Modern Optics
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Lecture – 28
Coupling of waves and optical couplers (Contd.)

So, we are discussing optical couplers coupling of waves. The last time we were saying that how optical fibre couplers the mechanism. The principle how this spilt light and several other application in this occasion we will continue the application of fibre fuse fibre coupler and then will continue with grating and prism couplers these are all very competing technologies used for coupling between waveguides coupling applied between waveguide ok.

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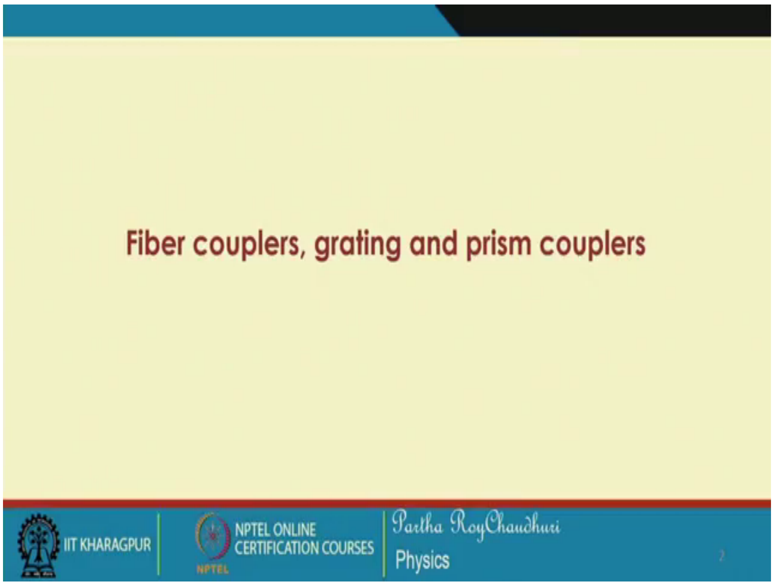

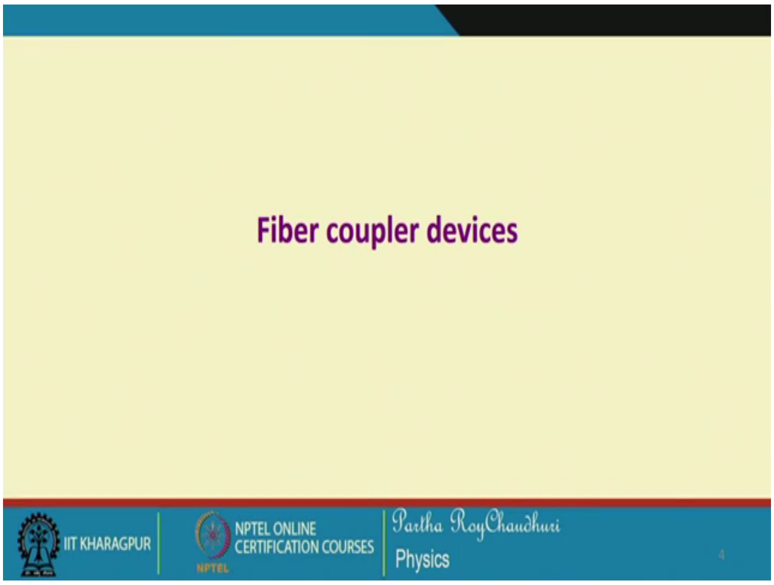

So, fibre coupler devices.

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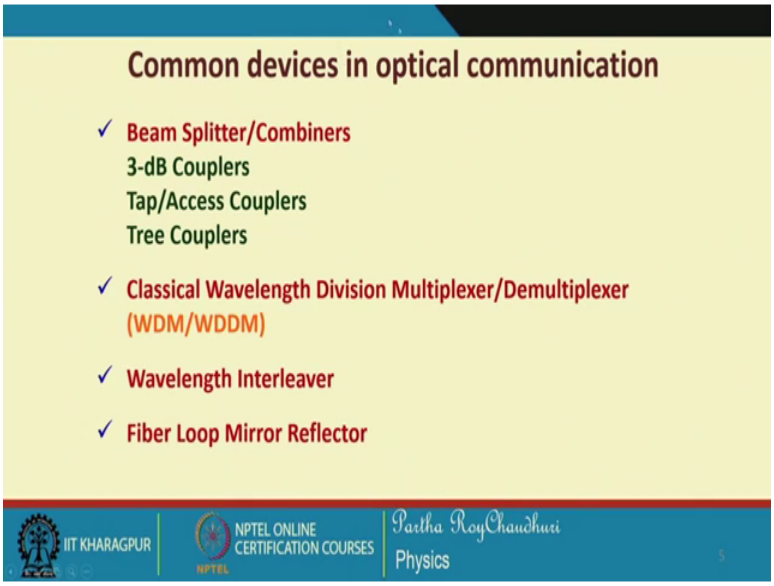

Fused fibre coupler which is mostly in telecommunication application, they are used as beam splitter and combiners 3 d B couplers tap and access couplers 3 couplers and then wavelength division multiplexer demultiplexer wavelength interleaver, Fiber loop mirror.

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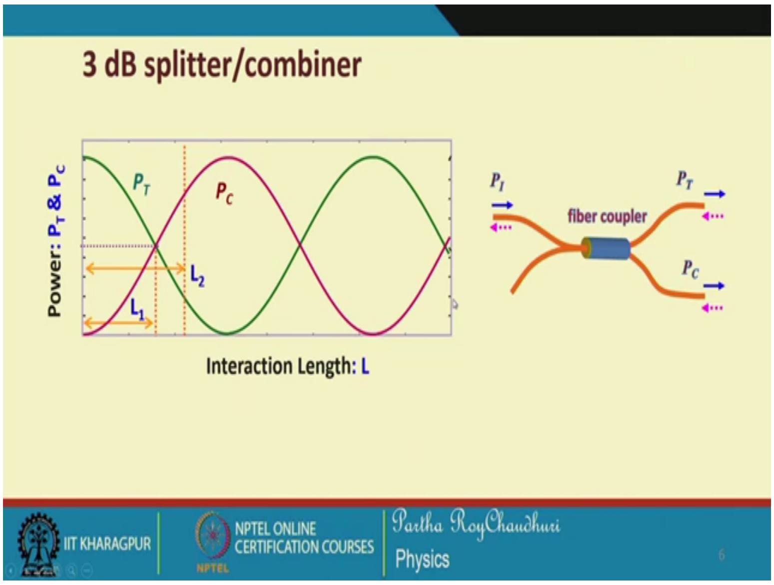

So, let us start with this 3 dB coupler that if you have an input light PI, then this will be split into 2 parts PC this and PT. But this splitting ratio is a function of the length of interaction over with these 2 fibers, the modes of the 2 fibers interact and also a function of the wavelength of the light which is used for splitting.

So, you can see that as a function of interaction length which is a sin square cosine square function, initial the power is all restricted into the through put port transmitted port here it becomes 0 some here and during that time the power of which was 0 in the couple port it becomes maximum and they will periodically exchange the power back and forth and as you continue with the length of interaction. So, you can see that if I want to make a 3 dB coupler we will have to stop and make the interaction length L1 and such that the power is just 50.

So, that is what is a 50 percent coupler or 3 dB coupler which is very commonly used in optical network and sensor technology also fibre optic sensor technology also. Because this can be used as a reference to monitor the resource fluctuation, to monitor the reference alongside the probe beam which are derived from this fibre coupler 1 is reference another is the probe.

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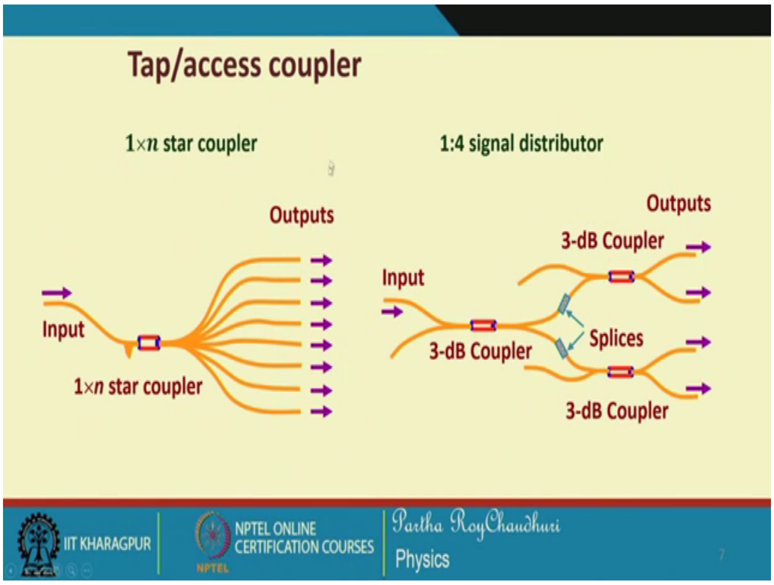

So, tap and access coupler you have input light put into 1, this is a 1 into 10 star coupler this is again the same technology you will have to put a large number of fibers together and fuse them. But this is a an advanced technology through which you can couple light from one input to a large number of outputs, you can see this is 1 into n star coupler because light rays are reciprocal. So, if you launch light from this side to all the individual ports they will combine and will appear at this output, so again this is a bidirectional coupler.

