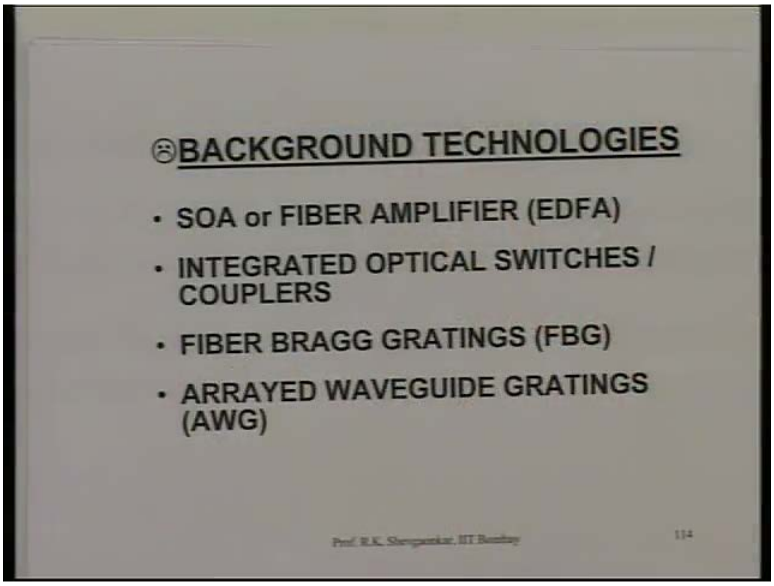
Advanced Optical Communications
Prof. R. K. Shevgaonkar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture No. #28
Integrated Optics - I

We have been discussing various components which are used in optical communication system. We saw that for wavelength division multiplexed system, we require variety of components, and last time we investigated one of the components, which was the optical amplifier.

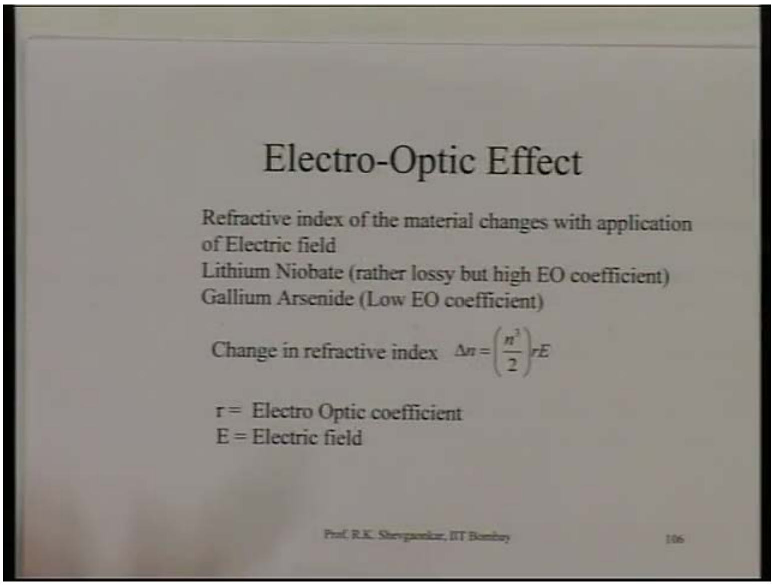
(Refer Slide Time: 00:49)



So, we have seen that we require a background technology for WDM systems, and that is we require optical amplifiers, we require switches and couplers, we require fiber bragg grating devices, and so on. And last two lectures, essentially investigated the optical amplifiers, and in detail we saw one of the amplifiers what is called the EDFA? We saw that if you take the normal fiber, and dope the core of this fiber with erbium. Then we create the energy levels such that we can amplify the light in the wavelength band of 1550 nanometer. So, typically we get a bandwidth of about 30 nanometer in that band. So, about 30 to 40 WDM channels can be amplified in one short by using this device.

The second class of devices which we require for WDM networks, a switches and couplers, they for in the category of integrated optical devices. So, infact as the name suggests, these are the devices which are fabricated on a wafer. So, you are essentially creating the light guiding environment on some substrate. So, the circuit essentially looks like an integrated circuit and that is how you do get the name of integrated optical devices. So, you are creating certain wave guiding structures on the substrate. The signals which come from the optical fiber is connected to this device. The properties of the light are changed and then the light is again blanched back on the optical fiber. At the heart of these integrated optical devices, we have a phenomenon what is called the electro optic effect.

(Refer Slide Time: 02:58)



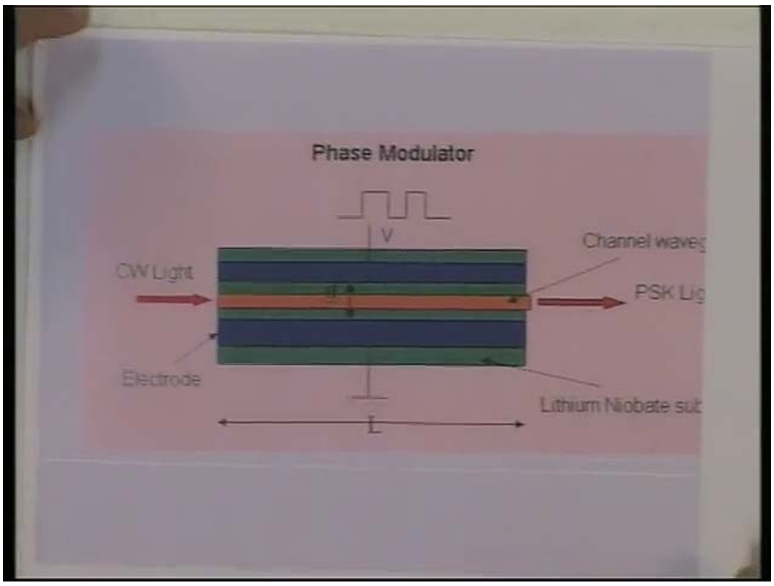
So, we have certain materials whose dielectric constant can be change by application of electric or magnetic fields. So, if you consider a material, we changes the dielectric constant when a electric field is applied across that. These materials are called the electro optic materials; whereas, if the properties are changed by application of the magnetic field, then we call those materials are the magneto optical materials. Here we predominantly make use of the material, which is electro optic and the effect that the dielectric constant of the material changes by application of the electric field is called the electro optic effect.

