Fiber Optics

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Lecture – 28
Optical Fiber Components and Devices- I

After having understood the propagation characteristics of optical fiber, now we would look into how we can make components using optical fibers. The question is why do we want to make components using optical fiber and what kind of components do we require.

We are going to use this optical fiber in telecommunication system or we can also use it in a sensing system. So, when we use the fiber in a system we require several components. And if we have the components which are all optical then the data rate is not compromised also the complexity of the system decreases. So, we would like to have as many components as possible in optical domain itself and preferably in optical fiber, because when we make components out of optical fiber then it is easy to splice them with the transmission fiber or sensing fiber, the insertion loss is low compatibility is better.

So, in the next few lectures we are going to study some components and devices made in optical fiber itself or using optical fiber. What kind of components or devices we want to make or we want to study here are switches, and then we have power splitter, wavelength filter.

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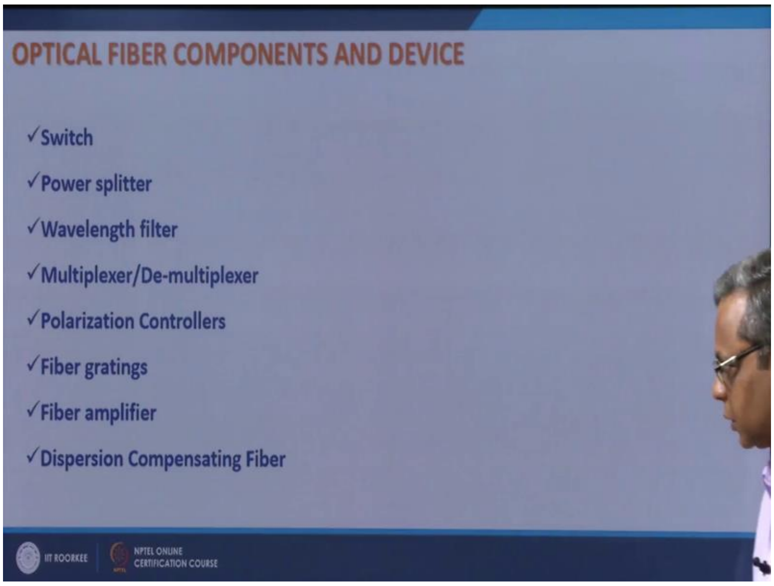

We may require multiplexer, de-multiplexers, polarization controllers, fiber gratings, fiber amplifiers and dispersion compensating fiber. So, we are going to study these components and devices in the next few lectures.

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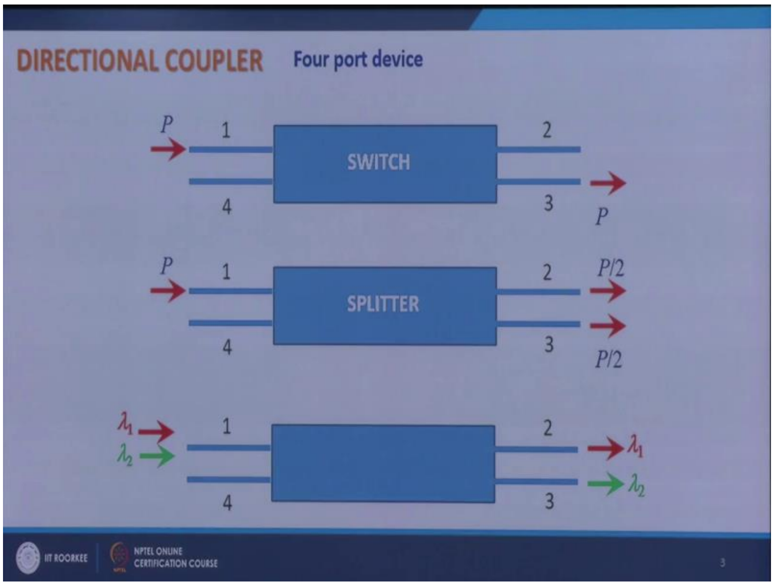

A very basic components and very important component using optical fiber is directional coupler. What is the directional coupler? It is essentially a 4 port device. So, we have a fiber here a fiber coming out here, a fiber coming out here, and fiber going inside here. What we can have using this well if we launch power P in port 1, depending upon the parameters of this device or this component the entire power may come out of port 3, then it is basically a switch. You are switching power from port 1 to port 3. It may also happen that if you launch power in port 1 then 50% power comes out of port 2 and 50% out of port 3, then it is a power splitter.

Or you can have a desired ratio of power here. You can also have if you launch two wavelengths λ_1 and λ_2 in port 1, then it may happen that λ_1 comes out of port 2 and λ_2 comes out of port 3. Then such a component is de-multiplexer. You can also input λ_1 from here and λ_2 from here and both the wavelengths may come out of port 1 then it is wavelength multiplexer or WDM coupler. And all these components can be made out of directional coupler.

So, what is a directional coupler if we have 2 cores which are put together very close to each other and we launch light in core 1.

