon the characteristic which we have. So, for one of the states, the power will get connected to this waveguide. When other state comes, the power essentially comes back to the second waveguide. So, by switching now the voltage across this electrode, we can connect the power here or here.

Say, if we monitor the output only from one of the ports, infact it will have the variation intensity exactly same as this data. So, when this is 1, we have a light connected here; when this is 0, light is connected here. So, no light is connected here, so this is 0 and on the other port, you will get compliment of it. So, when this is 1, this is 0; when this is 0, this is 1. But if we consider one of the outputs, essentially we have created amplitude shift keying or intensity modulation. So, by making the directional coupler on an electro optic material substrate, we can create the intensity modulation or the amplitude shift key. We can develop further based on this principle now.

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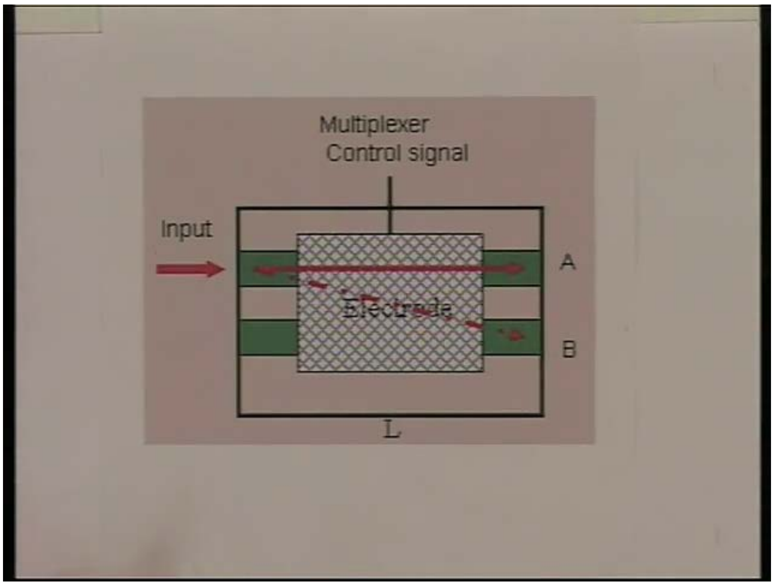

So, again we take the same configuration here and now you got a electrode signal which need not be data; but which is certain voltage which you can change between two levels and the level change, essentially now changes the coupling length. And because of that, for a given physical length of the directional coupler, the signal may get transferred to this waveguide or may remain with the same waveguide. So, essentially by applying this voltage or not applying this voltage, I can connect the optical signal either to this port or to this port or in other words, we have realized a multiplexer in optical domain. So, I can connect the light from either this port or this port by applying the control signal to the electrode. And then again I can build around this; so that, I can do the complex multiplexing of the optical signal by giving proper control signals. So, you can have amplitude modulator; on the same principle, you can realize the multiplexer.

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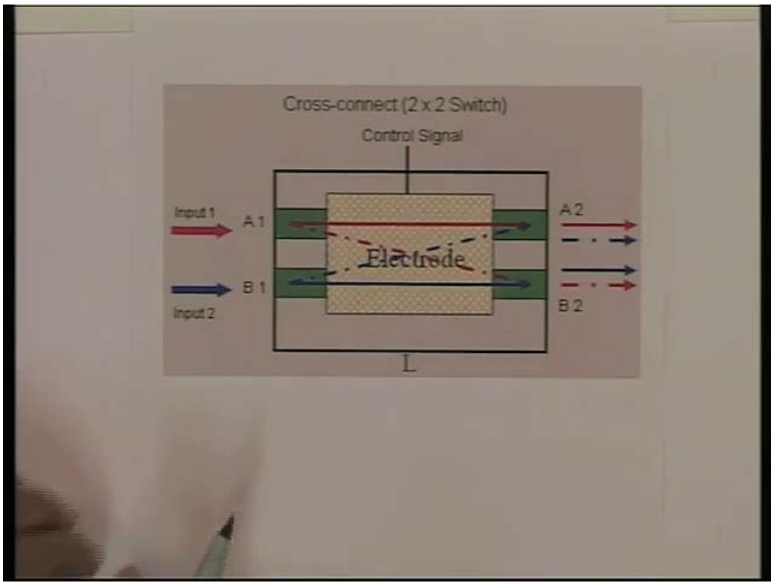

You can go further and sort of see the same principle can be extended to create what is called a cross-connect. So, again idea is same. This is the input which you are giving here, red input. Now, if the control signal is such that this gets connected to this and when the control signal is not applied, this will get connected straight to this. So, by changing the control signal, I can connect to this port or this port that for the thing which we saw for multiplexing. But at the same time suppose I have another input which is connected to this port, then when this signal get connected to this; this signal will get connected to this. So, in one of the states of the control signal, you have a cross-connect created like that. In another state when this gets connected to this, at that time this will also get connected to this. So, essentially what we have done is we have created a cross-cross connect, which is the 2 by 2 switch; which two states, one is what is called a bar-state and other one is called a cross-state.

