Fiber – Optic Communication Systems and Techniques
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Lecture - 45
Couplers, Circulators, FRM and Filters

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In the last module, we discussed or we introduced a lot of WDM components and in this and in the next module; we will look at these WDM components in slightly more detail.

We will try to keep the mathematics as simple as possible so that the basic idea or the physical operation behind or the physical ideas behind the operation of these devices is what we will stress on. We will start with one of the most basic device called as a coupler ok; this coupler as we have seen comes in at least 2 varieties.

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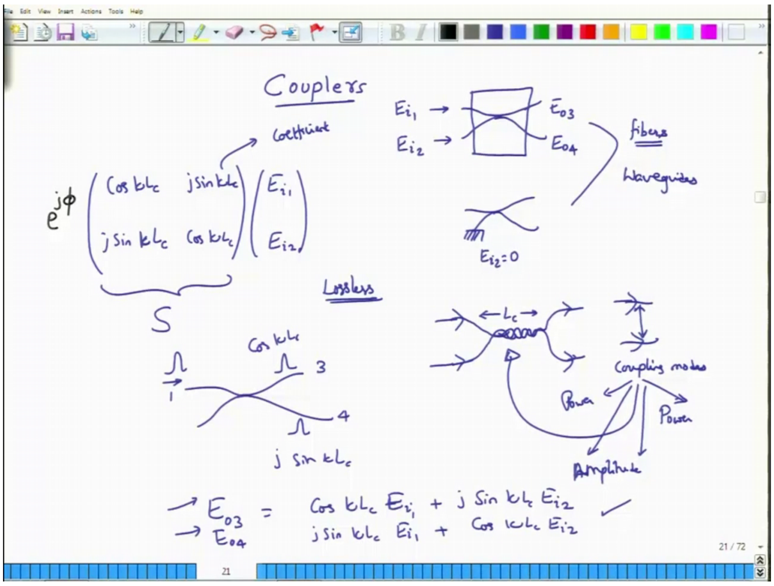

One is what is a general coupler and a general coupler which is also called as a 2 by 2 coupler; because there are 2 input ports and 2 output ports. Usually the job of this coupler is to take the input from the 2 ports.

Let us call those inputs as E i 1 and E i 2 which stands for the light waves that are applied to the 2 input ports of the coupler. And then of course, you have the 2 output ports we will call those output ports as E o 3 and E o 4 indicating that these are the light waves that would be there at the output of the coupler.

And there is a ; So, this is the general formalism and the 2 types of couplers that I talked about was the coupler which is used to combine signals at the 15 50 nanometer range or even up to say 1600 nanometer range; those are your regular couplers. And then there is a special type of a coupler which will couple signals at 980 nanometer which is the wavelength of the laser diode; that is used to pump the erbium doped fiber amplifier as we have seen.

So, coupler which couples the 980 nanometer pump signal with the 15 50 nanometer signal itself or the optical signal at 15 50 nanometer is usually called as a pump WDM coupler ok, but in.

So, the operation principles are slightly different we are not going to look at the pump WDM couplers, but rather we look at those couplers which are used to combine or split signals in the 15 50 nanometer band. So, all this discussion of couplers will be restricted to these couplers only.

So, in that band these couplers actually are 2 input ports and 2 output ports in general. Of course, you may also find couplers which have only 1 input port and 2 output ports.

In this case the assumption is that the second port is not fabricated. The principles are slightly different in the 2 cases, but for mathematical convenience; we can take the second input port has not been fabricated or the second input port signal E i 2 is actually equal to 0.

Of course, you can get the same kind of a coupling performance when you say E i 2 equal to 0; in this 2 by 2 coupler as well. But as I said the operational principles of these 2 are slightly different and moreover, these couplers can be made entirely by fibers or they can be made with wave guides.

The advantage of making them with wave guides is that you can use the silicon or you can use the integrated optics technology. So, that these devices can be made more compact, but then coupling of light from the fiber to the waveguide and from waveguide to the fiber is a task that still remains.

However, if you make them and all fiber coupler; then you do not have to worry about this fiber 2 wave guide coupler. And again the operational principles are different, but we will not go into those difference principles at all.

