Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – IV
Module – II
Propagation of Electromagnetic wave

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Hello and welcome in this module we will look at propagation of electromagnetic wave or light inside phase modulator and then we will also if possible we have time we will also look at propagation of wave in a amplitude modulator that is to say we consider the physical basis of phase modulator and amplitude modulator okay we have seen that an electromagnetic wave light is an electromagnetic wave and this electric field or a magnetic field of the electromagnetic.

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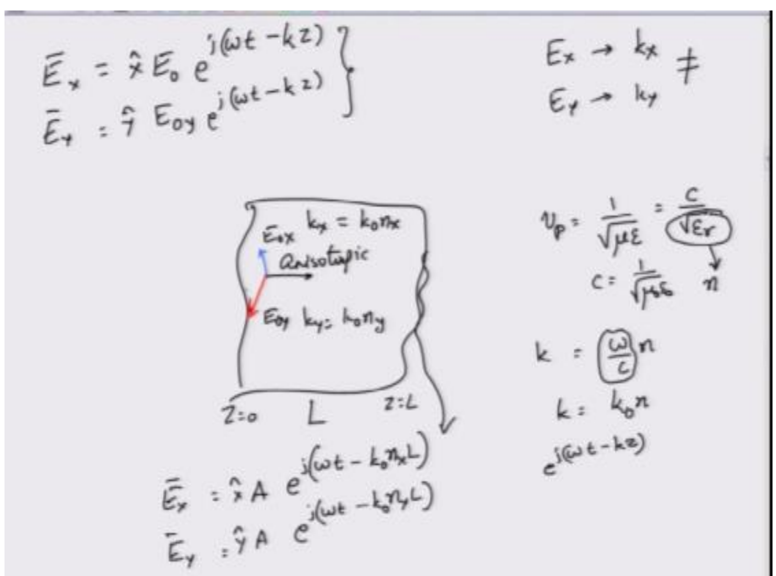

Wave which is propagating along a particular direction so let us say propagating along the next polarized wave which means it is electric field will be oriented along the x direction and it will have an amplitude of E0 and it will have a certain frequency ω prorogation constant k z okay so this particular electric field corresponds to a propagating wave where the wave is propagating along x direction.

I also know that if there was one more electric field so this is x electric field if I had one more electric field which is polarized along the y direction then that electric field can also have a different amplitude it assume that it will have the same frequency because we want to consider that scenario and then it will have certain k and z right so it will have a certain k vector or the propagation constant and it will be propagating along set this equations hold when the medium is linear homogeneous and isotropic.

Now let us assume that the medium is linear and homologous but let us now assume that the medium is an isotropic okay if we assume that the medium is an isotropic then what happens the corresponding Ex component will see a propagation constant which is k Ey we will see a propagation constant which is ky and this kx and ky are not general equal okay so this is the result of propagation through an isotropic medium so we will not look at an isotropic medium form now we will receive this treatment of an isotropic medium later.

But then what you can imagine is that if I take an isotropic medium I will not go into details but I am trying motivate the phases modulation to you if I take an isotropic medium of sum length L okay and then I have wave which as both E_x component as well as E_y component okay and it is propagating along the z axis.

So you have both E_x as well as E_y components right and then the wave is propagating along this sis the E_y component this is the E_x component the wave is propagating along the z direction okay so at z = 0 let us assume that both amplitudes $E_{ox} = E_{oy}$ okay so this is $E_{ox} = E_{oy}$ let us assume that at this stage both amplitudes are the same they have the same frequency they are propagating along the z axis.

So this is at $z = 0$ this is at $z = L$ now because this is an x polarized wave it will see a propagation constant k_x okay and I know that the relationship between k_x ω and v_p correct so k_x is given by ω / v_p phase velocity v_p is given by $1/\sqrt{\mu_\varepsilon}$ okay this can be written in rewritten as $c/\sqrt{\varepsilon_r}$ where c is the speed of light in vacuum given by $1/\sqrt{\mu_0\varepsilon_0}$ and ε_r is the relative primitively of the medium okay this $\sqrt{\varepsilon_r}$ in optical literature or in fact in literature is actually denoted by n standing for refractive index of the medium from this relationship I can go back and write.

So I have k = ω/c x n right and then go to kx and ky, so k = ω/c x n this ω/c is a number that is determined by the frequency and speed of light in vacuum or in free space, right. So that is denoted by k0 so k in generally is k0 x n where n is a refractive index of the medium, okay.

Now if the medium is an-isotropic then the refractive index n or equivalently the permittivity ε will be different for an x-polarized wave and it will be different for a y polarized wave so if you are considering the x component then this x component must see $\sqrt{\varepsilon_{rx}}$ whereas the y component or the y polarized wave will see $\sqrt{\varepsilon_{ry}}$ equivalently x polarized wave will see nx, y polarized wave will see ny, okay.