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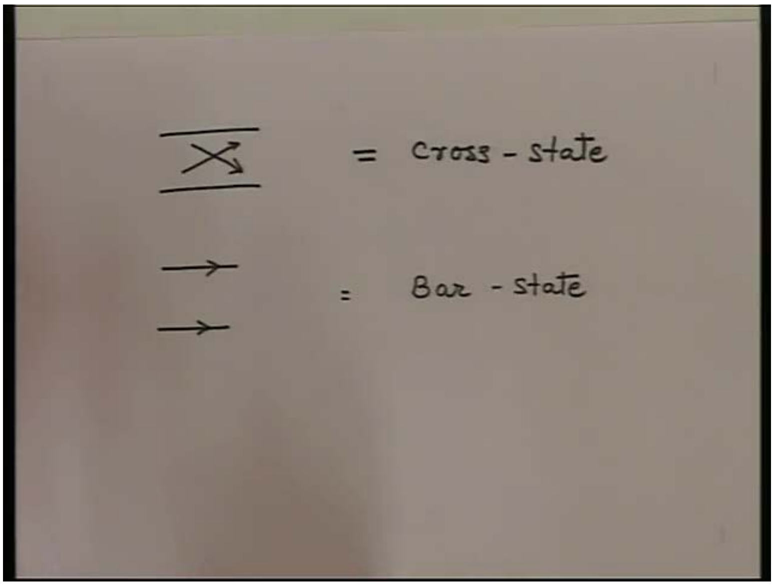

So, we have situation like this, where this gets connected to this; this gets connected to this; this we call as the cross-state and other situation is this is connected to this; this is connected to this; this we call as the bar-state. And that is what essentially you need in any of the switching device. What you need is either I should be able to connect in a cross fashion or we should be able to connect in the bar fashion. If you could do that, then I have got a basic switching model with us, which can dynamically either connect this way or connect this way. So, if we take the directional coupler and make this on an integrated optical device, then by applying the control signal either I can put the connection in to cross mode or you can apply by not applying the signal, you can put the signal in to the bar.

Once you are having this basic configuration, then we can build the complex switching network around it. So, what we have done essentially by this that now we have created a mechanism, by which the light can be routed to different destinations. It can be switched from one port to another. So, earlier if you wanted to switch the signal, we had to convert the signal in to electronics and then we could do switching. Now, we see by using this device without converting the signal, right in optical domain we can switch from one port to another port and the light can be routed as per the desire. So, now let us say suppose we had a 3 by 3; 3 inputs and 3 outputs which were there, we have a situation something like this.

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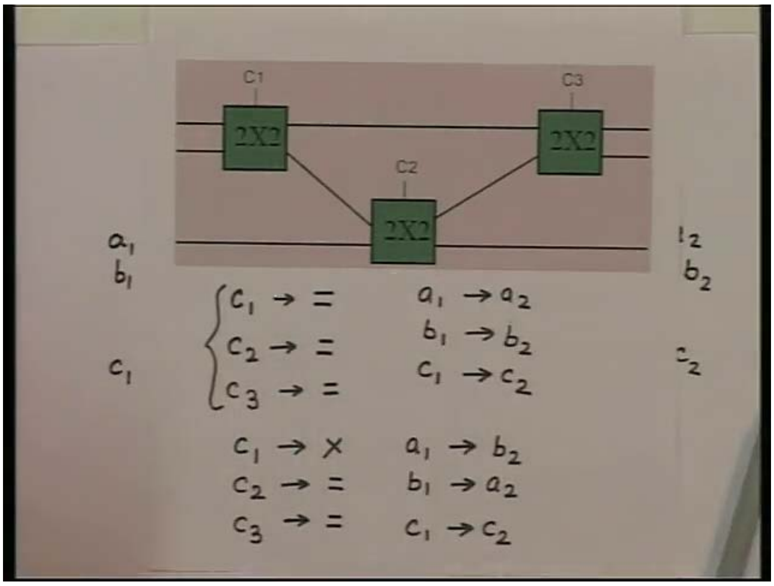

So, there are three signals which are coming. I can put one 2 by 2 switch here; I can put one 2 by 2 switch, another 2 by 2 switch and I can make the connections like this. So, let us say suppose we had three inputs; let us say a 1, b 1 and c 1 and I have corresponding outputs which are there a 2, b 2, c 2. If c 1 is in bar state, a 1 will get connected here; b 1 will get connected here. So, let us say we have c 1 in bar state. If c 2 also is in bar state, then we get b 1 getting connected here and b 1 comes here; c 1 will come here; this is in bar state. So, I have c 2 also in bar state. So, c 1 appears here; b 1 which came here appeared here and let us say c 3 also was in bar state.