Strictly from the black box point of view if you imagine that this device has been given to you and you have no idea what is inside except that you know that this is a coupler; then you can characterize this coupler by these input and output relationships. What are the input and output relationships that we need to think of? Well we have E i 1 as the input in port 1 and E i 2 as the input in port 2; we can collect them together to form a vector.

And then we say without telling you; how this comes about I am just going to write down the characterization matrix. So, these are kappa and cosine kappa lc where this lc is called as the coupling length.

So, if you actually look at how they are made using the fibers; then you can actually make them by twisting the fibers in this fashion over a certain length and then separating them out. Twisting causes the modes which are essentially propagating individually in these wave guides and which essentially separate out after the coupling region.

These are the individual modes of the individual wave guides or individual fibers. So, this is fiber 1 and this is the np 01 more for example, of that one this is fiber 2. And there is an lp 0 1 mode for that. And far away from the coupling region again you have independent or individual modes that come out ok.

But in the coupling region which has a length of lc that is the length that we have used in this matrix as well. It turns out that the modes in one fiber you can talk to modes in the other fibre or at least we imagine that they are talking to each other ; meaning we are coupling the modes from the 2 individual fibers.

And this coupling will take place not at far away distance from the coupler, it is actually taking place right in the center or right in the region where coupling is expected to happen. There are two forms of coupling one is called as the power coupling ok; in which the power of one more couples to the power of the other mode.

When we say coupling what we mean is that there could be some exchange of the quantities of interest. So, in the power coupling mode power of one waveguide or power of one part of their mode will depend on the power of the other one. But there is also another more common type of waveguide which is basically the coupled amplitude or amplitude couplers.

And this is the amplitude coupler that we are talking about we are not talking about the power couplers; although when you order a coupler I know to your laboratory, you will normally be talking about the coupling ratios in terms of the power. So, you would say give me a 50 coupler.

That means that I will take 50 percent of input 1; 50 percent of input 2 and then put it on to the output. Alternatively I will take one you know half portion of the signal 1 and half portion of the signal 2 and then give out onto the appropriate outputs.

So, they have these different ways of talking about a coupler, but the most important thing is to note that coupling happens only in the region where we have defined the coupler or we have actually physically you know made the coupler. And the distinct point of this coupling region is that it will take the modes which are essentially individual in the 2 fibers or waveguides and then make them talk to each other.

And if that talking is in the form of power to power talking, then we have a power coupling of powers or you have the more common coupling of amplitudes and this is the amplitude coupler that we are talking about. So, when you take this coupling matrix as we would call this in this particular form, we are also assuming that the coupler is lossless.

What we mean by this? Will be known very shortly, but I have the 2 input electric fields E i 1 and E i 2 they multiplied 2 cosine kappa lc and this factor of j is very important ; this indicates that the 2 arms or actually phase shifted by 90 degrees. What we mean by that is that ; if this is my coupler and I send in a certain optical signal on to this ports.

So, this is the port 1 and on port 3 and port 4, I will get an appropriate amplitude pulses at the output; the amplitude being distributed in terms of cosine kappa lc and sin kappa lc; this is how the split of the amplitude has happened.

But in addition to the split in terms of the amplitude; there is also an other phase shift of j which comes through this or j is basically pi by 2. So, you have a cosine kappa lc and a j sin kappa lc as the output.

So, indeed you can write E o 3 as cosine kappa lc; times E i 1 plus j sine kappa lc E i 2. And of course, you can also write the same thing for E o 4 instead of having cosine kappa lc E i 1, from the coupler metal it is clear that it will be j sin kappa lc E i 1 plus cosine kappa lc E i 2 and kappa is called as the coupling coefficient.

So, kappa is called as a coupling coefficient lc is called as the coupling length. And these equations essentially follow from the matrix times vector multiplication that we have already indicated. Now we have said that we can have a lossless coupler and what is the meaning of a lossless coupler?