So the corresponding propagation constants kx will become for the x and y polarized wave they will become kx = $k_0$nx and ky = $k_0$ny is that okay, now at z = l these waves have now propagated, propagated a distance of l so what will happen to the electric field E_ox? Well E_ox or the x component electric field it will propagate like this E_ox $e^{j\omega t}$ – $k_o$nx and what is the distance it has propagated? L, why this l?

Because you have an equation which says $e^{j\omega t}$ – kz where z would be the distance of the propagation, tight so z is at any point along the space y here I am considering the plane which is z = l so this would be $e^{J\omega t}$ – k0nxl sorry this j is for the whole thing, similarly the y filed would also arrive we had said that the amplitudes of these two are equal so we can stick to that condition and call the common amplitude as A.

So A stands for the common amplitude of the x field or the x wave and for the y polarized wave you have the amplitude A and ωt is the same but then its propagation term will be different because K vector will be different l is the same but k vector is k0 x n by for the y polarized wave is that okay, so this has to be written sorry with x and y ^ because I have vector quantities on the right hand side.

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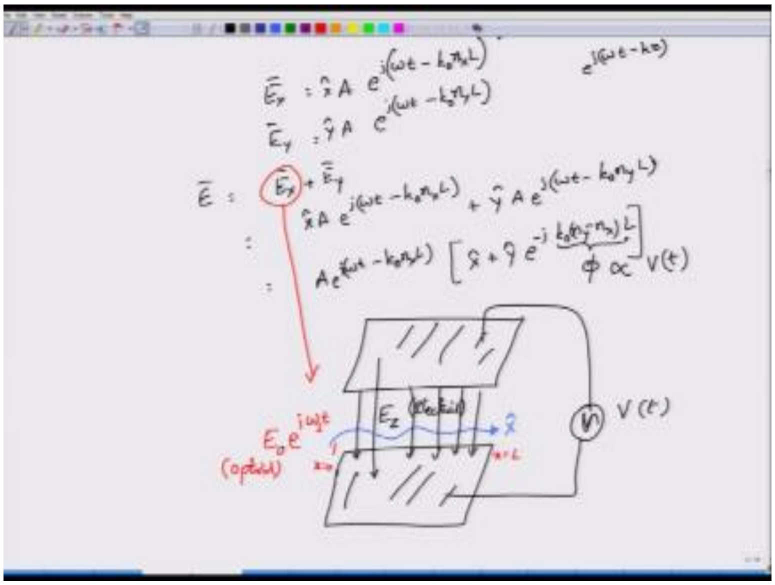

So these are the x wave x polarized wave and y polarized wave which are propagating here, initially this total wave was a combination of x and y polarized wave correct, initially it was linearly polarized because x component wave was equal y component amplitude was equal they were both in phase with respect to each other because they were coming from a homogenous linear isotropic medium.

Now once they have entered on an isotropic medium and their refractive indices are different right because one is x polarized wave the other one is y polarized wave their refractive index is are different their propagation constants are different and when they exist the an-isotropic medium you will see that there is essentially a phase difference between the two because the total electric field can be written as Ex + Ey which is x ^ A $e^{j\omega t}$ – $k_0$nxl + y^ A $e^{j\omega t}$ – $k_0$nyl you can take this A $e^{j\omega t}$ as a common factor.

And infact you can take this $Ae^{j\omega t}$ – $k_0$nxl as a common factor, okay and then what you are left here will be x^ + y^ e^j or other –j $k_0$ny – nxL this term $k_0$ny – nxL will give raise to a phase shift between the two components okay, so what you have seen is that, there is a phase shift between the two component and if for some way if I can make this phase shift be a function of the external applied voltage then I have obtained phase modulation, correct.

This would actually become amplitude modulation because this phase modulation gets converted into amplitude change as well if instead of having two components I take only one component okay I take only one component that is say Ex term or the Ex x-polarized wave which has an electric field component Ex. So if I take only this term pass it through a medium not an-isotropic medium this time I mean the medium could be an isotropic but you do not want just an-isotropic in this case you want to have a medium which will relate.

The phases shift to the applied voltage okay so let say I have a certain medium which is you know this particular medium I will call this direction as the z axis and call this as the electric field Ez these are conductors okay these conductors I will maintain a certain voltage here so I will maintain a certain voltage V of t which is a function of time in this particular case I know that for two conductors.

If I maintain a voltage difference V then I will generate an electric field inside right this electric field is directed along z axis and the wave is now propagating instead of z axis the wave is propagating along x axis it has a certain initial amplitude it has a certain amplitude initially that is outside this particular region so these electric field lines are directed form the top to the bottom they are uniform they are assuming that the plates are very wide area and their placed very close to each other so the electric field is uniform down there okay, so this is E_0 which is the amplitude at the outside of the region where the electric z exist.