This is one example of 3 dB couplers are using 3 such 3 dB couplers how, you can you can make a 1 is 2 4 signal distributor. So, you have an input light here which will be split into 2 parts and each of these will be again interns split into 2 parts. So, effectively we will get for output, so if we start with 1 milliwatt power for example, then ideally if there is no loss then will get 1 fourth of a milliwatt output at all the 4 ports ideal. So, this is how this distributor couplers are used in the tele telecommunication fibre optic telecommunication networks.

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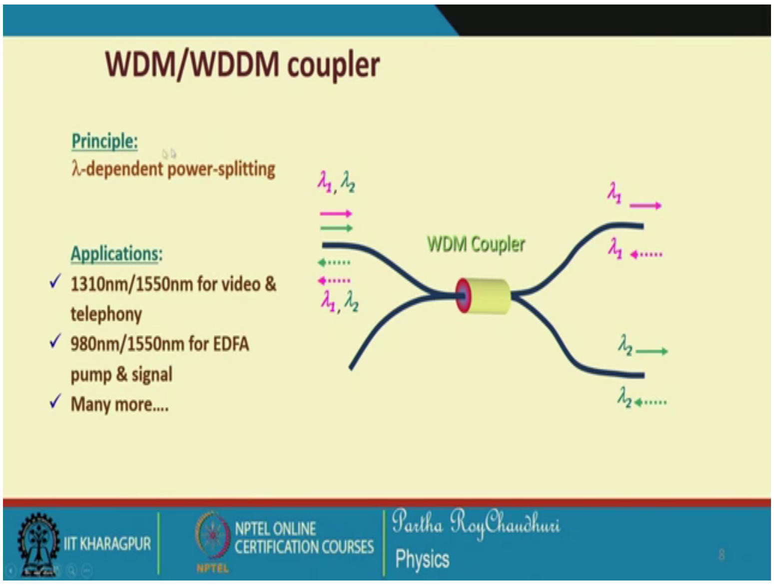

Now, there is another very amazing application of this WDM coupler, where you have you have a fibre coupler in which if you inject 2 wavelength lambda 1 representing this pink colour. Then lambda 2 which is represented by this green colour both of them are injected into this fibre coupler and interestingly this coupler can be made in such a way that only lambda 2 lambda 1 is coming out here and this green light lambda 2 is these are only the examples of green and pink colour.

So, lambda 1 comes out from here lambda 2 comes out from here and because this is bidirectional. So, this is what is called the demultiplexing operation you have 2 wavelengths put into one fibre, but they are intern separated out. But the other way round it is also true that if you launch lambda 1 and lambda 2 into these 2 ports then they will be combined and will be available. So, this both the things are the are necessary for multiplexing and demultiplexing operation in a signal distribution network. For example we have to one is let us suppose one wavelength is for video, another wavelength is for telephonic then both of them video and telephonic both of them can be combined and can be carried out in the through the same fibre for a long distance and again at the output.

At the at the receiving end this placed in the other way in the opposite direction this coupler can separate them out lambda 1 and lambda 2 in the 2 different fibers and can be used for signal processing for the 2 different purposes so and also it is used as a pumped and signal mixer in the in the optical amplifier circuit and also for separating out the pump and signal at the output of the amplifier.

So, 9 18 15 50 or WDM dope fibre amplifier pump and signal they can be mixed and separated out. So, there are large number of applications of this coupler let us try to understand. The principle how these tapered fibre coupler can be used to separate or to combine 2 different wavelengths into one fiber or out from one fiber into 2 different fibers.

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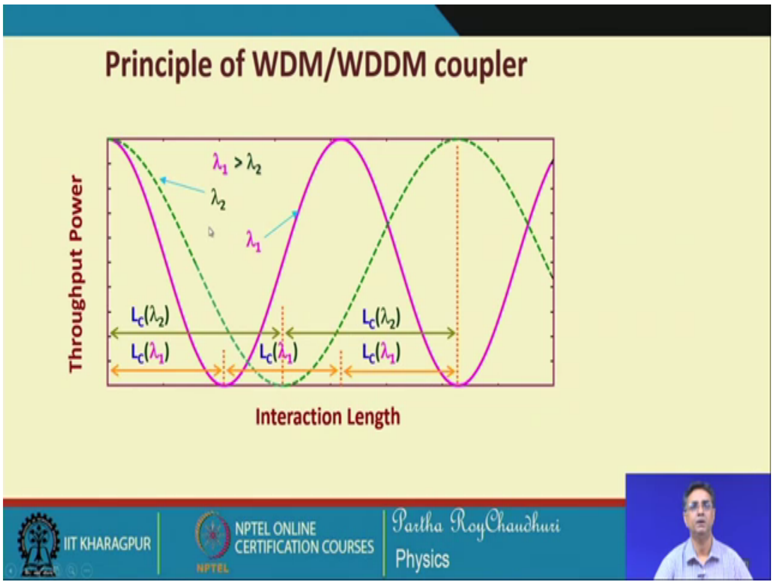

So, because we know that this coupling is a wavelength dependent property, the coupler is fixed; we have one coupler and if we use one wavelength lambda 1. If lambda 1 is smaller than lambda 2 then the coupling coefficient is such that the periodic exchanger periodicity is large that is the power transfer will be slow in terms of the interaction length. So, for lambda 1 which is smaller wavelength there will be a week transfer of power, for lambda 2 if it is larger than the transfer of power will be faster. Because for larger wavelength the coupling coefficient will be will you more than the coupling coefficient for lambda 1 for the smaller wavelength.

So, we can see that for 2 different wavelengths the power transfer date is different and that is actually exploited to design this wavelengths division graph, multiplexing coupler in this case lambda 1 is greater the pink one is greater. So, you have a faster rate of power transfer cycle faster rate, but the green one it has a slower rate of power transfer cycle.

So, it can so happened that at some length of interaction this power in the in for the for this wavelength that is lambda 2, for this wavelength lambda 2 which is a smaller wavelength it just. So, this is the this is the cross state for the lambda 2 that is the green wavelength and it is the cross back states. So, it comes back to the transmitted port again for this green wavelength, where as for the pink wave length this is the cross state this is the cross back state and it is again the cross state. So, it goes to these many cycles one 2 and 3, so it comes back to the couple port after this much of interaction length. Whereas, for this wavelength for this much of interaction length it comes to comes it goes through the transmitted port.

So, one of the wavelength is at the transmitted port the smaller wavelength and the larger wavelength is in the throughput port sorry in the couple port. So, as a result these 2 lights are 2 wavelengths are separated through this. So, this is very interesting to understand and it is the other way round because, if you mix these 2 wavelengths here then they will be separated. If these 2 wavelengths are inserted through these 2 ports they will be mixed and will be combined here.

So, it is again bidirectional that gives you this wavelength division demultiplexing and multiplexing both the effect the and the advantage of this fibre coupler is that it is very regards tabulate reliable, which are step to connect to the source and everything will be taken care by this coupler itself.

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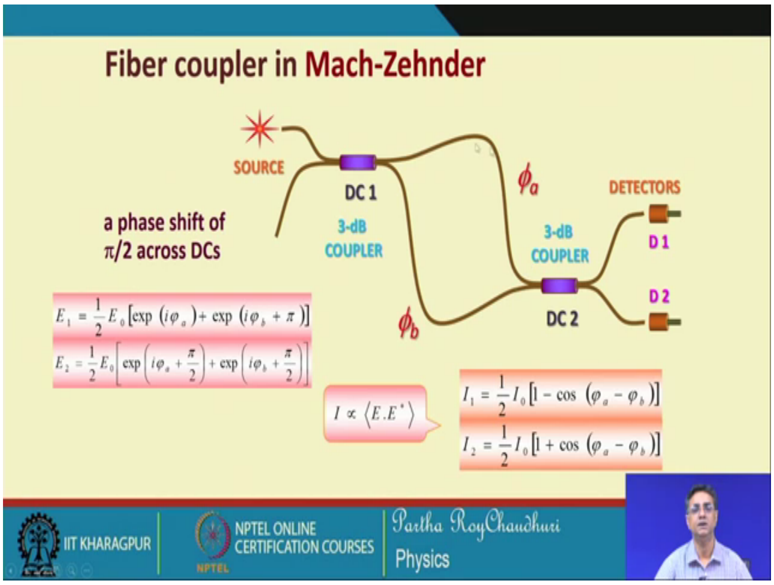

Now, we will see how this mach Zehnder application can be realize through this fibre coupler you have a source which splits light into 2 parts. We let us remembered that during our couple mode theory we discussed for identical waveguide couplers, whether it is a it is a planar directional coupler or it is a fibre coupler as per as the couple mode theory is concerned. That when you inject light into this fiber or this wave guide and the light which is appearing in the same wave guide that is in the transmitted or the throughput fibre or throughput wave guide there is no phase change.