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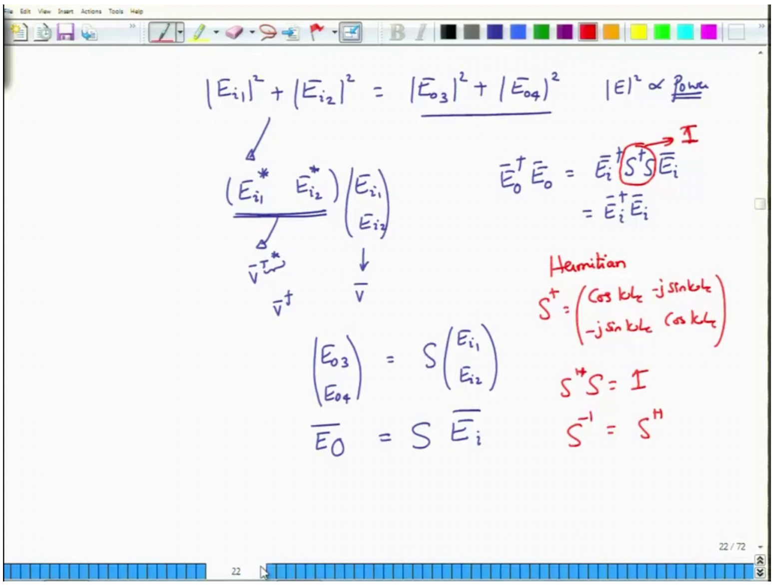

For a lossless coupler the total power must be equal total input power must be equal at the output as well.

So, that condition basically means that; I have E i 1 magnitude square plus E i 2 magnitude square that must be equal to the magnitude square for port 3 field plus magnitude square of the field at the port 4 ok. And it is important to note that these are magnitudes because the magnitude of the electric field is basically proportional to the power carried by that particular light wave.

Now we can express this left hand side relationship in a vector notation. So, what you can you can of course, see that this is essentially true if I can write down the vector E i 1 and E i 2 in the form of a row vector, but then also put a conjugate onto top of onto each of them and then I have E i 1 and E i 2.

So, when you now do the rho times column multiplication; you will end up with a scalar which precisely is given by E i 1 magnitude square plus E i 2 magnitude square; you can check this out. Now if I call this as a vector v then this is a and we will denote a vector v with a bar over top and this vector is essentially first taken the transpose and then conjugated it.

And this notation we will combine this notation of transposed conjugation into what is called as an adjoint symbol. So, what we have is for a complex vector v adjoint of that particular vector means that you first transpose the vector and then individually conjugate the elements of that vector. So, if you start off with a column vector ; you will end up with the conjugate transposed row vector as you can see here. Of course, we can do the same thing for the output electric fields as well and you can write down.

That and then using the relationships that we have already developed written down in the previous slide; you can actually substitute and painfully show that this equation will true will be true. But there is a slightly better way of doing it; we will go back to this coupler equation and then call this matrix as the S matrix. This is the coupling matrix I could have used B; but I am using S.

So, this is the S matrix and in terms of that S matrix; the output vector ; that is the electric field vectors at the ports 3 and 4 of the output can be written in terms of the matrix S times the input vector E i 1 E i 2.

Let us also invent a slightly simpler notation for this I will call this as E O bar; which is a vector to be equal to S E i bar. Please note that E i bar and E O bar are 2 component vectors which of course, are given above in this particular equation. So, this condition that E i 1 conjugate E i 2 conjugate is essentially taking E o and then taking the adjoint of that and then multiplying that one with E 0 vector itself ok.

And if you do that onto the right hand side right; so, this was the left hand side and if you do that onto the right hand side what you get is the input vector being a joint and S matrix which is being adjoint. And then you have an S and then you have a input vector as it is.

Now lossless condition means that this right hand side should be equal to E i adjoint times E i vector which clearly implies that the term S adjoint S must be equal to identity matrix.

And any matrix that satisfies this condition is called as a Hermitian matrix or a matrix with a Hermitian symmetry. What is S conjugate here or S adjoint here sorry that would be cosine kappa lc j sin kappa lc of course. So, minus j sin kappa lc cosine kappa lc ; now I will leave this as an exercise to you to show that S adjoint times S or S adjoint times S must be actually equal to 1.

And of course, you can also instead of using this adjoint, you can write down this as another symbol called H, which would then denote the Hermitian component of this one. So, this is the Hermitian property S Hermitian S is equal to I which also means that if you want to find out the inverse of S that is actually the Hermitian conjugate of S itself or the Hermitian of S matrix itself.

So, this is how we talk about a coupler in a very general manner and we can actually choose various coupling ratios; based on the matrix that we actually have.

