**Modern Optics**
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Lecture - 27
Coupling of waves and optical couplers (Contd.)

So, we visited this optical fiber the conventional step index fiber, in terms of its mode properties and then single mode operation v number. This single mode optical fibers and also multimode fibers they are very important member in the fiber optic system and the fiber best couplers are very important as per as this coupling of waves, optical waves is concerned.

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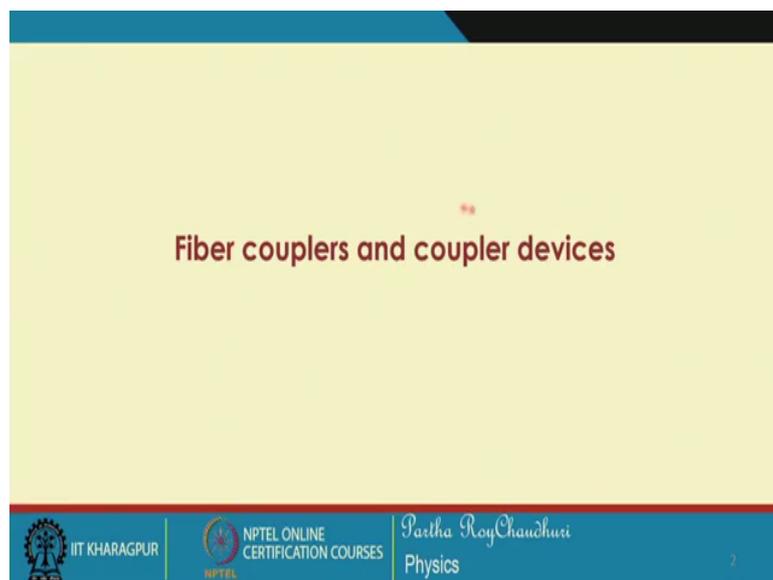
So, we in this occasion we will discuss fiber couplers and coupler devices, there are large number large variety of fiber couplers and components existing.

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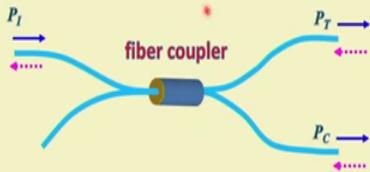
So, we will initiate the discussion with fiber coupler, fused coupler, basic structure, then super mode beating that is the mechanism by which this coupling takes place, fabrication of fiber coupler, some basic coupler characteristics and typical numbers, which are attached associated with these fiber couplers and some common coupler devices and their working principle.

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So, first see what is a fiber? A fiber coupler is one, that splits or combines light signal guided in the fiber. So, like a beam splitter, if we have an optical if we have an optical beam a light, which is injected here then this will combine this light will be split into two

parts that is a part will be will be traveling in this fiber, the other part will be traveling in this fiber.

So, these green lines are representing two fibers, which are in intimate contact at this region and this device is called the fiber coupler and we will learn how this coupler thing works.

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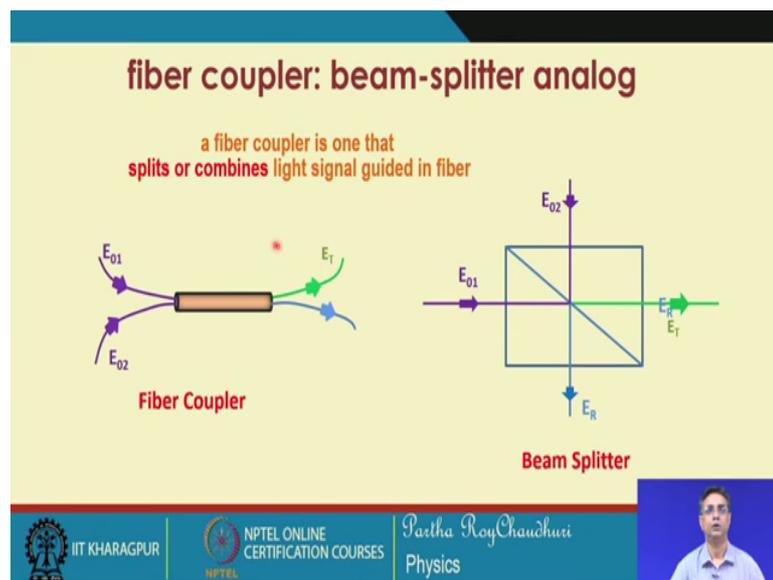
So this is an analogue of beam splitter. When we have a beam splitter we have an incident light, which is incident here a part of the light will be reflected and a part of the light will be transmitted. But it could as well happen from this side that the light is incident from here, then part of the light will be reflected here and part of the light will be transmitted. So, you have two inputs E 01 and E 02 these are the two inputs.

When you have these input, you can have two outputs reflected you can have two outputs transmitted, similarly if you have this input you can have reflected output you can have transmitted output. Likewise in the case of an optical fiber if you have an input in this it will be transmitted and a part of the light will be reflected similarly if we if we consider the other input that is if the light is injected into the coupler from this side, then it could be reflected into this port and it may be transmitted in this port. This port is called the transmitted port or throughput port, this will be the coupled port as long as this will be treated as the input port. The other way round that if this is the input port then this

will be the same fiber, will be the port that is constituted of the same fiber will be the transmitted or throughput port and this will be the coupled port.