Please note that this is a wave optical wave so this is optical wave where as this black one which I have written is the electrical signal or the field that is generated by the electrical signal or the voltage v of t okay so just before this region is there you can consider you can write down what is the electric field for the wave optical wave that would be $E_0e^{j\omega t}$ or we can write this as ejωst this can be directed along some axis but this is propagating along z axis okay so this optical wave is propagating along x axis okay so this plane is x = 0 this plane will be x= L so what will be the.

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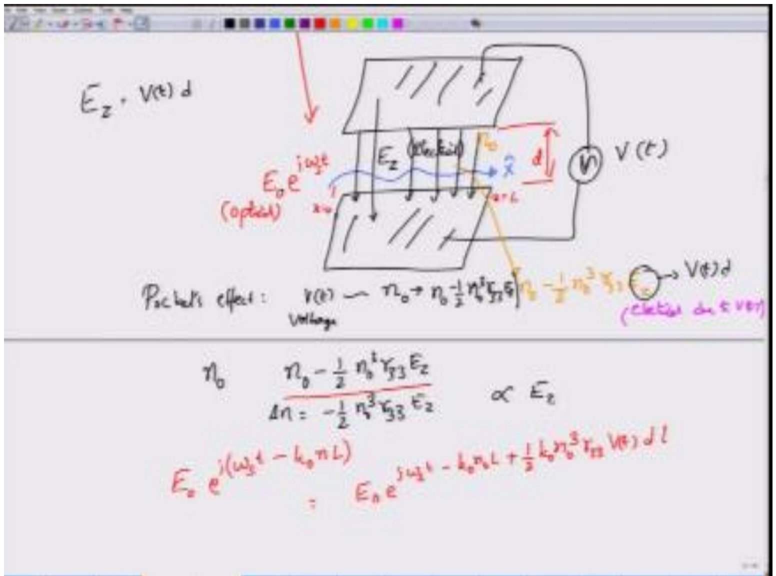

Electric field at the output region that is as the optical wave propagates through it is subjected to certain electric field okay and what happens is that this electric field will change the refractive index of the medium okay the refractive index of the medium before the application of the voltage v of t is N0 but after you have applied the voltage the refractive index inside this region that is between x = 0 to x = L becomes n0 – ½ $n0^3$r33z where Ez, Ez is the electric signal okay electrical due to v of t.

So there is this electric field which is generated because of the applied voltage v of t okay and that electric field E_z will affect this particular refractive index okay, sine E and V are related for a plane capacity type of a situation that we have considered E_z is given by v of t x d where v of d is the slowly varying function of time which we have assumed so you can substitute for Ez and write this as v of t x d what you have just absorbed is what is called as Pochal’s effect and what is Pochal effect implies that you can apply external voltages so this voltage or the potential difference and then change the optical properties.

That is you can change the refractive index from n0 to some n0 – ½ $n0^3$ r33 E_z okay E_z being the result of applying voltage v of t so Pochal's effect implies that you take voltage which is the voltage that you can apply and then change the optical refractive index okay this change in the refractive index which is $1/2n0^3$ r33 Ez will be linear in electric field correct initially the refractive index was n0 after you have applied it has become n0 – ½ $n0^3$ r33 E_z right so the change in the refractive index is given by $\Delta n = - 1/2\ n0^3$ r33 Ez this change is some constant times E_z.

So this is called as linear pochal's effect okay so this is the linear Pochal's effect so what is this effects implied to as is that the electric field of the optical wave after propagating through this medium when it comes out at x = L will become E0 it is amplitude has not changed $e^{j\omega st}$ – k0n x L correct n is the refractive index but I know that the refractive index n is given by n_0-1/2 whatever this expression, correct. So I can rewrite this as $E_0e^{j\omega st}$ $-k_0n_0L+1/2k_0n_0^3r_{33}v(t)dL$ where d is the separation between these two plates, okay. So this particular element on which we have deposited two metal electrodes and applying a voltage v(t) between them causing the change in the refractive index is coming from lithium niobate, okay so this material is lithium niobate in fact this is the crystal it would not look exactly like this it will actually be in the wave guide formulation.

So you have to actually make an optical wave guide such that you have a substrate, okay so you can imagine that this is a substrate that I have and on this substrate I put two metal plates, okay and then put a voltage between the two the light will enter from here this particular region so the light will enter in this region the electric field because of the voltage that we have applied is going through in this way and then as the wave propagates this x=0 and as the wave propagates, propagates and comes out at x=l its phase has changed, okay.

And the phase change would have been juts k_0n_0L if the electric field was not applied but because we have applied an electric field or we have applied a voltage difference the phase will be different.