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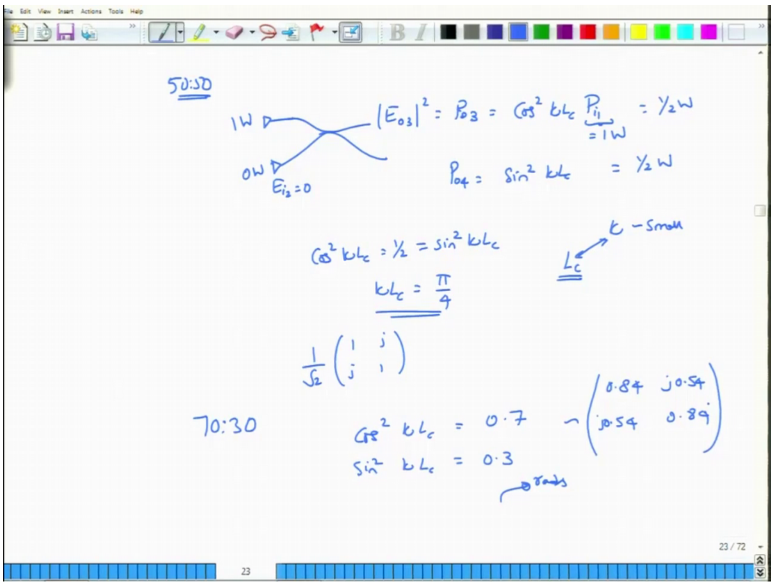

So, let us look at one or 2 examples here. So, let us start with a simple 50 50 coupler. What we mean by a 50 50 coupler is this; I have a coupler here I will send 0 watt of input which means to essentially say that E i 2 is set equal to 0 there is nothing specific about E i 2 you can do the same thing for E i 1 as well.

But if you send 1 watt in E i 1 with a 50 50 coupler; you expect that the output power which is magnitude of E o 3 which we will write it as P o 3 will be equal to cosine square kappa lc times the input power which is essentially P I 1, but P i 1 is equal to one watt. So, that is essentially gone and you can show that P o 4 will be sin square kappa lc and 50 50 coupler means that the split ratio or the coupling ratio is actually equal to 50 50 percent; 50 percent 50 percent.

So, this means this would be half watt here and this would also be half watt and clearly for that to happen cos square kappa lc must be equal to half which also is the condition on sin square kappa lc. And one possible solution for this equation would be to consider kappa lc equals pi by 4.

Of course, higher multiples are also possible and they are also equally valid solutions, but when you go to higher value say maybe for example, 3 pi by 4 ; then either lc is increasing or kappa is increasing right. In general what happens is that you have to choose lc because kappa is usually very very small ok. So, you have to usually choose a larger coupling length.

But the product is what determines how much power is getting splitted is not individually how much is the value of kappa and what is the value of lc, but it is the product which actually determines this particular condition.

So, with kappa lc equals pi by 4; the coupling matrix I will invite you to check this out is very simple this is the coupling matrix. For 70 30 coupling it is clear that cosine square kappa lc must be equal to 0.7; while sin square kappa lc must be equal to 0.3.

And again I will leave this as an exercise for you to show that this is roughly 0.84 j 0.54; j 0.54 and 0.84 ok; I did this one by considering them in the radians. So, when I use my calculator I have to use calculator in the radian mode or convert all the degrees into radians. And when I do this I roughly get this particular numbers; so I have rounded off these numbers.

There is one additional and last point that we can talk about and that will become important later on is that this matrix that we have written can also be multiplied without changing any of the properties by a phase factor e to the power j phi ok. So, this is important when you actually start putting multiple couplers together ok.