So, this effect essentially see means then the refractive index or the dielectric constant of the material changes with application of the electric field and there are two materials which have you studied in great detail. One is what is called Lithium Niobate and other one is the Gallium Arsenide. The Lithium Niobate is rather lossy material; but it gives the change in dielectric constant or refractive index relatively large; that is the reason large numbers of electro optic devices are based on the Lithium Niobate material. Other material which is Gallium Arsenide, it requires relatively high electric fields to realize the same change in the dielectric constant.

But this material has less loss. But it also has the low what is called electro optic coefficient. So, we essentially will talk about the devices which are based on the material, which is the Lithium Niobate material. So, basically if you consider this material, this material is an n isotropic material. So, the refractive index or dielectric constant in different in different reactions and when the electric field is applied, the dielectric constant change depends upon which direction the electric field is applied with respect to the axis of the crystal.

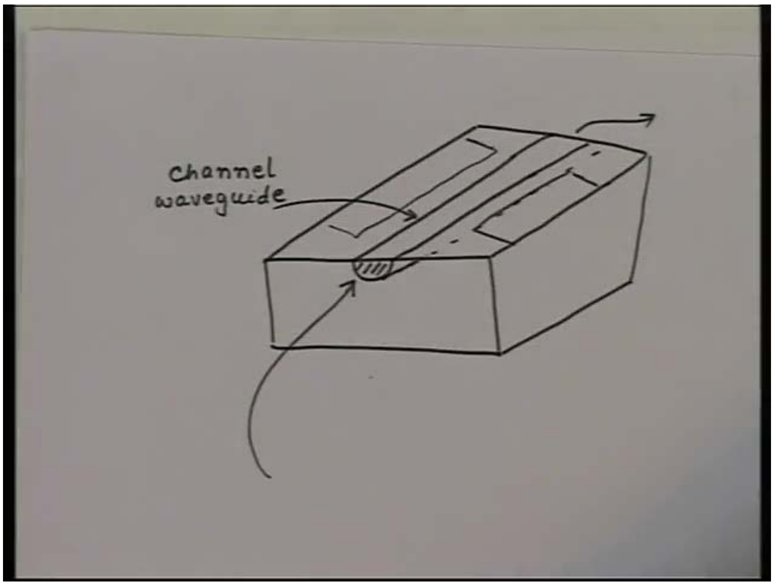
So, without going into the detail in short we can say that we have a martial; the refractive index of which can be changed by application of electric field and the change in refractive index delta n is equal to n cube by 2, where n is refractive index of the material; r this quantity is called the electro optic coefficient which is a material property and E is the applied electric field. This is also called the pocal effect that the refractive index is changing proportional to the electric filed. So, now by using this property of the material, we essentially can alter the characteristics of the light when light passes through this material. So, basic device which is fabricated by using this is what is called a phase modulator and the device is as follows.

(Refer Slide Time: 06:41)



Let us say we have a substrate here which is Lithium Niobate and then we do some doping of this. So, a channel waveguide is created inside this waver. So, let it be a show how three dimensionally it will look like.

(Refer Slide Time: 07:03)



So, if you have a Lithium Niobate substrate which is like this. By doing some ion implantation or something we can dope this; so if it look in 3 dimension, essentially we have created a semi cylindrical kind of structure, where refractive index of this region here along the length is relatively higher compared to the refractive index of the substrate. So, if you imagine like we had optical fiber and if you cut this optical fiber along the axis like half; that is the kind of structure essentially we have created here. So, here we have a refractive index of Lithium Niobate. Here, we have a refractive index which is little higher than the refractive index of the Lithium Niobate and above this, we have air which has refractive index 1.

So, essentially this structure is capable of guiding light along this; because you have higher refractive index in this region. So, though the structure is not symmetric in the cross section, but in principal light can be guided inside this; because this structure is similar to optical fiber, where core has higher refractive index surrounded by a low refractive index material. And that is what essentially is is shown here that you have a substrate (Refer Slide Time: 06:41) and you create this thing here what is called a channel waveguide. So, this thing we call as the channel waveguide. So, now what we do?

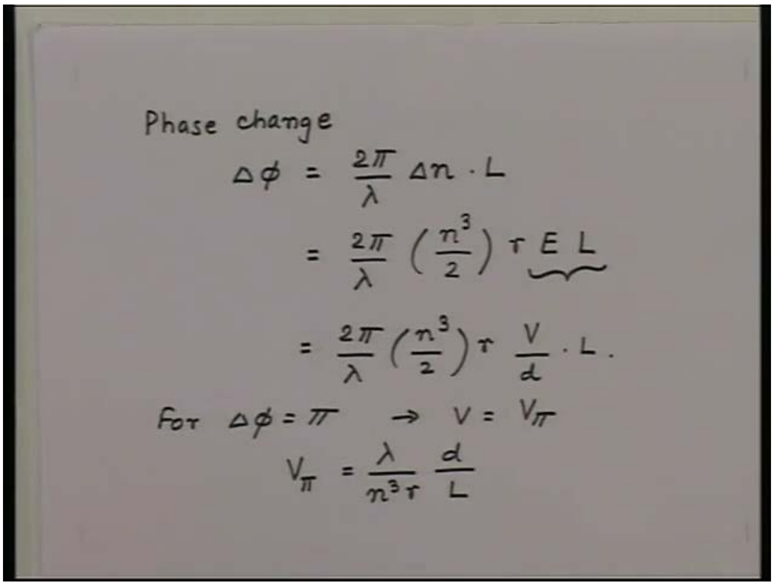
We bring the optical fiber from this connect to this. So, the light is brought from the optical fiber connected to this end. Then on the other end of this device, you collect the light from here and the light you will pass through this material and because of that, the phase of the light will change. And how much phase the light will change? That will depend upon then length of this channel waveguide and will also depend upon the phase constant of light inside this wave guiding structure. So, once these devices fabricated, you have a fixed change of phase between the input of the light and the output of the light.