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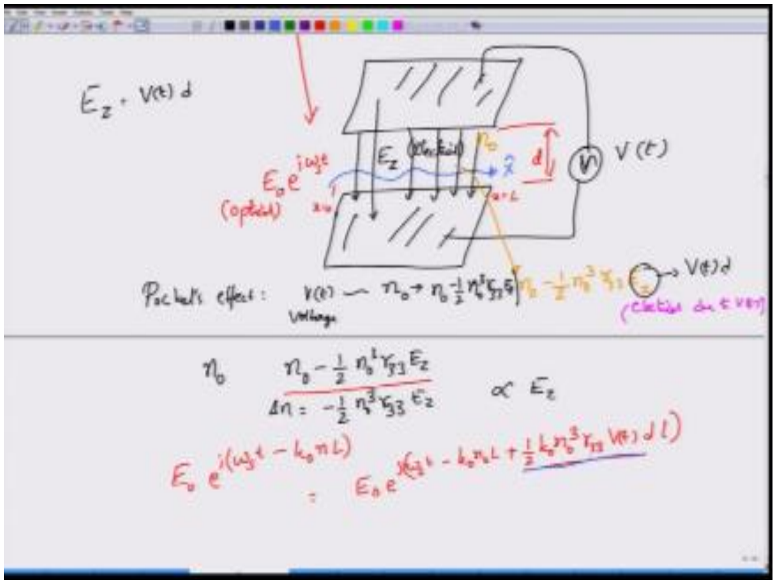

And in fact the phase is actually a function of time now, right the phase is now a function of time, this is very crucial. If v(t)=0 this corresponds to having applied no voltage and hence no electric field so this term would be vanishing, so there is just a constant phase shift there is nothing you can do just happily go home without constructing a phase modulator.

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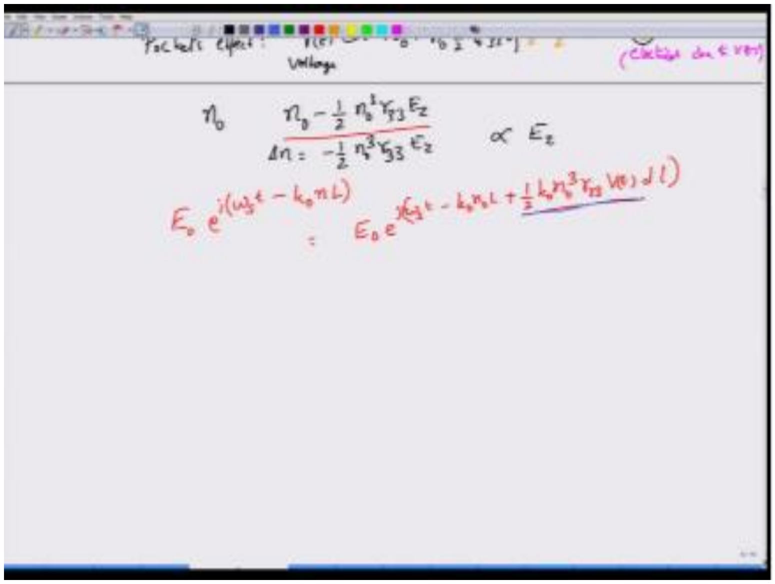

But now you have a situation where your phase is varying with time because you have applied a time varying voltage v(t) and managed to introduce a phase shift into the optical wave itself by applying a voltage v(t) you generate an electric field this electric field will influence the refractive index and that refractive index change when the electric, when the optical wave observes it will lead to a phase difference, okay or a phase shift which is now changing with time.

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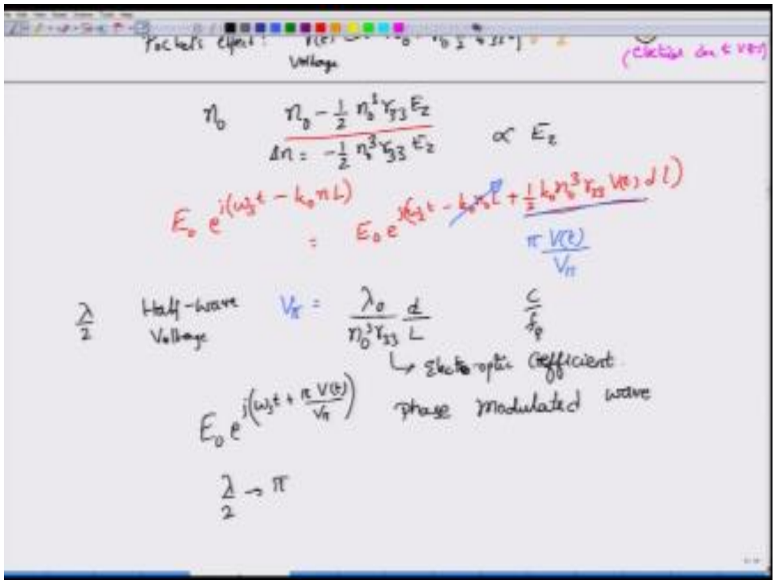

So I will remove this constant phase term not very important for us and I will simplify this remaining part, okay so I will write this one as v(t)/vπ, okay so I will write this as or rather I will write this as πv(t)/vπ and then I will leave this as a simple exercise for you to find out that this vπ is given as $\lambda/n_0^3 r_{33}$ L or rather d/L, L is the length of the phase modulator d is the distance between the electrodes that we have taken λ_0 actually λ_0 is the free space wave length, free space wave length is given by c/f_0 or f whatever the frequency that we have applied so our frequency was fs.