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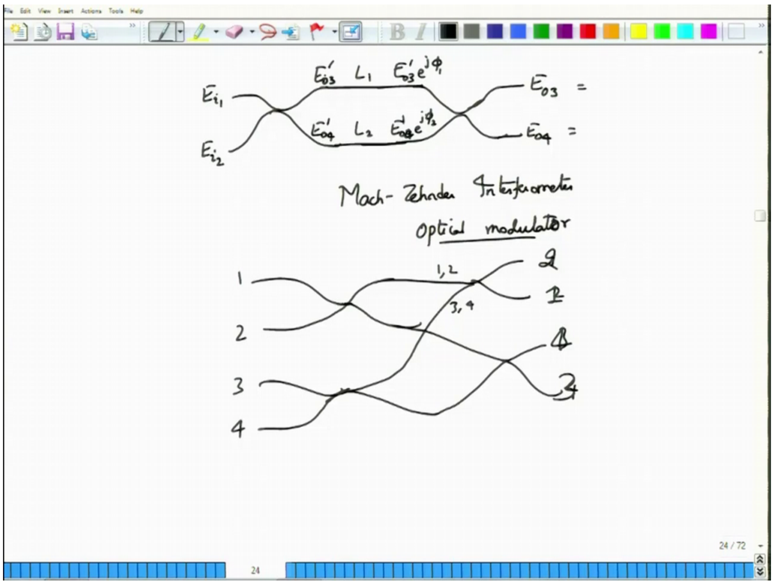

So, one of the interesting devices that we are going to talk about is called as a Mach Zehnder interferometer in which you take one coupler in this way maybe a 50, 50 coupler then put some line indicating optical connection out there and then put one more coupler here.

Pull it back in this way. So, I have another coupler right. So, this let us say has length L 1 this let us say I has length L 2. So, maybe L 2 is longer than L 1 or L 2 is shorter than L 1 you can adjust them. And this device is called as a Mach Zehnder interferometer ok. So, if you are looking at these interferometers one way to construct a fiber based Mach Zehnder interferometer is to actually do this thing. So, you have E i 1 here E i 2 and then you have E o 3 prime and then E o 4 prime just to indicate that these are intermediate signals.

And after propagating each of these terms will have a phase shift. So, E power j phi 1 E o 3 sorry E o 4 prime E power j phi 2 notice that there will also be an extra phase E power j phi that would go into one of these arms right because it is a matrix global phase that you have. And then finally, you can show that when you combine them; what you get will be E o 3 and E o 4.

And we will look at what is the expression for E o 3 and E o 4 later on ok. So, when we do this revise this thing; we will look at it later on and use this Mach Zehnder interferometer for optical modulation. So, this structure is widely used in optical modulators and we will talk about that one in the next module.

So, couplers are important and using these couplers you can make interferometers. You can also make a cross connect a static cross connect because you can then decide which way a coupler output would go. For example, if I have this coupler out there I have let us say one more coupler device in this way; and then I can couple this output with this and then couple this output with the other output that I will get.

So, you can see that signals from 1 2 3 and 4 while signals come out here the signal from 1 and 2 are being combined with the signal 3 and 4 here. And provided that your this one is all correct you know the adjustments are correct ; you can actually make one of those go into a interferometer condition such that you will get 1 2 3 and 4 at the output or you can actually get say 2 1 4 and 3.

So, purely 2 1 4 and 3; so, no other cross connects out there. So, this is called as a static switch or I know wavelength connector and you can actually do all these things by simple couplers which can be arranged in a certain manner.

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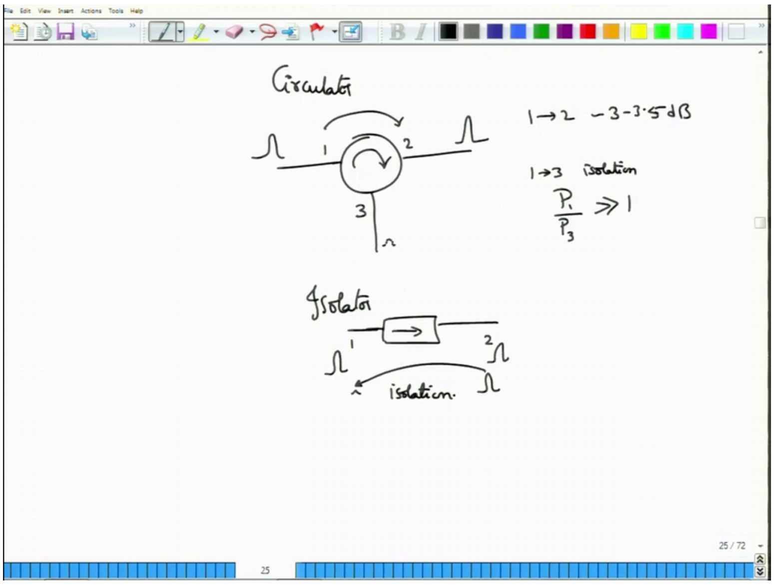

Let us move on to a circulator we have already talked about a circulator. So, I do not have much to add on to the circulator. So, I will just review this on108104113e ; so, a circulator is essentially or most of the times it is a 3 port device.

