Fiber-Optic Communication Systems and Techniques
Prof. Pradeep Kumar K
Department of Electrical Engineering
Indian Institute of Technology, Kanpur

Lecture – 46
Filter, MUX/DEMUX, Diffraction grating (FBG and Long period grating)

Hello, and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In this module, we will continue the discussion of a couple of WDM components. We talked about filters, multiplexers and demultiplexers in the previous modules. A filters can be used to implement multiplexers. Multiplexers are those devices which will take multiple channels of different wavelengths say lambda 2, lambda 1 and up to lambda N, and then there will be multiplex them onto a single line where all lambda 1 lambda 2 all the way up to lambda N can pass through ok. So, this is called as a N cross 1 multiplexer and another device which is 1 cross N demultiplexer will do exactly the opposite.

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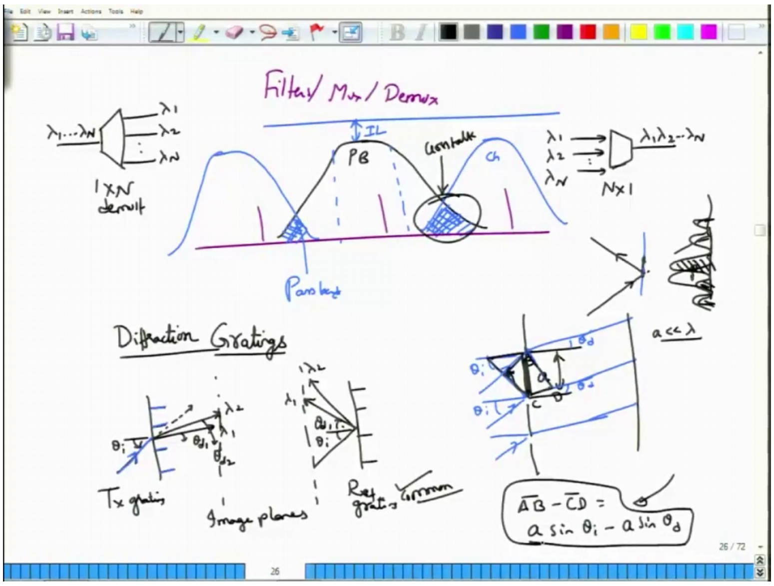

So, it will actually take input line lambda 1 to lambda N, and then put this out individually onto lambda 1, 2, lambda N. So, this is a demultiplexer which is called as a one cross n d multiplexer; although we are saying that lambda 1, lambda 2, lambda N are all isolated, but it in practice it is not because we have clearly seen that these multiplexers and demultiplexers are implemented in the form of filters, and filters have a certain region where the two adjacent channels are actually going to talk ok. So, this is the adjacent channel cross talk that you cannot avoid in any practical multiplexer demultiplexer or a filter.

Now how do we sometimes we can actually implement this multiplexer and demultiplexer in a different device configuration called as diffraction grating ok. We would not go into too much of a detail here in the diffraction grating, but the basic idea here is this. Suppose consider this grating called as transmitter grating which I have shown on the bottom left corner. So, what we have is light input applied at a reasonably far away distance, so that it can be approximated as a plane wave being incident onto this grating, because this grating is the device which is this vertical device out there with small slits here. So, these lines are actually not just lines, but there are small slits here. And you have to imagine, so for example, you can imagine that this is the grating that I have actually had, and these are all the small slits that I have, and then light is incident at a certain angle here.

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And then the light or then the light output would be coming out onto this side that is you know so these are the slits here, but I am not showing you the slits because the slit is assumed to be very small compared to the wavelength of the light that you have sending in. However, when you send light at this angle you can see that there is a certain angle theta I of incidence this is called as the grating plane. And at a certain distance output or at the output of this grating is called as the image plane which is essentially parallel to the grating plane and the light would be diffracted out.

So, diffraction means that the input angle theta I will usually not be the same as the angle theta d. And in fact, these slit which are present because the light is uniformly illuminating the entire grating plane, so the light which is incident here at an angle theta I will you will eliminate this slit, this slit, this slit and so on each of those slits will themselves act as a secondary source generator or secondary waves according to Huygens principle. And the at any particular imaging plane point the intensity is dependent on all the partial waves, the phase difference between all the partial waves and that is the principle of what is called as a transmission grating ok.