And r_{33} is called as the electro optic coefficient, this is called as electro optic coefficient, okay. So this vπ is called as the half wave voltage because your output which is now written as $e^{j\omega st}$+πv(t)/vπ right this is now a phase modulated wave, correct so this is a phase modulated wave, right and when v(t)=vπ the total phase shift will be equal to π, so that is why this vπ is called as half wave voltage vπ is called as half wave voltage, you might wonder why there is this half wave, half wave simply means λ/2 and we know that λ/2 corresponds to a phase shift of π, because λ corresponds to a phase shift of 2 by λ/2 corresponds to a phase shift of π.

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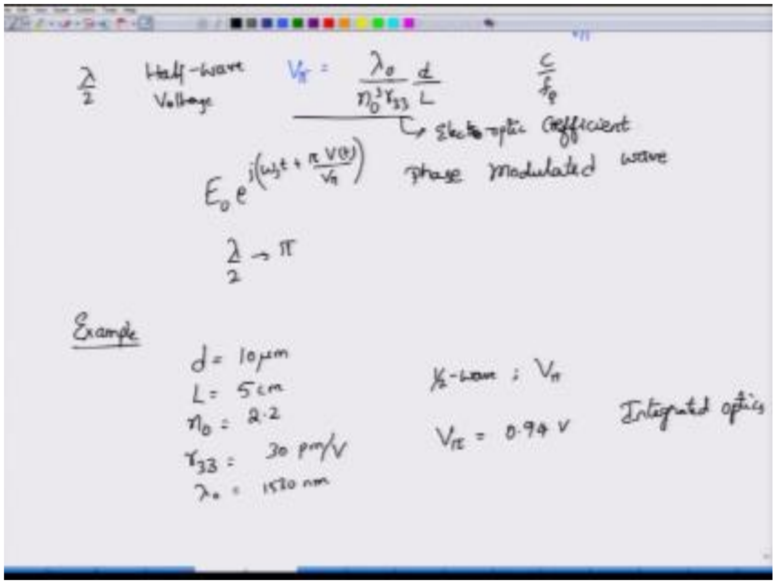

So this is called as half wave voltage let us do a simple example here, okay to calculate some numbers so let us assume that the thickness d is about 10 micron and let us say the length of the modulator is 5 cm, let us say in the absences of any input voltage n_0 is 2.2 the pocal coefficient r_{33} which is the electro optic coefficient or the pocal cell coefficient is given by 30pm/ v that is if you are apply one volt you will r_{33} of 30pm okay you can calculate what is the half wave voltage for this that is you can calculate what Vπ for this one, substituting the values so I have to give you what is λ, so let say λ is 1530 nana meters okay.

Substituting this in to the expression what you will find is that Vπ is given by around toughly about 0.94 volts okay. So calculate this by writing the formula $\lambda 0/ n0^3\ r_{33}$ d /l right okay so you can use this equation and then you can find out that Vπ is very small. In fact this is the magic of integrated optics you can by a lithium have weight crystal separately which will of this particular bulk region and you know this size crystal or smaller crystal and then put some electros from the top and the bottom apply of voltage externally.

Okay but because this D the thickness is very large right so the Vπ voltage will also be very large because it would be directly proportional to d so Vπ is very large for a crystal that you can purchase and then deposit certain electrets and then apply a voltage when in integrated form you're the separation between the two electrets is drastically reduce it is just about 10 to 50 micron and then the length is around 5 to 10 cm and then your Vπ is very manageable for you get in market phase modulator with a Vπ of about 3 to 4volt peak rf signal okay or 3 to 4 volt voltages.

So Vπ is just about 3 or 4 volts which is very small compare to about 100 volt Vπ that you will have you will normally get with a crystal operating alone, okay.