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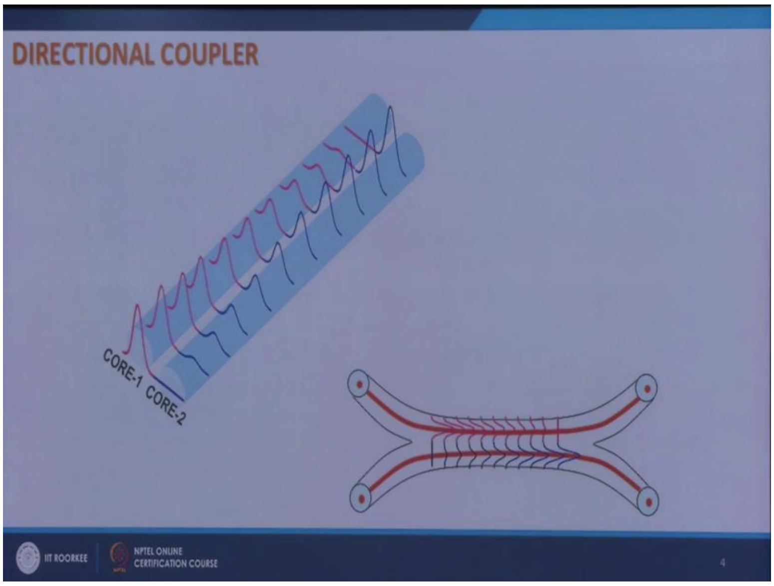

Then as this light propagates through optical fiber this composite system then, then there is a redistribution of power between the 2 cores and after a certain length all the power will come out of the other core. So, there is a switching of power from core 1 to core 2. So, if I look it look at it as a 4 port device then this is port 1, port 2, port 3, port 4, and if I launch light in core 1 then light may come out of core 2 in the output end.

How does it work? If I have 2 well separated course of course, there is a cladding.

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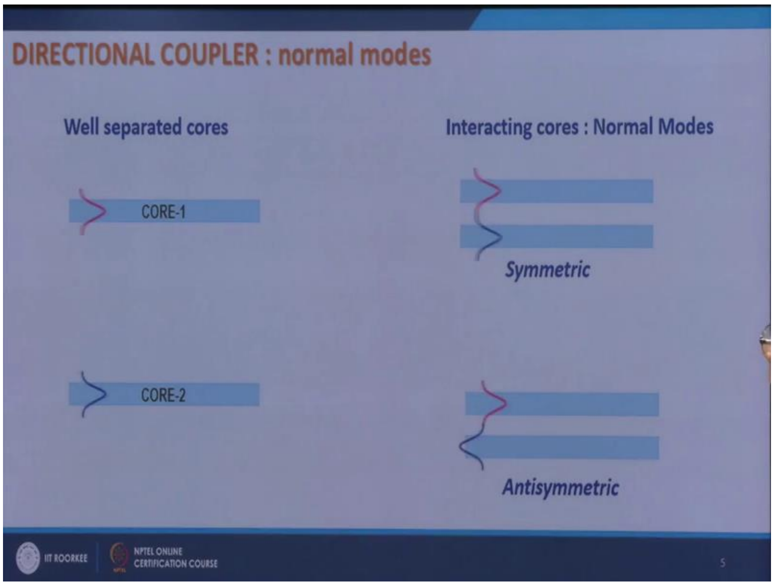

So, if I have 2 fibers which are very well separated and these are single mode fibers, then this fiber supports this mode this fiber supports this mode. And propagation of light in this fiber is not affected by the propagation of light in this fiber, because they are very well separated. But if I bring them closer then what may happen that now this is core 1.

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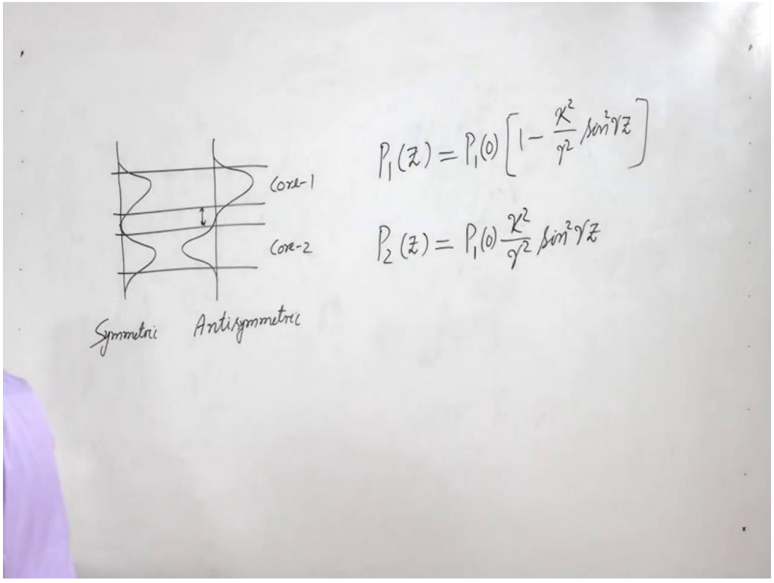

And this is core 2 then this fiber has mode which is like this, this fiber also has a mode which is like this.

