Indian Institute of Science

Photonic Integrated Circuits

Lecture – 08
Dynamic Devices

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NPTEL Online Certification Course

In this lecture we will discuss about dynamic devices.

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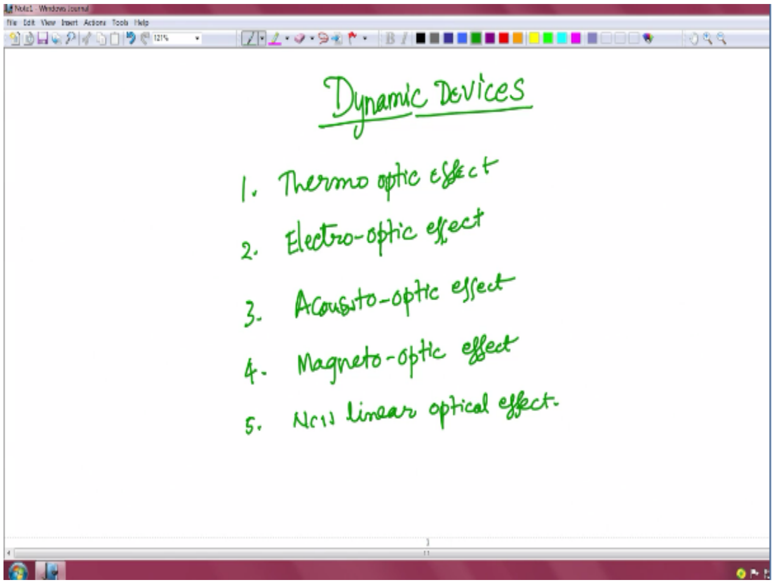

Dynamic Devices

1. Thermo optic effect
2. Electro-optic effect
3. Acousto-optic effect
4. Magneto-optic effect
5. Non linear optical effect.

We have already discussed about passive and dynamic devices very briefly earlier. So now we will go into details of how these function and so on and so forth. There are several effects which can be used to control the properties of integrated optical devices. To name some of them or thermo optic effect, electro optic effect, magneto optic effect and of course non-linear optic effects.

In all these cases the properties of the waveguide or the sub state are dependent on the external field that we apply to these waveguide. Just to take an example to tart up with, of course in all these cases w need materials which has these properties. For example, if you want to use the electro optic effect we need a material which has got electro optic properties, that means just to give an example the electro optic effect, the waveguide properties are dependent on the applied electric field.

So the material needs to be have such a property by applying electric field we should be able to change the properties easily.

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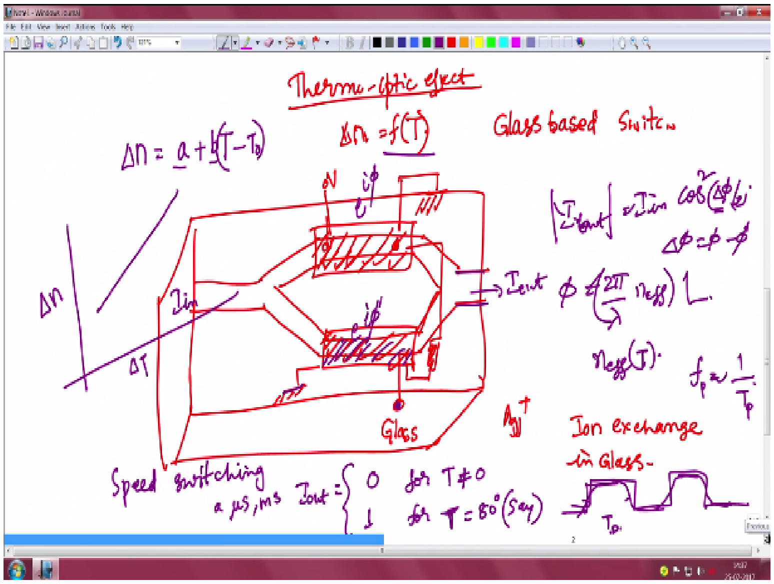

To start with let us look at thermo optic effect. Thermo optic effect essentially means the change of the material properties with applied heat, you can heat the material and then change the optical properties. In particular we will look at the refractive index of the medium that can change with temperature. So there are several materials which have this thermo optic properties to varying extents.

In fact most of the materials properties are dependent on the temperature. So we can make use of the temperature dependence of material properties for creating optical devices controlled by temperature. But of course, different materials have different effects, different or influenced to a different extent by temperature. So is the material response very well to a small change in the temperature, then that will be much more effective.

So Δn is the refractive index change of the material with the function of temperature. So thermo optic effect implies change in the refractive index of the material with temperature. To take an example let us consider a device, let us call it as optical switch based on thermo optic effect. As the example I am considering the interferometer, the same example that we have discussed earlier and interferometer made glass, I will take glass as example.

Let us call as a switch and I will try to explain the function of the thermo optic switch. This is the basic interferometer on glass sub state, so the sub state is glass, so sub state. And we would like to heat the waveguides by putting electrodes like this, this is an electrode, there is another electrode on top of this would like to the second part also, or the electrodes could form a part of the circuit to heat for example one of the waveguides can be grounded and voltage can be applied to this electrode typically.

If electron, we would look at the technological issues there how we can form the waveguides in various sub states, in the case of a glass for example you can form by diffusing silver into glass. So one of the typical process for glass is called the ion exchange, silver ion exchange in glass, this is a typical process. So where, and you can have an aluminum or titanium or electrodes which can be heated easily by applying currents, currents or voltages.