But if the light has to has to couple from this wave guide to this wave guide there is a change in phase of pi by 2 this we have seen. Let us recall that in the couple mode theory we have seen that there is a phase change of pi by 2 when switching from one fiber to another fibre, when switching from one wave guide to another wave guide.

So, I am you will use this principle to understand how this mach Zehnder thing works, you have a directional coupler here fiber coupler here it could be. So, this is the 3 dB coupler and at so when you have a light which is injected here. Let us let us think of that this will be divided into 2 parts and then again this light will be divided into 2 parts from here and from here this part light will also be divided into 2 parts.

So, effectively this will be a sum of the lights which are coming from this side and also from this side, again this will be a sum of the lights which will coming from this side and this side. So, let us try to look at the expression for this when you have light which is going from here there is no phase change there is no phase change there is no phase change along this fibre there is no phase change. So, here when it appears here this light has undergone only the translational change, translational change in the phase that is because of the traveling, but there is no other phase change.

So, which will be taken care by this phi a term which is a function of this length and phi b will be the function of this length and if you have light which is. So, there is no phase change except this phi a so you have only phi a, if I look at the output at E1 port this d one port E1 will be E0 half E0 that I into phi a and for this light because I want to see the light which is available here together. So, one light I have seen which is due to this then there will be another light which will be due to this, so there is a phase change of pi by 2 again there is a phase change of pi by 2.

So, total phase change that it suffers in excess of this phi b is phi 1 pi by 2 from here 1 pi by 2 from here, so total phase change is pi plus phi b. So, that is what it appears here phi b plus pi, so this I should be outside. So, so this I should be outside, so this again if I if I look at so this is the power this is the electric field of the light which is available at this D 1 detector and the other one for E2 that is electric field which will be available in this detector we can do the analysis in the same way.

If you inject light here there will be no phase change here, but there will be a phase change here. So, so in access of phi a there will be a phase change of pi by 2 here again let us look at this light, there will be a phase change of pi by 2 in the beginning but at the end there is no phase change. So, pi by 2 plus phi b and here pi by 2 plus phi a these are the 2 phase changer phi a plus pi by 2 phi b plus pi by 2. Now if you just take the mode of this that is E dot E star will give you the intensity I 1 and I 2. So, for each one E1 star E if I take I will get this expression and if I take E 2 star E then mod of that then it will give you this value.

So, you can see that this is exactly the mach Zehnder you know intensity distribution 1 minus cosine phi a minus phi b is the is the difference, in the phase difference into this these length phi a and phi b which can be expressed in terms of the effective propagation constant and length of the fibre effective propagation constant assuming the same. So, ineffective into L1 this will be ineffective into L2. So, so this will be L1 minus L2 into ineffective into k 0 will be this quantity and here it is this so this is the mach Zehnder can which can be realize through a very stable configuration using 2 directional couplers and it is very widely used in the photonics technology in sensors many other applications.

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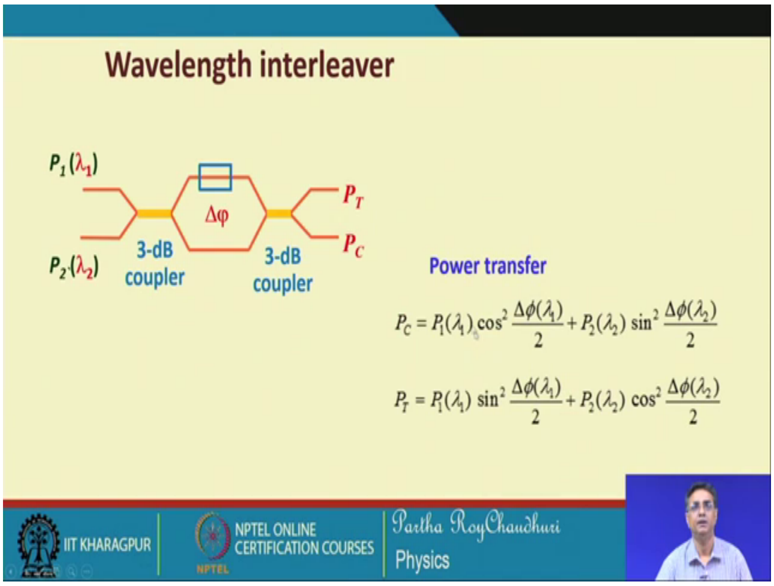

Then let us look at this wavelength inter leaver is a similar application the same configuration, but now that this way that one of arm is tunable and you can inject 2 different wavelengths. So, through a 3 dB coupler these 2 again they are decomposed and again they are combined at PT and PC, the power transfer can be represented by this equation as a function of lambda. When I inject this then it will be a cosine square function of lambda as well as it will be a sin square function, because I am looking at the couple port here. Whereas, in the transmitted port this will be a combination of P1 and P2 in terms of the sin square and cosine square function of this lambda 2 and lambda 1.

So, these are the 2 powers the expression for powers the amount of powers which will be available here, again they are sinus sin square cosine square term interestingly. If you make delta phi equal to 0 that is there is no phase difference you will get back to the mach Zehnder expression and if you make this phase difference equal to 2 pi or integral multiple of pi you can see that if this phase difference is 0 or 2 pi and if this phase difference is this for both the wavelengths that is for lambda 1. This phase difference is 0 but for lambda 2 it is pi then PT will be 0, because it appears like that one is pi one is 0 another is pi by 2.

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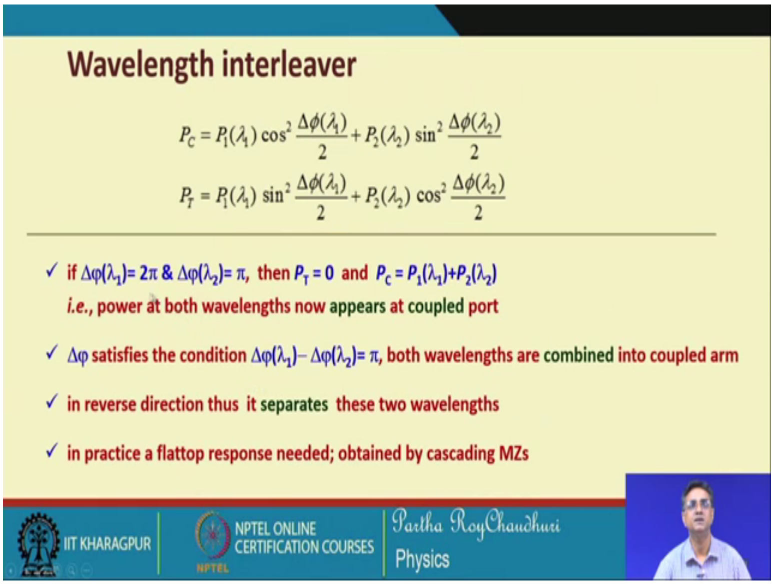

So, as a result because pi by 2 so it will make it equal to 1 this will be come equal to 0, so you get PT equal to 0 and PC become just P 1 plus P 2. So, these 2 wavelengths will be added up if I can tune the phi delta phi in such a way that for one wavelength it is twice pi for other wavelength it is pi, then both the wavelengths will be appearing in the couple port see both wavelengths now appear at the couple port. If delta phi satisfies the condition of this minus this equal to pi both wavelength are combined into the coupled arm that is this one, this is the difference in the reverse direction does it separates these 2 wavelengths.

So, both the wavelengths are now appearing into this wavelength, now if I inject both the wavelengths into this and I tune this so that the difference of the phase for the 2 wavelengths is just pi then it will be distributed into this 2. So, this operation is the wavelength interleaving which is very commonly used in the optical network. In the reverse direction it separates these 2 wavelength in practice we need a flattop response, we need that it should be the response should be flat over a what is the meet of the wavelength. In that case it can be done by cascading a number of such mach Zehnder configurations from which.