What we want the essentially is that a mechanism by which the phase of the light can be differentially changed by application of certain signal to this device and that is where, we want to make use of this effect what is called the electro optic effect. So, now let us say that around this channel waveguide, suppose we deposit the some conducting layers and apply certain voltage to that; that voltage will create some electric field; that electric field will pass through this and that electric field will change the refractive index of this material. If the refractive index changes, the phase constant of the light will change and therefore, we have additional phase change because of the change in the refractive index.

So, now you get the change in the phase of the light here depending upon whether the field was present or field was not present and that is what precisely is shown here (Refer Slide Time: 06:41) that you have this channel waveguide and these are the metal coatings what are called the electrodes. The light is input from this side which is continuous wave. Light passes through this and now we are applying now a signal to the electrodes, let us say in the form of some square wave. So, when the voltage is applied, the refractive index of the material will change and because of that, the phase of light will change.

So, you will have essentially two phase values of the light. One corresponding to this voltage; other correspond to this voltage and if this voltage is 0, then we say this will correspond to no electric field wherever this will correspond to when the electric field is present and consequently, you will get the change in the light phase in the output. So, we will get what is called the phase shift key signal at the output of this device; that is the principle of the phase modulator. So, what we are doing? Essentially, we are changing the phase of the light which is coming out from this device in accordance with the amplitude or voltage applied to the electrodes of this device.

(Refer Slide Time: 12:57)



So, now one can write the phase change which is going to take place because of this application. So, let us say now I have a phase change delta phi that is equal to the phase constant in free space which is 2 pi by lambda, where lambda is the wavelength of the light into change in refractive index which is delta n into the length of the channel waveguide and as we already seen, this quantity change in refractive index (Refer Slide Time: 02:58) is given by n cube by 2 into r into E. So, we can substitute into this. So, you get change in the phase which is 2 pi by lambda into n cube by 2 into r which is the electro optic coefficient into the electric field into the length of the device.

For a given device and for a given optical signal, lambda is constant; n is constant, the refractive index of the substitute material; the electro optic coefficient which is the material property is constant. So, essentially we have only the product of this e and L; that is the thing which one can vary, when one designs this phase modulator. So, if you have the high value of the electric field, then essentially we can have very small dimension. The length required for this device may be reasonably small. (Refer Slide Time: 06:41) But what one can note is that this quantity which is change in refractive index which we have here is generally very very small.

So, when we apply the electric field for changing the refractive index of the material, the change in refractive index typically is of the order of 10 to the power minus 6. So, what that means is that to get a substantial phase change in to in to the light signal, we require a significant length for propagation of light. So, it is then immediately clear that since this quantity delta n is very very small, you require a length which is typically of the order of about few millimeters to get a significant phase change in the light output. Also there have we have to create certain mechanisms, by which the electric field is large for the typical voltages which we can apply to these devices.

So, let us say we are going to apply the signals typically of the order of about 10 to 15 volts. This v voltage is practically in the range of 10 to 15 volts, then the electric field can be enhanced by essentially decreasing the separation between these electrodes. So, bringing the electrodes close to each other, the electric field can be enhanced and consequently, the size of the device can be reduced. Nevertheless, the size of the device cannot be miniaturized to a great extent and you will require atleast few millimeter length for interaction to get a substantial phase change in the device. If we now want to create signal here which is binary phase shift keyed signal; that means we want the phase change in the output corresponding to two levels one 0 phase and one pi phase.

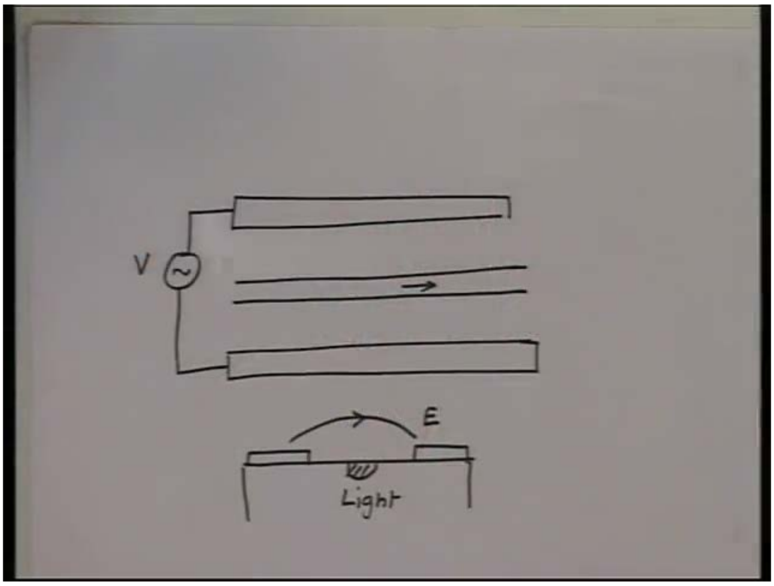
One can essentially ask what is the voltage required to get the phase change, which is equal to pi. So, let us say if the voltage difference between these two electrodes was V and the separation between them is d, the electric field can be approximately V by d. So, we can write this here; this is 2 pi by lambda n cube by 2 r electro optic coefficient V by d into L. So, one can ask what is the voltage V by voltage which will get which will give me the phase change of pi. So, when I apply now voltage, this delta phi is equal to 0. So, I can say that corresponds to my reference phase. When I apply voltage V, the phase must change by pi. So, let us say I call that voltage is V pi.