So, we see a very close similarity in terms of the principle of a beam splitter and a, but the advantage of this the light is guided, the light is in the form of a mode of an optical fiber, and that it does not require any alignment and it is once you have coupled light, everything is automatically done ok.

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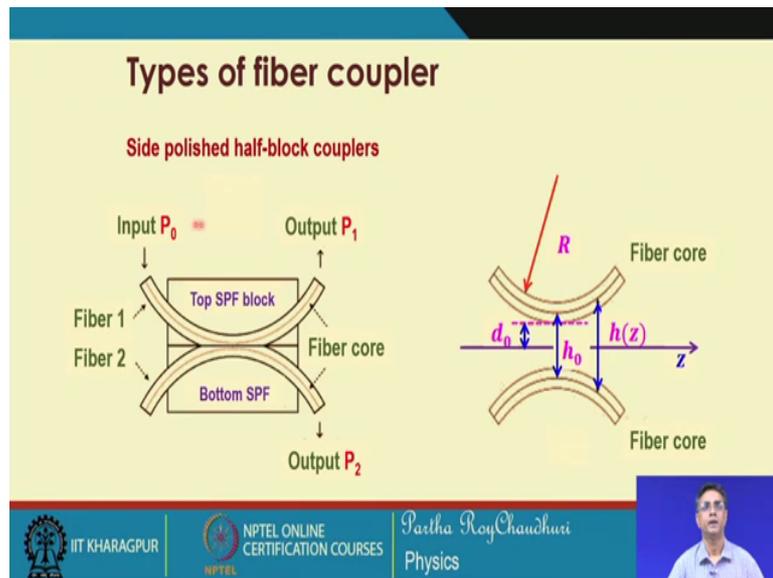
So, the coupler, but one thing that this is one member of this fiber coupler that, how this coupling takes place there are ways to couple light from one fiber to another, one mechanism is that side polished half block coupler.

So, in that case what we do? You have a you have a block glass block quartz block in which you make a groove and place a fiber. And you have another such groove in which almost identical fiber block half block groove. This is called half block because it constitutes half of the total system, you have a fiber you have a block, similarly you have a fiber you have a block this is the top side block side polished block and then this one this block is now polished at this region individually each of them.
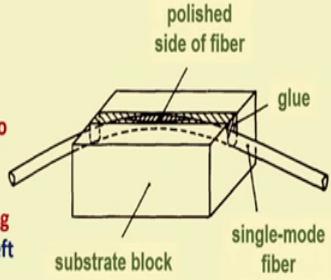
So, that a part of the a part of the core is a cladding is left out and you reach almost close to the core. Then these two fields can interact evanescently and the light which is given as input into this can couple into this, and part of the light will be transmitted through

this. And this is the schematic of the system, which helps to calculate that the coupling coefficient and the strength of coupling the power splitting etcetera.

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Right this fabrication method, this is the overall schematic of the system the fabrication method is that you take a substrate quartz block, and then you make a groove and in which you place an optical fiber then put some epoxy resin, put some epoxy resin then this top part is polished.
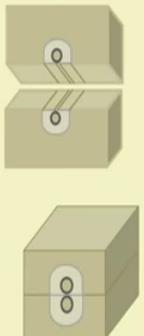
Polishing is performed upon a plane which is tangential to the fiber core using fine diamond paste in some polishing machine you can polish the top part of this. So, that part of the cladding is removed and you can approach very close to the core almost one or two microns, left few microns of the cladding is left the depth is calibrated by using power monitoring. While doing this polishing thing, if you monitor the power if you launch some input light then you can look at the output of the power and knowing the output for this much of polishing, we can actually calibrate how much is the depth that has been polished.

So, this is one very beautiful technique to calibrate, that the depth of polishing by real time monitoring of power.

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Now, we have one such block, which is called a side polished fiber half block. So, the fiber is side polished, but it is held it is mount in a in a in a block, two such blocks are put together two such half blocks are now placed on top of each other like this you have one half block here you have another half block here both of them contains fiber and then you place like this. This is a very clear picture to understand how these two fibers are laid side by side, and when they are laid then you can fix you can put some resin and mount them. But the good thing about this system is that tunability you can move this half block with respect to this one in the lateral direction as well as in the longitudinal direction. To tune the splitting ratio wavelength dependent ratio many of the targeted specifications to realize this flexibility exists, because you can give a relative motion between these two.