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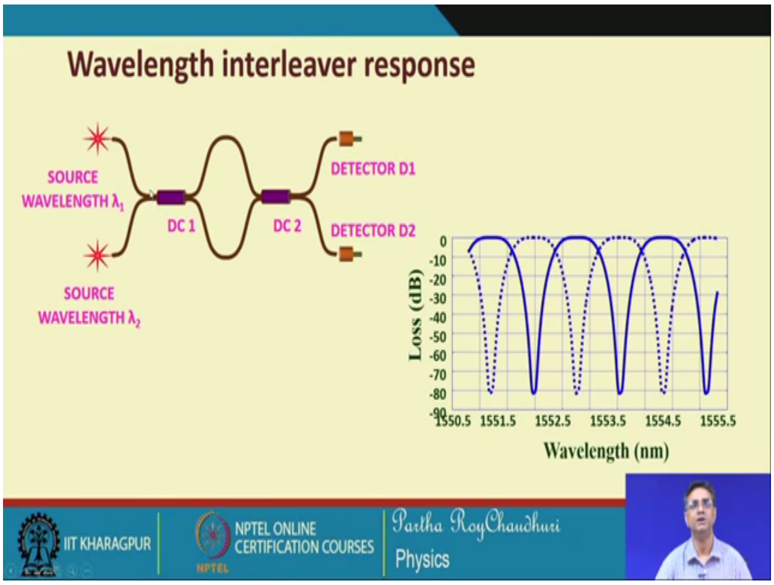

So, you can see that you have a mach Zehnder made out of 2 fibre couplers you have 2 source wavelength and you are looking at the detector 1 and 2. So, you have a you have a flattop response the over this bandwidth that is from here to here over this range of wavelength it remains almost same and this becomes minimum and it happens for this the solid line and for the dotted line these are the 2 different ports. So, you get this kind of response for 2 different wavelengths, so you have 2 different wavelength which will be appearing periodically and ovaries. So, these this is the range of wavelength which can be used for interleaving there is the very beautiful application and ok.

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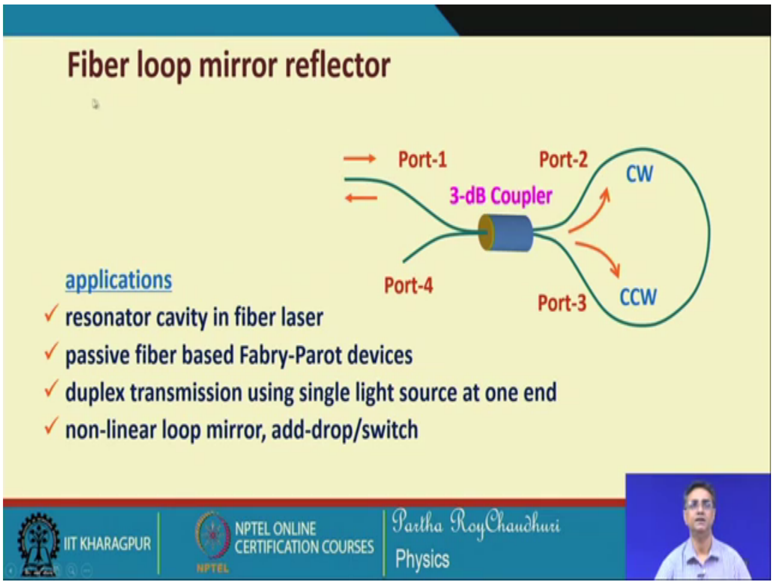

So, then there is another very promising and very useful device which is made out of this fuse coupler, if you have a 3 dB coupler and if you just concatenate if you just connect the sorry not this one.If you just if you just close this that is if you just splice this input the 2 outputs together and you form look then what happened.

The let us look at the look at the principle then it will be very interesting to understand let us suppose that you have this is the input port. So, the light which will be which will be travelling across this coupler will have a phase difference of pi by 2 and it comes to the couple port, but there is no phase difference when it goes through this port.

Now, this light so there is let us restrict to one wave that is clockwise, when this light goes through this circuit there is no phase difference there is no phase difference all along this. It is only the way translation of air then there is again no phase difference when it comes through this port, because every time it is restricted to the same fibre which is the input and output. So, when it appears here it is only a constant phase, but if you look at the other part of the wave that when it comes from this side to this side there is a phase difference of pi by 2 again this light and counterclockwise light when it comes back from this fibre to this fibre there is a phase difference of pi by 2.

So, these 2 phase difference of pi by 2 added up will give you a total phase difference of pi, so this will have a phase difference of pi which extra when you compare the light which is travelling in the clockwise. So, clockwise light will have a phase difference which is let us suppose 50 then the counterclockwise light will have a phase difference which is 50 plus pi.

So, now these 2 waves when they appear they are out of phase, so they will destroy each other they will interfere destructively as a result there will be no light output here. That means, the entire light will be reflected that we can do the operation for the other part also that is when you have light which is injected here. So, first there is no phase difference here it goes through this, but there is a phase difference of pi by 2 when it comes back to this port.

If I consider the light coming back come out of the same input port the other 1, when there is when there is a when it comes from the throughput port to the couple port there is a phase difference of pi by 2. Then again there is a phase difference there is no phase difference, so these 2 phase differences are the same because it is only 50 plus pi by 2 for this case it is only 50 plus pi by 2 so they are same. So, they will constructively interfere so the inter light will be reflected back into the same fibre, so there are lot of applications.

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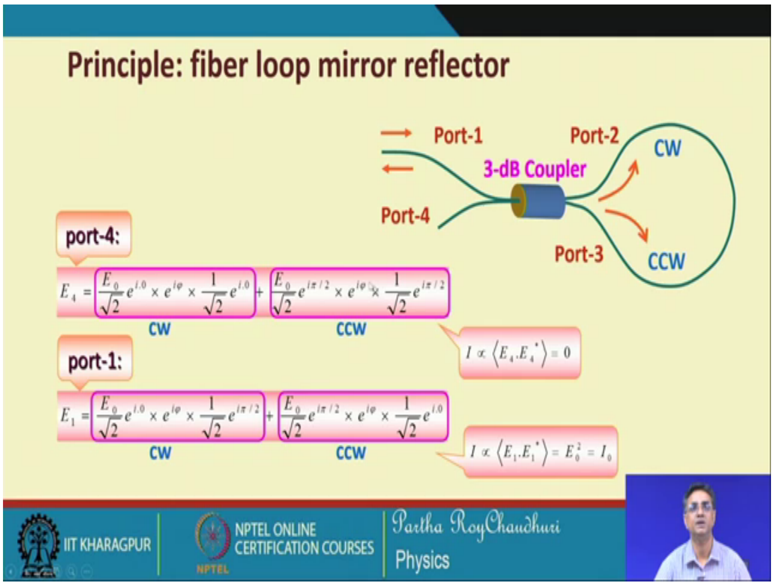

Let us try to understand the mechanism once again I have explained this that for the clockwise light clockwise light there is no phase difference there is no phase difference there is no phase difference. So, I have put 0 and this is only the phase difference due to this n 0 phase difference due to the length of this, but for the counterclockwise light you have a phase difference of pi by 2 you have a phase difference of pi by 2, in access of the phase that is due to the length of the fibre.

So, put together you get the port 4 which will give you 0 because you have a defective phase difference of phi, where as for port one that is in this port you have a phase difference of 0. But there is a phase difference of pi by 2 because, each time it goes to this once it goes to the couple port next time it is in the same port but and again it is in the same port next time it is in the couple port.

So, as a result in both the both clockwise and anticlockwise day actually come across the same phase change that is pi by 2. So, which put together you get that the light which are meeting here they are in phase, so it will constructively interfere will get back. So that means, when you have an injected light injected into this port through this loop mirror they will be reflected back into the same fibre. So, this is a mirror but it is in the form of an optical fibre so it is a guided mode mirror and you do not need any external mirror to reflect the light back.

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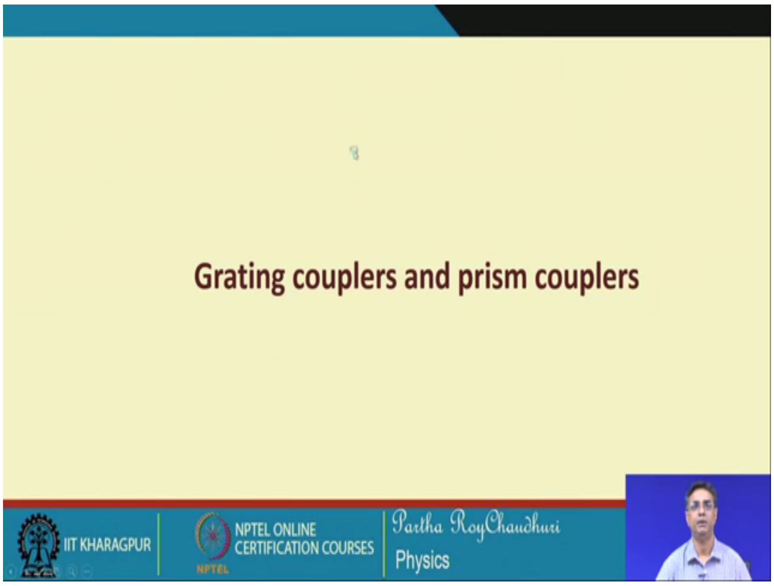

This is a beautiful application.