But instead of a transmission grating, if you actually make these surfaces reflective ok. So, instead of making them to be this is slit actually, but then you coat them with a reflecting surface, then light instead of being transmitted out would actually be reflected. But the same idea applies each slit will act as its own source of light or a secondary source of light. And depending on the phase shift that is introduced, we will actually have different points and the intensity will change. The intensity will also change depending on the wavelength of the light that is incident, and therefore, these devices can be used to separate out the wavelengths ok.

Of course there would not be an ideal separation of the wavelength, because the energy will actually split over into other parts as well as you can go to an in diffract optics book and then look at how the diffraction of light would work out. You must have certainly seen these kind of a pictures right. So, these are the interference pictures, but this is essentially the diffraction ideas as well. You normally pick energy in this part or the main peak, you do not pick the energies here and they are essentially lost ok and when you have another wavelength that energy would be spilling out in this manner.

So, you have this crosstalk thing that I talked about. So, the two closely spaced wavelengths will be split at two different points, but their points may not be sufficiently large that you can actually consider them to be individually isolating that whole thing. And of course, all of this depends on the exact design of the diffraction grating and that is a big area by itself which we are not going to cover in this course.

But the basic idea or the basic principle is this same to have light incident on the grating plane, and because of diffraction the different wavelength components would actually be collected at different points on the imaging plane ok. So, this can be done in both transmission mode or in the reflection mode although this is much more common ok. So, this is the diffraction grating. And if you want to know little more about the operational principle, you can look at that these are uniformly placed gratings ok.

Let us assume that the grating to gratings are the slit to slit spacing is about a, and please remember that is much smaller than lambda so that we can neglect any phase shift across this. And when you send in light at an angle theta I then this light would actually be diffracted away at an angle theta d. And the extra assuming again as I told you all these are uniformly illuminated each of them is at an angle theta i by itself and each of them are coming out at an angle theta d. The extra or on the image plane the signals that would you know essentially be collected and then determine and then how the false is determined by actually the path length difference that you will see.

And the path length difference is essentially this extra path that this ray of light has to travel in order to reach the image plane or at the input plane itself. So, calling them as CD and AB you can show that the path length difference AB minus CD is given by is actually equal to a sin theta i minus a sin theta d. And you can see that this is actually true because you know you know what is the angle of incidence and this is a right angle triangle. So, for this grating plane you can find out what is this extra distance that one needs to cover. And you can also similarly by looking at this right angle triangle determine what is the length AB sorry this length and then determine what is the length AB that it needs to cover. And from those you can actually obtain this equation it is a very simple trigonometric relationship between the adjacent side, hypotenuse and the angle between them. So, I will leave that for you to work it out. So, this is essentially the path length difference.

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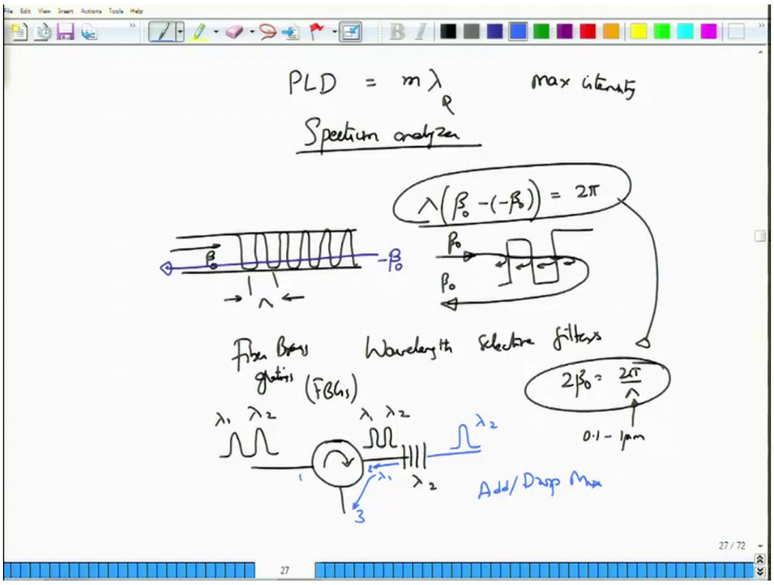

And provided that this path length difference which we will call as PLD, this PLD is equal to some m lambda depending on whatever the angle theta i, theta d and a. If this path length difference for that particular lambda happens to be an integral multiple of the wavelength itself, then you get a max intensity at that in image plane; otherwise you will get a minimum intensity or different intensity. And clearly this equation is lambda dependent, because even though your angle theta and theta d could be the same for all wavelengths which they are not in some sense they also change slightly.