So, for delta phi equal to pi, we get V is equal to V pi. We can substitute in to this and we get the V pi voltage, which is equal to lambda upon n cube r to d upon L. So, that I mentioned since to get this value, this we put equal to pi; delta phi equal to pi. So, now I require substantial L to get the corresponding value of V and as I mentioned, this V value should lying in the range of about 10 to 15 volts; TTL kind of signals. d also cannot be reduced significantly for the simple reason that (Refer Slide Time: 06:41) if we try to reduce d, then the electric field is going to be partly inside partly outside. And then the field strength might become larger than the breakdown fields and then you may have a sparking between this.

So, the separation between the electrodes cannot be more than few microns may be more than that. So, essentially the d cannot be arbitrarily decreased to get the value of V pi. So, we see that there is the limitation of all these quantities here. We cannot reduce d significantly and that is the reason, essentially when will require the substantial length to get the V by voltage reasonably low. So, this is the basic now module which we have, which works on the principle of electro optic effect and the phase of the light can be changed by application of the signal voltages across the channel waveguides. As the frequency of this signal increases, there are certain implementation problems for this.

One is if you have the electrodes which are of few millimeters size here, we have a substantial capacitance which is going to be there between these two. And when you connect the signal which is coming from some source, it has some internal resistance impedance and that resistance combine with these capacitances essentially has a time constant. And therefore, this voltage cannot be switched at a very high speed; because you have a RC time constant associated with the system. So, you have a switching speed limitation for this. The improvement of this could be that one can treat this structure like a travelling wave structure.

(Refer Slide Time: 21:32)



So, one can have a situation where these are the electrodes and these electrodes can be treated like a transmission line and then we have channel waveguide in which the light is travelling. So, we can connect the signal between this, which is the signal which we want to apply the voltage. And since we are having this voltage at reasonably high frequency right few gigahertz, there will be a signal travelling on the structure with phase velocity and the light will be travelling inside this in the channel waveguide. So, now if I look at the structure (( )), essentially the structure looks like this. We have these electrodes which are here, where the voltage wave is going to travel and we have a channel waveguide which is here, where light is going to travel.

So, here is light and here is the voltage or E field. So, since now the radio frequency or the signal frequency is much lower, it is typically in the range of let us say few gigahertz. You have a substantial field lying outside the substrate; whereas, the light is more or less confined inside this region. So, as a result what happens is the refractive index seen by the wave corresponding to this voltage is different than what refractive index the light seen. And consequently, the phase velocity of the light signal inside the channel waveguide is quite different. Then the phase velocity of the voltage wave which is going to travel on the structure.

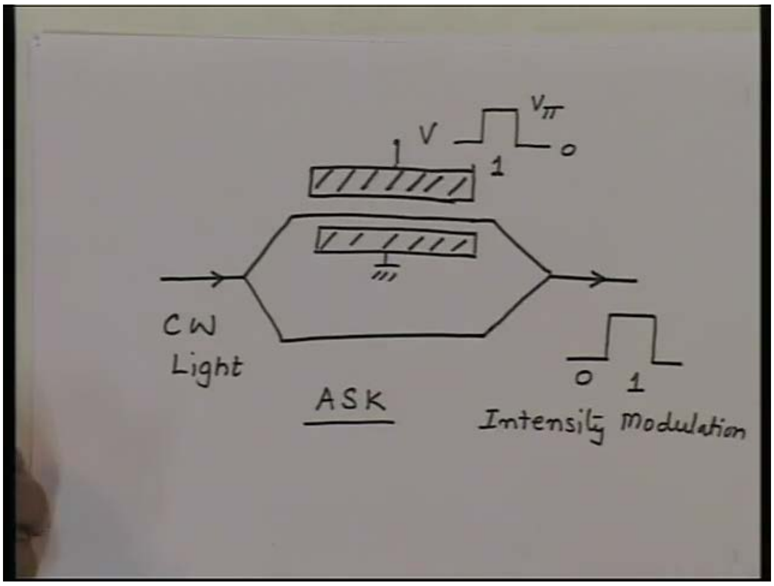
So, we have what is called a velocity mismatch between the optical signal and the modulating signal radio signal, which is going to modulate this light. So, if there is a velocity mismatch for a certain portion of light, you will see that for some time the signal voltage is positive both are travelling together. But now since they are not travelling with the same same speed, sometime we will see positive voltage and negative voltage here interacting with that light. After sometime when the light is moved to this location, there is a difference in phase or here this is become positive; this becomes negative. So, phase is reversed. So, ideal situation as we increase this (Refer Slide Time: 12:57) length, the phase would have accumulated.

It would have increased linearly as a function of length. But now we see that, that is not happen; because the voltage signal which travels on the electrodes has different phase velocity than the phase velocity of the light, which is confined inside the substrate. So, one then has to do some innovative ways to create the structures. So that, the electric field and the light both see the same refractive index and therefore, they travel with the same velocity and you get a better velocity match. So that, you get effective accumulation of the phase change and then which is small length, you will be able to get the desired phase shift. So, these are certain practical aspects which are there in the design of the phase modulator.