So, these 2 model fields may combine like this, if the separation between the 2 course is not very large. So, there are there is possibility combining these 2 fields in 2 ways, one way is they combine like this, another way is that the field in one core is like this and in another core it is like this. So, these 2 fields may combine like this or like this. We can see that this is symmetric field this is symmetric about this point the middle point. And this is antisymmetric. Then what happens is that when you bring 2 course together then this is not the mode of the composite system. The light in this core is affected by this core and the light in this core is affected this core.

So, these are no more the modes of the system that is if I launch this pattern it will not propagate as it is it will not retain it is shape. Similarly, if I propagate this distribution in this course it will also not retain it is shape. So, these are no longer the modes of the system, but now the modes of the system are this and this. So, if I launch this distribution then it will retain it is shape. It will propagate along the composite structure without any change in it is shape. And it will propagate of course, at certain phase velocity. Similarly, this distribution will also propagate without any change in it is shape. So now, the modes of the composite system are this and this, and these are known as normal modes of the system or super modes of the system.

So now if I launch this pattern into this core then this can be understood as the super position of these 2 modes. When I launch this it means I am exciting this mode and this mode equally, because you can see if I add them up then this plus this will give you the power in this core while they will cancel out. So, there would not be any power in this core.

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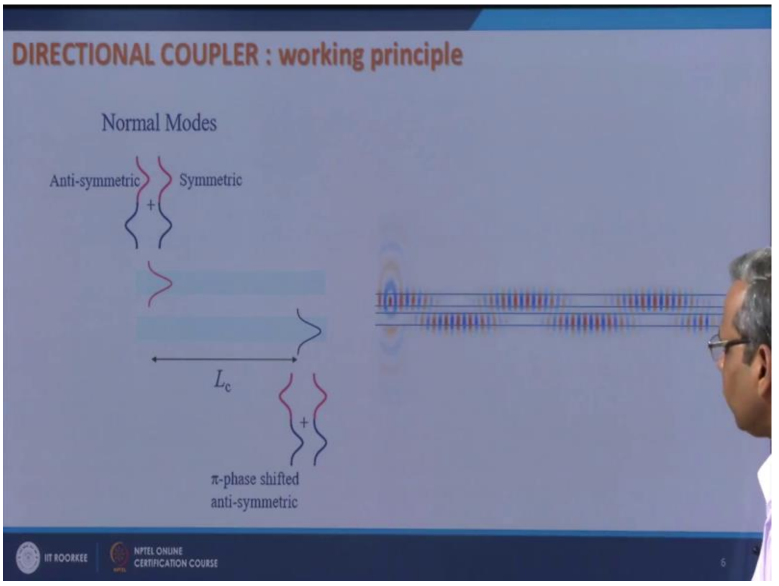

So, exciting core 1 with an appropriate field pattern is equivalent to exciting symmetric and antisymmetric modes equally.

Now, since these are the modes of the system they will retain it is shape. So, I can understand the propagation of this in the composite system in terms of propagation of symmetric and antisymmetric modes because they retain their shape, but they have different velocities. So, as they propagate, there is a phase shift accumulated between them and if it any intermediate distance I want to know what is the field distribution then I will have to superpose these 2 modes with their accumulated phase shift. And that will give me the resultant field pattern.

Now, if after a certain length the phase shift accumulated between them is pi then effectively this mode flips with respect to his mode. So, if now I am interested in finding out the resultant then the super position of these 2 will give you cancellation of fields here and addition of field here. So, the resultant field would be only in this core and no field would be in this core. So, this is how there is switching of power from one core to another core.

So, if you launch light into this, then after a certain distance which is known as L_c the coupling length. The minimum length at which the entire field couples from core 1 to core 2 is known as coupling length, then at this length entire power will get transferred into the second core. I am assuming that these 2 corers are identical. If I let it propagate further then it will switch back to core 1 and then again to core 2; so there would be periodic switching of power between the 2 cores.

I can understand this with the help of a very simple example of a couple pendulum. I can take an analogy of couple pendulum. So, this is the refractive index profile of the composite system, where I have 2 cores and this is the symmetric state and I can also have antisymmetric state.