But if you assume or if you neglect that part then you can see that path length difference will not be the same for every wavelength right. So, they will be slightly different for different wavelengths. And therefore, on the image plane they will be separated in terms of their wavelength, in fact, these gratings are so good that they are actually used to analyze all the wavelengths that are present in the input light. So, they are actually used in spectrum analyzers. They are actually very important components in a spectrum analyzer. A different kind of grating also exists. And there are of course, problem with the grating that I talked about, but we would not go into the detail.

Different type of a grating is one in which a fiber is made its core index is actually varied in a certain periodic manner. And the period of this variation is now let us take it to be this big lambda. And we launched light in one directions, so with the propagation constant beta 0. And then because of this periodic nature ok, some regions having higher refractive index, some region having lower refractive index there will be a backward traveling wave ok. There will be a backward traveling wave with exactly the same propagation constant.

And whenever this forward propagating constant minus this backward propagating constant that is if you look at the propagating constants of the forward and the backward wave and then take the difference between them. If this happens to be equal to 2 pi sorry propagation constant x over the pitch value or the period value lambda happens to be equal to 2 pi or some integral multiple of 2 pi, then you will actually see that these two modes are coupled and you will get that particular wavelength actually instead of being transmitted it would be reflected back.

So, light would be traveling. It will generate from the first refractive index difference that it encounters it will generate a backward propagating wave, some portion will travel, but it will also generate a backward propagating wave at the next interface where the index is changing, and similarly, similarly right. So, all these waves will have the same propagation constant. And eventually the propagation constants of these two at a given wavelength of lambda 0 for which beta 0 as the propagation constant satisfies this equation, then in that particular lambda will actually be reflected off, whereas all the other lambdas will actually propagate in the same direction.

So, these are actually used as wavelength filters and wavelength selective filters of course, and these devices are called as fiber Bragg gratings ok. So, these are called as fiber Bragg gratings. And they are indispensable in any optical communication system and especially useful in optical sensor work. And this condition of course, can be rewritten as 2 beta 0 equals to 2 pi by lambda.

And we have assumed that beta 0 and minus beta 0 that is forward and backward waves are the ones which are coupling to each other right. Again there is a notion of coupling here and because beta zero is usually very large 2 beta 0 is actually quite large, and therefore you can actually choose lambda to be much smaller. So, this would be just about one micrometer or even less than that. So, anyway let us say from 0.1 to 1 micrometer the exact length and depends on the index profile that you have.

But the idea is that if you have an F BG, so let us do a simple characterization now we know the circulator and then we have a fiber Bragg grating. So, let us put them together.

So, I will launch light at two different wavelengths lambda 1 and lambda 2 and neglecting any losses in this circulator both will be transmitted on this port correct lambda 1 and lambda 2. But if I tune this F BG to lambda 2, then what will happen at the output lambda 2 would come out of the filter with certain amount of loss.

But then lambda 1 will be returned. And lambda 1 instead of going to the port 1 here right of course goes to port 3, and this is precisely what we used in the add drop multiplexers right. So, we talked about that if you want to route lambda 2 onto this fiber and you want to route lambda 1 on this fiber, this is one simple way of doing it. And this can be done by combination of a circulator and fiber Bragg grating.

Fiber Bragg gratings are also quite sensitive to temperature, in fact, they are used in temperature sensors, they are quite sensitive to acoustic phonons in the fiber they are used for acoustic sensing. Fiber Bragg gratings are used in general for the structural and structural health monitoring of the buildings. It has lot of uses. So, most sensors use fiber Bragg grating in one form of the other, and they are very specifically used in all those cases.