You have port 1, port 2 and port 3 and you know that when you launched pulse in port 1 only signal that would go to will be port 2, but port 3 also will usually have some signal and the difference in the power levels is essentially the isolation.

So, 1 to 3 is the isolation or the isolation port and how much it is isolated defined by the power in port 1 to power in port 3 which usually is quite high ok. And sometimes you also use P 2 as a reference, but that is something again is a convention, but port 1 to port 2; you do not normally expect a loss, but there will be a 3 dB loss out there.

So, port 1 to 2 is called as the transmission port or port to port transmission loss this is also usually in the form of 3 to 3.5 dB in many practical scenarios. 3 is the absolute minimum, 0.5 is the excess loss that you will actually get.

And then you have what is called as an isolator isolator is used to send light in only one particular direction. So, in contrast to a coupler where you could change the input and the output port an isolator cannot be changed in that way. So, if light is sent in 1; it will come out in 2 with some amount of loss, but it will actually come out in 2.

But when you send in port 2 that is if you send light in port 2 ok; the signal that would come out in port one will be very very small. Again this difference is called as the isolation of the isolator and you would like this isolation to be as large as possible.

There are different types of isolators; so, there is one thing which is called as a polarization dependent isolator. And this polarization dependent isolator goes something like this.

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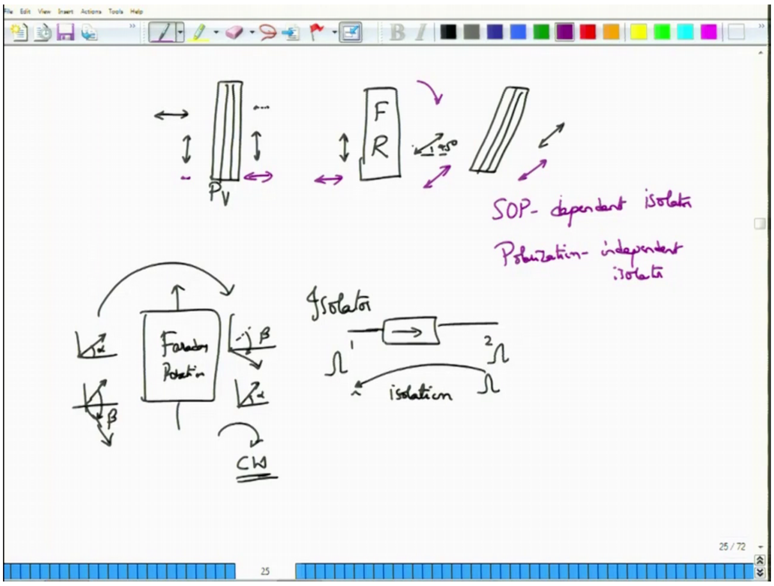

Let us assume that I have a polarizer kept here ok. Polarizer is an element which simply allows the transmission of light in only one polarization.

For example, when I send in a horizontal polarized light into this vertical polarizer ; then I will call the polarizer as P V; then this output will be 0 or it will be very very reduced so, that you can almost connected to be 0. However, when you send in a vertical polarized light it will transmit that light almost without any loss onto the other side.

So, this is the polarized light that would actually come out then this light would propagate and land into another device called as a faraday rotators. What is the faraday rotator do? It is a very interesting device; it will take I will do it separately over here.

So, this is your faraday rotator you need to apply a voltage. So, that there is actually a is actually a magnetic material. So, you have to apply a magnetic field in order to make this faraday rotator work. The basic idea of the faraday rotator is if you send in light at any polarization does not matter at any polarization which is at an angle say alpha then it will rotate this polarization by an angle beta in only one direction.

Because when you send light into this you know this is how the forward propagation, but when you send in light at this angle let us say alpha onto this side; you would expect it to rotate in the opposite direction, but no it will again rotate back in the same direction.

So, compared to this alpha which was here it would again be rotated on to beta. So, into is own it will only do on one type of a rotation; in this case we have chosen the rotation of polarization to be the clockwise direction. ; so, that is what the faraday rotator will do.