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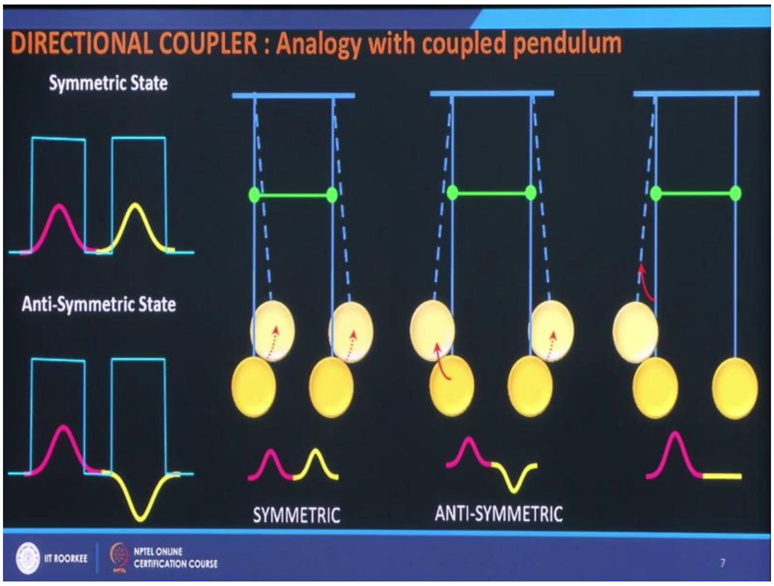

So, I have symmetric mode and antisymmetric mode of the system symmetric normal mode and antisymmetric normal mode. This is equivalent to the modes of a couple pendulum; if I have a pendulum like this which I have coupled with the help of this small string. Then now if in this kind of pendulum I push these 2 bobs in one directions simultaneously and then release them then the oscillations would be like this. And this will keep on oscillating in this state for infinite time if there is no air resistance.

So, this is the mode of the system. And since both of them are going in the same direction simultaneously they are moving they are moving simultaneously in one direction and moving together, and then it is symmetric state equivalent to symmetric mode of the directional coupler. I can also have another possibility that I push one bob like this and pull another like this, and then release them then they will do like this. And they will keep on doing like this forever if there is no air resistance, then this is nothing but antisymmetric state or which is equivalent to antisymmetric super mode of or antisymmetric normal mode of the system.

Now, what happens if I displace only one of them. If I displace only one of them and then I release then what happens, we will see. Then this is equivalent to this is equivalent to putting power into one core of the directional coupler. So, if you look at the actual picture, then this is the symmetric mode.

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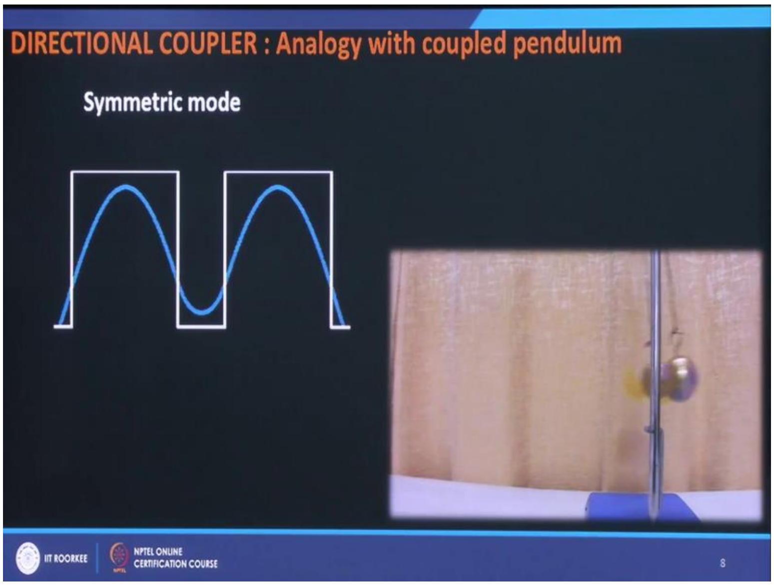

This color is changing it indicates that the power is going along the length of fiber along the length of the directional coupler. So, this is the field distribution at different lengths of the fiber as the color changes it means the length is changing. So, I am changing the length, but it retains it is shape. So, the symmetric mode it retains it is shape, and this is equivalent to the couple pendulum when these two bobs are moving together. And they keep on doing like this.

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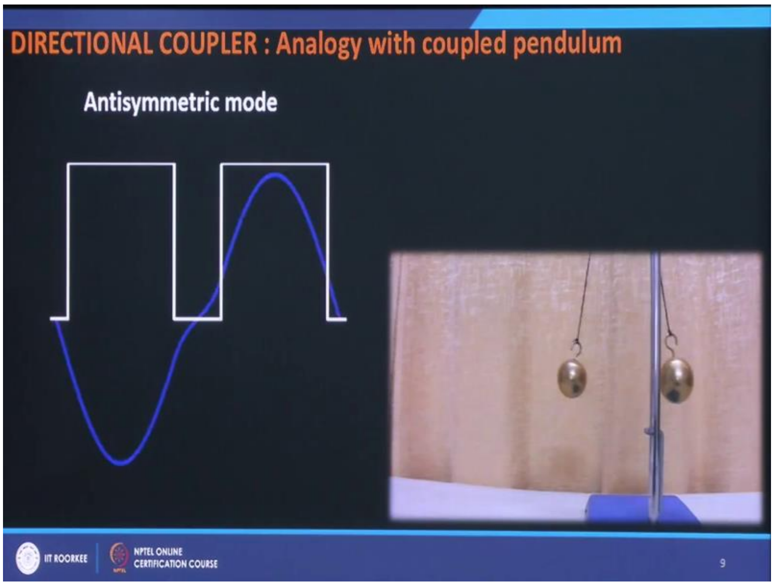

So, this is symmetric state of the couple pendulum this is symmetric normal mode of the directional coupler. I can have antisymmetric when I displace one on this direction another in this direction. So, they will keep on doing like this. And this is how this field is also retaining it is shape when it propagates along the length of the fiber.

