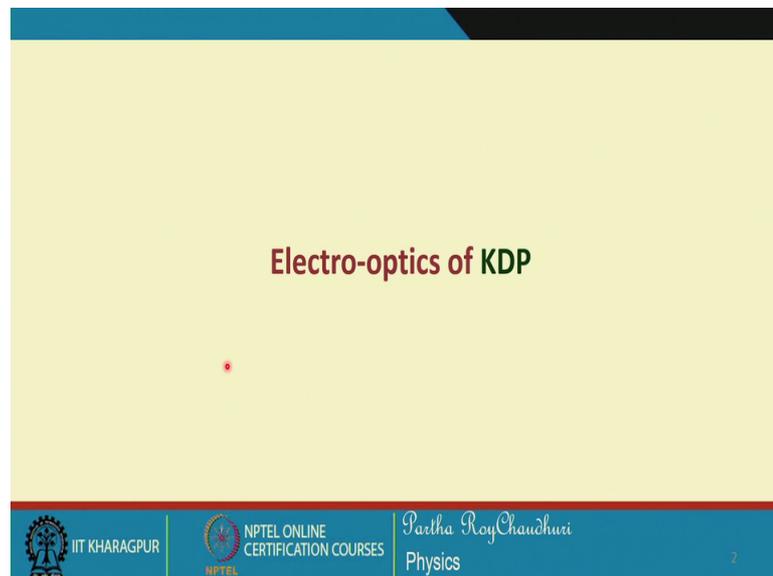


Modern Optics
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Lecture – 37
Electro-optic Modulators and Devices (Contd.)

We were discussing the electro optics of KDP crystal, anisotropic crystal and we have seen that how this crystal can be configured for longitudinal mode of operation. You have seen that how this half voltage thing can be designed for switching of the modulator.

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Contents

- ✓ **Transverse** configuration of **KDP**, induced birefringence, phase retardation, half-voltage
- ✓ **Modulator design**, geometrical aspects, Gaussian beam diffraction, optimum performance, reduced half-voltage

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So, now will continue this discussion with the transverse configuration, and in this transverse configuration will see how this induced birefringence and the consequent phase retardation, can be used to switch the modulator. And, what will be the requirement of this half voltage in this case, we will see that this improvement is substantial is quite considerable, which will be many times more than the ones which we have seen in the case of isotropic crystals and anisotropic in the other modes.

So, this mode then we will look at a very different aspect of this geometrical side of this modulator a design consideration. How this modulator has to be design to get a very good performance, whether from kilo volt is started of our switching voltage that is half voltage, we can bring it down to some 10's of volt.

Then we will look at this Gaussian beam and its diffraction through the crystal, then for optimum performance of the crystal what will be the geometrical design, geometrical aspect that we will see with a bit of algebra. And, then we will recalculate the half voltage the reduced half voltage, have to see that the performance has really improved by incorporating this geometrical aspect of the crystal to operate as a modulator ok.

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Transverse configuration of KDP
Retardation, Modulation

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The slide features a yellow background with a blue header and footer. The title 'Transverse configuration of KDP' is in red and blue, and the subtitle 'Retardation, Modulation' is in black. The footer contains logos for IIT Khharagpur and NPTEL, along with the presenter's name and subject.

So, the transverse configuration of this KDP crystal you will look at the retardation and modulation aspect of this under this configuration.

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Longitudinal configuration

In longitudinal configuration

- ✓ Retardation is **independent** of crystal's length
- ✓ But it **depends** only on the applied voltage

Further in this configuration

- ✓ Voltage is to be applied **along**
- ✓ **length** of crystal/**direction** of light propagation
- ✓ this is achieved by **transparent electrodes**
- ✓ leaving a **hole at the centre** of electrodes

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The slide features a yellow background with a blue header and footer. The title 'Longitudinal configuration' is in red. The content is organized into sections with sub-headers and a list of bullet points. The footer contains logos for IIT Khharagpur and NPTEL, along with the presenter's name and subject.

So, in the what we have seen in the longitudinal configuration, the retardation is independent of the crystals length that we have seen. Because, you have v by l which is to represent $e z$, and you have the length of the crystal l . So, this l and l cancels, as a result this the retardation that is the phase retardation phase delay it does not involve the length of the crystal. It is only the voltage that is proportional that this retardation is

proportional to the applied voltage that is it depends only on the applied externally applied voltage. Then also in this longitudinal configuration we saw that voltage is to be applied along the length of the crystal, that is the voltage has to be applied along the direction of the light propagation so, that the voltage that is the electric field and the propagation directions are the same.

This is a little trouble some in the sense that, when you apply electric field you have to use appear of electrodes on the front phase and at the back phase that is the input side and output side of the crystal. These electrodes come to be transparent because otherwise this and it has to be transparent in the frequency in the wavelength range of the light, that will be modulated that will be propagating to the crystal. So, this is a little inconvenient, but this is achieved by putting a transparent electrodes usually titanium oxide any transparent oxide, which is transparent at this wavelength or by making an annular hole at the input side.

So, that you can apply the electric field from the ring shaped electrodes, but the electric that is the light can propagate through the narrow hole, which are fixed on the which are kept on the electrodes on the either side that is at the input side and at the output side. So, put together this is a small inconvenience it from the design point of view in the longitudinal mode of operation whereas, in the transverse mode of operation this does not appear.