The combined structure acts as a coupler as modes of the neighboring waveguide interact. These two waveguides in this waveguide, there is a there is a field and this can also support a mode. So, there will be an interaction, as a result the light will travel from one fiber to another through the evanescent coupling of the modes. So, light launched into one fiber couples with the neighboring fiber, power c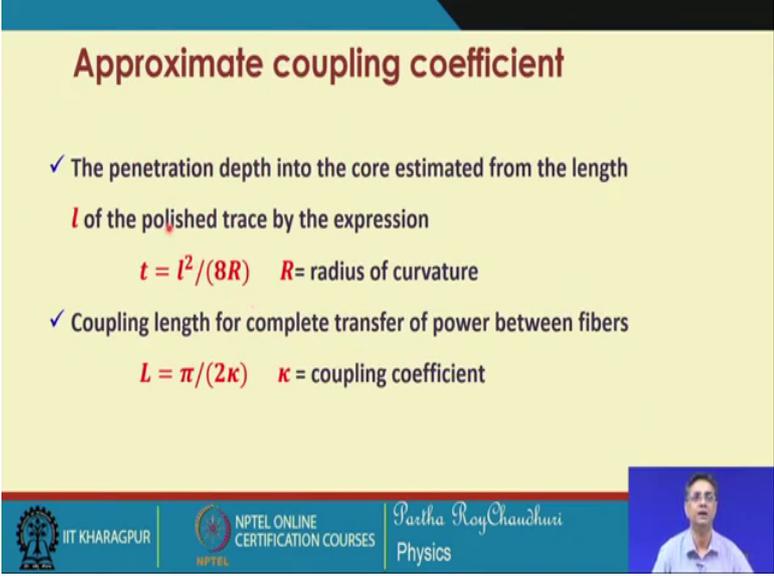oupling depends on the interaction length and the wavelength. So, these are the two important things about a about an optical coupler, the length of interaction over which the system interacts and also the wavelength it is the wavelength that decides what will be the strength of coupling.

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We will see that the penetration depth into the core is estimated from this figure, from this figure.

Numerically theoretically you can estimate that the depth of penetration, where R is the radius of curvature think we have shown this is the R radius of the curvature. And the coupling length for the complete transfer of power between; this is again known that this we have discussed in the couple mode theory, the length over which the complete transfer of power takes place that defines the coupling length L or L c where k kappa is the coupling coefficient.

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And this coupling coefficient is little algebraic operation requires to come to this value of to this expression for kappa, which includes that substrate refractive index the core refractive index effective index and this delta which is defined by twice pi d by lambda, where as alpha is defined by twice pi a by lambda, 2 d is the spacing between the fiber core boundaries and k the modified Bessel function of the second kind. We have seen this gain in the case of fiber; optical fiber this delta 2 d is actually this is the analytical expression you can do with little bit of geometry, can be expressed as 2 d 0 plus 2 R into 1 minus cos x by R whole square.

So, and d is the lateral misalignment have to look at this if they are misaligned laterally by an amount delta. So, you can and this is the structure d 0 this at any finite distance from the center of the two fibers. So, delta is the lateral misalignment.

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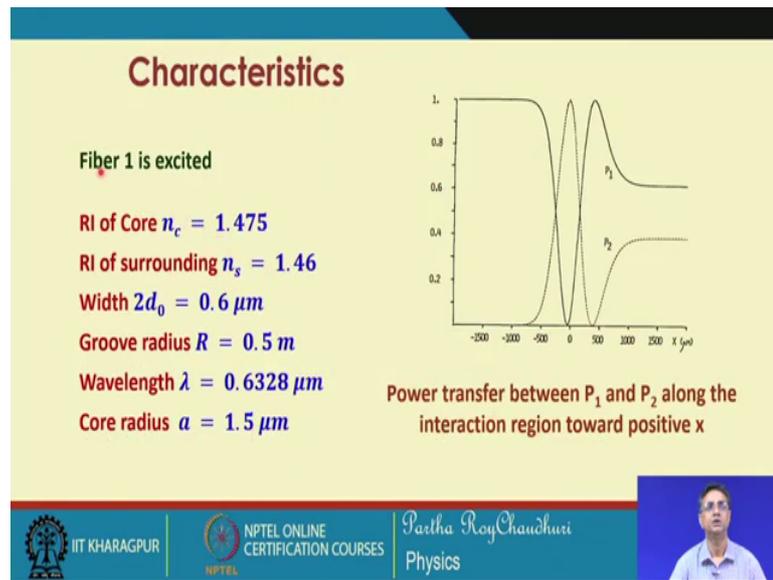
So, a fiber which is excited if you have one fiber, which is excited with power core refractive index is; this cladding these are the typical values, practical values which are used 2 d 0 equal to 0.6 micrometer groove radius is about this 0.5 meter and wavelength is the helium neon laser wavelength, core radius of the fiber is 1.5, then for this is the typical power transfer characteristics between P 1 and P 2.

So, initially you have maximum power P 1 then it comes to 0 at that time the maximum power at P 2 is this, which is the complete transfer of power point and then again it falls to 0 it takes over to P 1. So, this is again a periodic exchange of power between the two fibers, through evanescent coupling at the length at the region of interaction. So, P 1 and P 2 along the interaction region towards the positive x direction, which is the length of the which is along the length of the fiber.

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So, this SPF couplers are inherently very useful because it is widely tunable through varying the displacement position, relative positions of the two 2 SPF's to control the coupling coefficient and intern it can actually help tuning the wavelength the power splitting ratio, but another important characteristic of this SPF coupler is that, it can it can be used as polarization splitter.

