Indian Institute of Science

Photonic Integrated Circuits

Lecture – 01
Introduction to Photonic Integrated Circuits

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NPTEL Online Certification Course

Hello my name is T. Srinivas associate professor in the EC department Indian Institute of Science. This course is called photonic integrated circuits. So this is a brief outline of the course, in the first lecture is on the overview of photonic integrated circuits.

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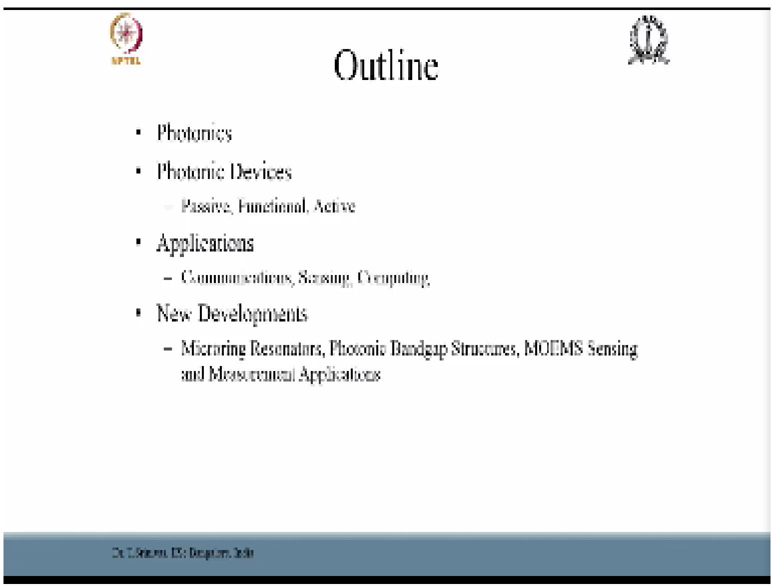

So we will start with voice meant by photonics, what are photonic devices, various steps of devices like the passive devices, the functional devices, the active devices and we will look at some applications. And also if possible we will try to do some new developments in this subject in this overview lectures.

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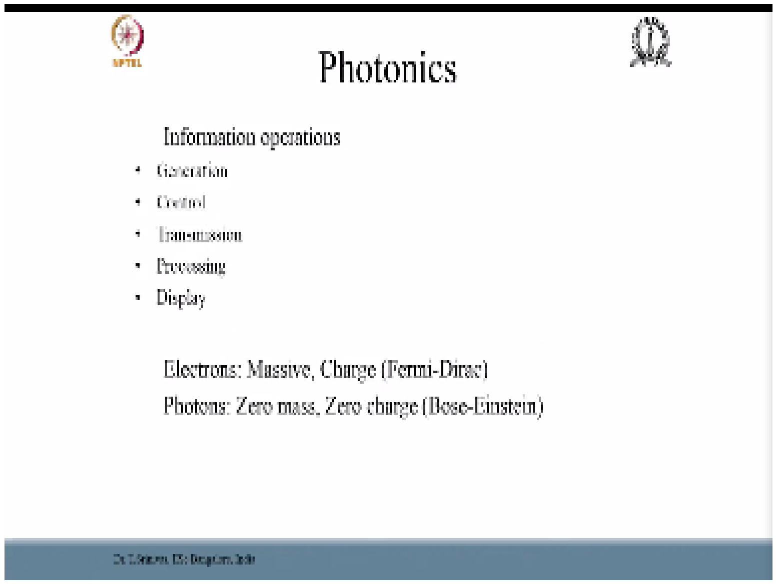

Photonics can be considered as analogous to electronics. In electronics as you know the fundamental particles of nature, the electrons take the prominent or all the devices that you see around like the laptops, the computers, the TV are all electronic devices, because the electrons flowing in the wides are silicon devices or the ones which take the main functionality. In comparison we can say that photonics is the subject involving light particles.

So we can say take photonics as analogous to electronics. I have put a few information operations that we usually do with electrons. As you know we can generate signals, we can control the electronic signals, we can transmit from one point to the other, with process we do off the signal processing and finally we may have to display all these information. So all these operations we do with electrical signals and electronics in the conventional technology.

And it is possible to do most of these functions with light that is the subject of photonics. So if you go to a fundamentals as you know the electronics involves the Fermi-Dirac statistics, in silicon it is used Fermi-Dirac statistics to study the properties of the materials. And as you know the electrons are massive they have a certain charge and so on, these are the fundamental properties.

It will contrast you how photons have zero rest mass and no charge, and use Bose-Einstein statistics to study these properties. So what are the advantages or why photonics is becoming important in the present day world, the demonstrated is already in there. For example, all the transmission is taken over by electrons, by photonics now. So in future you can expect that many of the functions that we do with electronics will be taken over by photonics.

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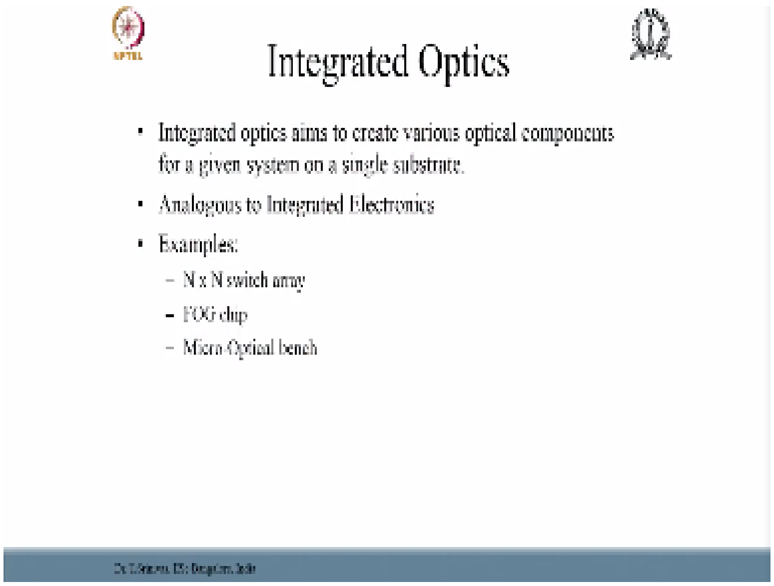

The photonic integrated circuits or integrated optics can be considered as analogous to electronic integrated circuits. In olden days we used PCVs, then the bed boards etc, to build electronic systems. So now we have all these systems on to a chip, so you can say that integrated optics is analogous to integrated electronics where the main area is to create various optical components necessary for a given system on a single sub state.

So there are several examples in use today like N.N switch matrices chip for the fiber optic getescope, and even a micro optical bench where all the optical components where build on a new symbol silicon basis.

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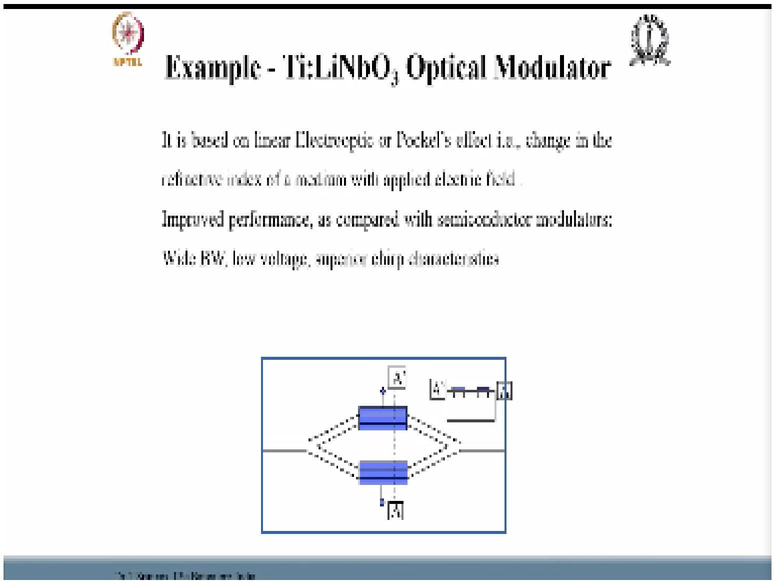

I would like to take the example of an modulator, so optical modulators on a Lithium niobate this is a typical example and this is a commercial device today. It is based on the electro optic effect or the Pockel's effect that is a change in the refractive index of the medium with the applied electric field. The picture shows the top view of the Lithium niobate optical modulators, we observe the branching circuit, the double lines that you see are wave grades and light can be propagated through these wave grades.