So, I have c 3 which is also in bar state. So, a 1 will get connected to a 2; b 1 will get connected to b 2 and c 1 will get connected to c 2. So, we have connection a 1 to a 2; b 1 to b 2 and c 1 to c 2. Suppose we take c 1 in the cross state, so I apply control signal to this; so that, it goes in to cross state and these two still remain in the bar state. So, we say this is one possibility. So, c 1 is in cross state; c 2 is in bar state and c 3 is in bar state. Since now c 1 has cross state, so a 1 will get connected here; b 1 will go here and other two are in bar state. So, we have got a 1; so bar state a 1 is connected here. Through that, it is connected here.

But this is bar state; whereas, b 1 which came here through the bar state it got connected here. So, now what we got a 1 is connected to b 2; b 1 is connected to a 2 and c 1 is connected to c 2. So, now see by doing this complex architecture which we are developing now, we can have n by n switch created by using this basic device; whereby appropriate control signals any of the input can be connected to any of the outputs. And by proper number of this 2 by 2 directional couplers, you can essentially create a non-blocking switch and the optical signals can be routed and switch by using appropriate control signals to this device.

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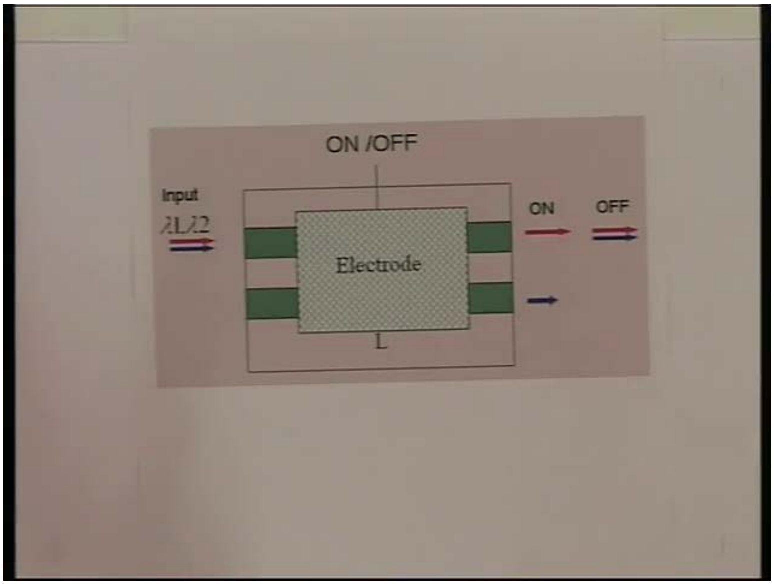

Another important application which you can have for this one is for the wavelength dependent switching and that is, as we have seen that the coupling coefficient depends upon the wavelength. So, the coupling length will depend upon the wavelength. So, even without the electrode, if we design this in such a way that for one of the wavelengths, you have this length equal to coupling length and for another wavelength, this is even multiple of coupling length. Then this signal will get connected here; because it is even multiples for red and odd multiples for blue. So, if you design the device in such a way that for one of the wavelengths, the length of the directional coupler is equal to odd multiples of the coupling length and for other wavelength, it is even multiples of coupling length.

One of the wavelengths will appear here and other wavelength will appear here. So, essentially we have created a wavelength filter. We can separate out two wavelengths by using this device. We can go further and say if we make this device on the electro optic material, then I can change the coupling length and then I can either connect the two wavelengths to this port. So, for both the wavelengths, this length is even multiple of coupling length and by applying certain voltage, one of the wavelengths becomes the odd multiple; other wavelength, it becomes even multiple. So, that wavelength will get connected here and if we do not apply signal, then both the wavelengths will appear here.

So, we have created essentially a wavelength dependent dropping device. So, the signals were coming which were flowing on this. Essentially by applying a control signal, one of the wavelengths is dropped at this location. So, in a complex WDM network where large numbers of wavelengths are moving, if you want to drop a certain wavelength at a certain destination, we can introduce this device; apply the control signals in such a way that the particular wavelength can be dropped at that junction and essentially we have created a wavelength drop multiplex. So, what we have seen essentially in this lecture is that we have a device what is called the directional coupler, which works on the principle of interaction of the fields the evanescent fields.

And this device essentially can transfer power between one channel waveguide to another channel waveguide without physical contact between between them and then by innovative designs, we can create the 3 dB power dividers, we can create tapping devices, we can create amplitude modulators, we can create simple multiplexes, we can create add drop multiplexes, we can create wavelength filters and a variety of devices. So, infact now these integral optical based devices which we have discussed in last two lectures. They give you now the basic switching modules, which can be used for routing optical signals in the complex WDM network.