So you may also have to have a circuit to, this can be called as a load resistive load you can have, you control the amount of current that you pass through this. So the electrodes could be heated by passing current and the refractive index changes with the temperature. There will be other configuration this could be a different electrode with this the circuit being made like this and it ground it other and you apply the voltage and here also you can think of applying only to this electrode and this will get heated independently.

From the function of interferometer you know that the phase shift can be given by $e^{i\phi}$ where ϕ is the phase shift. And this could be a different ϕ phase shift and this could be different due to the temperature change, with and relate for example the phase with the propagation constant 2π/λ effective refractive index of the waveguide to be the propagation constant multiplied by the length of the electrode.

So here the effective refractive index is the function of a temperature. So we can expect the phase shift to result in the intensity change Iout to input here and the output here. We can say that output is dependent on the phase shift. As you know for interferometer we have output = Iin maybe let us take out only the magnitudes of this waveguide in terms of $\cos^2\Delta 2\pi/2$. So depending on the phase shift $\Delta\phi$ we can have a low or high intensity at the output.

For example, when the temperature is applied the output can be 0, and when there is no temperature applied the output could be maximum or let me say 1. So for T not equal to 0, let me say they are identical and so the phase shift is 0, and for some value of T say 80° or so, the output is maximum and we can switch between 0 and 1 by switching between 0 and 80°. This could be called as a binary on, off switch using the thermo optic effect. So we need to understand how much the temperature affects the refractive index change.

So for that purpose we need to know what is this function in a simplest case we can say the temperature coefficient of refractive index as a function a+bT where a and b are coefficient and T is the temperature maybe temperature difference most of time T0 is the ambient temperature of the bias value, and with respect to that we measure the T and say that the refractive index change is with temperature as follows.

We can also plot a graph between the ΔT and Δn, for example, as the temperature increases, temperature can increase or can increase the refractive index or reduce the refractive index if you say that with the given range of operation the temperature is changing the refractive index linearly, say for example 1% you can find out the coefficients a and b and use it to design the thermo optic switch.

One of the limitations of thermo optic effect is the speed, so it depends on the speed, switching speed the speed with which we can shift from 0 to 80° most of the materials will take certain time to relax between 0° and 80° and so the speed of switching is limited if the time required to switch between 0 and 1 is given say for example if you micro seconds or milliseconds we can calculate the pulse rate with which we can modulate this is witching diagram where you can switch between the 0 level and 1 level of course there will be a small time delay and switching back also will have certain time delay and based on this we can calculate what is the maximum data rate we can go.

So typically it is of the inverse orders suppose if the switching speed is say 3b switching speed is some Tp then we can go for switching speeds or frequency of on off modulation of the orders of 1Tp.

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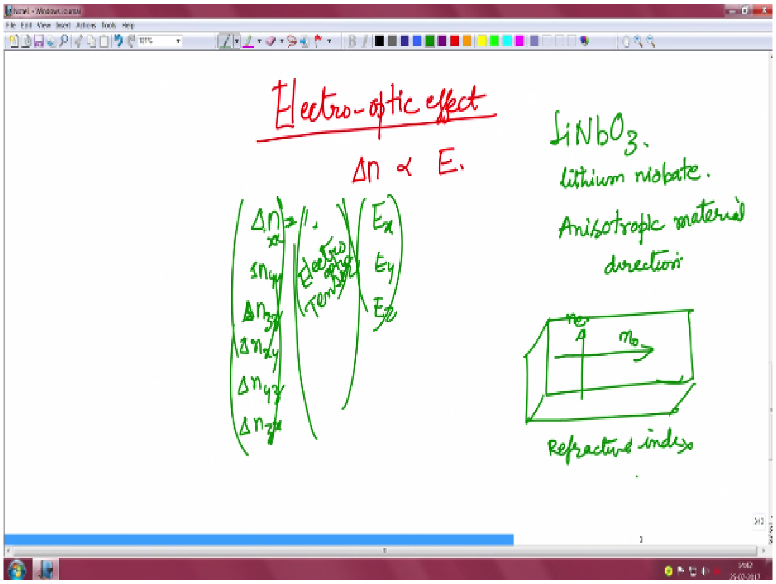

Now let us look at another effect which is most popularly used in integrate optical devices called the electro optic effect, the simple way we can say the elector optic effect consists of changing the refractive index of the material with applied electric field, so there are several materials which have got electro optic effect there is change in the optical properties of the medium with applied electric field typical one the most popular one is the lithium niobate, so a few properties of lithium may be how to be considered first.

Even though we may not go into finite details of light propagation in an isotropic materials lithium niobate is a typically anisotopic material which means the properties of the refractive index properties of the lithium niobate vary with direction, so typical anisotopic crystal if light propagates in one direction it has got certain refractive index called the ordinary refractive index and if it propagates perpendicular to that it has got another refractive index called the extraordinary refractive index.

In bulk optics shifting all the n ordinary and nx ordinary but in the most general case we can say that this is tensor, refractive index is a tensor or the relationship between the refractive index and the applied electric field can be expressed in the form of a tensor so we can express it as follows, we can also express the refractive index as a function of a Taylor series refractive index let me call it let us in the most general case later let me call it if you have electric field as different components Ex Ey Ez and Δn as several components.

So the refractive index Δn can depend on any of these or more than of this so we can Δn in x by fill the x direction and refractive index changing x direction we can express this as matrix, yy / Δn changing in the zz these are all different coefficient of the refractive index Δn xy. Δn yz and so on, so we have a matrix which will express the relationship between Δn in terms of several fields, so this is a tensor called electro optic tensor, so such material properties could be expressed as tensors in many other cases.