And if you now have this vertical polarized light coming in all the way then you will see that at the input you still have a vertical polarization light. And at the output let us say we take it to be some 45 degree that is we have chosen this angle beta to be such that it is 45 degrees. So, this is how the output would turn out to be.

So, this is 45 degree for you; now what I do is I will actually put in a 45 degree polarizer. Please note that this is not slanted in the usual sense I am just slanting it to show that this is a 45 degree polarizer.

There is no brewster angle idea going on here at all; please do not think of that way. So, this is a 45 degree polarizer and because this is lined up nicely with 45 degree output will be coming out at 45 degrees and you have essentially transmitted the light. But what happens when you send in light let us say at the same 45 degree here at the output you still have the 45 degree no problem, but then when you come to this side of the faraday rotator ; this faraday rotator will always rotate in the same direction.

So, there is only a clockwise rotation. So, clearly it will make it into another 45 degrees which causes the 45 degree polarized light to become horizontal polarized light. And now get the horizontal polarized light as input to the polarization or polarizer here. And unfortunately this output will be very very small because this is a vertical polarization selection device whereas, the input that you are sent is a horizontally polarized device. So, this one is called as a SOP dependent.

Because this will work only for the vertically polarized light; so, this is called as a SOP dependent isolator, but in practice of course, you do not have any control over the SOP of the input signal that would come in.

Therefore, you need to actually have isolator which is polarization independent. And you might have guessed that one way to do it is to actually split the input signal into 2 portions. So, one of them will be vertical one of them will be horizontal you place faraday rotators on both arms let them go and at the output; you can combine them.

And then when you try to propagate in the backward direction it will not really work. And we will study the polarization independent isolator in the assignment. So, this will be studied in the assignment the basic idea is just the same.

So, you have a faraday rotator and remember the filed a rotator will always rotate in only one particular direction ok. So, it will not really work in any other direction ; so, that is about the isolator device. We will now move on to another device which is called as a filter.

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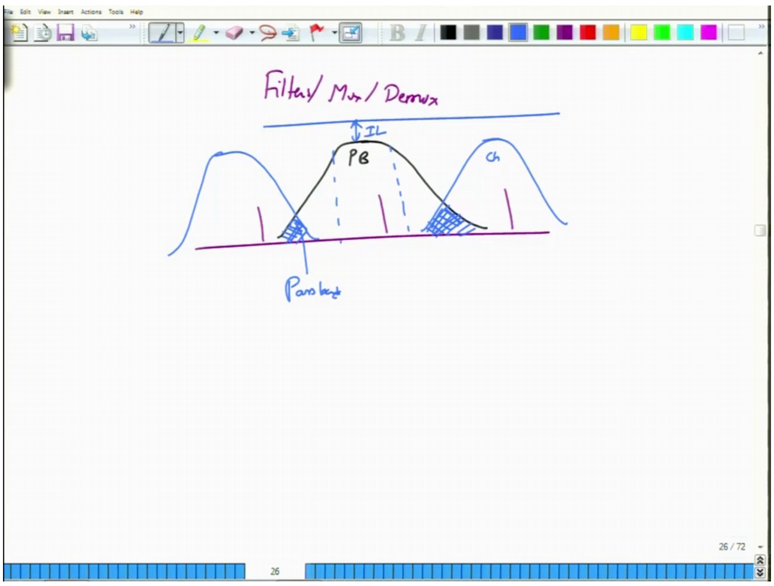

Filters, multiplexers, demultiplexers all are of the same family. But in the WDM scenario where you have multiple channels a filter is expected to look something like this.

This is called the pass band of the filter ; whereas, one would expect the filter to have an ideal pass band and then cut off abruptly, but in practice you know that this brick wall characteristic just cannot happen. So, what you have is one device in this way and then there is the pass band here again and there are these skurds as we would call them. So, these are called as the pass band skurds.

And there will be some amount of crosstalk. So, when the spectrum occupies this region there is a crosstalk between the 2 adjacent channels. And how lossy is the device can be determined by the insertion loss of this filter. How much of this channel adjacent channel has been attenuated depends on the overlap between these 2 and that is called as the adjacent channel isolation of the filters and this is the other side of the filter as well.

This is again the hatched area representing the crosstalk or the adjacent channel isolation

Thank you very much.