And you also see a branch this is a wide branch where the light could be divided into two parts and there are two electrodes where you can apply the electrical signal and light could be effected by this electrical signals to the electro optic effect and finally it is combined back at the output combiner giving as the modulated light output the modulation happens with the change in the refractive index electro optic effect as I said implies a change in the refractive index would be applied electric field as you know the light prorogation can be described why $E^{\omega}T- \beta Z$ and when you apply voltage to these electros you can say that the propagation constant of the light propagation in this wave guides changes and effectively phase modulate in the light that is propagating through that.

So you can expect at the output a modulated light so this can be used for very high speed modulation of the orders 10 Gb per second or more, so there are many other improved properties like performances is very good in terms of the voltage required the band width and chip characteristics and so on, just to compare if you would like to do this directly with a semi conductor laser diode you need to manipulate the modulating injection current of the laser diode.

So it is not advisable to it is not preferable to disturb the properties of this semiconductor diode so for high speed operations which is very preferable to use an external modulate like this is a typical example of an integrate optical modulators.

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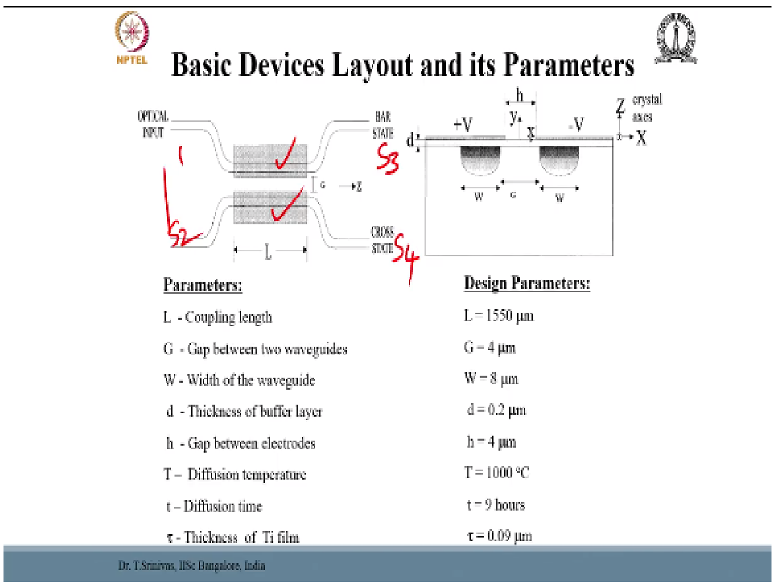

Another example is the directional couplers where you 2 wave guided very close together these are two wave guides very close together and this could be fabricated by standard lithographic process once again how we use the electro optic effect where there are 2 electrons placed on the wave guided and the light propagating in one wave guide could be effected by the light effected by the presence of the other wave guide for example you design such that the light propagating in first optical wave guide could be transferred entirely to the second or the fourth output port.

Creating what can be called as a cross over state, similarly if there are two signals S_1 and S_2 so these could be exchanged to S_3 and S_4 so S_2 can go To S_3 and S_1 can go to S_4 creating the cross over state and by applying voltages we can effectively change the refractive index so that the light from fourth one can go back to the S_3 and light from S_2 can retrace back to S_4, so this is a basic function of an optical switch when there is voltage it is in the bar state when there is no voltage on the electros it can be in the cross over state, so I am showing you a few parameters of fabricating this device.

Typically the lengths are of the horse of a few millimeters and the wave guide width are of the horse of a few biros and the spacing also of the order of few micros four micros typically and we process this by defusing titanium into the lithium bit at 1000^0 C for about 9 hours so typical thickness of the titanium film also are of the hours of a few angstroms, so this another example of an integrate optical device.

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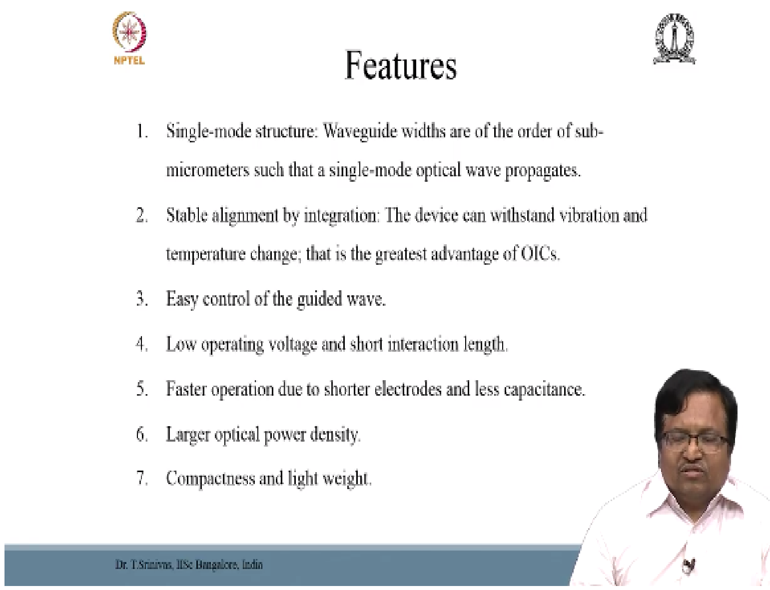

S there are several features of photonic integrated sets the most important one being the signal mode operation all the wave guides are designed such that they operate in single mode so this is in combatable with the fiber optics where we use signal mode optical wave guides, alignment is an important problem in optics which can be solved by proper packaging and these devices can with stand vibrations and we can also manage the temperature changes and so on.

This is the one of the greatest advantages of using photonic integrate circuits rather than discrete components it is also possible to control the wave guides, as you know in free space or in fiber optics it is also most impossible to control the propagation of light particular for example in a networks or in switches if you want to change a direction of the paths are as we saw earlier modulating characteristics it is not possible to do in a free space around environment.

It is possible to do in photonic integration circuits in a very easy manner as we will see as we go along so another important advantage is compare to the bulk devices is low operating voltages and short interaction lengths these because the wave lengths involved and the dimensions of the devices are very small so for example the spacing between the guides very small so you can have very low voltages for control operations and also faster operations also possible due to the small space in between electrodes and less capacity effects the power density of light propagating this waveguides is very large so you can expect many non linear effects which can be used effectively in photonic degree rated circuits.

Of course like in realizes circuits these are very small so they have they are very compact and like weight the consume less power they can be used back production can be used to fabricate devices and so on. These are the generic advantages of going for minutes registration and that production in photonic integrates circuits.

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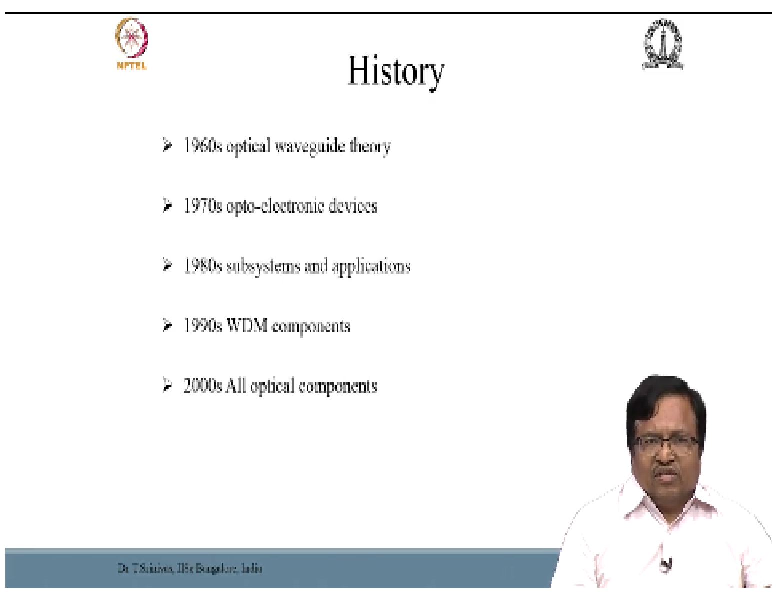

So historically we can say that during 1960s just of image of a laser most of these technologies have developed in particular the work on optical waveguide theory had historical, historically have been than during 1960s then we can say that during 1970s is the year of Opto- electronic devices were all these principles were translated on to some electronic devices creating many. Many more devices like very manage raised lasers and of the electronic module later in so on. So you can say that in 1980s is the year of implementation leading to launching.

A sub systems and many applications in 90s we can say is the development of WDM networking is important development during 90s requiring lot of devices for the networking applications so now we can say that all optical components is the order of the day where we try to do as many function as possible on a single chip this is a brief history but finite the lot of indicate developments that you can see on in the reference is given at the end.