For example if magnetic fields applied and refractive index changes in different directions the coefficients which express this can be called as tensors and represented some time the matrices but more extended mathematical forms, so in the present study we will not go into details of how the material properties vary with applied field or how it should be calculated exactly but we will try to take an applied approach were we express the refractive index as a function of electric field in various ways.

And see how it could be applied to practical devices, of course if you look at the nods some specific examples of refractive index variation in different directions in the applied field are given.

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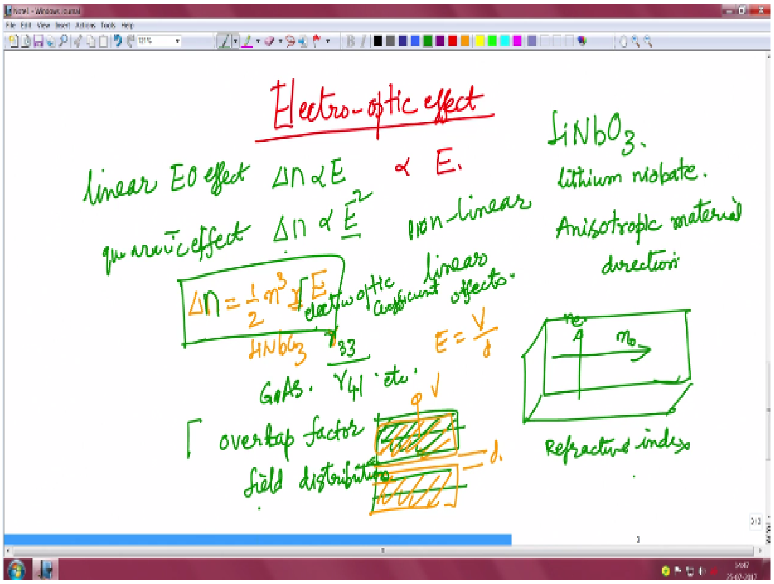

So first let us call linear electro optic effect means Δn is a function of electric field alone, and if Δn is a function of this square of electric field ort the intensity of the fields we can say that the intensity is proportional to is E^2 so if then refractive index is a percent to intensity of electric field, then it can be called as a quadratic effect.

Or in general the if the properties of the medium depend on the fields that are within the medium all this fall under what can be called non linear effects and if the medium properties do not depend on the field in particular the field that is propagated we are in the linear region, linear property, linear effects. So when the specific case I will just give a small formula which is useful to express refractive index profile as a function of electric field.

So in the case of lithium niobate we have this r this can be called as the electro optic coefficient I will use some other color, there are the matrix forms more specific case r33 is one of the matrix coefficients which is very useful and which has got large value similarly in the case of other materials like Gallium arsenide etc.

We have other coefficients like r41 etc, so this is a very simple formula which can be used to calculate what is the change in the refractive index when you are applying electric field, if the electric field is applied using a electros for example if this is a wave guide this is another wave guide and we apply the electric field to these electrodes I will draw a proper picture later on there is a small gab between these fields and if the voltage apply this v we can express E in terms of v/d of course we have to solve the electro static problem to find out is the actual nature of the field but is the d is the gab.

Based on that we can improve up on this and usually you include an additional factor called the overlap integral I will put it somewhere here over lap factor for overlap integral to express the effects of the eclectic field and optical felid it depends on the field distributions, distribution of the mode field and distribution of the electric filed we will go into slightly more detail in a few minutes.

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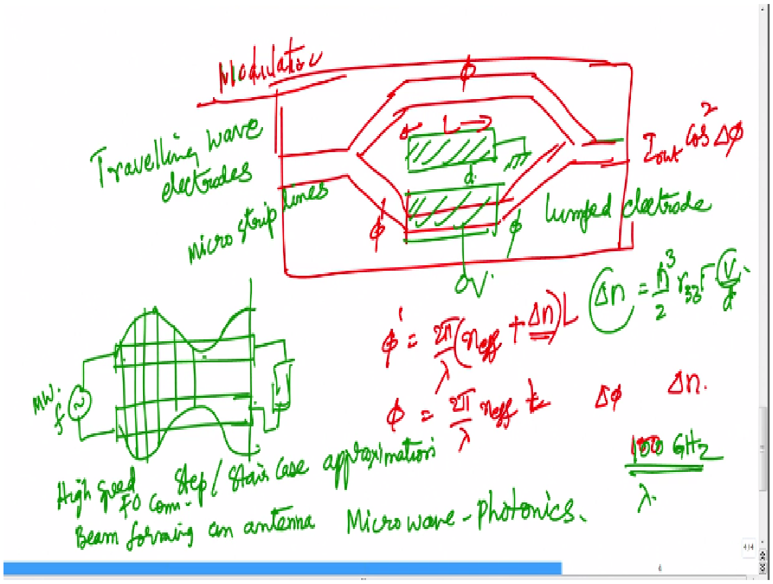

So let me taken up an example of a modulator one of the very conman applications of electro optic effect is a modulator I will once again use an MZI this assume this as a standard magazine intra parameter module, intra parameter where you can put electrodes and may be let me put another crowd electrode or sol very close by. So this is a gap between them and the phase of this can be shifted by planning the electric field, so Δm is a function of the electric field r_{33} this one particular geometry r_{33} x Γ v/d $n^2 r^3$.