So, it can split power, polarization, mode and also wavelength if it can split the wavelength we call it is a wavelength multiplexer or demultiplexer will see with fiber fused coupler example. Power splitting is simply the beam splitting, which is very common. Polarization splitting that is te and tm polarizations can be two can be separated out using this there are technologies and methods. Two modes fundamental and first order mode first order and second order modes, they can be selectively also filtered using this technology.

So, this is a very powerful technique we use variety of applications are there in power splitting and polarization splitting. One of the important aspects of this SPF, best fiber coupler is that it gives you very good repeatability in fabrication because the process here is reproducible and you can get back to the same kind of specification every time you fabricate under the similar condition experimental fabrication condition also it is rugged and very stable device. But it is slightly bulky in view of the competing technology of fused fiber coupler, we will see that fiber coupler of other kind that is
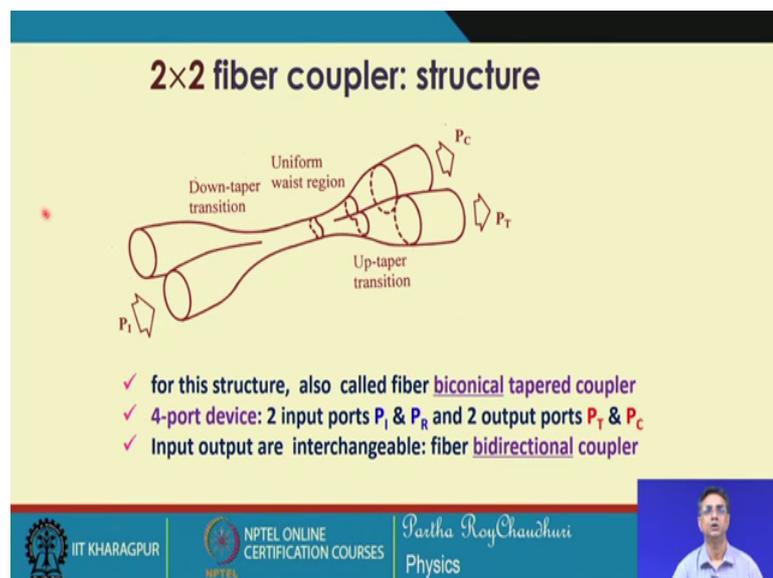
fused coupler is very thin and is a very small space it occupies, and that way it is slightly more bulky.

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Now, with this background we will we will switch over to these fused fiber couplers and devices, we have learnt what is the basics of optical fiber.

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Now, these two optical fibers if they are placed side by side with their jacket with their plastic remote, that is only the core and cladding glass fiber two such fibers are placed together, and then they are in contact with each other. If it is now heated fused and

pulled, then it will form a down taper transition here, there will be a uniform waist here and there will be an up taper to form to the optically isolated pair of fiber.

So, we started with two optical fibers which are isolated, but we brought them in contact to each other and then we fused and pulled. So, that the idea is that when the dimension of the individual fibers will be reduced, the core radius will become very small and relatively progressive proportionately it will be reduced cladding will also become small. So, it will see a common cladding, where the field will be flaring up more and it will heat the second waveguide as a result there will be an optical interaction, and light which is launched into one of the fibers will be coupled into will be available in both the fibers.

So, it behaves as a beam splitter normally. So, for this structure also called biconical tapered structure, because we have two conical taper structure one is here another is here. So, it is called a PT coupler, and it is a four port device you have two input and you have two output ports, but these two output ports can also be treat as input ports light is bidirectional, where reciprocal reciprocity of light. So, therefore, this coupler is also called bidirectional fiber coupler.

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Now, light injected into one port appears at either of the output ports, one of the ports or in both the ports in some ratio, this all depends on the design parameter and the structure of the coupler.

So, these two things that is the wavelength and the design and the and the structure they decide how this fiber coupler can be utilized for various numerable applications. But wavelength dependent splitting is a very important part, which decides how it can be used for selective excitation of wavelengths, that is wavelength division multiplexing and demultiplexing we will see that example also.
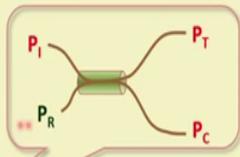
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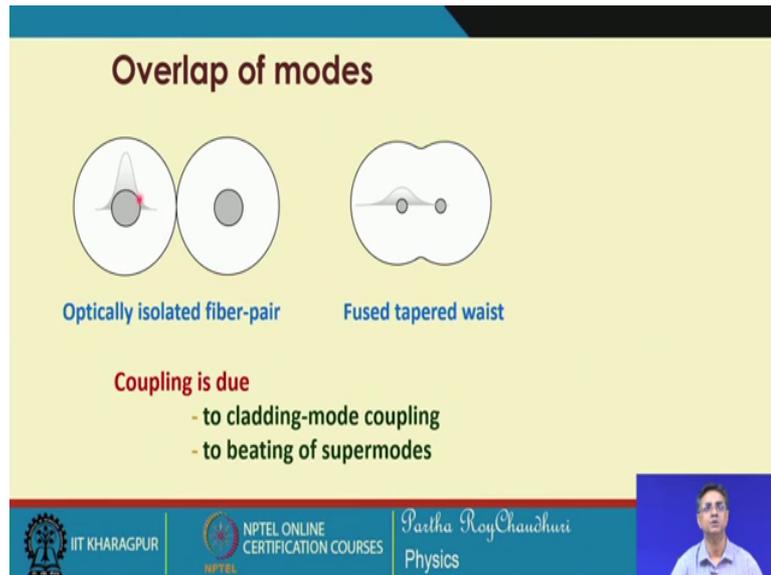
To understand how this coupling takes place. These are the two optically isolated fiber when you are here, when there is no interaction. So, it looks they are just in contact with each other and it is only the cladding outer boundary of the cladding, they are in contact. So, the field does not see the presence of the other waveguide, but at the at the tapered region and on the uniform waist region can see that, the core becomes very small and instead of two different cladding you have a common cladding in which you have two cores.