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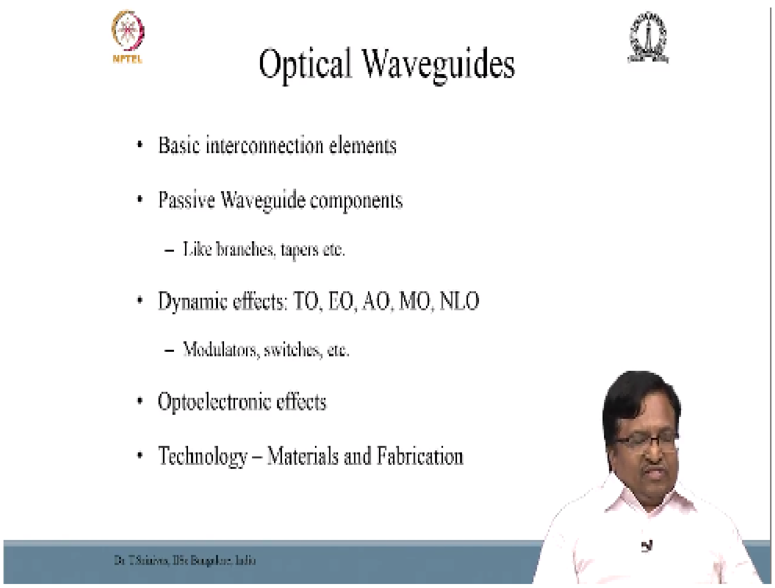

So let us start the talk with optical waveguides which are the basic interconnection elements in integrate optical like why it is in the electronics we can say that optical waveguides are the basic elements soon the connecting various components on the chip then the waveguides can be used for making many passive devices or passive waveguide components you call like branches, tapers, couplers and so on and so forth an as we saw earlier with the electro optical effect lot of dynamic effects can be used.

To control the properties of these devices on waveguides so the dynamic effects include the thermo optic effect the electro optical effect the acqu strophic effect the magnetic optic effect and many non linear optical effects so typical devices are the modulators switches followers and so on of course the lot of opto- electronic effects where the electrons play an important role we can control the properties of the materials while changing the electronic properties the optical properties can be changed with.

Electronic properties of the device and the materials and finally of course the technologies are most important element in the development of these technology we need to consider the various materials and the fabrication technologies involved in fabricating these devices.
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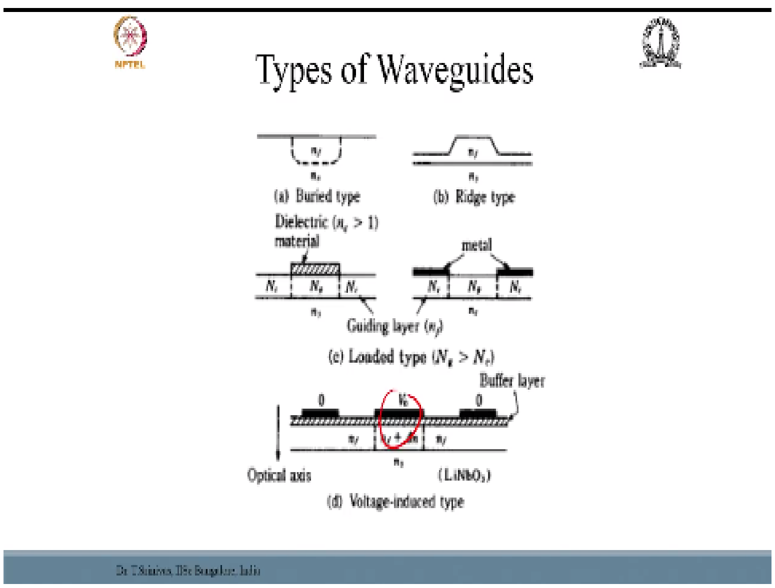

So these are the typical optical waveguides so we come across in integrate optics these are all the cross sections and showing you the first one is the worried type of optical wave guide then the next one is the ridge wave guide were you have we can deposit the material on the sub state and the H out unwanted regions and then we have the loaded type of waveguides were you can load another material on top of a slab type of wave guide and change it is properties and you can also use other materials to load these waveguides.

And finally I am showing you a voltage in use of type of waveguides where as we have seen earlier we can use electro optical effect or some other effect to change the refractive index so what is shown here is a sub state with a slab wave guide and top of these you have a electrode place and by plane voltages we can reduce the waveguide.

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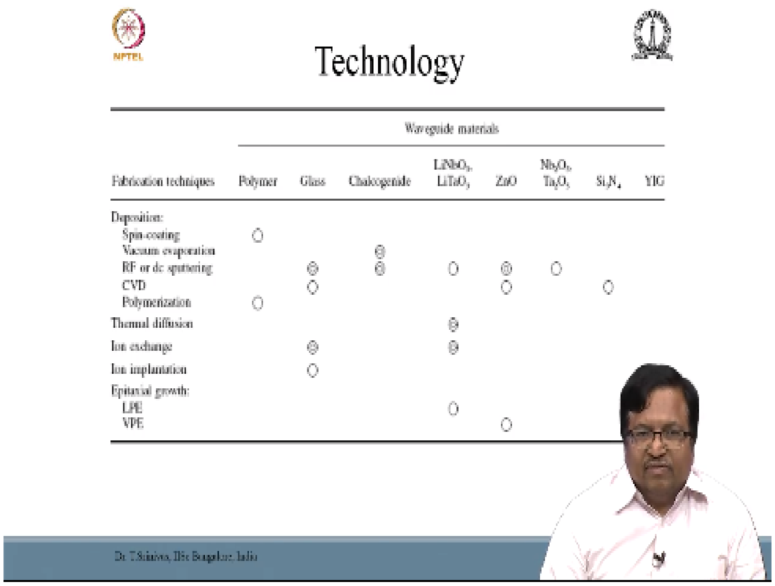

So these are brief radio of technology that is used in the in fabrication of DH devices then I am showing the various waveguide materials like polymers class and crystals then of course the silicon and the magnetic materials and so on so forth so there are several fabrication techniques based on the materials chosen how deposition techniques like the spin coding the vacuum evaporation, RF and dc sputtering, chemical vapor and depression methods, polymerization and so on and we also have a diffusion techniques.

Ion exchange process then for semi conductors you have know epitaxial growth techniques like liquid phase and vapor phase epitaxial growth and so on. So the circles indicate the importance or the level of development of the technology the double circles imply that it is much more effective and more utilized.

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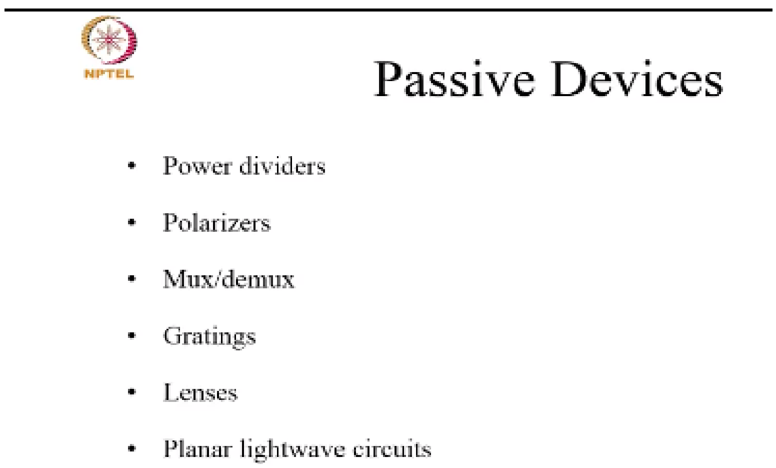

Now let us go into some passive devices like power dividers, the polarizer's, the multiplexers and demultiplexers, gratings, lenses all these place from the optical wave guides, so the generic name given to many of these is the planar light wave circuits.

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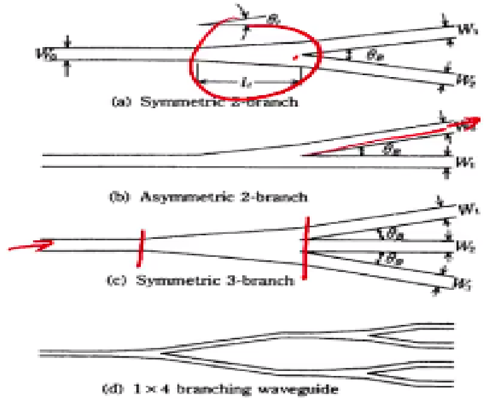
Power Dividers



So there are some examples of the power dividers you observe that there is a single waveguide at the input and which is branched into several waveguides at the output there are several interesting features of these devices that you can observe that as a light propagates if the waveguides as you know in terms of its modes where you have get to these mode theory later in but the light you can say that the light propagates in terms of modes and the modes characteristics are dependent on the size of the waveguide.