So Γn depends on the applied voltage so like in the case of thermo optic device for say that this could act as a intensity modulator output $\cos^2$ Δϕ if this is ϕ0, ϕ and this is ϕ' where ϕ' is expressed at 2Π/λ x (nf + Δn)L length of the electrode. So this Δn is an additional factor for ϕ' or ϕ you do not have any additional refractive index change and you have a Δϕ depending on Δn, so this can effective as a effectively a phase modulator.

Now of course you can change the applied field very rapidly and you can get very high speed modulation, typically if you want to for a high speed modulation of the orders of several Giga hertz say 100 Giga hertz we can use an electro optic modulator, so as you may have noted that this is a microwave range and high frequency and you can express the wavelength of microwave that is brush upon that.

This particular example shows a lumped electrode that means the electric field is uniformly distributed and does not change very rapidly so you can use lumped electrode configuration to study the properties as a parallel plate capacitor and we can determine or calculate the band width of the operation and so on and so forth, whereas for a high speed operation these electrodes are no longer lumped electrodes.

But you should consider them as a travelling wave electrodes, that means let me draw redraw so that means the electric field that is impressed upon that is distributed on this electrodes as travelling waves so let me just as a example let me take that electric field is distributed as follows. That means there is see okay let me to in order to analyze these electrodes you have to treat them as micro strip lines.

These are effectively waveguides of microwave frequencies where the microwave can be guided along these strips, typically you need to have a load and your source microwave source at the other end, so this is microwave source of certain frequency and the guided wavelength and so of the properties of this micro strip lines will determine how the field is distributed and at every point there is a different value of the electric field so at each point the electric field is varying.

So you need to calculate the refractive index variation at each step and then calculate what is the total phase shift, so you can use a step or stale case approximation. For the applied electric field and then calculate what is the phase shift the phase shift could be very rigorously calculated by considering the wave propagation along the micro strip lines and the light wave propagation align with them and the velocity of force are different.

Micro wave and optical velocities of the medium of the wave in the medium are different and so using rigorous techniques you can analyze what is the propagation properties of this at their electro optic properties. So this subject of applying or combining microwaves and light waves is called the micro wave phonics, it uses microwave techniques or application to light waves optical problems and optical techniques to study micro wave properties of the devices.

Typical applications or high speed communications high speed fiber optic commendations where you modulate the light wave with a high speed micro wave and also the other application of using the light waves or micro wave obligations is for a beam stage applications beam forming or stealing and antenna, for example if we form a beam starring circuit with optical fibers we can obtain delays that require that are required for beam forming an antenna.

This could also be obtained by using integrate optical devices like waveguides delay lines and inter formulators to achieve the required delay so that the intra beam could be directly in some particular directions.

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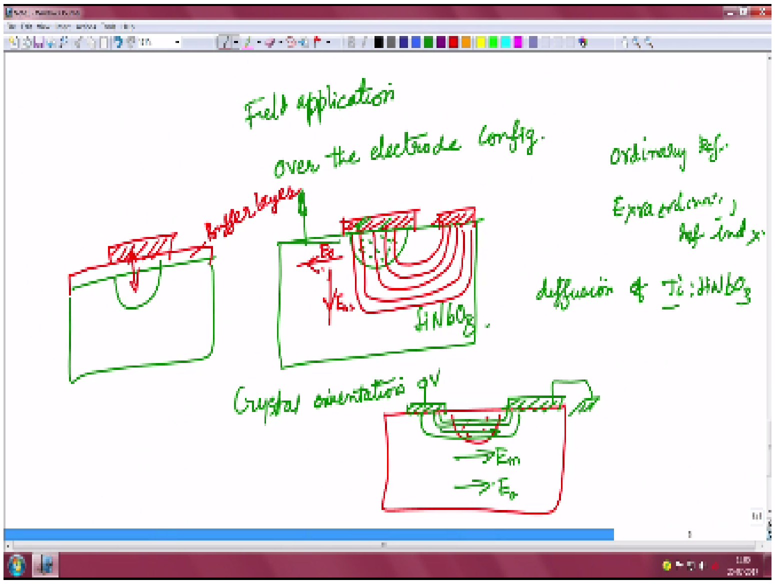

So we will get a few more details about this electro optic effect for we include, so the electro optic effect is heavily dependent on the direction of the application of the fields. In simplest case what we have considered is call the over the electrodes configuration. So I am drawing the cross sections where you have a light wave bellow let me simply say lithium near bit based device where this is the optical waveguide for typically formed by diffusion of impurities like titanium into lithium waveguide.

And few traces of titanium metal diffuse in lithium waveguide wave can be formed this optical waveguides and of course I am showing you only one waveguide the electrode could be adjacent to this or I will first let us take the over the so the electrode could be placed over this, this is the electrode metal electrode with a ground electrodes at some other points, so the field there microwave field or applied electric field could be set to be forming a field lens as force.

So if you are considering the light wave of TE mode which is oriental in this direction and microwave is oriented perpendicular this, this is one direction of the optical field this direction of the microwave field in the over the electrode configuration, similarly we can also think of the electrodes which are aligned across the waveguide so in such a configuration you have electrodes placed like this.

Let me say this is the microwave wave guide and you can consider electrodes placed adjacent to that, so let us say this is the ground electrode this is the signal electrode and the fields are can be expressed to be parallel to the direction of the field this is E microwave field and if you are considering T mode, E optical also is in this direction. So there are various configurations that are possible and also you talk in terms of the crystal orientation.