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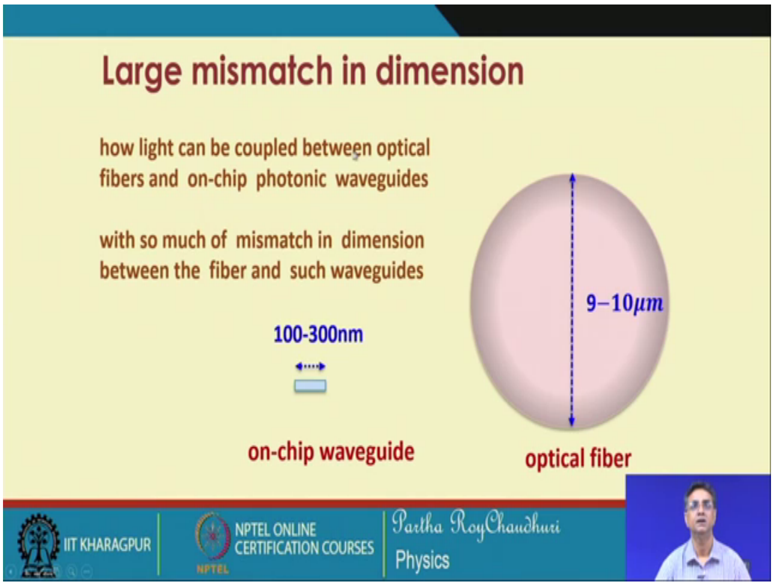

Then we will discuss this other computing technologies for optical coupling and this is one that very often come across is that how you have an integrated optic devices which are the dimensions are very small 100 to 300 nanometer, whereas optical fibers are 9 to 10 micrometer core diameter. So, in the huge mismatch in the diameter and in the mode field in the in the near field, where you want to couple the light from here to here the overlap is very poor. So, that is a very big problem in coupling light between optical fibre and integrated optics both of this is one very very much useful very important requirement in devising. The optical system in photonics system with so much of mismatch in the dimension between the fibre and such waveguides it becomes really difficult one has to think how the light can be effectively coupled from fibre to waveguide and waveguide to fibre back.

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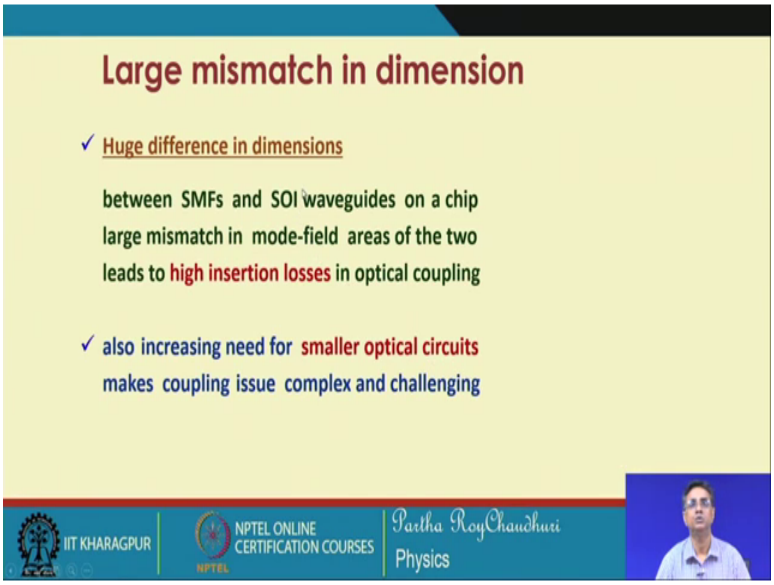

So, between SMFs so this silicon on insulator is a very competing very new technology ah, in this case also this large mismatch in the mode field area and as a result there will be high insertion loss most part xof the light will be lost during coupling. Also the problem comes from that more number of users the chief density more number of integrated optic device are to be integrated into a smaller. As a result this waveguide dimension becomes smaller and smaller which makes this issue more complex and challenging.

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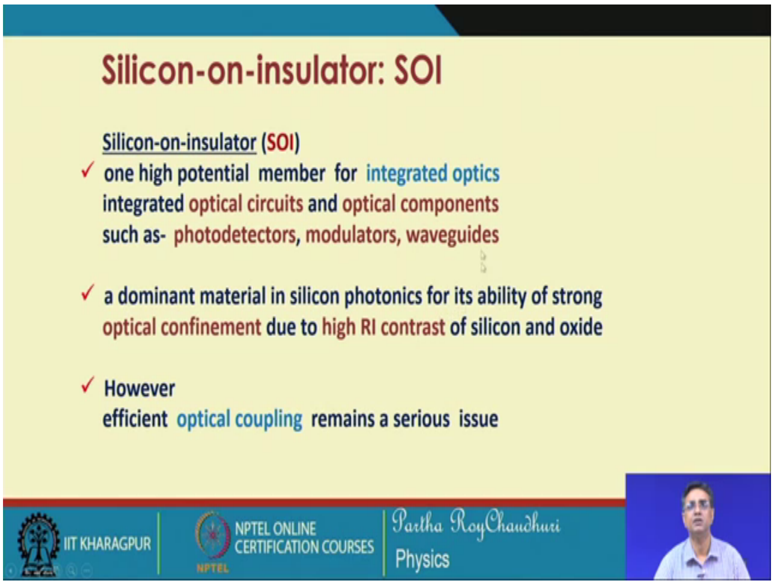
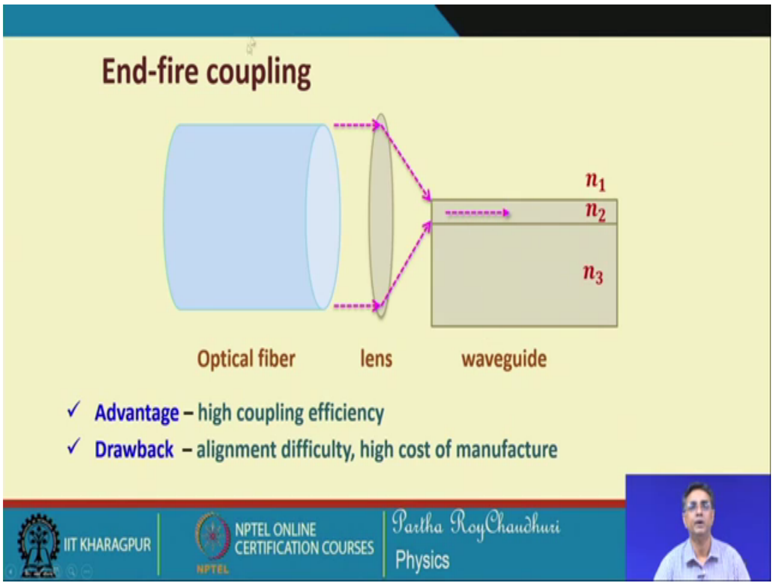


So, this silicon and insulator for this there are lot of applications photo detectors modulators optical waveguides ah, so this confinement and high refractive index contrast. However, this these are the advantages but the problem is optical coupling.



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Now, we will look at this end fire coupling which is a very popular and well known methodology, this advantage is a very high coupling efficiency. You have an optical fibre you can put a length and through the lens you focus the light into a very small numerical aperture small geometrical aperture and with this the entire light can be coupled into this waveguide. Which is which is you see an integrated optic waveguide very thin layer and thin film waveguide. But the drawback is alignment difficulty and very high cost of this manufacturing not very simple and straight forward.

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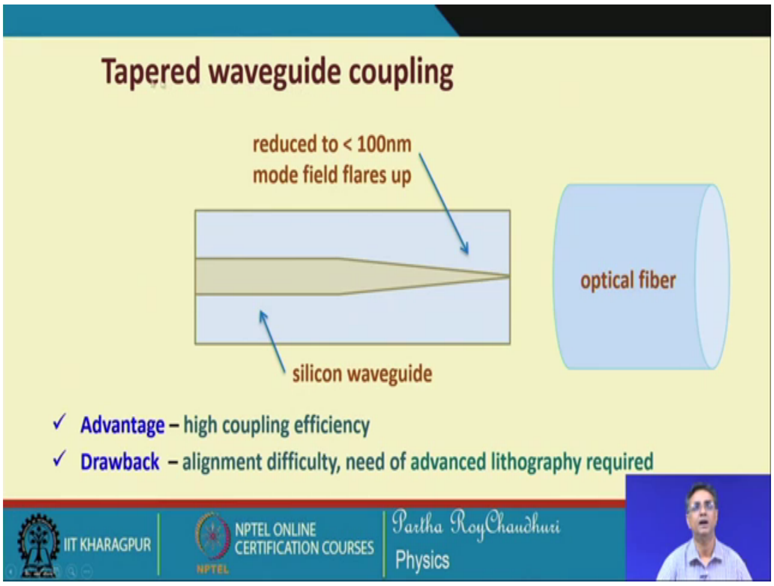

The other way of tapered waveguide coupling, this integrated optic waveguide is made in such a way that it forms a taper and you know that when it is in this region the mode is very nicely good tightly confined into the into the core region. But if it is the tapered region the mode will flare up it will be it will be flaring up and will leak out of will move out of the part of the most part of the of the wave with the mode field will be outside the core. So, the model field effective area of the model field becomes very large and then there will be a very good you know overlap between the optical fibre and this again.So, the coupling efficiency becomes very high so this is again a very high coupling efficiency device this technology. But again the problem is alignment difficulty need of advanced lithographic requirement for making this kind of devices.