So, this is antisymmetric mode of the system this is anti-symmetric state of couple pendulum. If I now displace only one, then what I see that after certain time the rear one is stopped and the other one is in full swing. Then the front one is stopped and the rear one is in full swing.

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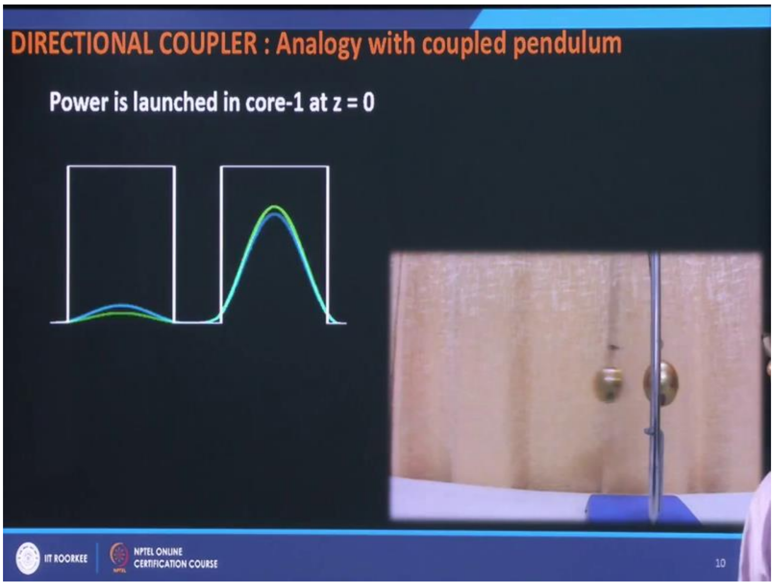

So, there is periodic exchange of energy between the two bobs. Similarly, here if I have all the powers here at z = 0, then as the power propagates along the length of the system then the power periodically transfers from one core to another core. So, there is periodic coupling power couples back and forth between the 2 cores. So, this is how by just a simple analogy of a couple pendulum we can understand the phenomenon of coupling of power from one core to another core.

So, how the power evolves I can write the down the power as a function of z. z is the length of the propagation, for a generalized case for a generalized case where I have 2 cores brought together separated by a low index medium which is cladding.

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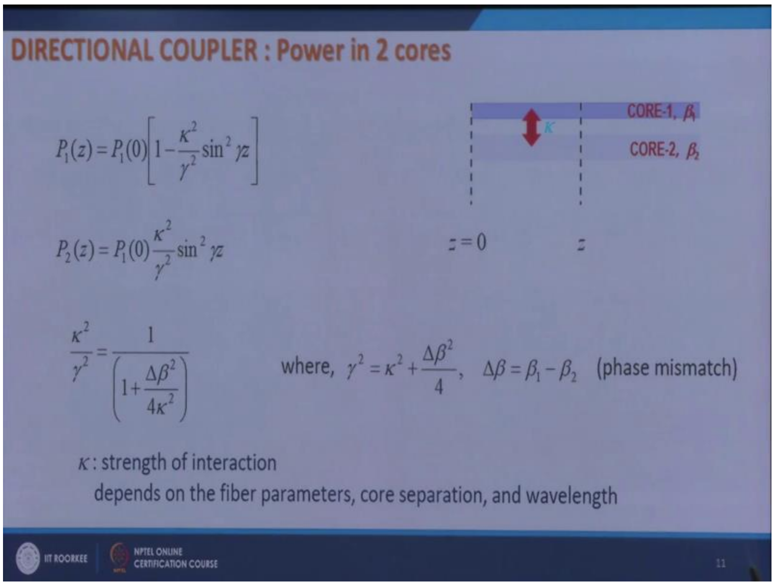

And I take a generalized case where these 2 cores are not identical. So, the core 1 supports a mode which has propagation constant β_1 and core 2 supports a mode which has a propagation constant β_2. Then at z = 0 if I have entire power in core 1 that is $P_1(0)$ is the power in core 1. Then as the light propagates along the structure the power in core 1 varies according to this and power in core 2 varies according to this.

So, what we have? $P_1(z) = P_1(0)[1 - \frac{\kappa^2}{\gamma^2}\sin^2 \gamma z]$. $P_2(z) = P_1(0)\frac{\kappa^2}{\gamma^2}\sin^2 \gamma z$. This can be obtained by using what is known as couple mode theory, we are not going into the details of that here in this course. What is κ and γ? Well, $\frac{\kappa^2}{\gamma^2} = \frac{1}{(1 + \frac{\Delta\beta^2}{4\kappa^2})}$.