So crystals are defined in terms of their orientations in particular the direction of the way the crystal is cut defines the axis, so the classical optics we talk about the ordinary refractive index and extraordinary refractive index and extra ordinary refractive index, so based on the cut orientation and propagation of the direction of light wave we can choose the, we have to choose the appropriate coefficient and calculate the refractive index variation there are many, many other practical issues for example a metal could not cannot directly be in touch with optical field.

So we need to have a buffer layer before we do that in the case of electrodes which can be placed over the waveguide we form a buffer layer and then apply the voltage this could be buffer. But that would isolate field a little bit and you have to account for the variation of the field in the buffer layer it may increase the amount of voltage that we apply to the electrode.

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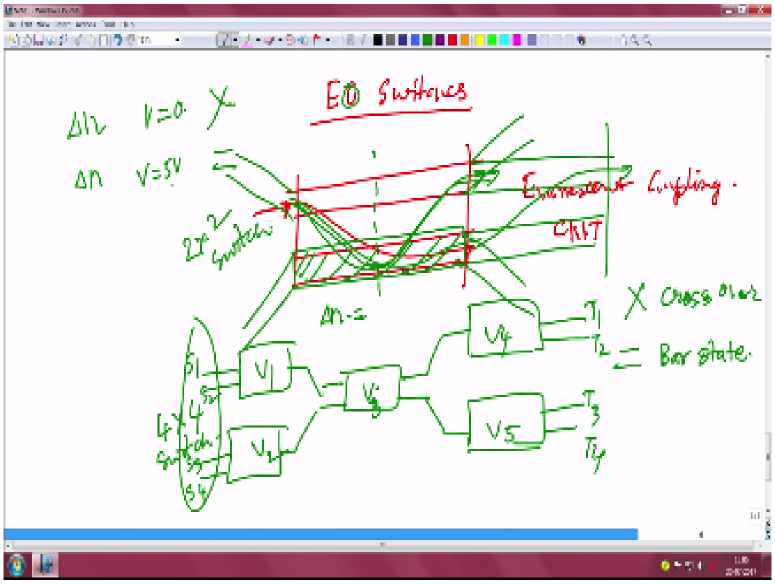

We do another affect, one more application we can think of with electro optic is the electro optic switches, when we discussed about the directional couplers we considered two parallel waveguides and said that if you launch light into one of the waveguides it is possible to design the directional couplers such that the signal comes out of the opposite port. So this is due to the it can be called as evanescent coupling.

We have studied this using the couple mode theory, now suppose we would like to create a situation where the light demonstrates into the first port exists out of the first port itself, so in order to do that one of the best ways that you can think of this to have a long directional coupler of double the length so that the light goes back into the first port, so the previous state could be called as a cross over state and the present one can be called as a bar state.

But the length of the device could not be changed easily once you fabricate that you do not have any control on the configuration, so we can think of a possibility where you apply voltages or use the electro optic effect so that this function could be realized. So the requirement here is we should change that refractive index Δn such that within half the lengths of this device the power is exchanged to the other port and in the remaining half of this the light goes back to the first port.

So we can think of and the Δn is or let me put it, let us say that we are changing the Δn with applied electric field or voltage, so when there is no voltage the designs for cross over state and when you apply voltage the refractive index changes such that switches into the second mode, second waveguide and goes back into the first, so cross over state for certain amount of voltage say for example 5 volts.

So this could be called as an electro optic switch when the voltage is 0 it is in the cross state when the voltage is applied it is in the bar state. Once again you can think of several configurations and other technical issues like the switching speed and so on and so forth. There are many, many other variations of this electro optic switches like this split electrode configuration and then also practically speaking there are tapper sections you have to take care when you want to couple the light into and out of the device and so on and so forth.

So it is also possible as we have seen in one of the earlier talks that we can cascade these electro optic switches to make high order switches this can be called as a 2x2 switch, and you can cascade them such that you can get high order switches. Let us say this is a I will put, I will use a block instead and this is in 2x2 switch, two input ports and two output ports and it could be in the cross state or bar state depending on the voltage that we apply to this control we can call it as a control voltage.

And you can cascade five of them like this and obtain a 4x4 switch, but as discussed earlier it is then how to be possible to get any combinations here let me say this is a signal 1, signal 2, signal 3 and signal 4 or port 1, 2, 3, 4 and output ports T_1, T_2, T_3, T_4 we can work out a combination of switching states. For example, you have switching states V_1, V_2, V_3, V_4 and V_5. So you can program these values into voltages such that you can obtain a proper switching configuration.

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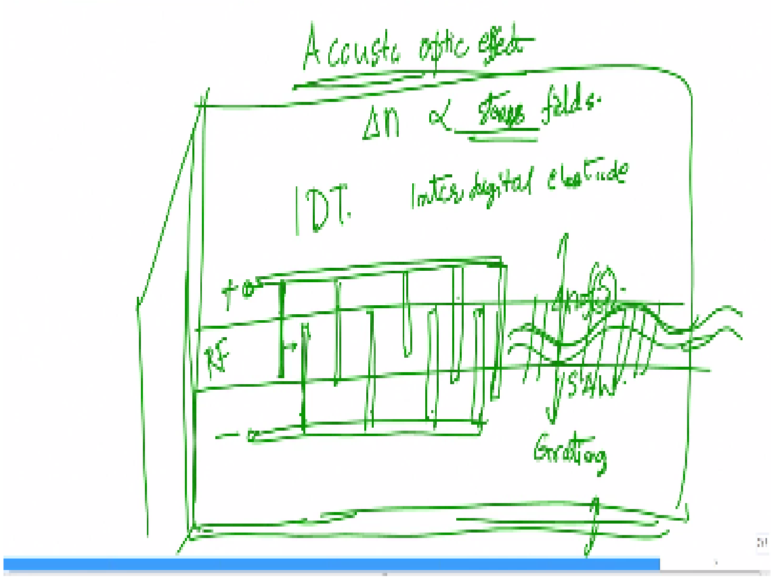