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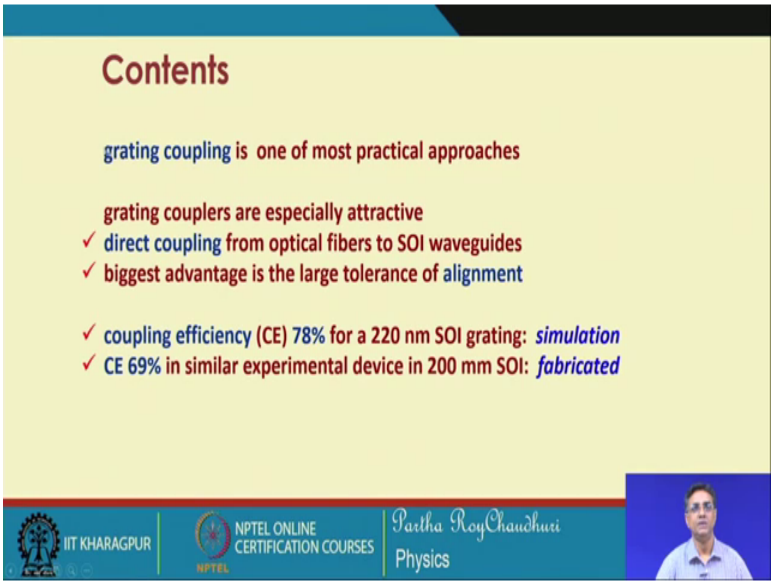

Right then another very promising technique is the grating coupling and grating couplers are essentially very attractive direct coupling from optical fibers to silicon integrated optics coupling efficiency is very high, so the principle of this is that you have an optical fibre.

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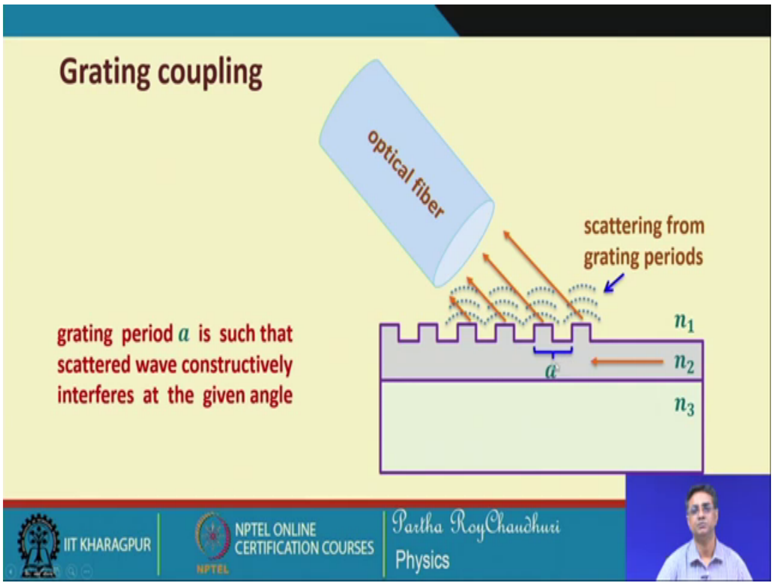

So, the light is there in the integrated optics device so and this is a grating in periodically etched grating and this from because of the grating the light will be periodic structure light will be scattered and this scattered light will be collected by this optical fibre, where there will be a phase matching condition that is satisfied. So, the period of this grating will be such that the scattered light wave will meet here with a constructing interference at a given angle.

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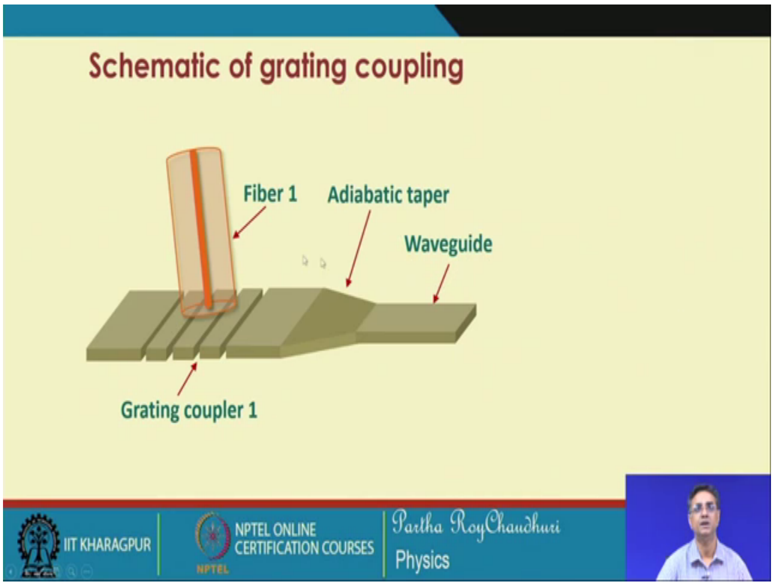

We will see that how it happens this is the either schematic of this waveguide coupler you have a grating coupler, you have an optical fibre which is placed on top of it and the light from this wave guide goes through an adiabatic tapered, so that very smooth and cosine static transition from a smaller waveguide to a larger waveguide dimension and then this grating will scattered the light which will be collected by the optical fibre.

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Actually this is the fabricated grating structure and this one is the are magnified image of this same grating how is a top viewed out to the fabricated structure.

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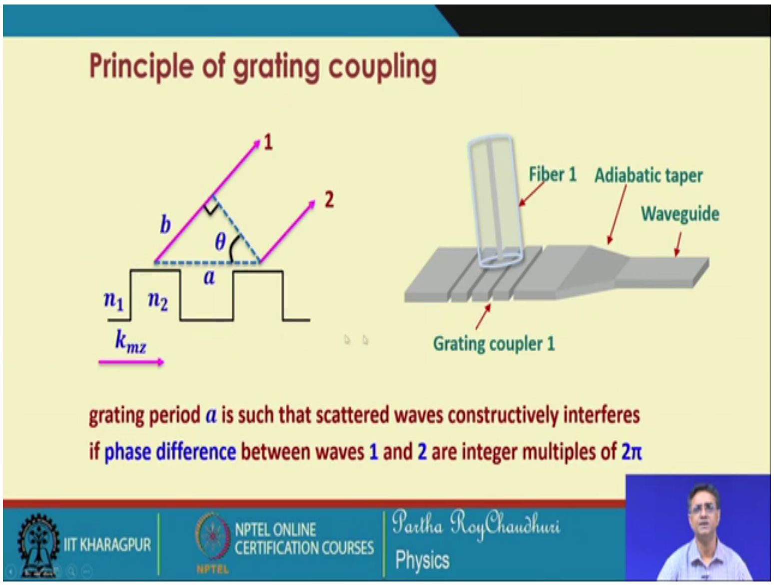

Now, to understand the mechanism of this grating in optical fibre coupling, we can see that this the way which is travelling. In this direction the mode which as a the mode effective refractive index in effective is give a or the propagation constant is given by the z component of the propagation k mz m h mode, k mz z component of the propagation vector and for the light which will be which will be scattering from this surface the wave which goes out from here and the way which goes out from here effectively this would be in the same phase along this light.

So, this is the extra path which the wave have traveled, whereas the way which has travelled from within the waveguide from this point this point this is the extra part. So, this extra part into the effective index of the mode must be equal to the effective index of the light and this extra part there should be equal that is the phase matching condition.

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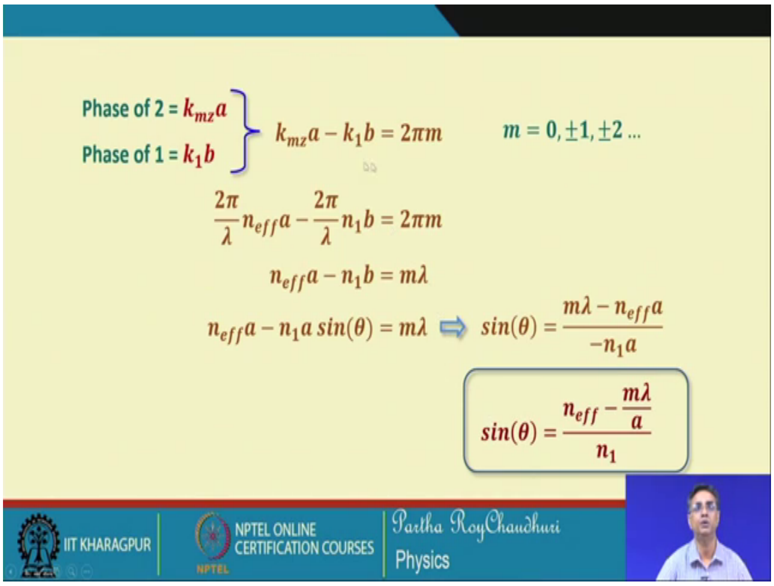

We will see how it works so the phase of 2 phase of 2 phase of 2 will be the light which has travel from here to here this much, which has travel from here to here that is a distance of a with the ineffective value a into z component of the propagation vector and phase of one will be k 1 that is this it could be k 0 if it is in the phase space k 0 and then this length so this will be the phase of one.