So, this core the light will be because of the reduced dimension of the core the light will be will be flaring out and will be hitting the second waveguide, this is also a guiding region. So, the wave the light wave will interact with this waveguide and will get guided through this. So, this is the basic principle. Now this is not an evanescent coupling, but this is a cladding mode coupling because now, it is the light which is within the cladding common cladding.

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And we can again apply the super modes beating structure, which we have used for the planar dielectric planar directional coupler the same principle.

So, this is PT will be equal to PI this would be a suffix. PI cosine square kappa l, PC is sin square. So, this is sin and cosine dependent sin square cosine square variation of the power which we have seen in the super mode beating structure in the in the couple mode theory earlier.

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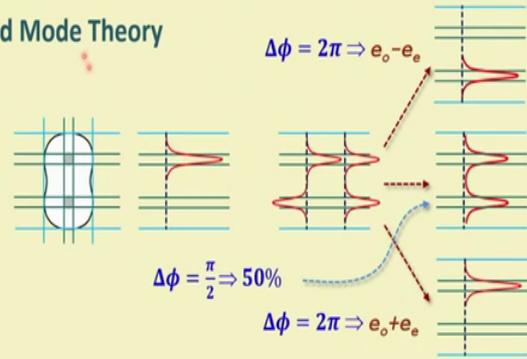
So, to understand the same thing in the case of an optical fiber, you have a core here you have another core here, and light is sky is launched into this waveguide and at z equal to 0 if we consider that, this light this mode which is in the first fiber is a combination of the two lowest order super mode. Super modes by saying that the normal modes the modes of the composite the total structure, this total structure can have the fundamental mode like this and the first order mode which is of this.

So, these are the two lowest order modes of the total structure of the complete structure composite structure not the individual structure. So, if we take at z equal to 0, the phase difference between these two modes because this mode has a slightly lesser propagation constant this is slightly more propagation constant. So, the velocity of this mode will be more than the velocity of this. So, there will be a phase difference between these two, but at z equal to 0 these two modes; at z equal to 0 that the starting point the two modes their phase difference is 0. So, if the phase difference is 0 then we can add these two and they will be subtracted. So, it will result in only one lobe of the mode profile, because these two will be added and these two will be subtracted.

So, you get the light which is confined into one of the which can be thought of as the input light. So, this input light now gets divided into two modes of the complete structure the symmetric mode and the antisymmetric mode, that is the first order and the fundamental mode they are now traveling in the waveguide, and it will. When the phase difference between these two is 0, you have seen the power is the light the lobe is confined into the first waveguide, but if the phase difference is this would be oh there is a mistake, this would be pi this would be pi.

If the phase difference is pi then the there they will be subtracted as a result the light will be a confined only into this waveguide. But there will be a somewhere in between this phase difference 0 and phase difference pi, somewhere in between these the phase difference will correspond to pi by two then the light will be split 50 percent into the lobe there both the lobes identical lobes will exist in both the waveguides provided these two wave guides are identical, two fibers are identical.