So, $\gamma^2 = \kappa^2 + \frac{\Delta\beta^2}{4}$ where $\Delta\beta = \beta_1 - \beta_2$, which is also known as phase miss match because β_1 represents the propagation constant of the mode of core 1. And β_2 represents the propagation constants of the mode of core 2. So, of course, if β_1 and β_2 are different so there is a phase miss match between them. And κ is called coupling coefficient and it represents strength of interaction between the 2 cores.

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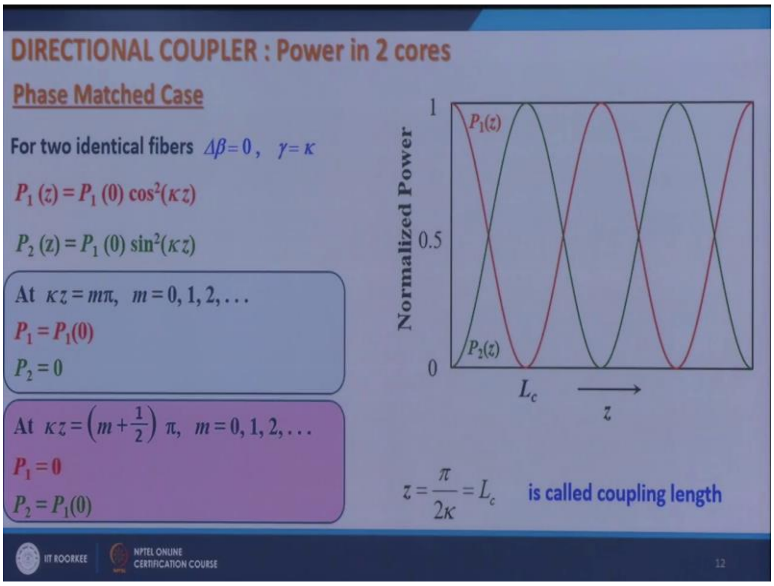

It depends on the fiber parameters, the core separation and the wavelength. So, if I have 2 identical fibers then $\beta_1 = \beta_2, \Delta\beta = 0$. And if $\Delta\beta = 0$ then $\gamma = \kappa$. If you go back to this expression let me retain this expression in on the board that that $P_1(z) = P_1(0)\cos^2 \kappa z$ and $P_2(z) = P_1(0)\sin^2 \kappa z$.

So, now if $\Delta\beta = 0$ then again if I go back here if $\Delta\beta = 0$ then $\gamma = \kappa$. If $\gamma = \kappa$ then I will simply have $P_1(z) = P_1(0)\cos^2 \kappa z$. And $P_2(z) = P_1(0)\sin^2 \kappa z$. If I plot them with respect to z then I can see that $P_1(z)$ is $\cos^2 \kappa z$ varies like this, and $P_2(z)$ is $\sin^2 \kappa z$ varies like this.

So, these are the lots of $P_1(z)/P_1(0)$ this is $P_2(z)$ over $P_1(0)$. So, it is $P_1(z)$ normalized with respect to the input power in P_2 normalized with respect to input power. What do I see here that at $\kappa z = m\pi$, where m has integer values, then $P_1(z) = P_1(0)$ and $P_2 = 0$, which means that at these points where $\kappa z = m\pi$ I have entire power in core 1 and 0 power 0 power in core 2.

On the other hand at $\kappa z = (m + 1/2)\pi$, $P_1 = 0$ and $P_2 = P_1(0)$, that is at these points at these points where $\kappa z = (m + 1/2)\pi$ entire power is in core 2, and the power in core 1 is 0. So, so at this length entire power switches from core 1 to core 2. The power in core 1 drops down to 0, the power in core 2 increases to 1, normalized power. So, the minimum distance this is the minimum distance at which the complete coupling takes place then it is known as coupling length, which corresponds to which corresponds to $m = 0$ here. So,

$\kappa z = \pi/2$ and $z = \pi/2\kappa$. So, the coupling length is $L_c = \pi/2\kappa$. So, it depends upon what is the coupling coefficient. If the coupling coefficient is large then the switching of power from one core to another core would happen at a very short distance.

Let us have a feel of some numbers. If I have a typical single mode fiber and I am working at a wavelength 1300 nm then typical value of $\kappa = 0.2\,mm^{-1}$.