(Refer Slide Time: 06:41) Once you have created the phase modulator, then we can essentially build around this now. So, what it appears is that by choosing the electro optic material, changing the phase of the light is the simplest thing. But once the phase of the light is change, then we can create some kind of a interfering mechanism; so that, a change in phase can be converted in to change in amplitude. So, though in principle we are having a device, we generate the phase shift key. We can convert the phase shift keying device in to the corresponding amplitude shift keying device. Or a device which can give you intensity modulation for the light and that device is what is called the Mach-Zehnder interferometer.

So, idea here is very simple. Essentially as the name suggests, you have interferometer here. So, you take the light; let the light go by two paths. One of the paths is like a phase modulator. We change the phase. When the light is combined back, you have interference. And depending upon how much phase the light is gone in one of the arms, you will get the corresponding light output. So, basic Mach-Zehnder interferometer structure is as follows.

(Refer Slide Time: 27:05)



You have the light coming in; you divide this light into two parts; it goes by two arms; you combine this light back in this and you get the output. This is the device which is what is called the Mach-Zehnder interferometer. So, what we are showing here? We are showing here the plan on the Lithium Niobate. One of the things on here is like a phase modulator. So, you are having a substrate here, which is Lithium Niobate and on the Lithium Niobate, you have created now the channel waveguide structure which will look like that. So, the light is brought here you have a two way power divider. So, light gets equally divided in to these two parts. It propagates in these two arms and again it combines here it equal combiner and you got the light output.

Assuming that these two are exactly identical paths; when the light reaches here, it will reach in phase and therefore whatever signal you are giving here, the whole signal will appear at this point. Let us now say that we put the electrodes around this. So, we have created phase modulator around one of the arms of this Mach-Zehnder interferometer. So, we apply say voltage which is this; let us say this is voltage, which is V. So, we are applying here now a voltage which goes like that; this is 0, whereas this voltage is V pi. So, when the 0 voltage is applied, these two arms are exactly identical and then the light coming from this path and this path undergo the same phase change. So, you see the constructive interference of light and we get the light output.

Whereas when this voltage is V pi, that time this light will undergo a phase change of pi and therefore, the light reaching from this arm and this arm will be 180 degree out of phase. So, we will have destructive interference of light and we will not see any light coming out of this. So, we will get zero light. So, if we have now the light, continue wave light here CW light. Whenever we have a 1 level here which represent V pi, that time we will get the light output which will be 0 and wherever we have low voltage applied which corresponds to 0, we will get the constructive interference and we will get light intensity like that. So, if this was your transmitted signal 1 and 0, then the output we will get essentially complement of that.

There will be no light here; this will be 0; this will be 1. So, essentially we will get here the intensity modulation of the light with inversion. So, whenever the signal was 1, that time we get no light intensity. So, we have essentially inversion which has taken place in this device. But otherwise, the amplitude modulation characteristics of the signal are transmitted to the optical signal. So, you got light here which is intensity modulated. So, what you are seeing now is that the using the basic device which is which is this. (Refer Slide Time: 06:41) We can build on this and then we can build the amplitude modulators. So, by using the Mach-Zehnder interferometer geometry, we can create the amplitude shift keying or intensity modulation.

So, in those applications when we go for the high speed transmission, normally we do not modulate the lasers directly. We have seen earlier that if you are using the low data rates by changing the current of these devices, the light intensity can be appropriately changed. So, when we talked about LED or when we talked about lasers; we saw that by changing the current of the laser or the LED, we can create the intensity modulation. However the direct modulation is good, when you are having the switching times which are long or when the data rates are not very high. If the data rates are very high, then directly switching the currents for the lasers on and off create deviation of frequencies which is not very good.

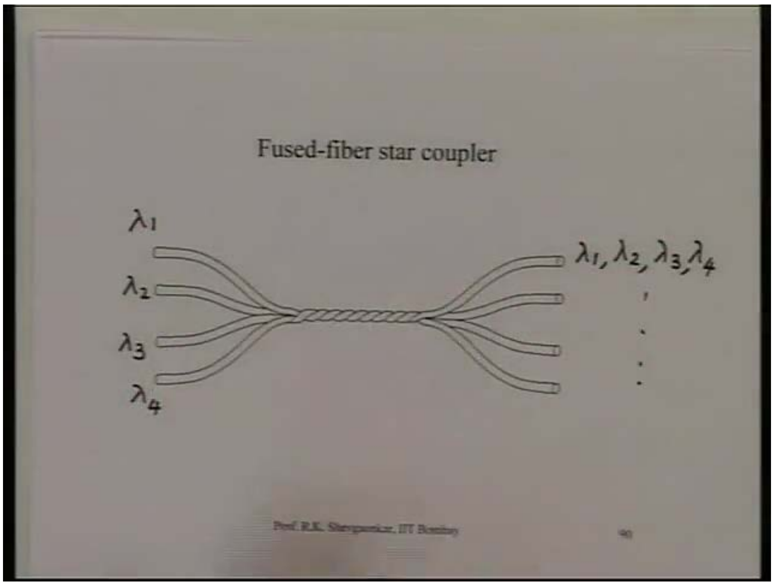
So, normally what we should do is we should do the way normally the electric engineers would do. An electrical engineering when we create a modulation system, we never modulate the oscillators directly. We have an oscillator which generates a continuous wave. Then we give this continues wave to a modulator, where the modulating signal and what is called a carrier or the continuous wave are combined together and then we get the corresponding modulated output. Same thing essentially we have to do now when the data rates are high. So, by using this device essentially what we are going to do we have a laser which is continuous. So, we are not switching the laser on and off.

So, we can avoid all the frequency instability, which are going to be there. Then we give the continuous signal device to this device here. Apply the data; this data is going to change the properties of the light and we will get the corresponding intensity modulation. So, when you go to the high frequency operation high speed operation, essentially one have to use the external modulators to modulate the characteristics of light and even the intensity modulation may require a device something like this. You can also create the amplitude modulation by another device, which is very powerful which is what is called the directional coupler. We will have discussion on that little later.