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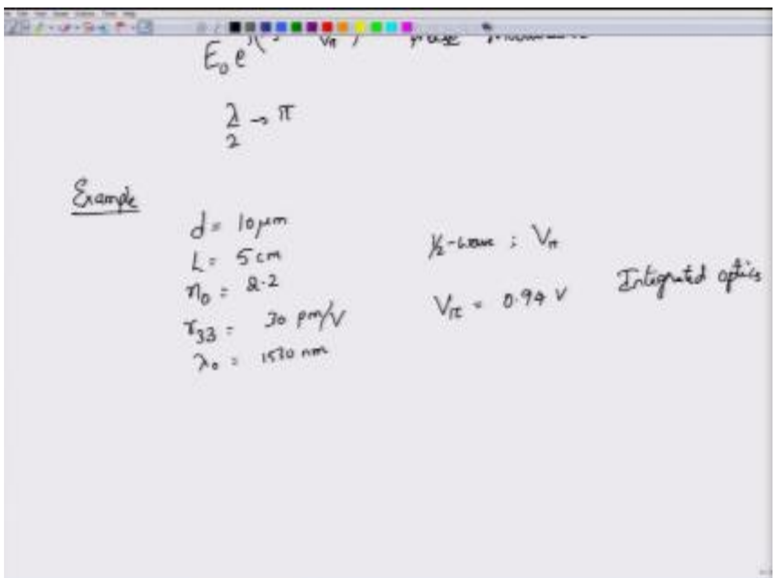

So what we have seen is that it is possible to talk about the phase modulator by having electro optic crystal okay.

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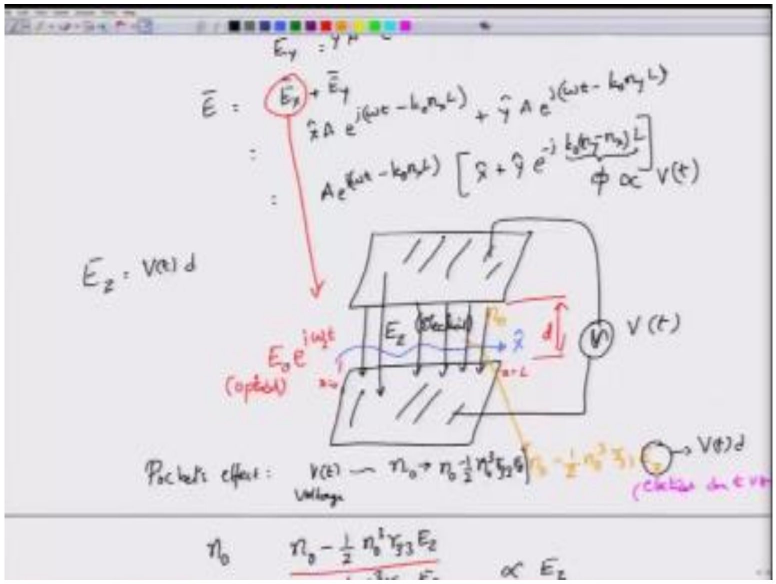

And then putting them in the integrated optical frame work one last point this crystal is usually as I said lithium Moabite crystal and the way which we have indicted here is that the lithium they have it crystal is cut along the y axis okay it is cut along the y axis the wav is propagating along the x axis and the electric field is indicated along the z axis this is called as a y cut lithium Moabite it is the most important configuration for lithium Moabite optical phase modulators.

In fact all optical modulator are may dote of lithium Moabites commercial optical modulators which are operating for optical communications are may dote of lithium Moabite modulators they are all usually y cut and you have x propagating wave but please remember what is y cut what is x cut and what is z cut is the crystal frame of reference not our frame of reference okay so one has to perform some crystallographic studies in order to locate the principle plans and then cut your crystal along that particular plan.

So this is the y principle plan that you will have to locate and then cut along that particular plan of the crystal.

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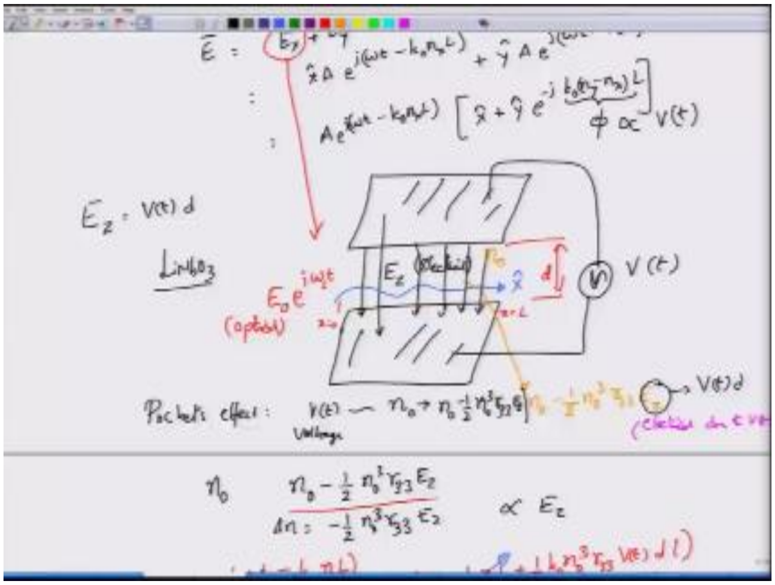

So what we have seen is that if you just take such a lithium Moabite crystal and apply a voltage we will be able to induce a phase shift and if the voltage is that you have applied is veering with time you have actually managed to obtained phase modulation right.