So, this is how the splitting of the light takes place in the light of the couple mode theory that is the beating of the super modes the interference of the super modes across the along the length of the two fibers who are lying side by side.
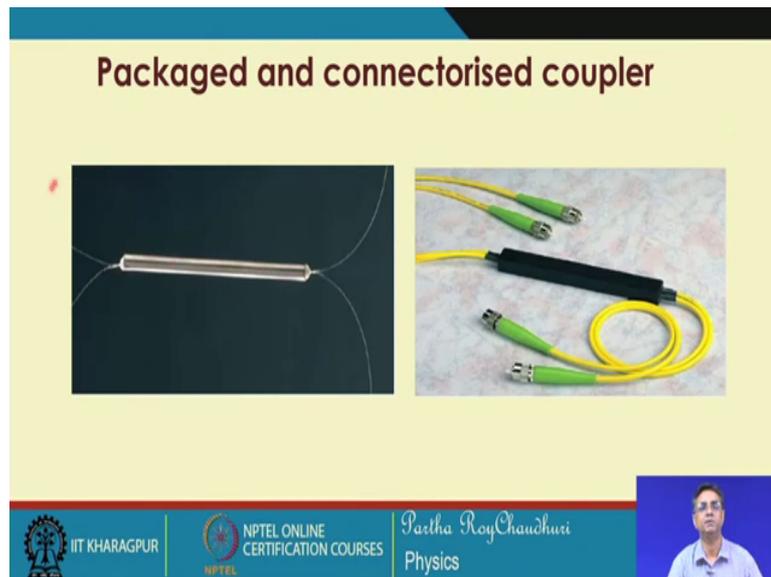
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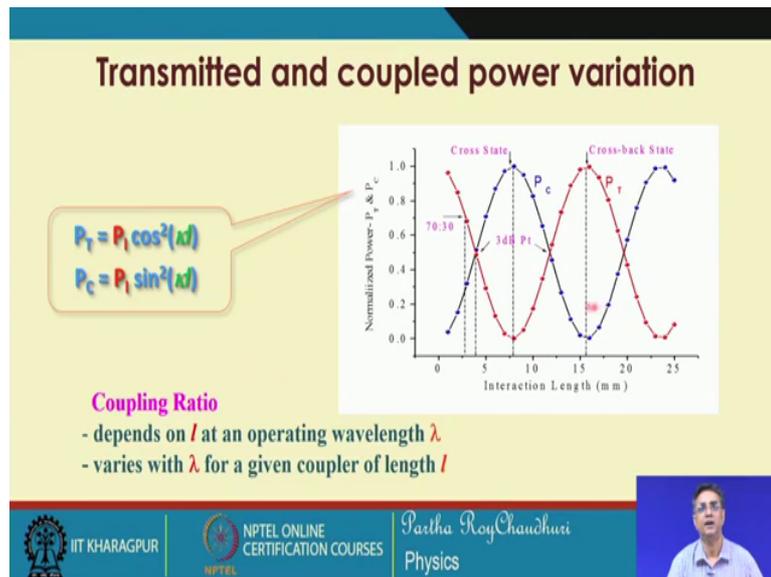
So, this power transfer as we have seen, can be represented by sin square cosine square function of this and you can see that this input power is maximum at z equal to 0 when the length of interaction is 0, then there is a periodic exchange of power between the two waveguide this we have called this cross state this is the cross back state and you can see that it gives rise to a 3 dB power that is 50 percent power splitting at this length of interaction. You can also have any desired ratio 70 30 20 80 any ratio just you will have to stop the you will have to restrict the length of interaction.

So, you can design any power splitting you can have the same thing after large number of periodic cycles. So, this coupling ratio coupling ratio that is the splitting ratio that depends on l at an operating wavelength lambda, and it varies with lambda for a given coupler length. If the length is fixed, then it depends on wavelength, but if the if the wavelength is fixed then it depends on the length of interaction.

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So, this is the basic principle couplers look like this is a fabricated coupler and just protected with a capillary slip, and this is a packaged and characterized fiber coupler you have two input ports you have two output ports.
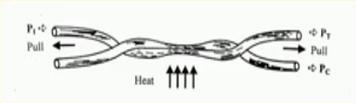
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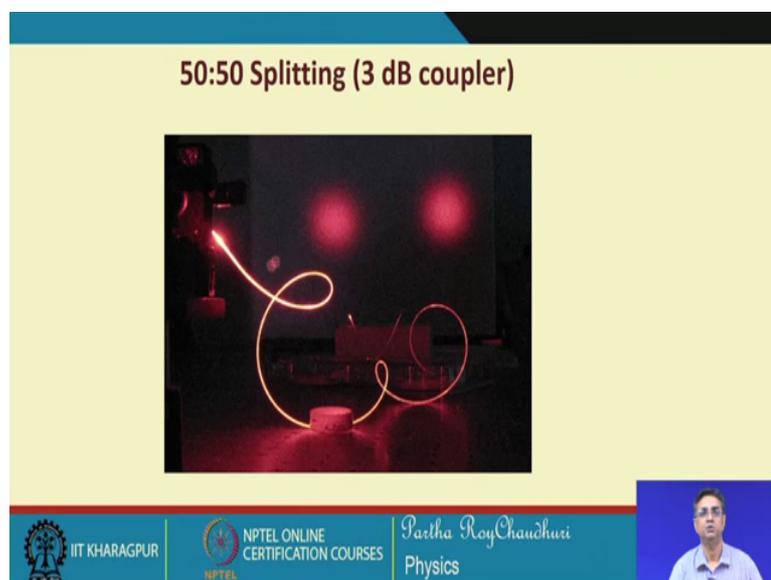
Each of them can be used as input or output and when illuminated with light the two output ports give you almost equal distribution of the light power you can see that 50 percent.

So, this is a 3 dB fiber coupler very beautiful to see.

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The fabrication technology how we realize such fiber, you have these two optical fibers which are removed from their plastic jacket and then heated in a micro flame, then simultaneously elongated. The name by the vary method is called that fuse pull taper method, because you have to fuse, you have to pull and you have to taper.