Put together if it is this phase difference is an integral multiple of twice pi m equal to 0 1 2, then this phase matching condition is satisfied which will eventually result in the time theta equal to. So, this is the condition for the grating coupler we tried to understand in a very simple and received way.

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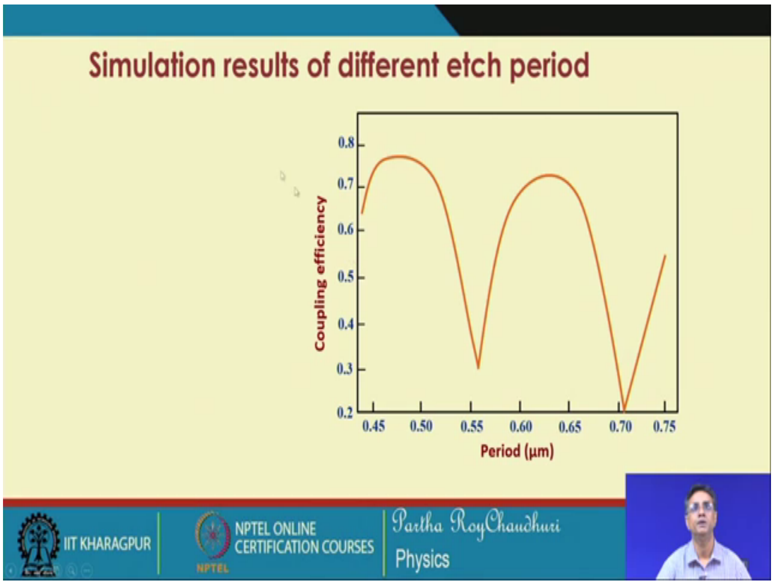

These are the simulation results for different etch period of the grating and you look at the coupling efficiency. So, this is how it periodically goes to 0 and it becomes maximum there is a beautiful signature of this grating coupling.

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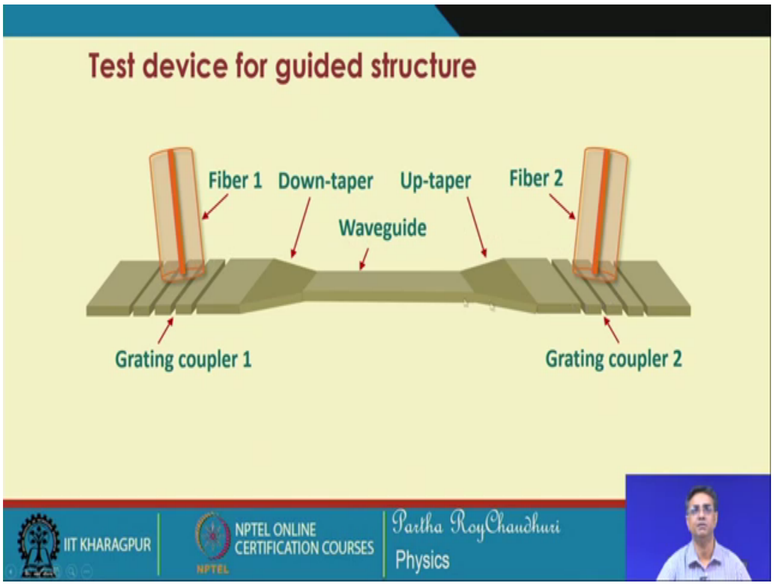

This is a test device you have to launch light from this fibre, then it is coupled into this waveguide again the light is available from this. With this you can actually characterize the device how much is the coupling in how much is the coupling out and so on.

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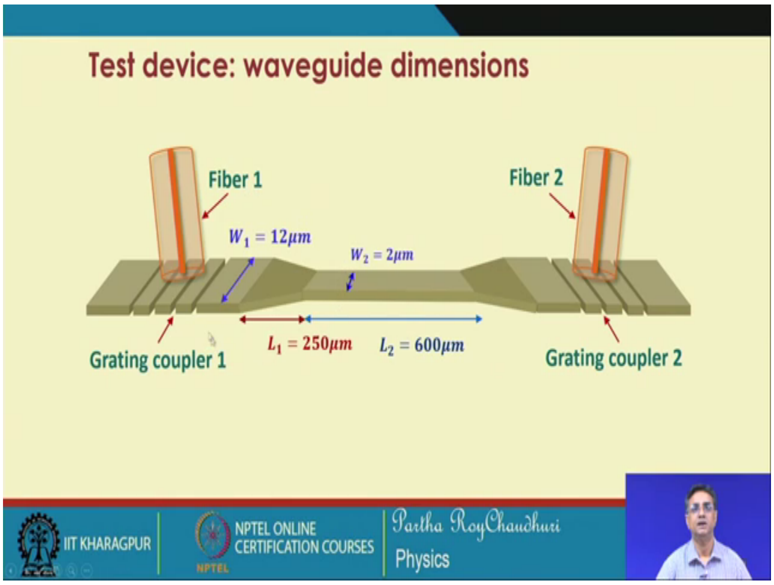

So, these are these are the typical dimensions about 12 micrometer this is about 2 micrometer this length is about 600 micrometer this length this tapered length is about. So, these are the typical numbers which are used for fabricating practical grating coupler waveguide grating and this is a coupling efficiency this is all experimental.

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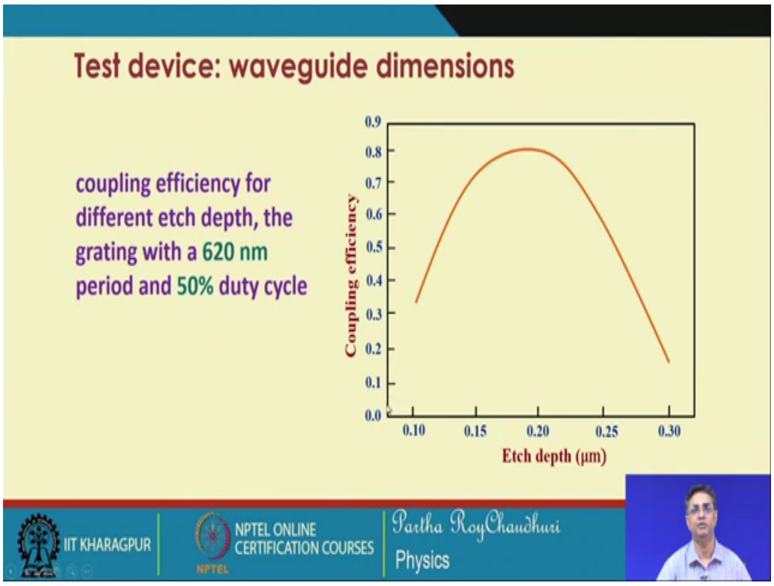

So, with the etching depth how you can see that can optimize the depth of etching to get them best coupling efficiency for a given system with the given conditions.

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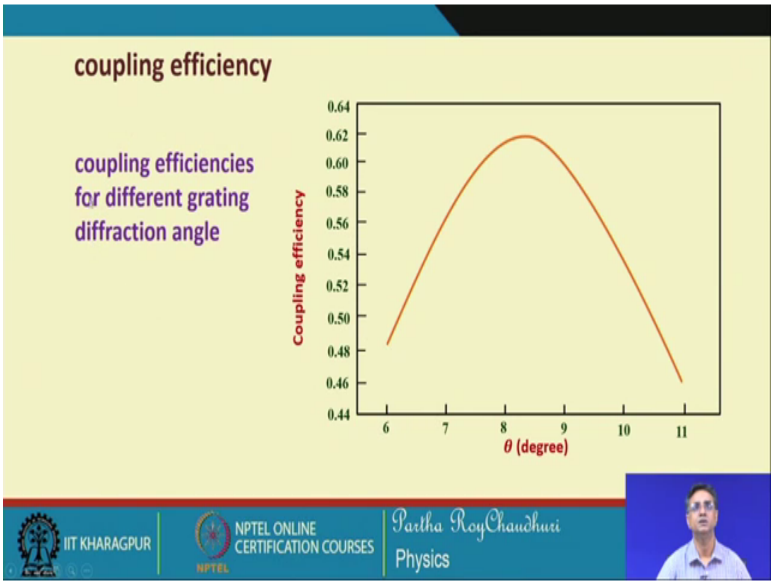

So, this is coupling efficiency for different period of at different angles changing angle, how so these are the different parameters that you have to characterize for optimizing the performance of the gating.