In particular the width of the waveguide so the top view of this power dividers show one input port and several output ports, first one is a symmetric two branch power divider where you have a straight waveguide and tapped region to tapper out the input modes into two output modes and there is a junction which is also interesting case here and finally the output waveguides bits are also chosen.

Such that they are all once again single mode, another important feature is at the angles involved in order that the losses of the power dividers are very less you need to choose angles very small as we will discuss later on in the course, similarly the second with the device that you showing a symmetric two Branch consists of a bus waveguide from which the power can be capped out into the output port, so this asymmetric compared to the previous one you can also think of a symmetric fitting branch waveguide where you have a input bus waveguide and three output ports of course this is not the output distribution is not symmetric but depends on many factors including the placement and the tapering portion this one and so on so forth, so we can create higher order branches from using by using one by two waveguide branches.

For example here it is shown that you can make a ¼ branching waveguide power divider using 3 ½ power dividers.

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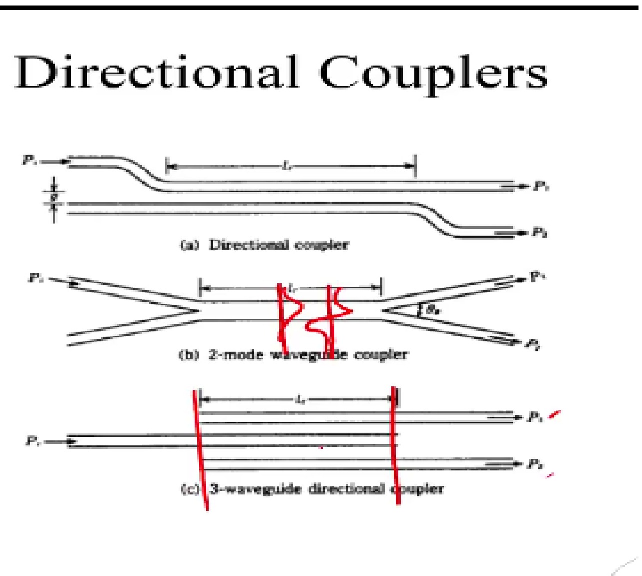

In the beginning we have seen a directional coupler wave light could be exchanged from the input port to the any of the output ports but even though there is a higher refractive index reason the waveguides and lower refractive index region in the inter medium, so we saw that the light could be tunneled from input port to the opposite port so directional couplers are very useful for many applications for switching the power between different ports or re-distribution and so on.

Directional coupler is typically consider as a multipurpose device which can be configured for many purposes, in particular region association with other electro tropic effect and so on we can say that this is a multipurpose device. The second pictures shows the two more waveguide coupler waves the inter mediate region there can be two modes of this wave guide and there can be inter relationship between them leading to some re-distribution of the power at the output ports.

And it is also possible to use a coupler in the backward propagating mode also that means power injected with the port 1 is re-distributed across all the 3 remaining ports but many important applications, typically to extend in the part c in the figure c we have a 3 waveguide directional coupler wave light could be exchanged between 3 waveguides in the intermediate region, for example the power at the input port could be re-distributed across 2 output ports.

Or if the mediate port is extended could be distributed across the output port also not exactly equally across all this but could be calculated and arrived at what is a ratio of the power across each of the output ports.

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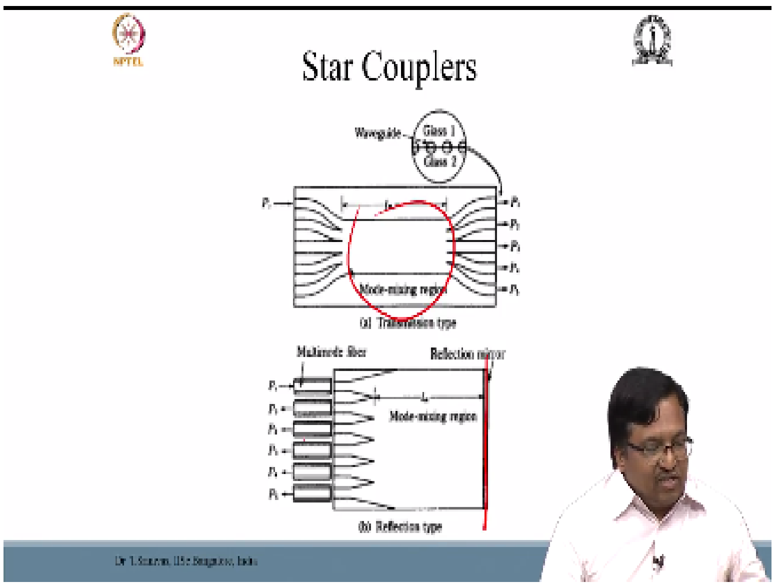

Star couplers are very important devices in many applications like in WDM systems where you need to distribute the power across many users, so in here the part A I am showing at transmission type of star couplers where light is injected into one of the ports and is redistributed across the output ports. The important feature of the star coupler is a mixing region where the light injected into input port can get mixed up and redistributed across the output ports so very difficult to analysis the operation of this except in some very group manners.

The second one shows a reflecting type of star coupler where the light input from one of the ports is reflected into the reflecting error and then redistribute across the output ports including the port that from which the light came in, so this regions are called the more mixing regions and could be analyzed by using geometrical methods to find out how much power comes out of each of the output ports.

You can easily expect that the power distribution is not uniform and it is an important challenge for the designer of star couplers.

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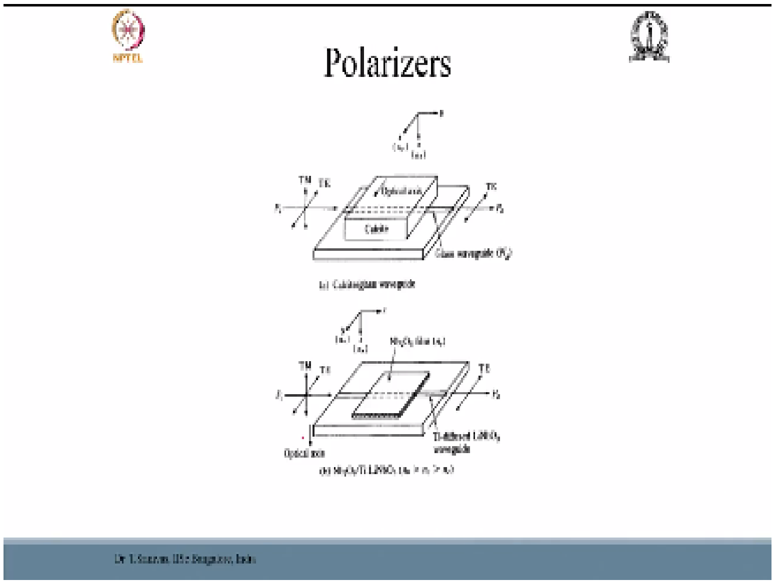

Polarizers are important devices in optics because light has got different polarizations infactly how all the six components of the electromagnetic field it will be manipulated and controlled. So in order to build polarizers you need to choose materials which I have got anisotropic properties where the refract index of the material changes in different directions, so here is shown class wave rate based called the part in the figure ratios class wave rate based polarizer on top of which you coated anisotropic medium like calcite.

So what is shown here is a wave guide the glass which is controlled by the loading anisotropic wave guide at the top. Based on the axis chosen of the anisotropic crystal you can choose one of the polarization there are two polarizations at the input TE and TM and you can choose one of them based on the polarization based on the orientation of the crystal that you choose. Similarly the second one shows polarizer on little a bit the subside itself is anisotropic and it can support based on the design both the polarizations but you can coat a medium oxide film or top of that and change the properties to get only a TE polarize slate output as shown in the figure.