Now let us go to another important effect call the acoustic optic effect, acoustic optic effect essentially implies the change in the refractive index of the medium with applied stress fields in a very simple way we can say by applying the pressure variations or sound variations, let us simply may say this stress strain fields. So application of the creation of the stress fields could be obtained in various ways one of the important ways that is done in acoustic optic devices is to use what is call an IDT pattern, Inter Digital pattern, Inter Digital electrode.

So a typical Inter Digital Electrode look as follows, you have a combination of high and low voltages like this so I will draw in a very simple way so let me say this are the electrodes which are it connected and this I will need to replace the double lines with single lines. All these are electrodes of certain thickness typically these are connected to the opposite polarities + and -, so 9 voltage is applied to this electrodes alternative electrodes and negative or – voltages applied to these electrodes and this is varied rapidly at a certain rate by applying an RF voltage, so a micro wave could be applied to this to alternate these + and – at a certain rate.

So due to the distributed nature of these electrodes it is possible that the field across this is changing and can create a propagating wave. The electrode there is a wave which could be launched on to the crystals suppose if whole of this IDT pattern is printed on to a acoustic optic crystal on the surface of a acoustic optic crystal it is possible to create a strain wave depending on the voltage that you apply, so the property of the material is we are trying to create a stress field or a strain field by using a electric field.

Electric field is only incidental to create this but ultimately the effect implies the strain field that is propagating on the crystal this is can be called as a surface acoustic wave, surface acoustic waves are waves that propagate on the surface of the crystal and they have a certain properties govern by acoustic equations and so on and so forth. For today’s discussion we can just simply say that there is a stress variation of on the crystal due to the, so it can be either in terms of the phase change of the acoustic waves or intensity changes of acoustic waves.

Ultimately we are interest in refractive index varying with stress field, so since this is the periodic property we can assume that they can refract index is also periodic and effectively creating a grating. So optical grating is created by this surface of acoustic wave that is the final effect and once you have grating you know the properties of the gratings and let me identify for the dibbing with the slab wave guide, you have a slab wave guide on which you will propagate surface striver.

So the optical field and the surface acoustic wave are confined to a certainly thickness of the waveguide and the confinement of the light field is only in the depth direction it could of course spread in the across the waveguide and we can also think of creating a channel waveguides or which you can create gratings. So we can create waveguide gratings by using surface acoustic waveguides.

These waveguide gratings as we can have seen earlier in one of the initial lectures have several important applications. So the simplest case we can think of.

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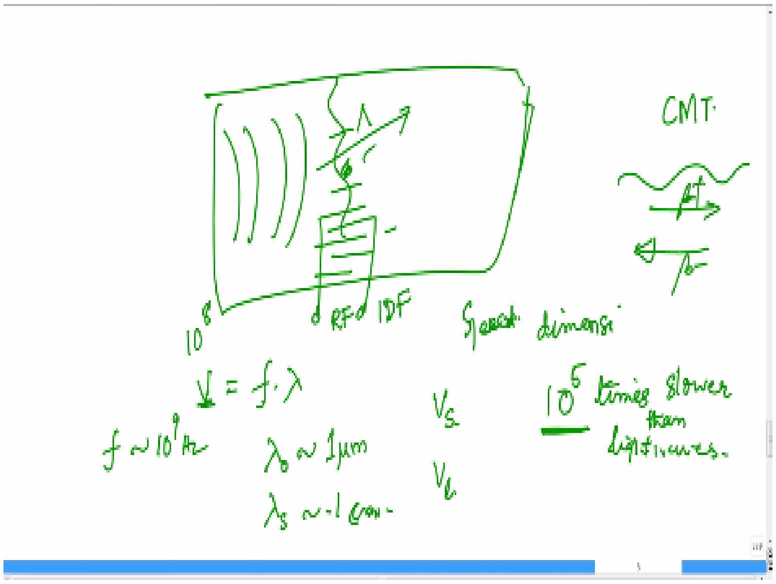

Δn as a function of strain field, so Δn is the function of strain and this is the periodic function that is he important one. Δn is a periodic function of s, Δn z let us called so there are many applications one of important applications of the waveguide gratings is to deflect light across different directions. Just too given an example we have a devise within acousto optic cell so call acousto optic cell. Just a minute I am just wrong it IDT pattern, let us consider this as a very crude IDT pattern we can apply RF to this and create a surface acoustic wave in this.

So if you launch light across this grating acoustic grating you can expect the light to be deflected in particular direction based on the grating pitch. So grating pitch is define as the distance between 2points of high refract index or lower refract index, so I will called as pitch capital comma it is a pitch. So the grating to be analyzed various ways in particular by using couple amount formalism where there is a forward propagating wave and backward coupling wave.

So the grating theory is based on the coupling between the forward propagating wave and backward propagating wave, there are many other applications we have discuss Interviewer: eh earlier or we may discussing in the future course of action. The speed of the oxto optic devises or the dimensions involved the grating features involved is a very interesting relationship as you know the sound waves are of they are about 10^5 times slower than light waves, the sound waves are sound waves in crystals are 10^5 times typically 10^5 times slower than the light waves. So you can think of in terms of velocity I am talking about in terms of velocity of sound wave compare to velocity of light waves.