So, this fuse pull taper method is a very reliable and very widely used technique, to make this fused fiber or coupler devices. Heating and pulling is discontinued because while fabrication you will have to monitor the power there will be input and output power and as soon as you get the splitting of the powers in the transmitted and couple port, which is your requirement 30 70 or 20 80 or 50 then you just discontinue this heating and pulling. The P C this system is governed by a the system is basically a computer controlled automatic fabrication system, through which it is fabricated to get the reproducibility and almost you know same commercial requirement to meet that ok.
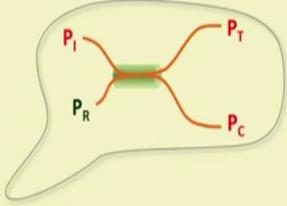
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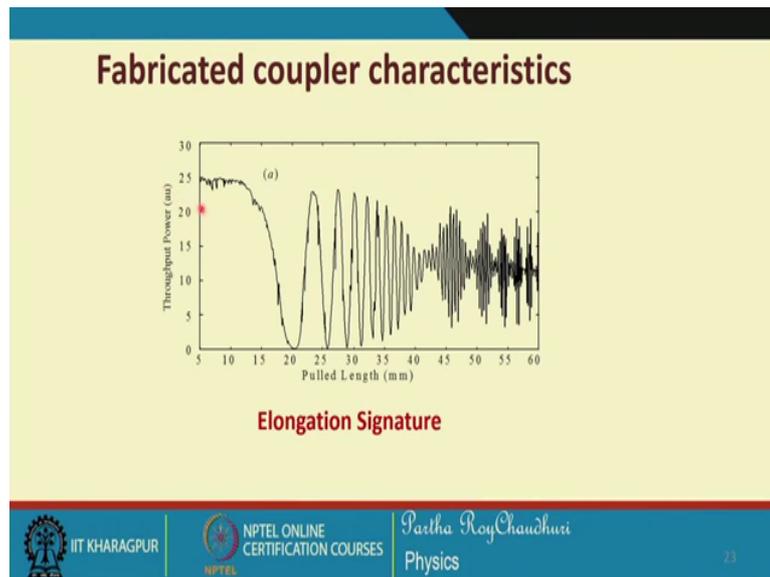
When you fabricate in the real time monitoring system, you can see the signature coupling signature. I you monitor one of the output ports that is the transmitted port initially you have the maximum power then it falls it becomes 0 of course, at the time the coupled power must have been maximum. When the throughput power the transmitted power is 0 then again it becomes maximum minimum and then you have a periodic bunching of effect and the power also this is because of the polarization nature because when the two fibers are fused together if you look at the cross section, there is a form birefringence geometrical birefringence along the one side the width is more, the other side the width is less and because of that there is a polarization interference beating and these are the modulation. Also that when the fiber is pulled then more and it becomes thinner and thinner and as a result the periodicity also becomes very close to each other each of them are very quickly quick transfer of power takes place in a very small length.

So, it is useful it is useful to control the power splitting when you are in the first few fabrication cycle.

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Now, these are the typical characteristics which are attached to an optical fiber best coupler devices it is. In general true for all optical couplers splitting ratio between the two ports, you have excess loss which is given by the total output light with respect to the total input light and log of that. So, insertion loss is the loss along one particular path that is either P c or P t then return loss a part of the light will be reflected because of the Rayleigh scattering imperfection and other things.

So, and then wavelength isolation issue this is true for the WDM system we will shortly discuss.

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| Characteristics of Power Splitters			
Characteristics	SMF @ 1310 nm	SMF @ 1550 nm	SMF @ 632.8 nm
Splitting Ratio	10% – 90%	10% – 90%	20% – 80%
Excess Loss	0.1dB – 0.3dB	0.1dB – 0.5dB	0.6dB – 1.1dB
Return Loss	40dB – 60dB	40dB – 60dB	50dB – 60dB
A typical WDM @ 1310/1550 nm			
Characteristics	@ 1310 nm		@ 1550 nm
Wavelength Isolation	16.4dB		14.7dB
16dB Isolation Bandwidth	60nm		50nm
Excess Loss	0.61dB		0.37dB