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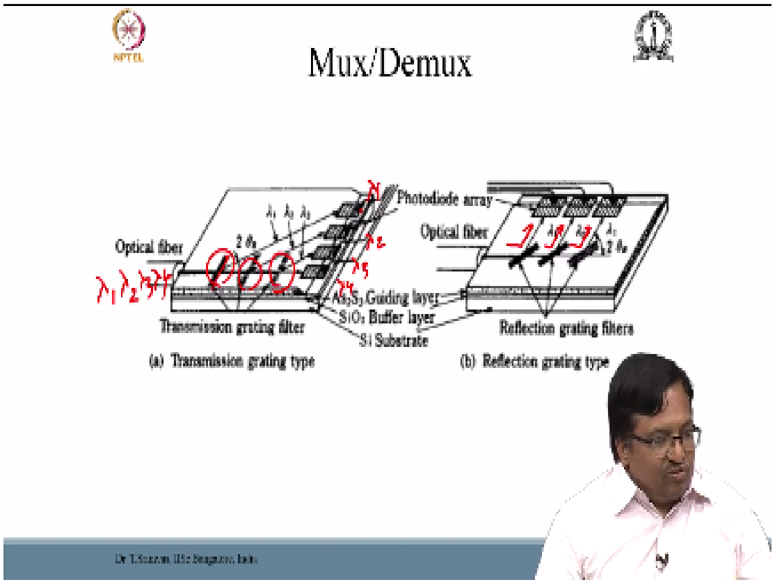

So multiplexers and demultiplexer are necessary in all communication applications so the important requirement here is the input optical fiber brings in light from different channels. Let us say the channels are the wave lengths λ1,λ2,λ3 and λ4 which carry independently modulated light signals and the requirement is that they have to be separated out at the output these are the output ports, the requirement is that first port should tap one channel second port should have second channel and so on. So all the four can be de-multiplexed at the output ports by using the wave guide elements and in this particular case I am using gratings these three are gratings designed to tap different wave lengths.

So the first grating will deflect the light the first output port and all the other three wave lengths are passed unaffected and the second grating will deflect the light into the second port and so on. So it is possible to design a device like this called the transmission grating filter to de-multiplexed all the signals. The other one the example b shows the reflection type of grating where the input light is reflected across different output ports rather than transmitted.

So all these are based on giving slap wave guides as you see here the basic substrate is chosen the slap wave guide is made and according to the requirement channel wave guides are induced and gratings are used to deflect the light across these ports.

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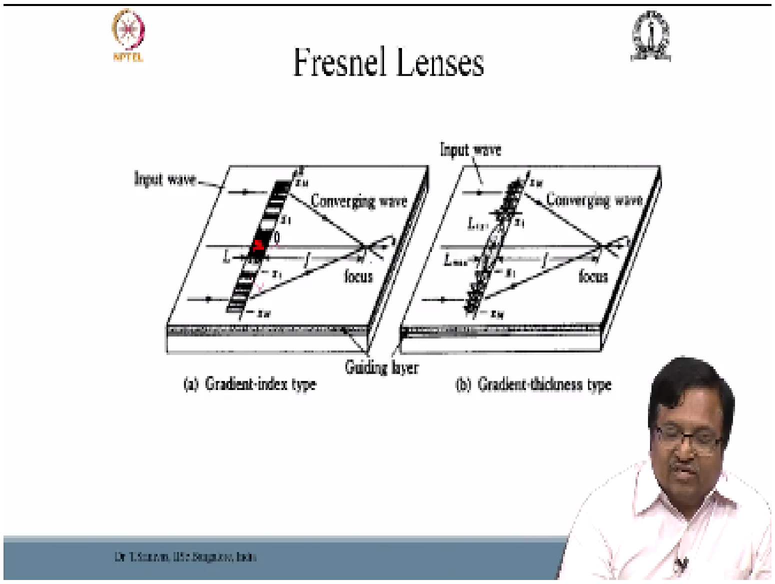

So lenses are also an important elements in optics in the conventional integrated optics people have tried to imitate whatever is there in the bulk optics or to integrate the optics lenses are one of the important components which can be used for converging and diverging signals and imaging and so on and so forth. The figure a shows a gradient index type of Fresnel lens where the refractive index gradually varies across the lens, across the width.

So there is MAXOM refractive index in the middle and gradually reducing refractive index are outside and according to particular given pattern so we can say that there is a refractive index pattern or a profile across the width of the wave guide which can be designed to make a converging type of flex. So the input wave is shown as broad wave spread across the width of the lens and focusing at on particular point. So we can contrast this with the conversional bulk lenses where we have a three dimensional spread of the wave here the wave is spread across only the width of the lens, and it is been conversed that given point.

So we can also think of a gradient thickness type of lenses where the thickness is varying across the width and the refraction being same and it can converse a light to a particular point.

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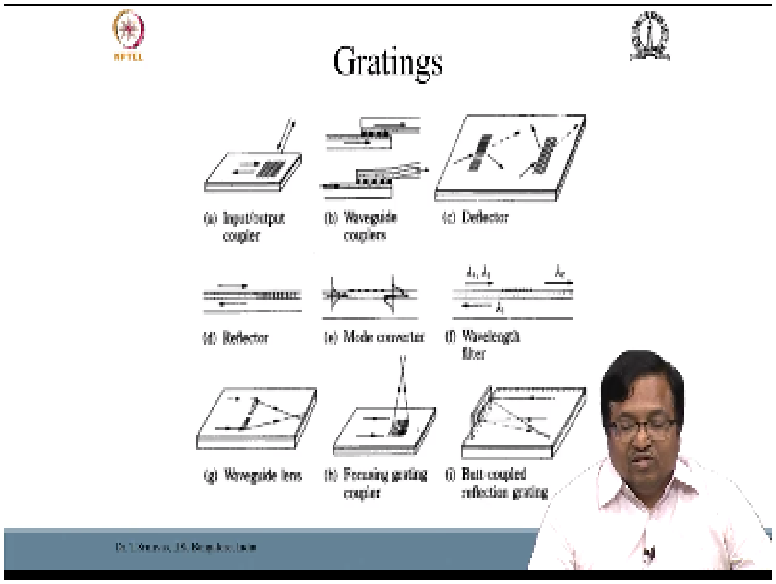

So gratings or have many functions many applications in optics and integrated optics I am showing some applications the grating can be use as an input or output coupler this is one of the important applications presently one of important problems I can mention in integrated optics is a coupling light from input optical fibers on to the chip and gratings we have a very good job in this connection. So here we have in the figure A we have grating printed on the chip and light is launched from outside on to the chip.

So the great input direct all the light that is input on to this in to the chip very efficiently. So there are many, many other application I could mention that the mode converter if we have two modes two or three modes you can convert between the modes or select some particular modes using this gratings. So typically a grating is formed on the waved guide and light is pass through that and the mode could be converted.

So another application is wavelength filters when you have several wavelengths coming in grating can chose a given wavelengths like λ2 is shown here, and all other wavelengths are rejected. It can be opposite also like all the wavelengths are pass through the gratings except to the one which matches with the grating pitch. So you can have a wavelength filters based on the gratings.

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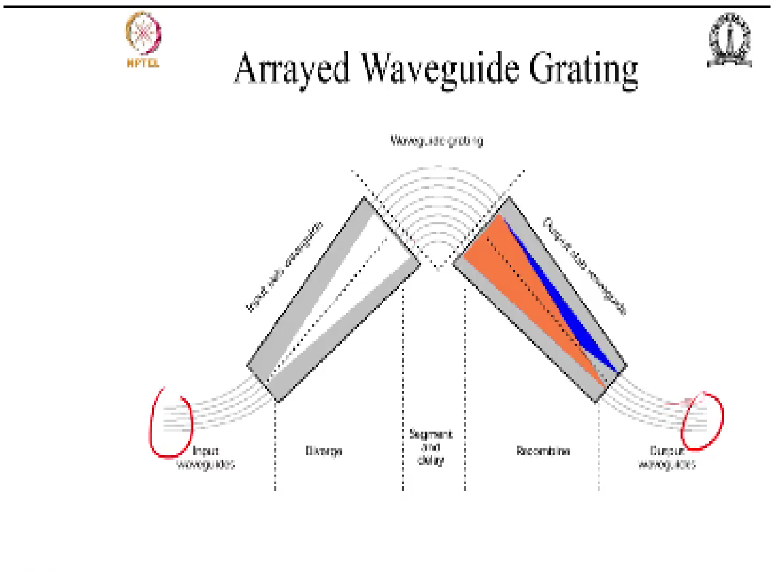

So these typical commercial application that is available called arrayed waveguide grating this is available on silicon wafer and I am showing a static of this the functionality of first let may discuss functionality there are several input waveguides and there are several output waveguides to handle and light could be pass through any of the input waveguides in optical fiber and all this see all the entire thing what is shown here on the chip there are three regions so one is input region then we have the slab regions mixing slab regions and there are variable wavelength variable lengths waveguides.

So the operation is like this first of all the light is mixed up in the regional redistributed across the all the inputs of the waveguides and the waveguide lengths are unequal creating different face shift across the output of the waveguides.