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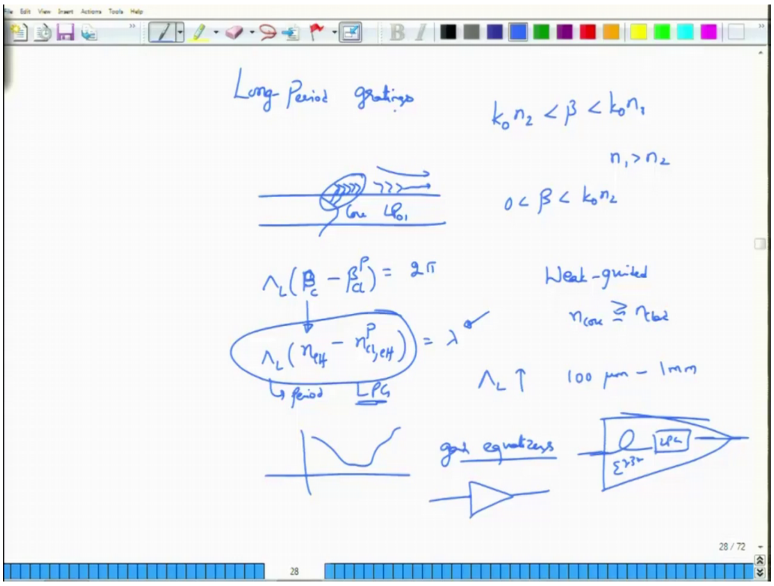

Now, in addition to fiber Bragg gratings, there is something called as long period gratings ok. In the long period grating, remember we talked about a fiber and then we said that for the fiber modes to be propagating, your beta should lie within k 0 n 2 and k 0 n 1, of course, n 1 is the core refractive index and clearly must be greater than n 2. But if beta happens to be less than k 0 n 2, it does not mean that there would not be any modes outside the core actually there will be mode which are called as cladding modes. But the cladding modes do not propagate too far they actually decay out rather quickly, but if you now have a forward propagating mode in the core coupling to the cladding some portion of the energy can be coupled to the cladding modes and they can propagate ok.

So, and these also exhibit a certain kind of a resonance or a Bragg grating condition. In that if you have the propagation constant in the core minus the propagation constant in the cladding, which we will call as beta Cl of the Pth order mode that is propagating. So, unlike a core which usually is a single L P 0 1 mode, the cladding can be supported with many cladding modes will be many such modes. But if you consider the Pth such mode if this difference over whatever the propagation length lambda L happens to be equal to 2 pi, then these two modes will be coupled of course, the mode propagating inside the core can be thought to have the effective index of n effective. And the mode that is propagating in the cloud will have its n effective, but that would be the cladding ineffective. So, multiplying these 2 with lambda L will be equal to lambda ok.

So, this is of course, the period of the long period grating or the LPG as we would call it. And this is the wavelength of the light that is propagating in the device right. And because this effective index is between core and the cladding are very close to each other. Remember we are working with what is called as weak guided approximation. Most of our fibers are made in such a way that n core is approximately equal to n clad, it is just slightly greater than n clad, but it is approximately equal to n clad.

So, the effective indexes will also be quite small which means lambda L has to be very high; it has to be about at least 100 micrometers or about a millimeter long ok. And this is precisely the reason why they have to be millimeter long. The main use of LPG is that they can be used you know in gain equalizers for erbium doped fiber and in fact this is all erbium doped fiber amplifier we will have two parts, one is the erbium doped fiber itself and then followed by a LPG, so that you will have in total an amplifier which has a equal gain for almost all of the C band that we continue to use. So, this is the long period grating that I wanted to talk about ok.

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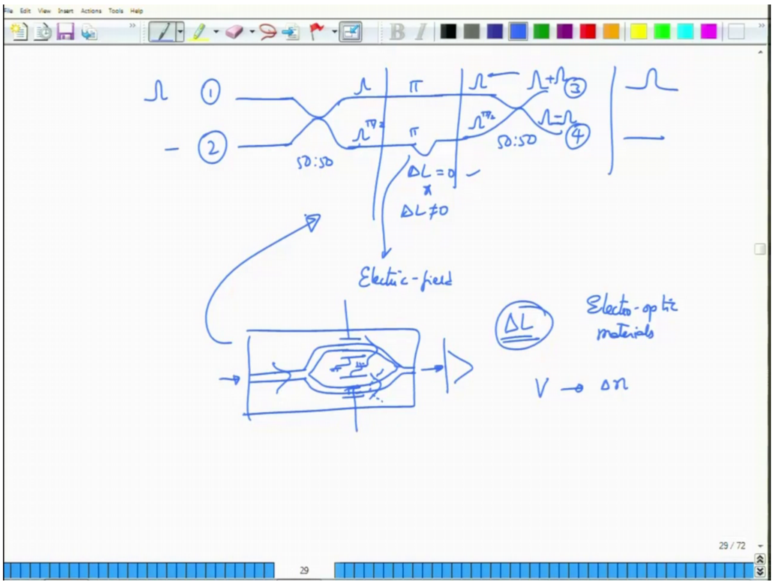