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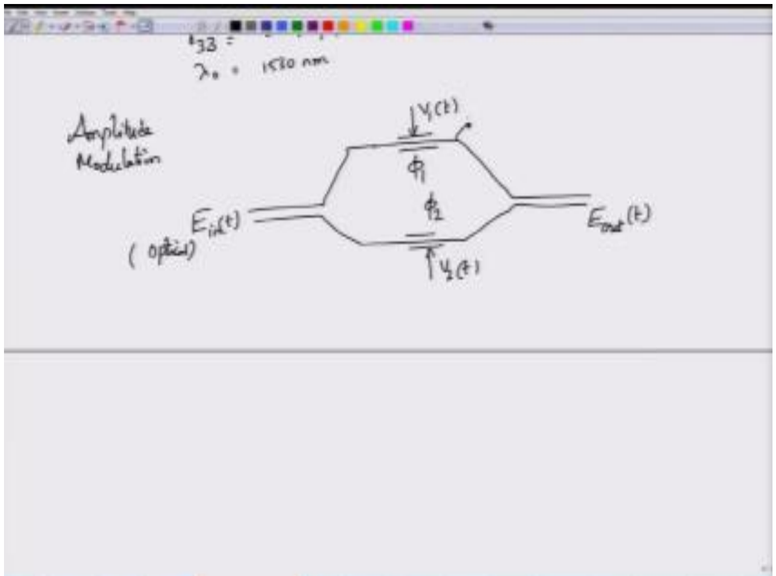

Now there is also amplitude modulation correct how do I obtain in amplitude modulation well we have already seen this amplitude modulations structure so you take a wave guide and then split this wave guide ion to two, portions right and then you put 2 electors here right each of this arms by themselves are phase modulator right so you can apply a voltage v1(t) you can apply a voltage v2(t) to this one.

And then combine them in to one wave guide I should have combine them in to wave guide type so each of the can be combine in to a wave guide now if you supply a wave optical wave it could electric field is en(t) you get an optical wave at the output whose electric field is e out of t you have applied v1(t) so you cause a certain phase shift 51 in the upper harm you apply v2 of t you cause a certain phase shift 52 in the lower arm.

And then you combine the light intensity over here right so when you do that I am not going to derive this but you should be able to derive it as an exercise because you know how this can modeled as a splitter assume a 50, 50 splitter you know how to obtain the eclectic field here because this is simply phase modulated wave this is one more phase modulator wave and then you know how to combine them, so when you do all that you will see that Eout (t) will have components which is $e^{jлV1\ (t)/Vл}$ $+e^{j\ лV2\ (t)/\ Vл}$, and there will also be $e^{j\omega st}$ term, there will be some additional amplitudes here, that I don't want to really worry about it.

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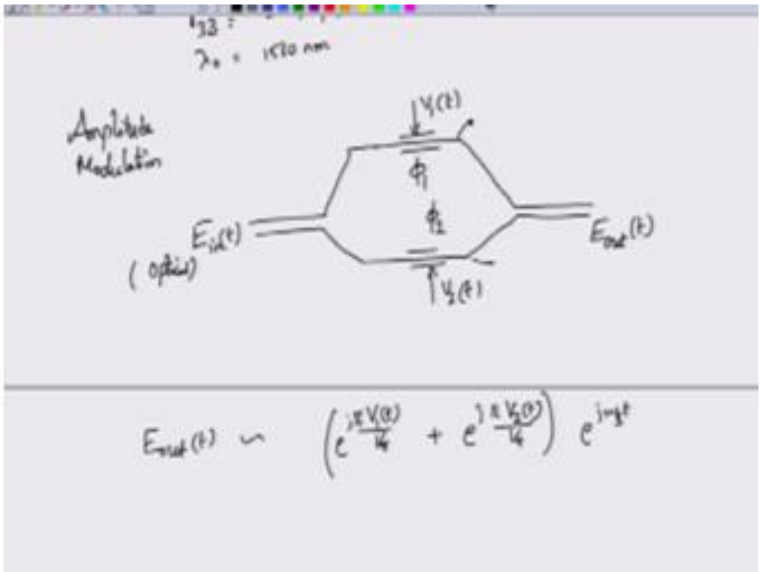

So there will be some additional factors constant that we can eliminate, now what we normally do is, we eliminate this $e^{jлV1\ (t)/Vл}$, that is we take this as common and end up here as $e^{j\ лV2\ (t)/\ Vл}$. Then we also take this V2-V1 outside, so that I have $e^{jлV1\ (t)/Vл}$, then there is also $e^{jл/2Vл}$, V2 (t)-V1(t), this is all common and inside what you get is cos л V2(t)-V1(t)/Vл. So you can see that by changing the operating point, by choosing V2-V1 difference, I can choose or I can make into different biasing points for the operation of the amplitude modular operation.