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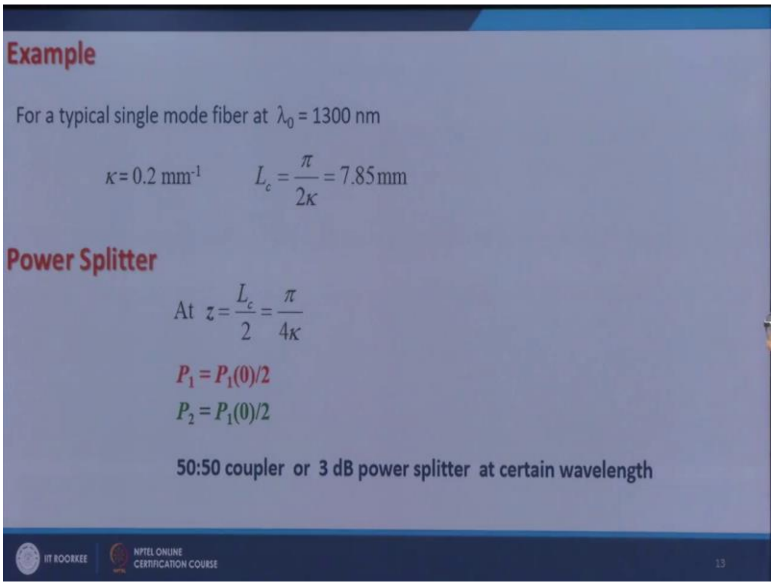

So, L_c would be about 7.85 mm close to one centimeter. So, in this length the entire power will get coupled from core 1 to core 2. I can also make a power splitter out of it if you work at the point where you have the power in both the course equal than it is 50:50 coupler. So, you can work at this length if the interaction length is this which is $L_c/2$, then 50 percent power will be in core 1 and 50 percent power would be in core 2 than it is power splitter. You can have any ratio depending upon depending upon the length you choose you can have a ratio. For example, if you choose this length then, 75% power in core 1 and 25% power in core 2. So, you can choose any ratio for a splitting of power depending upon the coupling length.

So, when $z = L_c/2$ or $z = \pi/4\kappa$ I see $P_1 = P_1(0)/2$ and $P_2 = P_1(0)/2$ then there is a splitting equal spitting of power between the 2 cores then it is known as 50:50 coupler or 3 dB power splitter and this will happen at certain wavelength because kappa is wavelength dependent. So, if it is 50:50 power splitter at lambda not is equal to 1300 nm. Then if I operate the same coupler at 1550 nm the ratio of splitting would be of course, different because κ is different.

So, that was the phase matched case where $\Delta\beta = 0$ in general if I have 2 non identical wave guides then $\Delta\beta \neq 0$, and then the fraction of power that appears in core 1 can be given by $\eta = \frac{P_1(z)}{P_1(0)} = 1 - \frac{\kappa^2}{\gamma^2}\sin^2\gamma z$.

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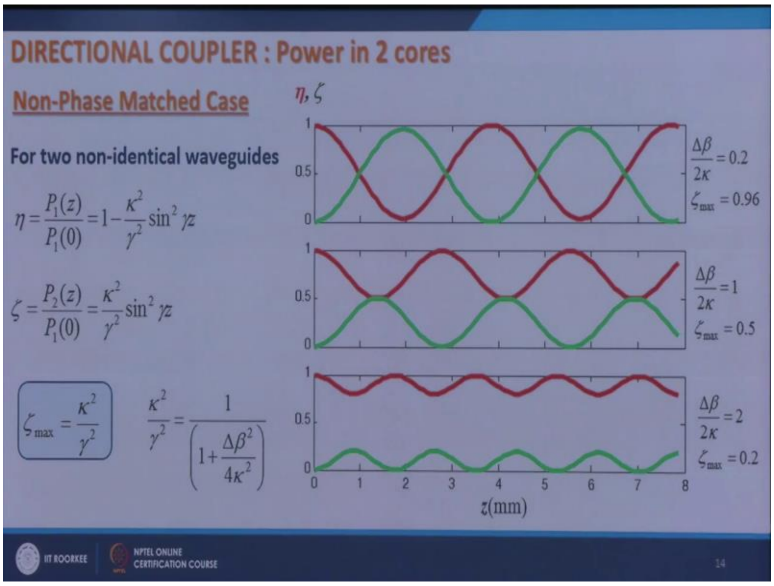

And the fraction of power that appears in core 2 is $\zeta = \frac{P_2(z)}{P_1(0)} = \frac{\kappa^2}{\gamma^2}\sin^2\gamma z$.

Now, I just look at it, if you look at this expression then I have this κ^2/γ^2 sitting here which means that, which means that I cannot have the maximum value of ζ_{max} as 1. Of course, the maximum value of $\sin^2\gamma z$ is 1, but because of this factor I cannot have maximum value of ζ_{max} as 1. It depends upon what is the value of κ^2/γ^2. So, zeta max is kappa square over gamma square $\zeta_{max} = \frac{\kappa^2}{\gamma^2}$, which is equal to $\frac{\kappa^2}{\gamma^2} = \frac{1}{1 + \frac{\Delta\beta^2}{4\kappa^2}}$ since $\frac{\Delta\beta^2}{\kappa^2}$ is always positive. And here it is 1 plus this thing. So, this κ^2/γ^2 will always be less than 1. So, I cannot have 100% coupling from one core to another core, let us see how much we can have.