Couple of additional devices that we will look at is the Mach-Zehnder interferometer. We will need to look at the Mach-Zehnder interferometer. We have already sketched how the Mach-Zehnder interferometer would look like. So, I have one coupler here. Let me redraw the coupler at this point. And then I have this coupler and then I will say there is some delta L length difference between the two ok. So, when there is a length delta L between the two, I can again have a coupler at these output ports. And I will call this as the port 3 and port 4 of the coupler, this is port 1 and port 2 of the coupler.

We have already seen how these two ports are there. So, when delta L is equal to 0, and you launch light only into port 1 it will split out the output into two ports. And there will also be a pi by 2 phase shift here ok. And assume that these two are fifty-fifty couplers, so that makes our life little bit easier to work with. So, when I send in light only at port 1, then this port 1 signal will be split into 2. There will be a pi by 2 difference ok. When delta L is equal to 0 right or you have delta L not equal to 0, so delta L is equal to 0 is the first case that we will consider these will propagate with the same phase relationship. I am writing this pi by 2 just to indicate that these two components are pi by 2 phase shift away from each other ok.

So, now you have E i 1 you know as far as the second coupler is considered you have an E i 1 and an E i 2. And then you have to look at this output now the idea here is that this light would be come out with the same phase as the input here; however, the light that would be coming at here will be shifted by pi by 2. Now, pi by 2, pi by 2 shifting and in the if you look at the directions appropriately you can actually arrange that this direction will be pi shifted, but there is also another global phase right. So, they would actually be pi is shifted in total by pi by 2 plus pi that is if you arrange these lengths to be say pi and pi, then you have a total phase shift of pi plus pi by 2 plus another pi by 2 that would essentially be 2 pi and then this would add up onto this light in the port, whereas, you have a light signal, but then you have a pi by 2 pi, but then you have another pi signal out there, so that would actually make it ok.

So, if this is not clear from the physical point of view, do not worry about it, you can actually write down the matrix here correctly you can write down the matrix here. And then finally, write down the matrix at ports 3 and 4. And then show for yourself that all the energy that is launched in port 1 would turn out in port 3 and no energy would turn out in port 4.

Of course, the roles will be reversed when you send in light in 1 and light in 2 ok. We will have more to say about this Mach-Zehnder interferometer. In fact, we want to make this delta L not equal to 0, and we can actually do it by applying a electric field ok. To do so however, we require them to be not in the form of a fiber, but in the form of a waveguide. So, this is the device that we are going to study. This is an optical signal coming in, but this is a waveguide device. So, I have a waveguide here which branches out into two portions. So, this is the waveguide that is branching out. So, this is how it would branch. And then I will combine them, this is the waveguide again ok.

And I will place two electrodes here I will place two electrodes here with such that this is grounded and this electric field here or this electrode is grounded and this is another light out there. So, you can see that I am able to change delta K not by physically stretching the fiber, but actually changing the refractive index around that medium. And this I can do so because these materials are called as electro optic made. And with electro optic materials the idea here is that when you apply a certain voltage V, then that will go and change the refractive index by a factor of delta n. And you can actually obtain a phase shift between the two arms desired phase shift between the two arms, and then formulate a Mach-Zehnder interferometer here.

Of course, in this Mach-Zehnder interferometer, there is only one input port and one output port. So, when this device is made in you know in this way and you launch light and then you keep the phase shift between the two arms to be the same, then these two ports will propagate no meet and then be reinforced with each other. However, when you make them to be pi that is one of them is pi, the other one is 0, then they will launch I mean they will be propagating, but the other one will shift it is signed by because there is a pi by pi phase shift. And when you combine them, you will actually get 0 output, ok.

So, this is the analogous waveguide analogous device or the waveguide device analogous to the fiber Mach-Zehnder interferometer. So, we have looked at a reasonably large number of WDM components, but the modulators that I talked about just now we will revisit them in the next module, because modulators are much more important in fiber optic communications than the one than some of the devices that I have discussed because that is the way you can actually change the information in the electrical format onto the optical format which is then suitable for transmission over the fiber. So, we will see in the next module the working of optical modulators.

Thank you very much.