But let us see now that by using this integrated optical effect electro optic effect, we have created integrated optical devices which look like the integrated circuits and which can alter the characteristics of light. Like, it can create the phase modulation or it can create the amplitude modulation. The another component which we require in the WDM system are the couplers. So, essentially you are having a light which is coming from somewhere and you want this light to get coupled to some other device. Or let us say if I have a light which is coming from somewhere and I want to distribute this light to various users, I require essentially a device which is like a power divider.

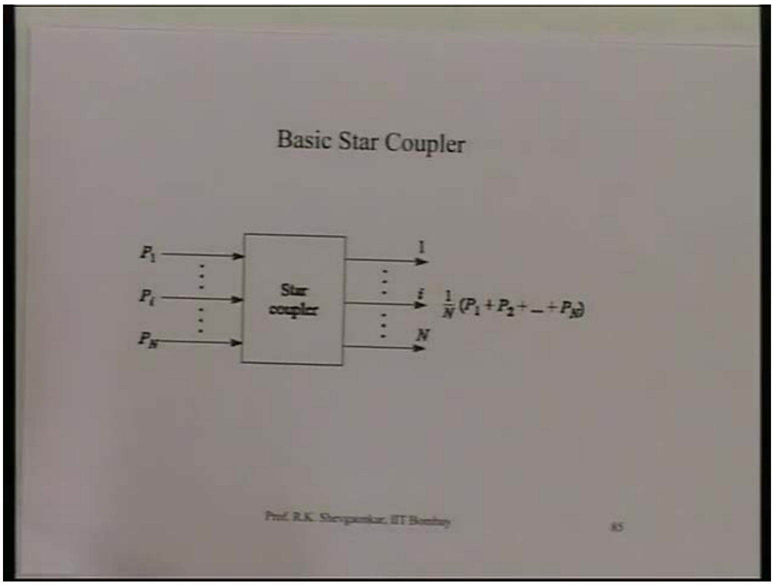
So, light will get divided in to multiple paths and it can be distributed to various users. Or I can have n fibers coming; each one is carrying their own optical signals and I want that all of them should be distributed to all the users, which are there on the other side. These kind of operations are carried out by the device what are called the couplers and there are two types of couplers. One is the simple fiber fused couplers. We do not have great wave length characteristics or some selectivity or something like that and these are essentially used for distribution of light to various destinations.

(Refer Slide Time: 36:26)



So, here the idea is simple. We have large number of fibers. You simply take the fibers and twist them and fuse them; feed them some flame and slowly the cores of this fiber merge in to each other and you have created common region here, where all the signals essentially will be mixed together. So, if the signals are coming at different wavelengths, all wavelengths essentially will get combined into one and then from this common area, again all the wavelengths now will get divided into all the users. So, let us say if I have lambda 1, lambda 2, lambda 3, lambda 4 wavelengths, they all will get combined into this and each one of the output would have a wavelength lambda 1, lambda 2, lambda 3, lambda 4. So, what is coupler essentially has done it? It has combined the light which is coming at different wavelengths from different users and distributed each wavelength to each user on the other side. This is what is called the fused star coupler.

(Refer Slide Time: 37:50)

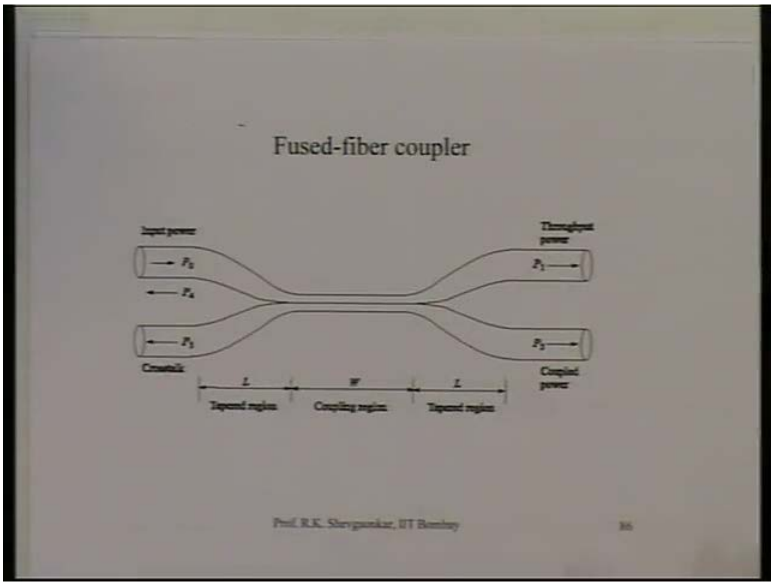


Schematically, then one can show this device which will look something like this. You are having a star coupler here and there are some n channels, which are coming in and the power essentially is distributed to all of them. But now seen the same power is distributed to all the people. Each channel essentially would receive one N th of a power. So, infact there is going to be limitation of how many fibers you can fuse together; because you will require atleast minimum power in each of these channels to get the proper detection of the signal.

So, you cannot arbitrarily increase the number of the input output for the star coupler. But the basic operation is same that you have a set of fiber, which are fused together and the light is combined into this and again gets redistributed to all the users. So, in a typical passive distribution network of WDM system, we would need a device which will be like star couplers. The other class of device which is far more power full than the simple fused coupler would be what is called the directional coupler.