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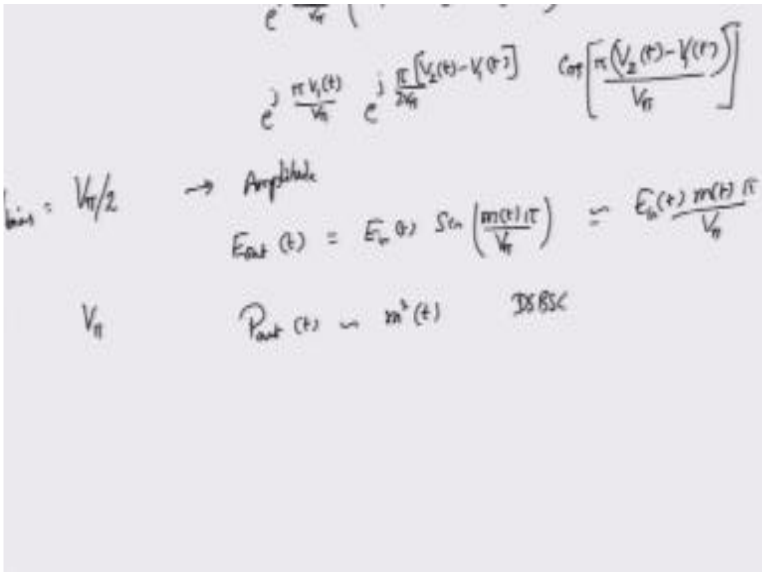

We have seen that when the bias is such that Vл/2 when the bias at Vл/2, you will end up having amplitude modulation, because you know we have seen this earlier, the output amplitude Eout will be equal to input amplitude Ein(t) times sin of whatever the message signal that you re transmitting times л/ Vл. And for small values of m (t), it is very nearly Ein(t) m(t) л/ Vл. So this amplitude is getting modulated into Ein(t), o this is basically a amplitude modulated wave, you can bias this one at different region.

So this is said you can bias at Vл and in that case is your output power will be very nearly equal to m square of t, this corresponds what is called a double side band separate carrier modulation. So these things I will give as n exercise, because it's simply coming up with together, but one thing I would like to talk about before we close the module is this expression. So if you look at this expression what you see is that, you can forget that this is the common factor, but then you will see that there is that this particular term.

This term which gives the overall phase shift, you have to combine both terms, you will get $e^{jлV1(t)+V2(t)/2Vл}$, this term which is the sum of two signals, л/2Vл can lead to what is called as chirping, because V is changing the incoming modulating signal which is E0 $e^{j\omega st}$, will pick up this additional phase and if V!(t) and V2(t) are changing with time, the overall phase will change with time. The overall phase in addition to amplitude, the will be a phase modulation.

So this change in the phase or phase modulation which is unwanted is called as chirping in the modulator, to avoid chirping you have to operate the modulator in it's push pull configuration that is, you have to operate dV1(t)/dt= -V2(t)/dt or V1(t)= -V2 (t)+ some bias voltage. So this is where the bias voltage and the different operating conditions coming, this is called s push pull configuration, so this is what I want to talk bout optical modulator structures. We have talked about phase and amplitude modulator structures. Thank you.

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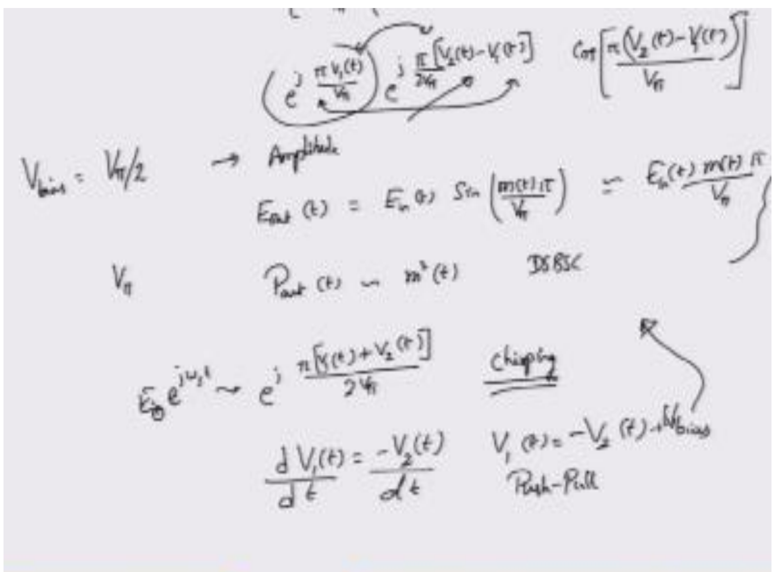

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