So, if I have $\Delta\beta^2/2\kappa=0.2$, I put it here then $\zeta_{max}=0.96$ that is 96% power can be coupled from core 1 to core 2 this is the variation of eta and this is the variation of zeta. So, you can see that only 96% power can be coupled from core 1 to core 2, but this is very small, delta beta is very small here. If I have $\Delta\beta^2/2\kappa=1$, then this $\zeta_{max}=0.5$. It means that it means that the maximum power that can be coupled from core 1 to core 2 is 50%. So, it the power in core 1 will oscillate like this, and power in core 2 will oscillate like this it will never cross 50% mark here.

If I further increase $\Delta\beta$, and it becomes $\Delta\beta=4\kappa$ 4, then $\zeta_{max}=0.2$ is only 20%. So, if there is a larger phase mismatch between the 2 cores between β_1 and β_2, then the coupling of power is not complete. Another thing that I see here is that the γ, what is the value of γ?

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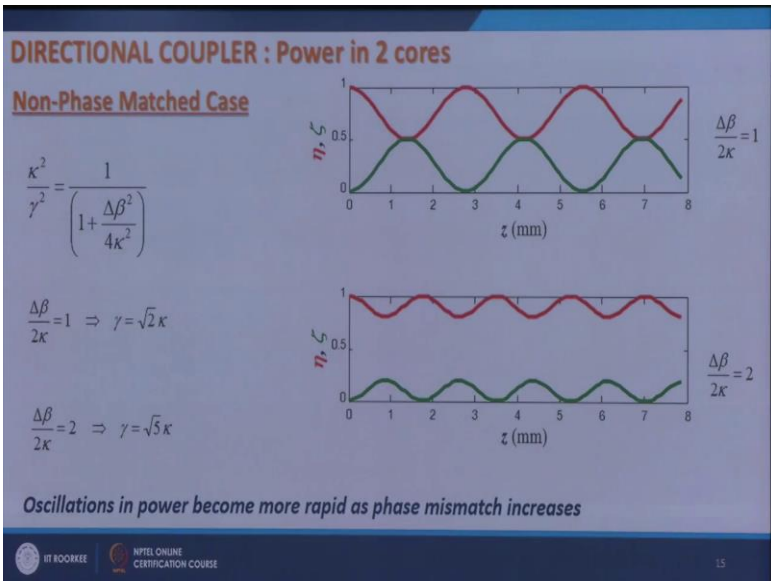

And if I have $\frac{\Delta\beta}{2\kappa}=1$ his is how the power varies, then $\gamma=\sqrt{2}\kappa$. And this γ basically tells you what is the spatial frequency of oscillation. If I increase $\frac{\Delta\beta}{2\kappa}\approx 2$ then $\gamma=\sqrt{5}\kappa$

then of course, the frequency of oscillations increases here. So, the oscillations in power become more rapid as the phase match as the phase mismatch increases.

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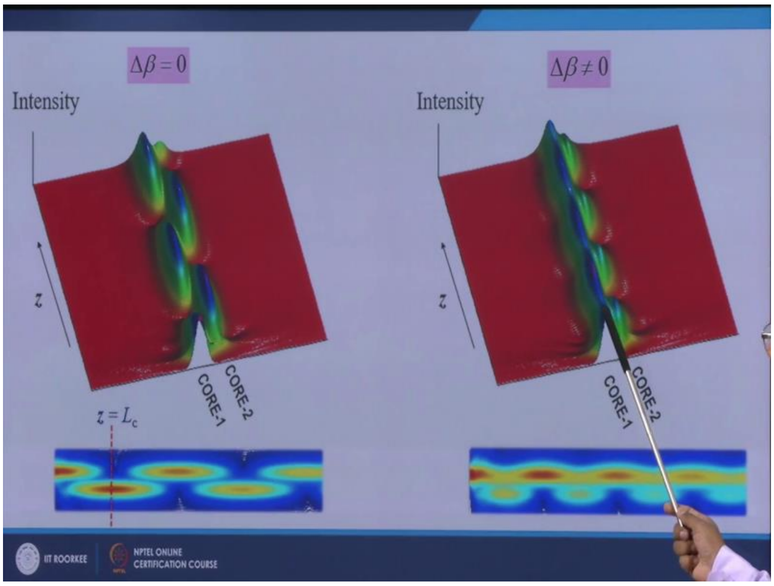

So, this is another thing that I see here. This is how a 3D plot shows the 2 cases when $\Delta\beta = 0$, I launch power in core 1 and then there is a complete transfer of power in core 2 at certain length. You can see a dip which is which goes to 0 here and you can see a peak which comes to 1 here. If I look it from the top and draw the contour plot then you launch power in core 1 and that z is equal to L_c there is complete power in complete transfer of power in core 2 and here the power in core 1 becomes 0.

While when delta beta is not equal to 0, then you can see that it is not maximized and there is a still some power left here. So, there is no complete transfer of power, this is much more clear from this contour plot. So, you launch power here, there is a transfer of power here at this distance the maximum transfer, but this is not this is not 1, there is no complete transfer of power.

So, in the next lecture, after having understood the mechanism of light coupling between the two cores in a directional coupler; in the next lecture we would look into some more components which we can make out of this basic building block directional coupler.

Thank you.