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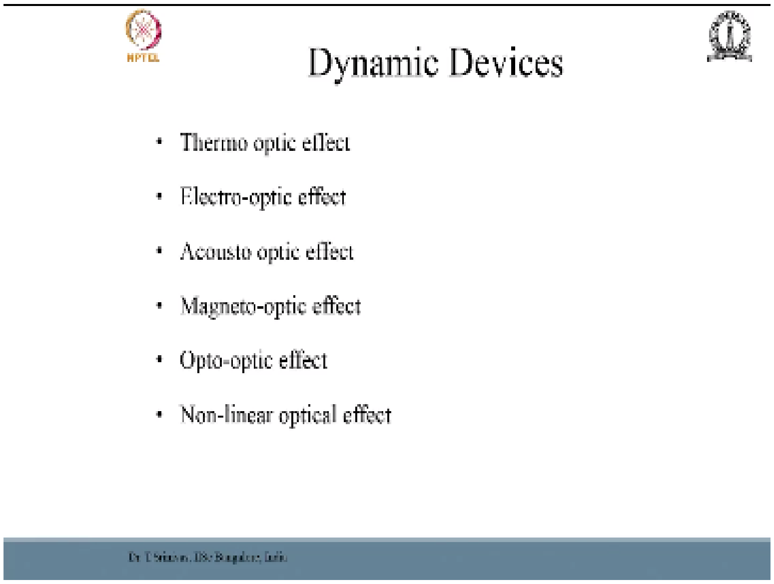

So the light coming across the first port has least delay and the one which is coming out of the out of port has the maximum delay and it could design the lengths could be design such that the face shift across each of this when combine that the output port could lead to super position only at one port for a given wavelength. So it is possible to focus each of these wavelengths such are coming from the input port at different outputs using such a structure.

This is analogist to antenna arise some of few must be familiar with where if you give a progressive face shift to each of the antenna elements you can beam forming one particular direction. Similarly by giving a progressive time delay across each of this waveguide elements we can form the beam attend a give on output port.

So there are many, many variations of this in practice to optimize a chip size and to reduce the properties and so on and so for. So let us get in to some dynamic devices where you can control the properties or the function of the devices by using many of this effects we have thermo optic effect where you can use the heating of the device you already seen the electro optic effect to where you can change the refractive index by applying electric fields.

You can also have what is called Acousto optic effect where you can induce refract index changes by using a strain or sound similarly Magneto optic effect involves using a magnetic fields to change the material properties optical properties of the material and finally you can also use an external optical signal to changes the properties of the light that is propagating in this. So non linear optical will be studied especially where a lot of industrial properties for many applications exists by the light which is propagating inside the valley itself.

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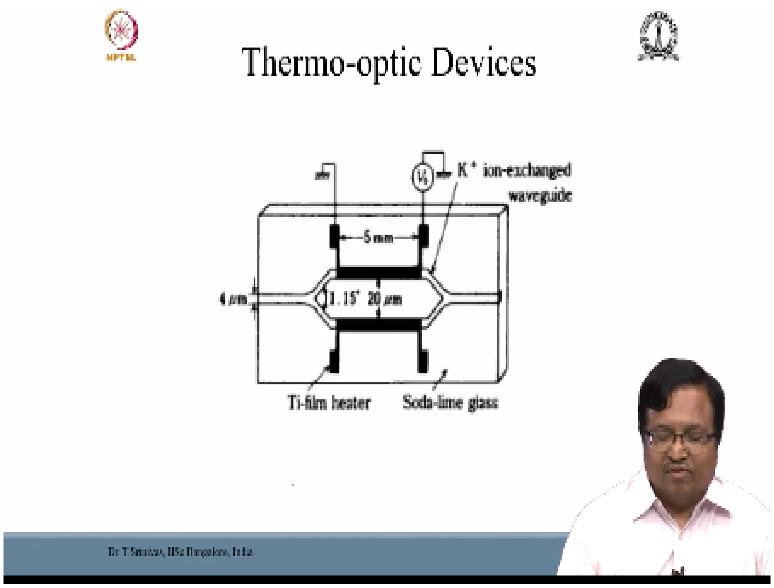

So thermo optic device on a glass of state you see thermometer that we saw earlier and the light could be launched through this input port. These are the two heaters and heating elements of the typical side of these microns. When apply voltage across these heated elements they will get below heats up by changing their reflects very little and we can switch the signal or we can change the properties of the signal based on the heat. So typically it is used this for on or off switch in the applications and you can also create the variable how to power based on the heat that you applied to this.

So this is one of the example Ti film heater and soda lime glass. One of the important disadvantages for such devices you can say that is heat because of the heat of heat involved and the process is slow compare to the other devices.

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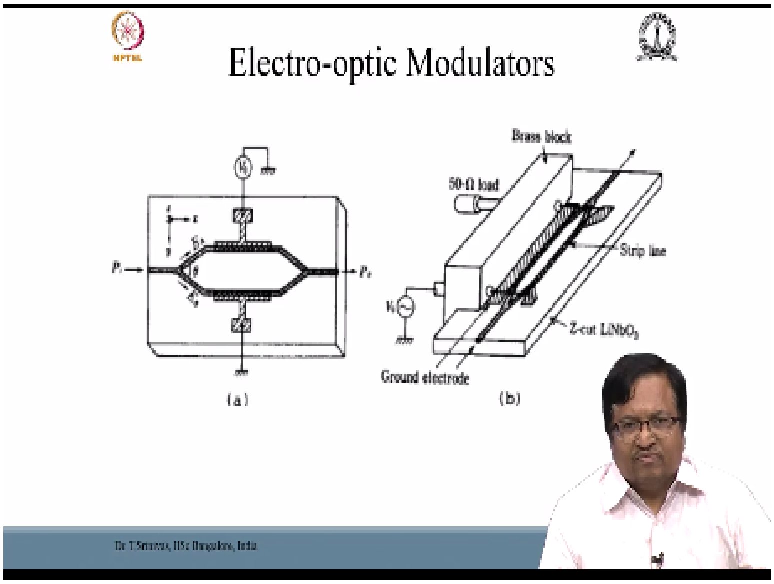

So we have already seen the electro optical devices example I am showing you the electro optical devices where you have electro that can be used to m where you have electros that can be used. On the right side we can device which can be used for the high modulation typically electros will be formed structure microwave signal is distributed among and there is variable voltage. Voltage that varies and the light that is propagating is effected by the microwave upon the electros. So this is good example of high speed operation typically microwaves are of threads, you can say these are the electric waves almost stationery compared to whether it is propagating.

But there is interaction between the microwave and light wave leading to very high speed operation, so typically it is made on the electro optical material and you need a lot of engineering like the matching of electro then the proper alignment of the electro waved and so on.

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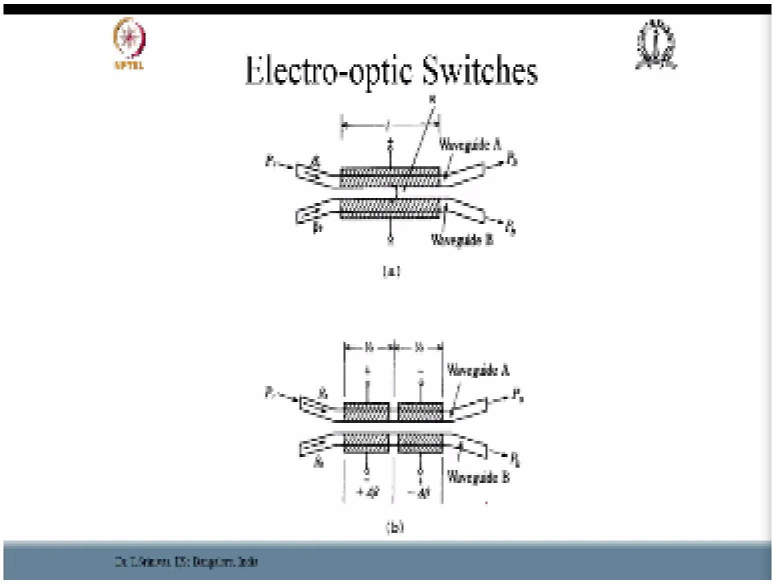

So these are another example electro optical switches already seen a lot of configuration we can think of. Typically I want to light on the second portion where you can choose the copular to change the properties and tune according to the format, and we can also compensate for the fabrication process and voltage variation and stable modulated voltage by such a configuration.