So and we can use the relationship with the frequency and the wave length, velocity is product of frequency and wave length and we can use this relationship between sound waves and light waves to inter link the dimensions of acoustic devises and optical devices in particular I have to mention that the light waves are of the order of wave length of light one micron typically visible lights from 400, 700 nm of the absorb 1 micron.

And this is optical wave and sound waves are of the orders of a few mm and cm say one cm, so because of the difference ion velocity is the wavelengths or of the orders of 10^5 different. Similarly we can also think of linking this light waves and sound waves and micro waves were micro waves have frequencies of the orders of a giga hertx, one giga hertx of the 109 hertx and once again the velocity are similar not exactly same but of the light waves and micro waves are of the same order 108 m/second and so.

We can use this process this relationship or this phenomena of acoustic waves to relate micro waves and light waves, this is the additional dimension to the microwave photonics. So the acoustic waves can link micro waves and light waves easily.

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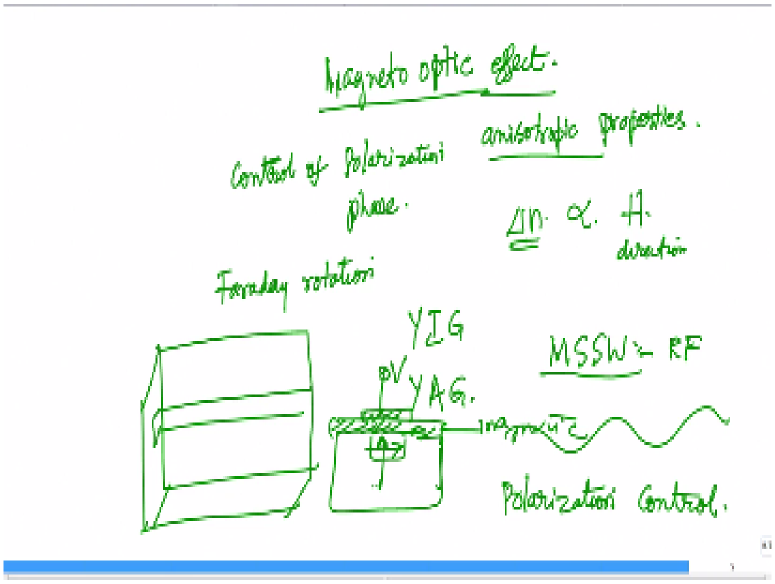

So now we will look at other important phenomena in particular the magneto optic effects, and we will highlight that we are dealing with highly anisotropic properties compare to other earlier fields that we solve is there is acoustic effects and the electro optical effect of course most of them are anisotropic but we can find the maximum anisotropy with magnetic materials.

And they could be used for many other important applications like in optics in add in integrate optics we need control of polarization and control of phase all these could be very well achieved by using magneto optic effects in particular if we are given a small relationship for example Δn is function of the H we can estimate what is the exchange in the refract index and of course this ios very important that we take note of the direction of a magnetic field and the component of the refractive index that is affected.

And this could be used in many ways for example Faraday rotation the rotation of the polarization state of a light wave can be achieve by applying magnetic fields. So I will give a small example of a device which use as magnetic optic effect, let us consider typical devices or garnets yttrium iron garnet or yttrium aluminum garnet these are some of the materials which have got magnetic optic effect and like in the case of acoustic waves we can also think of magnetic waves they are call the magnetite static surface waves.

So back to static surface waves we created and propagated on a crystal and a crystal like this magnetic crystals and some of them have wood optical properties so we can have good interaction between the electric and magnetic properties to achieve some good functions. So a magnitude of static surface we have also could result in grating like device so which the light could be propagate.

So the magnetic of immerse again the magnetic optic effect could be a function of RF to create gratings and so on. So another important way that we can use this magnetic optic effect is to coat a magnetic medium and toping optical wave guide let us assume this in optical waveguide in a cross section is like this and you can coat magnetic medium or top of it this may be a isotropic medium were not affect the properties of much but this could be a magnetic medium.

And let us say if we are controlling the magnetic properties by applying voltages so the magnetic properties are becoming a under voltage and so we could control the probation of like here this one of the we can say polarization state can be controlled and be achieved.

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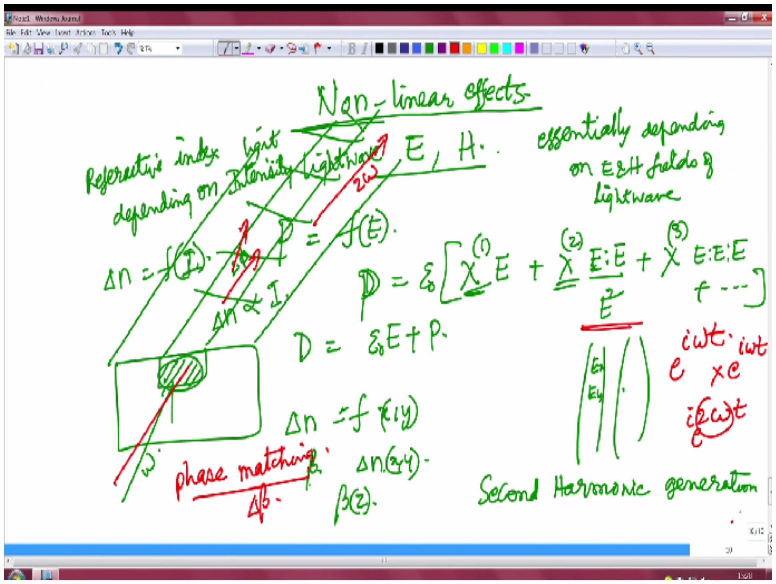

So another important category of effects are can be used the control of the properties of integrated optical devices can be called as non linear effects or non linear optical effects in the previous case the fields are been applied externally were as assume we may in gas that the properties are medium can depend on the light wave it may be propagating because light wave it has a electric fields and magnetic fields are associated with this.