Then the typical characteristics of optical fibers these are the numbers, which are the real numbers splitting ratio can be between 10 to 90 percent for single mode fiber at 310 at 1550 and also at helium neon laser wavelength 20 to 80 percent, excess loss could be somewhere between 0.8 to 0.3 this is 0.1 to 0.5 and so, on return loss is 40 to 60 d B minus of course, this is. Then it is almost same for all cases now there are typical w d m characteristics we will know what a WDM is that because how it can separate two wavelengths or it can combine two wavelengths, this is what we call a classical wavelength in that case we define the excess loss for this wavelength for this wavelength isolation this is by definition the 16dB isolation 16 nanometer.
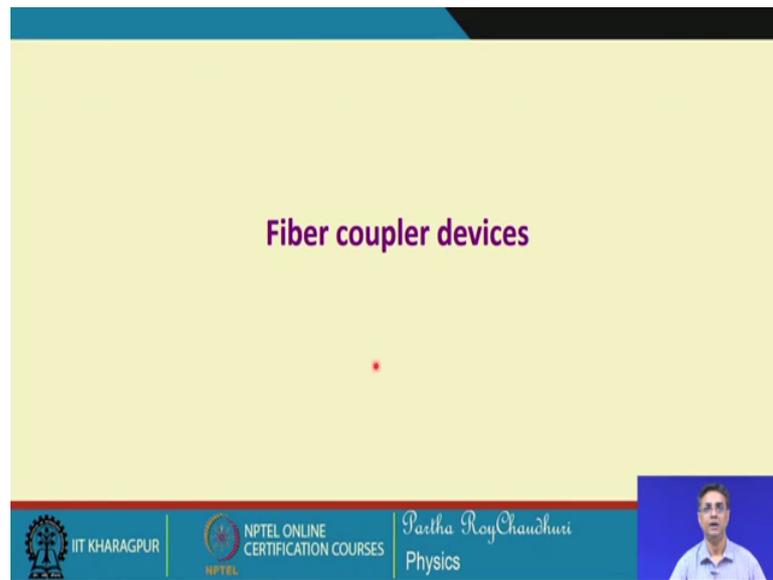
So, will see and now we will continue with the applications of this fiber coupler, and several fiber coupler devices which can be brought out of this building host of these two by two fiber couplers.
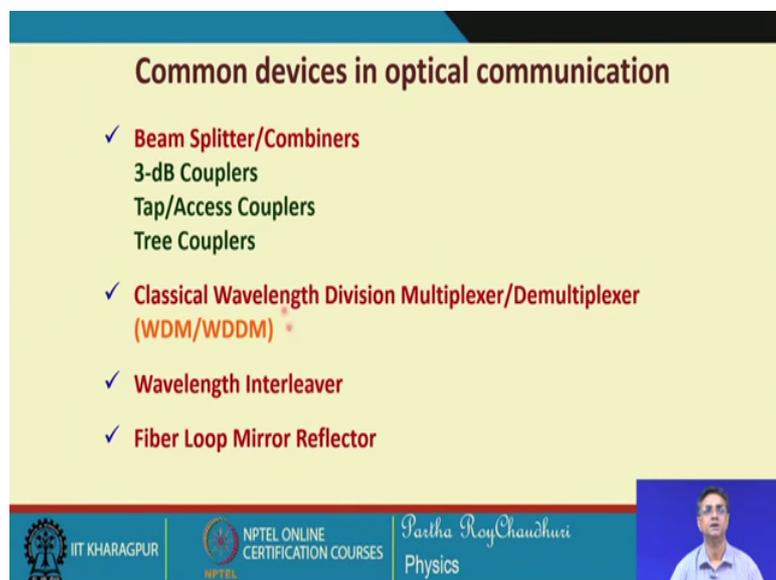
For example, the most common use is a beam splitter or combiner which we have compared at the very beginning as a beam splitter, then the beam splitter could be any 50 percent splitting coupler, it could be a tap or access coupler which are used in optical

communication optical communication system. They are very useful and important components in the building in the network, then tree and tap couplers that also will see.

We will try to understand the principle of wavelength division multiplexing in an optical coupler fiber coupler, then wavelength leaver there are many other applications then one very interesting application is the fiber loop mirror. So, this is again based on a 3dB fiber coupler where without using any mirror, the entire light can be reflected back based on these fiber couplers we can actually constitute Mach Zehnder fiber and many other devices some of these things, we will continue and we will look at this in the next section.

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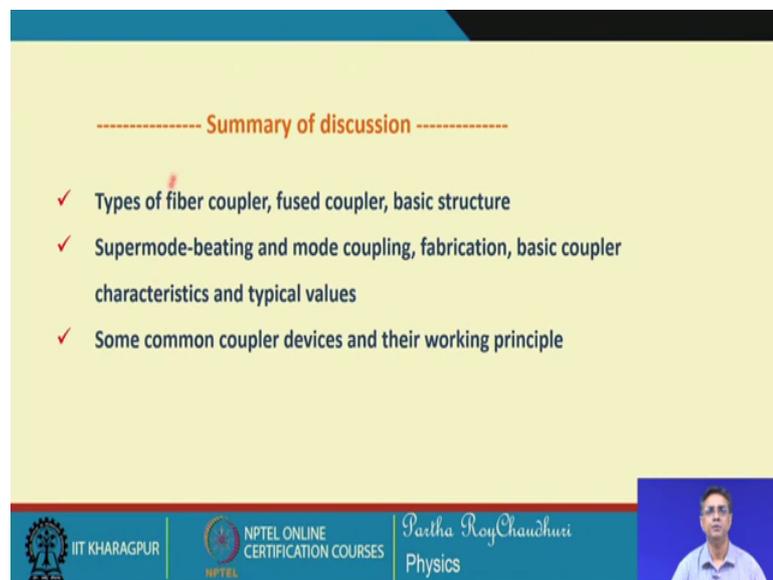
So, in this context we have discuss the types of fiber coupler, side polished fiber, coupler then fused fiber coupler and then their basic structures, but most of them can be explained from the super mode beating or the mode coupling, cladding mode coupling then we will the basic coupler characteristics and some typical values, some common coupler devices and their working principles part of this thing will be taken up in the next discussion.

Thank you very much.