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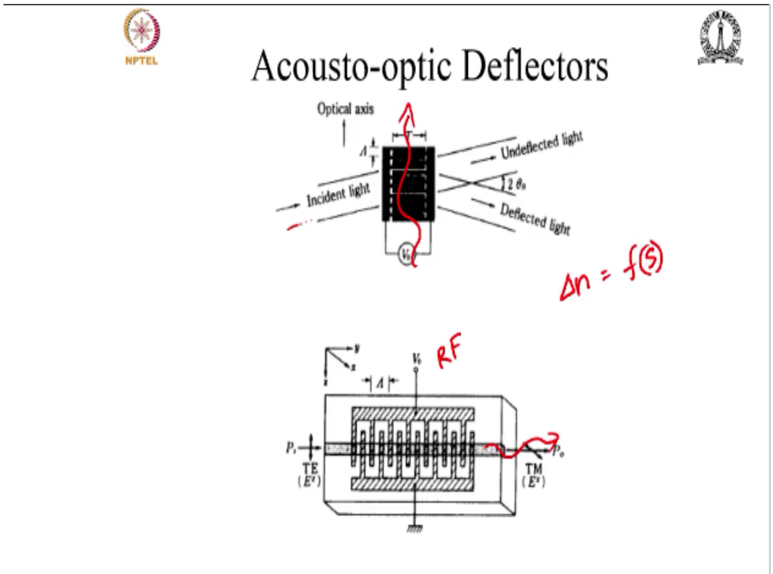

So acusto optic implies that you can change the properties of the medium by a stress way. Here what is shown which is highlighted below there is alternating positive and negative electro is shown and the wave length shown below. When you apply signals to these electros it is possible to stress the wave on the crystal. So here it is shown stress field is created in the direction and the function of the stress wave.

Stress wave is a periodic variation you can think of periodic variation of reflected variation. So if you create a grating this acousto optic effect the incident line will be deflected into any direction that is decided. So these acousto optic devices could be used as very well as a deflectors as been used very well as a deflector and many other or many applications so the magnet optic device or effectively based or not the magnetic properties of the material.

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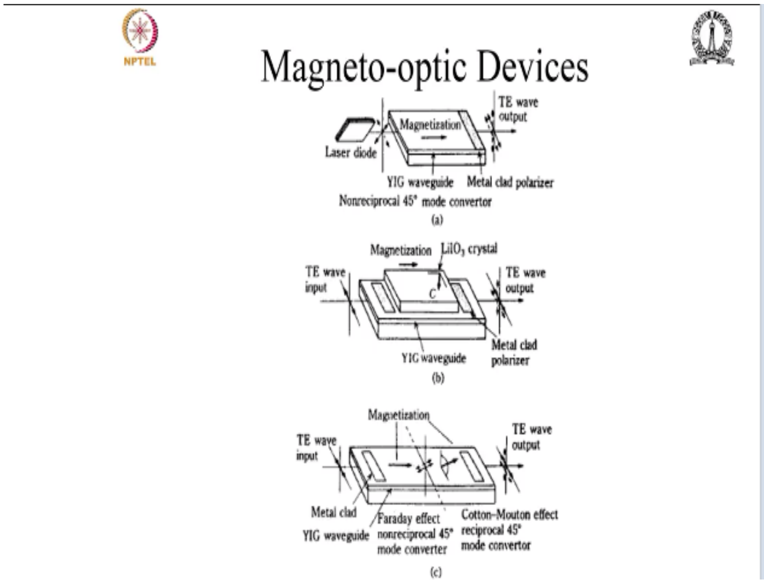

In the magnetical optical properties you can create a refrect induced change other changes in the unknown: extra property of by using the magnetic effects so typically we need the magnetic materials like carbonates interior alumium carbonates and so on and you can have special electrodes to magnetise the material and create the magnetic on the that .

Typically term on the that use is surface waves on the crystall magnetic microstatic surface case waves or creative by using the magnetic effects at variable frequency and these can be used in the many applications like mode convertions than the appoligiation control and so on so far so just a brief mention about the nonly refers in to going a refer notly effectively employ the properties of the medium or dependent on the live that is propergating this crystal.

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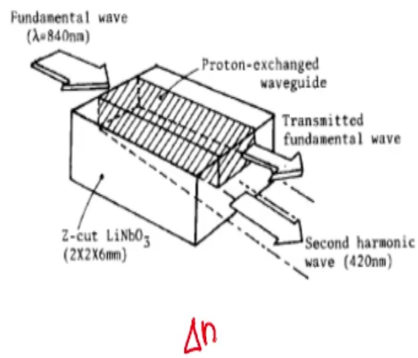
Nonlinear Optic Effect Device



It is the function of the electric field of the lighter so you can except the a particular intensity of the light for example the gentility of the light less than the lessee value the light look at the linear it could be operate linearly a just in it ware us the intensity of the light crossed the thrush old it can deflect or leaked out the subtitled in the declare of the moronic substation for a given light wave of the certain frequency.

You can create of the romantics of the that creating light wave of the certain different frequency for example the level of the frequency it also shown here once again the typically it as got of these interesting properties so here what we shown is the input wave of the light creating the second hormones at the 420 analysis. So let us look us some fiber optic system integral optics the application how the integral optocs are could be used in these application so you can have three examples in for the communication and so far the sensing application and then information process and application and so on .

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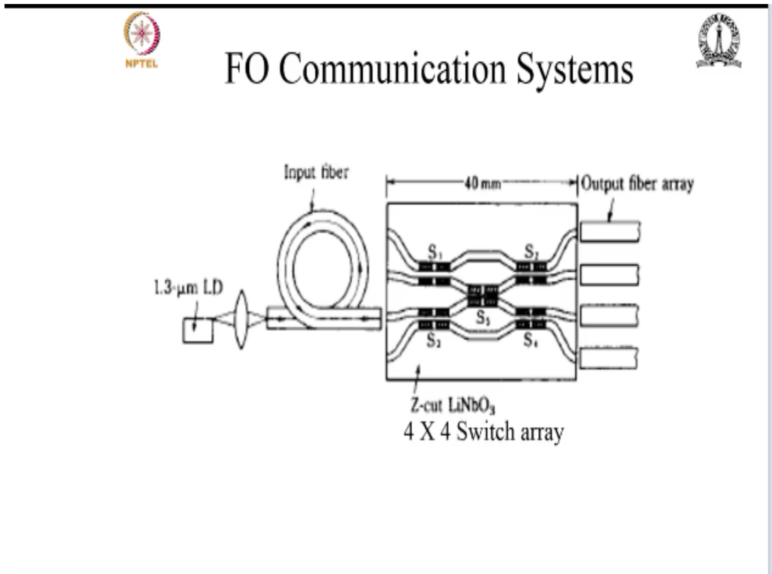

This is a typical fiber of the communication very typical communication and the link were given note in their network you need to the switch between the different output parts there are four notes to be addressed in the operating if the different signal so all the signals could be addressed in the optical fiber four input parts s1 s2 s3 s4 or x1 x2 3x x4.

And the requirement is the signal routed in to the any of the output course y1 y2 y3 y4 so the specification given in the transmission on the matrix for example as you know the operation of the optical switch the first example switch is crosses over the state or the bar state each of the programmed to the those state and it is possible to programmed thecae you can that desired connectivity for example 1 s2 s3 s4 all over in the cross over state and x1 will go to the last port and similarly if you put s3 and s4 in also in threw cross over state you candy also explain simultaneously.

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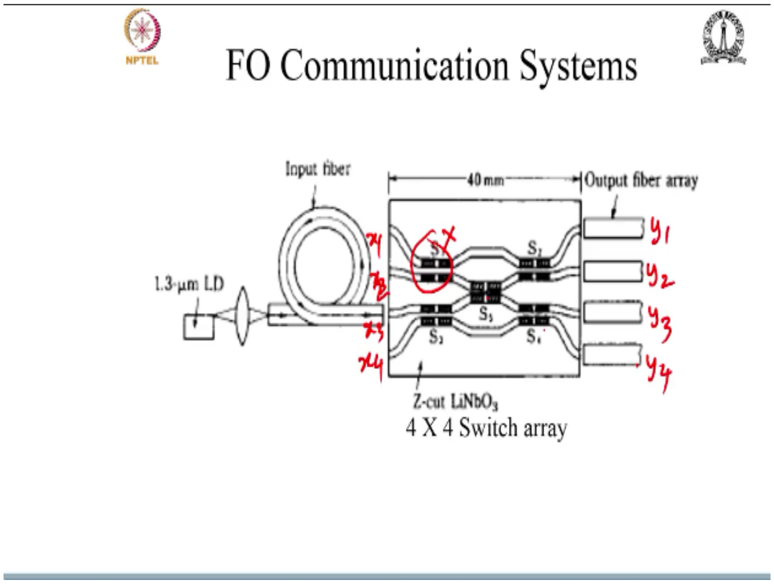

You can easily work out the all combination are possible and in the pin of the higher congregation is more switches to the in the connectivity. So this are the typical 4/4 switch array that is useful for fiber communication systems.