So the intensity is sufficiently enough this could have a very dominated effect on the properties of the medium and this will be called as non linear effects essentially depending on the E and H fields of the light wave here we are considering not considering the fields are applied externally but it is also possible to large light into the wave light controlled to the properties and the single could be a different light wave.

So we just consider one or two important cases and important applications so there are several effects most of them should be dealt with by using the polarization of the medium P is the polarization of the medium which could depend on the electric field so you look at the displacement vector and you can substitute this into Maxwell’s equations to derive the non linear equations.

So D is given as $£_o$ is the 50mm per the uniform medium or the free space and x or the coefficients suitability coefficients say of different orders x 1,2,3,4 etc and E are the electric fields is a second order that depends on E2 typically return with the column to sat this is not only E2 but various components of E are combining.

For example you have three components of electric field and various combinations Ex Ey is not exactly multiplication but Ex Ey could result in second coefficient and this is all are typically that can be sustainability sets and so on. So depending on the coefficient that we use we talk about non linear effects of that particular coefficient so this is P so D is expressed in terms of $£_o$ E+P so if we look at the wave equations of the right hand side it getting linear term but were as it is also possible to obtain squares and cubes of the electric field on the right hand side of the wave equations.

This which implies that there is a non linear phenomena the equations are not linked so the several effects that we can consider in particular reflects independent depending on intensity the light depends intensity so Δn is a function of light intensity so simple effect that we think of with such a phenomena is if you take the optical wave length normal course of non linearity there is no high intensity light incident into the wave light.

The time is not dependent on the not much dependent on the intensity but how dependent on intensity and we know that we have a modes part on certain shape so the refractive index is also a information of x,y so this is resulting a grade index wave light and modes part is modified including its propagation part is constant.

A propagation constant for grade index refractive index is different and so continually the propagation constant is the modified as the lights propagates along the wave light so each point we have a different propagation constant or we can say that β is depending on the propagation direction and its complicate based on the refractive index variations .

And you can think of the phase shift the phase change can be studied as like propagates along the wave light similarly in handling optical one of the non linear effects optical the second harmonic generations so you have a wave light which you launch a optical light of the certain frequency omega and the output could be of frequency two so this could be explained by using the second order effect were E^2 terms in each of the terms E are expressed in terms of E^{iwt} multiplication factor this also converted into effects explained.

But this si also possible to develop a couple more theory later in the incident field second harmonic fields and the total excited field to study how the coupling from the various components of the electric fields that they are in particular you can emphasize on what can be called a phase matching.

In case of optical wave lights in directional of example we have seen that the coupling between two wave lights is possible only then certain condition is satisfied and certain values integrated multiplies of some values similarly you can think of these non linear effects in particular this second harmonic generations is possible when there is phase matching between the light propagates in the different directions.

So I have just like note down that phase matching is an important factor in the non linear optical effects so there are many, many other effects that can used to control the properties of optical wave lights in this discussion we have consider only properties which are dependent on the external we are not consider the properties were there is interaction between the light and matter

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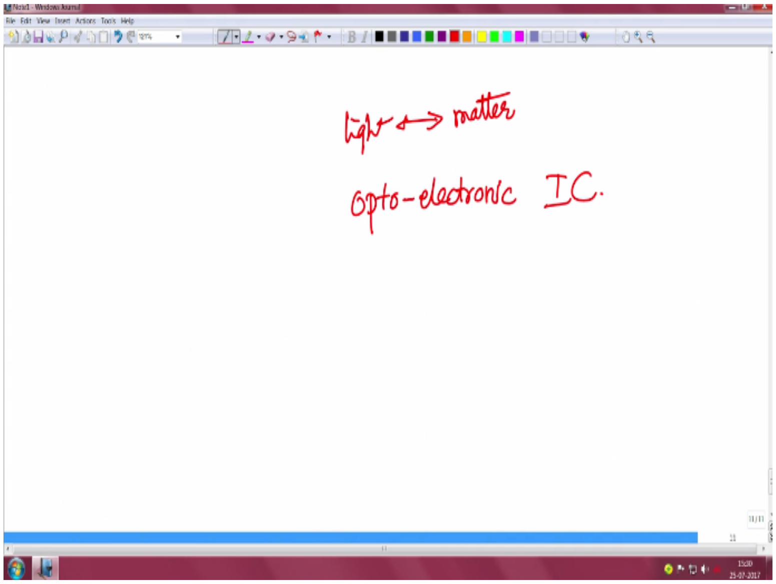

light ↔ matter

opto-electronic I.C.

For example the electrons of the crystal or it assuming the conducting material for example there will be interacts between the light and matter including the effects like the electrons of this effect or control of the optical devices by using applying the by injecting the charge and so on so this is commonly important to main of integrated optics that can be termed as optoelectronic integrated circuits which is slightly beyond this cope of these present of course thank you very much.