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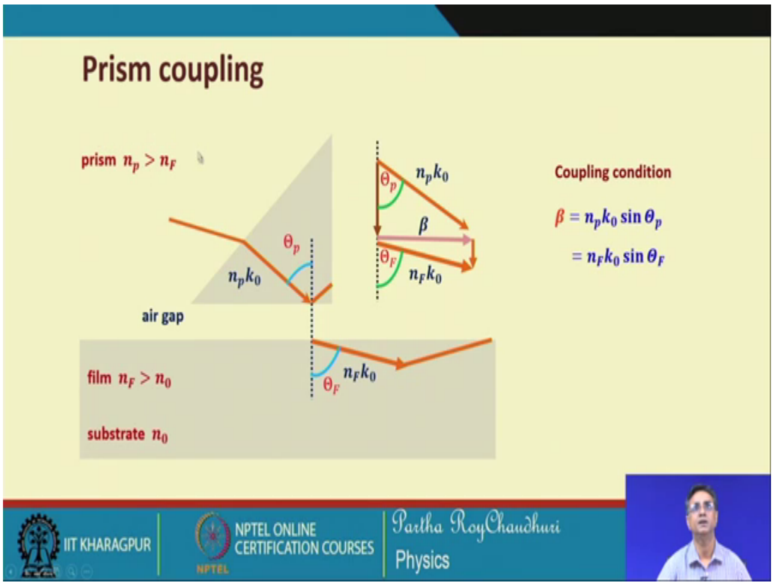

Then prism coupler in the case of a prism coupler you want to couple light into this waveguide. So, you have a light you have to use a prism whose refractive index is higher than the refractive index of the waveguide. So, this n P is greater than n F film. Film refractive index pre prism refractive index typically 1.6 1.7 this is 1.45.

Now, the light which hits the surface will be evanescently available here and then this evanescent wave because there is gap is very small. This evanescent wave hits the second structure which is another waveguide structure. As a result because it finds another waveguide where it gets guided this is also called the frustrated total internal reflection, you look at these principle that this is the way which is travelling the way which is guided in the structure whose propagation constant is beta, this beta has to be matched for both of them.

Now, if the if the wave is reflected back and forth with this angle, then the z component of this wave will be beta, so that is n F into k 0 the z component of this will be this into sin theta because this is cosine theta F. So, you have to take the component along these direction which will be nF k 0 sin theta that must be equal to beta and for this wave which is travelling along these direction. The z component that is the tangential component along this the component of this because this is theta so the theta so this component will be again sin theta.

So n P k 0 sin theta that must be equal to beta this is very clear from this picture, you have a wave which is travelling in this direction theta P is this direction. So, the sin component of this k 0 of this n P k 0 will be this which has to be equal to beta. Similarly n F k 0 which is the wave which is travelling in this the z component of this will be equal to beta, so that gives you the condition that beta must equal to n P k 0 sin theta P which is equal to n F k 0 sin theta f.

So, that give defines the phase matching condition for the for the coupling of the way from the prism to this and you can have maximum transfer of power from this phase space light through the prism into the waveguide and in the same way you can take the light out from the waveguide by using a prism, this is called prism coupling and decoupling technique.

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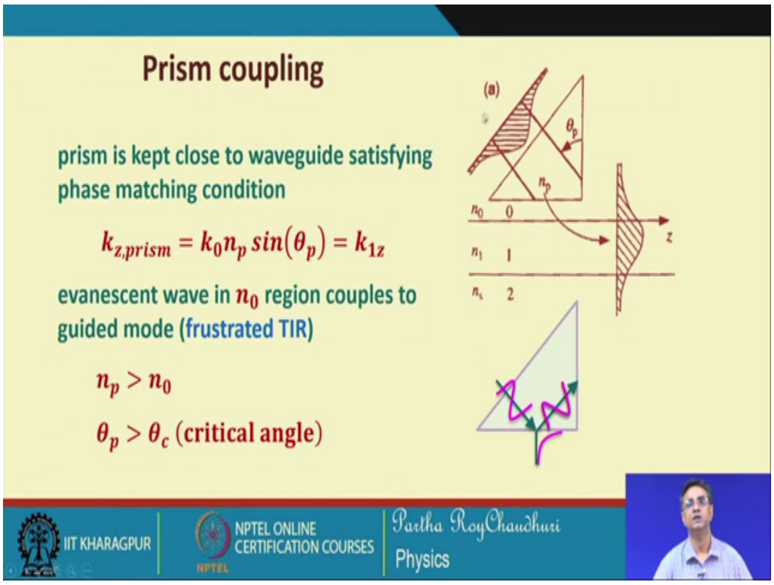

So, the technique once again that this I just have mentioned that this is the phase matching z component of the wave of this, this mode the z component of this will be given by k1 z for this and the z component of this wave will be given by this k z prism. So, they have to be equal z component of this wave and z component of this wave this will be actually beta and this will be in terms of this theta P and n p. So, if you put these 2 things together you get this is like a beam splitter, you have a wave which is coming here then there is an evanescent wave outside part of the wave is reflected. This evanescent wave now gets coupled into the second waveguide so this is how it work.

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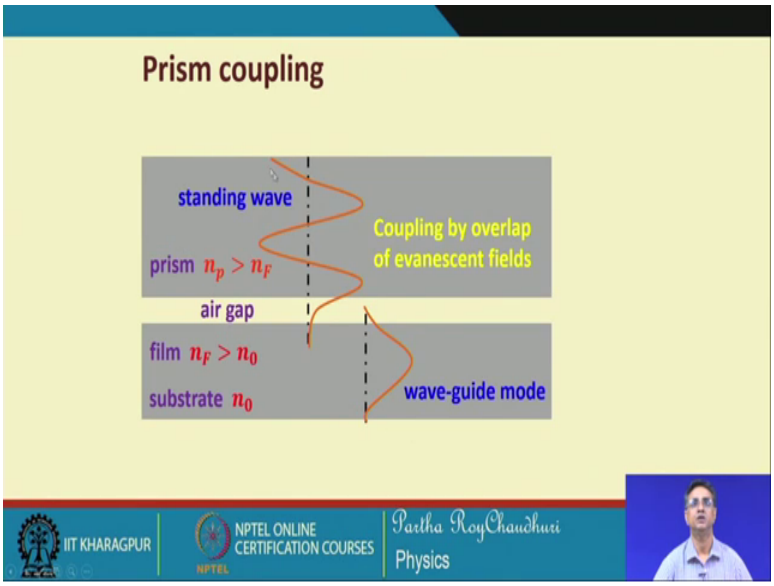

So, you have a standing wave pattern in the prism at this point, where as you have an evanescently decaying field in the air gap and this is again oscillatory because it is a waveguide and there is a coupling between these 2. So, this is how the several interesting methods of optical coupling we come across and there are many more applications in this field or coupling light from waveguide to fibre, fibre to waveguide, waveguide to waveguide and so on and so forth.

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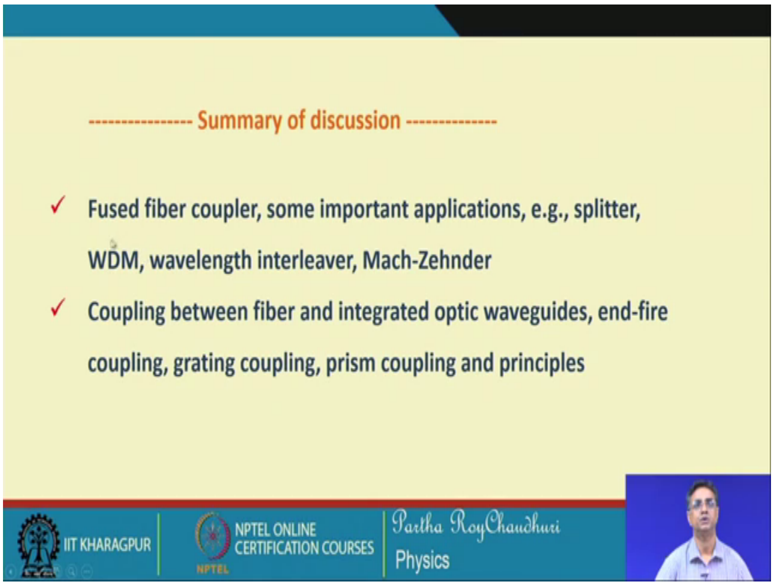

So, we in this context we have discussed fibre couplers some important applications, wavelength interleaver mach Zehnder coupling between fibre and integrated optic devices end fire coupling grating coupling and prism coupling and their basic principles we will try to understand.

Thank you very much.