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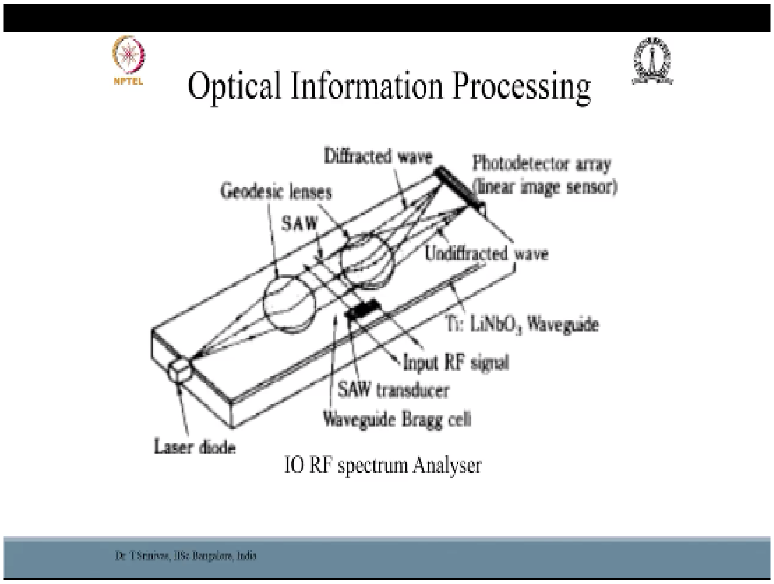

So these are optical information processing in the system the typical example of the spectrum analyzer you can see the chip in that slab wave which two lenses are impressed on it is called geodissilicenses by created by stress impressed of one those reasons. So there is a laser diode as a input and a photo detector array can capture on the scatted signal and this you have an actuator optics transistors here which will create a grating founded because using the grating and this grating is a one which will reflect the outputs.

The outputs codes lance is used plug the signal across the different output code. if I given RF signal at the accusers optical so the created grating follows the frequency of the RF signal and the reflection corresponding to the frequencies. Is there is a component signal here at the identity or the extra optical the composite gratings here and the output signal at the photo detective array then correspond to the distribution of the microwave RF signal at this input part.

So you can say the disk and act as RF spectrum analyzer. These also possible to configure this optical spectrum analyzer in by giving a constant frequency to the input signal and a variable input light spectrum. So you can configure this except the output corresponds to various components to the light spectrum. So you can configure this device as RM spectrum analyzer or an optical spectrum analyzer.

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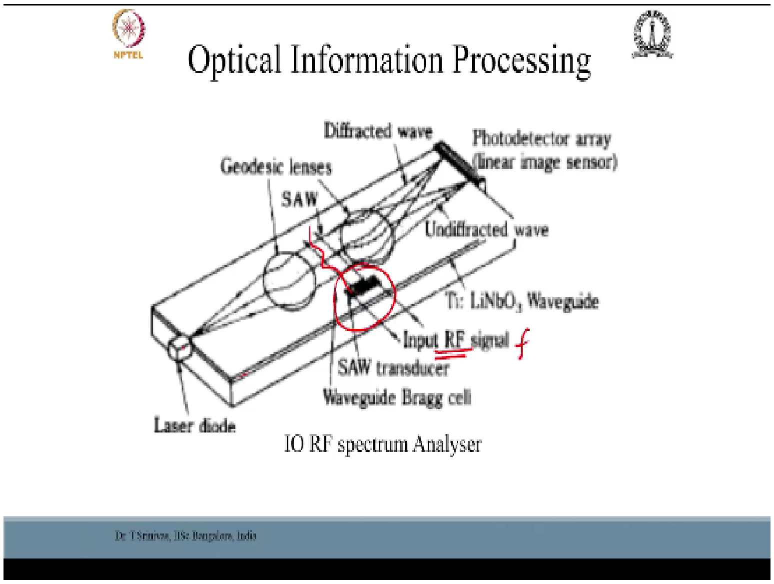

One more example of integrate optical device of the circuits in fiber optics Gyroscope chip is a sensor application. A fiber optic application typically has a coil of fiber several clouds and the principles of operations is based on the signet effect were you have a light passing through the coiling the clock wise direction and anti clock wise direction. So the face difference between the clockwise and the anti clock wise propagating ways.

These proportions to the angler velocity of the object on to switch case Gyroscope chip. So in order to function, these devices to function Gyroscope function it need several components. Like you need to split the light the input and output codes, you need to have polarizing devices because the all the devices all the operator single mode operation then for that you need a polarizer to be created o n the chip.

Then we need a modulator so that we biasing point of these faces should be shifted and so on. It is apparent to make note of a various component are necessary for a fiber optic Gyroscope chip. So fiber optical approach a very compact solution to create all these components of small chip. For this all the electronic involves for detection and processing and displaying the signals and so far. So whatever you given the application is accept. Several components necessary for many application files like sensor could be fabricated or a single chip.

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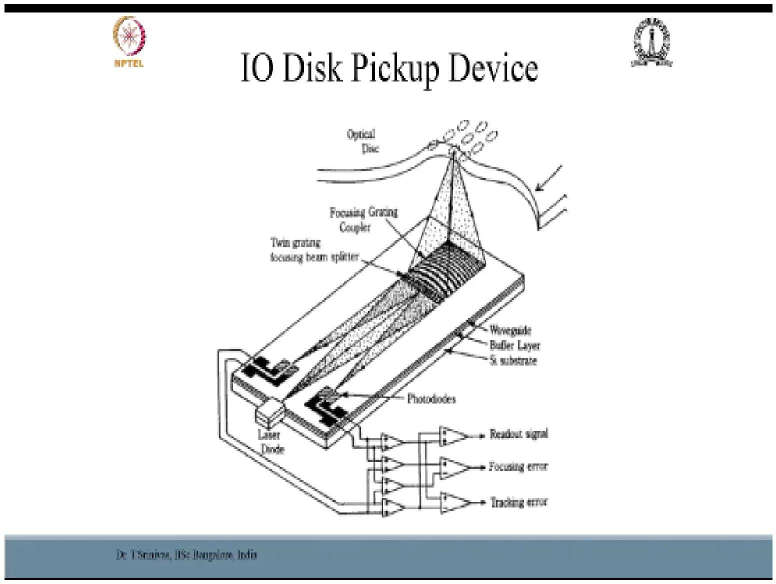

So this the final example called a IO disk pickup device, while popular sometime ago, so it has got the main application is that is a optical disk here which is very finally control of the angler size are very finally controlled. And the requirement is the optical repairmen is the each of these interest is very very finalist. So that you can have a high density storage. So you focusing grating lens is used here to read and write the signal. So such devices also be abbreviate on a small chip and the whole entire system is very compact when used of integrated optical devices. Of course lots of electrical devices are need for processing these signals.

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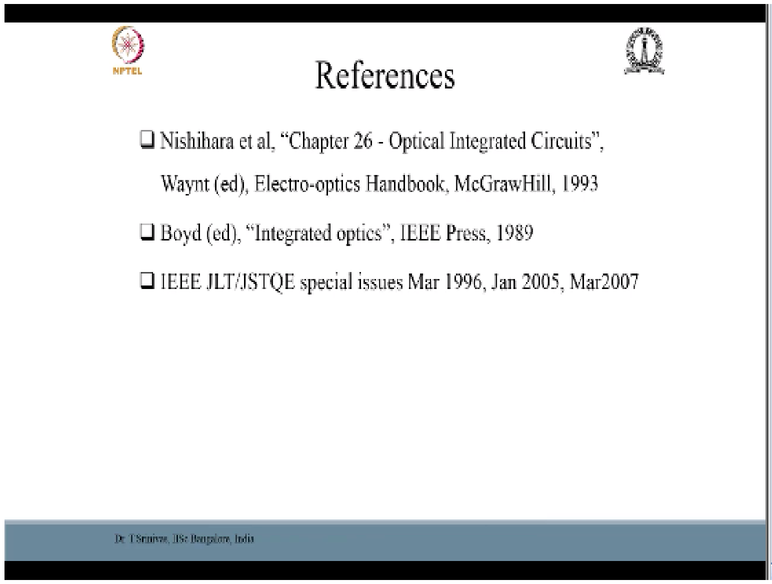

Finally we could said that integrated optics are very useful and very interesting subject in the modern optics an may a optical communication sensors and so on for it is. We can say that all the optical operations are most important directions in which in the integrated optical circuits or living to wards. There are several fervent literatures available in factories and I shown the few of these and I hope this course in very interesting to, thank you very much.