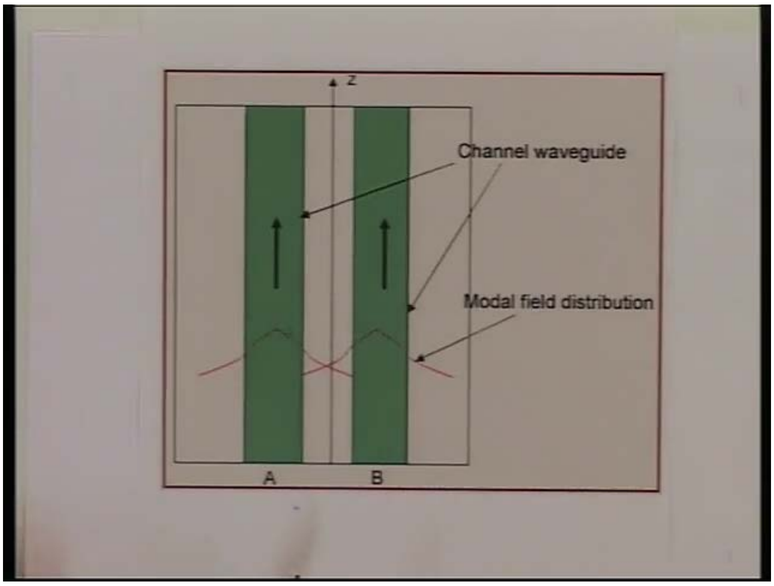
So, we will see that if we take the two fibers and suppose we bring the fibers very close to each other. Now, if you are having the cladding on the fiber core, then just by bringing together or even touching together nothing great will happen. But suppose we remove the cladding of the fiber, so that now the core get exposed and consequently, the field of the light which is propagating inside that core now extends much outside. Now, if you bring these two together, their fields will start interacting with each other and that is the basic phenomena we want to exploit that now when the two fibers have come close to each other. Because of the interaction of the fields on these two fibers, some exchange of power can take place; that is the basic principle of the directional coupler.

(Refer Slide Time: 40:25)



So, in principle essentially what we are doing is we have these two fibers which are there. We bring very close to each other and that the filed start interacting with each other and then during this process, some exchange of power takes place and we will see in detail what the characteristics of this exchange. So, we have a coupling region which will decide how much power gets coupled and how much power remains with same fiber and so on. But essentially by bringing the two optical channels close to each other without actually making physical contact, just by the interaction of the evanescent field which are going to extend outside the cores, we can make the coupling of the power between two optical fibers.

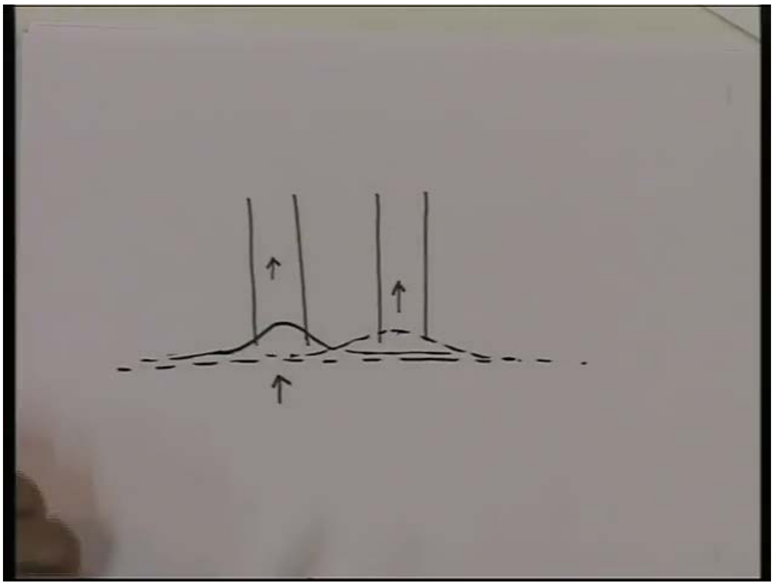
(Refer Slide Time: 41:27)



So, schematically let us say what we are saying. We are talking about essentially a configuration something like this. This is now like a channel waveguide. So, we have a substrate and we have created now the two channel waveguides; one this; one this; which are close to each other. So, now we are not talking about optical fibers here. We are talking about integrated optical devices in which there are two channel waveguides, which are sitting next to each other and the optical energy is primarily confined to this channel waveguides.

But you have a evanescent field, which extents in to the substrate. So, we have this two waveguides here A and B let us say, which are channel waveguides and we have these fields, which are the modal fields corresponding to these two channel waveguides. Let us make the analysis for specific application. So, just to make the analysis simple, let us assume that these two channel waveguides are identical. What that means is that the phase constant of these two are identical; the refractive index is identical; width is identical; everything is identical and then let us say we excite one of these waveguides.

(Refer Slide Time: 42:57)



So, idea here is as follows. We have one channel waveguide; there is another channel waveguide, which is next to it and we excite this waveguide. When we excite this waveguide, it is going to generate the fields. So, it will have a modal field distribution which will look like that and as you have seen, theoretically this field extends up to infinity which is evanescent field. So, if the second waveguide was not there, then this field will propagate along this structure in this with certain phase velocity. Now, let us say we have a another identical channel waveguide and we bring close to this waveguide without touching each other; just they are in the proximity of each other.

As soon as you try to bring this waveguide close to this, this field which is extending theoretically up to infinity is now intercepted by this. So, obviously this distribution cannot remain like this; because now the boundary conditions are changed. So, consequently some field will get induced inside this waveguide. But since this waveguide is a guiding structure and is identical to this, any arbitrary field cannot be excited inside this structure. What you can excite inside the structure again is the modal distribution. So, essentially the field which can get excited inside this will be the modal distribution which will be this; which will again extend theoretically up to infinity.

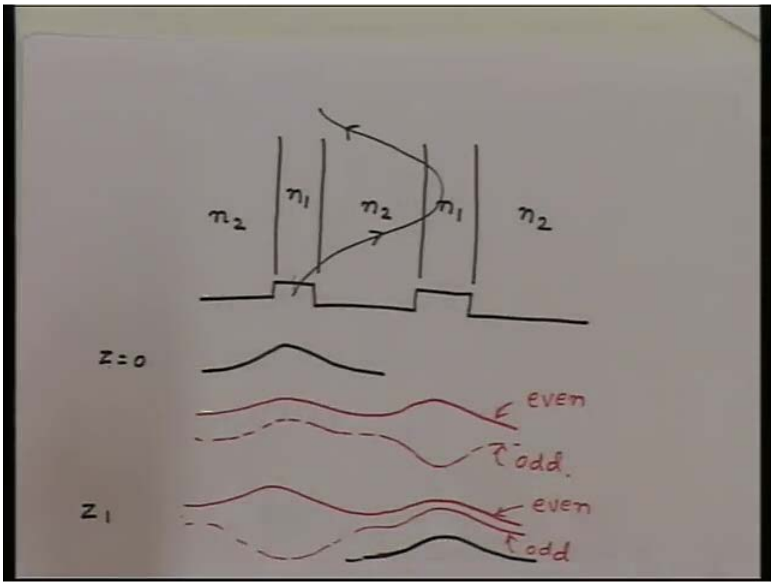
Now, this field distribution which we have here; this field is distribution is created because of this. So, if this one is moving with a phase velocity, even this will distribution will start moving. If it starts moving, essentially we have created now a wave which is going to move on the structure. Since the wave is moving on this structure, it will require certain energy. But we are not supply any energy to this waveguide. We supplied the energy to only this waveguide. So, from where the where the energy would come? It has to be tap from this source. So, initially although we excited this waveguide just because of the coupling through these evanescent fields, which are extending much beyond this channel waveguide.

The power will get coupled to this waveguide and not only that as this remains, the power will go on coupling to this waveguide and the power on this will go on building and the power on this one will go on reducing. So, what we find something interesting now that if you bring the two optical channels in the vicinity of each other, you can have exchange of power from one channel waveguide to another waveguide. Infact that will be true even for optical fiber that if you bring two optical fiber cores very close to each other, there will be transfer of power from one core to another even if there is no physical contact between the two cores.

Now, you recall when we are talking about optical communication, we are said that optical communication is very secured. The information cannot be tapped; but all that is true, if the evanescent fields of the optical signal which is going inside the optical fiber is not accessible. If the evanescent field becomes accessible, then you will have a coupling of these fields and then the information can be tapped. So, inside the optical fiber when you are having a cladding around the core, normally the field becomes negligibly small.

By the time, you come to the external boundary of the cladding and that is the reason, we do not have coupling of the signal. But if you remove the cladding from optical fiber, then this field will get exposed and then these fields can be tapped very easily. So, the basic principle of directional coupler is this that just by bringing the two channels in the proximity of each other. The evanescent field starts interacting with each other and because of that, you have exchange of power between the two waveguides. Let us now see physically how much exchange would take place between this and this qualitatively one can argue as follows.

(Refer Slide Time: 48:12)



So, initially when we started, we have now a structure which looks like that. These are two channel waveguides. We should have considering these two structures like two waveguides. We can say we have a structure composite structure for which the refractive index variation is this. This is what channel waveguide essentially does; gave a refractive index something here n 2; you have a refractive here n 1; here it is n 2; here it is n 1; here it is n 2. So, we can consider something like a super structure, which has a refractive index variation something like this and we have excited only this waveguide. So, we have to start with let us say at z equal to 0; some location at the input.

We have a field distribution which looks like that; this is what we started. Now, what we can do is we can visualize this field distribution as a combination of even and odd function. So, we can say this is equivalent to one structure, which is even function and one odd function. So, this is the even function; this is the odd function. So, at z equal to 0, this field distribution can be thought of x 2 field distributions. Super position of two field distribution; one is even; one is odd. Now, these two field distributions since they have relative variation of the intensity different refractive index medium, these two have will have different phase velocities. If they have different phase velocities as this start propagating, the phase difference between them changes.

So, if I go to certain value of z some z 1 such that the phase difference between these two fields has become 180 degrees, then at this location the even and odd function would become like this; the 180 degree phase shift. So, this will become… So, this is even function and this is the odd function. But now the odd function is gone phase change of

180 with respect to this. As a result, these two will cancel and these two will add. So, what we find is at z equal to 0, the power was here. But if I go to z equal to some z 1 where phase change is pi. The power distribution has become like that; it is it is here and there is nothing here. But in other word, what we are seeing is if you bring these two channel waveguides together, not only a small power will be tapped from this waveguide to this waveguide.

Infact after certain distance, the entire power will shift to the second waveguide. So, through the evanescent field, the coupling is something which can take away the entire power from the original wave guiding structure and that is very serious. Because now we are saying just by bringing the two waveguides in the proximate of each other, we can take away the entire power from the original waveguide to the second waveguide. But theoretically that is what would happen, if you consider the two waveguides like this. So, at a distance where this phase change becomes pi, the power will go from here to here. Again if you go a distance of same where the phase change will become 2 pi, again the power will come back to this.

So, essentially the power is going to now go like this. So, start from here slowly the power gets transferred to this waveguide; slowly the power gets transferred back to this waveguide and so on; that is the principle of the directional coupler. So, when we meet in the next lecture, we will write down analytical equations for this simple device directional coupler. Under the assumptions that the two waveguides are identical, and then from there we essentially develop the quantitative expressions for how the power is going to vary from one waveguide to another waveguide as function of length. And then we will see how can we make more innovative devices by using this device, which is the basic directional coupler.