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Advantage: transverse mode

In transverse configuration

- ✓ Voltage is applied in transverse direction
- ✓ Electrodes do not obstruct the light beam

Retardation

- ✓ is proportional to applied voltage
- ✓ and also to the length of the crystal

Half-voltage

- ✓ is proportional to ratio of width to length
- ✓ Ratio can be adjusted to tune half-voltage

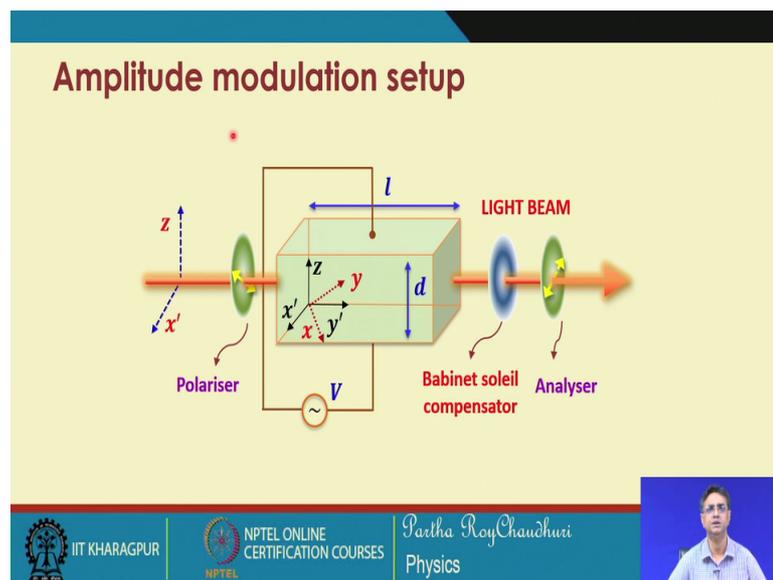
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Because you apply the electric field from the transverse side, that is from sideways. So, in transverse configuration voltage is applied in the transverse direction, electrodes do not obstruct the light beam. This is the advantage, this is something positive about this mode of operation in addition to mathematical figure of merit in addition to the performance of this from the design from the fabrication point of view this is the advantage.

And then the retardation in this case is proportional to the applied voltage and is also to the length of the crystal. This we have seen in our repeated discussions in several occasions that when you operate in the transverse mode, then the phase delay is proportional to the applied voltage as well as the length of the crystal, when you apply when you put in the configuration transverse mode of operation. And this half voltage is also proportional to the ratio of the width to length; we have seen in the last discussion also it depends on the ratio of the length and width.

So, this is one very useful aspect to design the modulator by very suitably by precisely designing this in terms of the width and length, you can reduce the half voltage as well as you can optimize the performance you can maximize the modulator performance. So, this ratio can be adjusted to tune the half voltage, you will see that particular aspect as well ok.

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So, this is the transverse configuration we have been repeatedly discussing on this your, this is your z polarization. In this case look at this now your orientation is like this is

your z direction, and I apply the field along the Z direction. So, that in the ellipsoid only e z terms will be there in the index ellipsoid of the electro optic crystal.

So, e z is now being applied and that results in e x dash and e y dash. So, these are the two new principal refractive indices. This is the old y axis this is the old x axis in absence of in its external field, but the moment you apply the voltage it is only this direction and these direction you get the refractive indices, which are these are the new eigen axis in which the refractive indices are proportional to the applied voltage and you put this. So, you have an input polarization which is halfway through z and x dash z and z dash are the same in any case because we have seen that when you apply this electric field along z direction, then it undergoes a rotation about the z axis, but z axis does not get disturb.

So, z and z primes are same therefore, therefore, you apply the polarization which is halfway through z z prime and x prime. So, that light is now launched into the crystal, you will see that this compensator which is a Babinet Soleil compensator which a provides the necessary optical biasing to shift the operating point at the desired position. So, that you get a linearity in the modulated light and you have an analyzer which is at crossed position with the input. So, this is all by now it is known and you apply the modulating voltage across the crystal in the z direction. So, that you get the electric field active across this z direction.

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Transverse configuration

- ✓ Incident light is polarised at 45° to x' in $x'z$ plane
- ✓ In the crystal light propagates along the y' direction
- ✓ The polariser and analyser are at crossed position
- ✓ A Babinet-Soleil compensator placed before analyser to provide optical bias to push the modulator operate in the linear region of transmittance versus applied voltage

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So this is the configuration incident light is polarized along 45 degree to x prime in the x z plane I just now I have explain that 45 degree to x z plane; so, halfway through your x dash and z dash. So, that is the incident polarization in the crystal light propagates along the y direction only it propagates only along the y direction you see this. So, this is your actually it is the y dashed y dash direction, because after this is your this is your x this is your y, this is your x dash this is your y dash. So, in the y dash direction the crystal within the crystal the light propagates along the new principal axis eigen axis that is the y dash axis. So, light propagates along this is important.

Now, the polariser and analyser are at crossed positions, a compensator is placed before the analyser, to provide optical bias to push the modulator operate in the linear region of transmittance. So, voltage versus transmission is in the linear region, which is actually with this we have seen in the earlier discussion how it can be pushed right.

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Induced birefringence

Without field....
 two components along x' (x) and z see RI's: $n_{x'} = n_o$ and $n_z = n_e$
 Polarisation parallel to xy plane sees RI = n_o

With the field....
 two components along x' and z see RI's: $n_{x'} = n_o - \frac{n_o^3}{2} r_{63} E_z$ and $n_{z'} = n_e$

$$n_{x'} = n_o - \frac{n_o^3}{2} r_{63} E_z \quad \text{and} \quad n_{z'} = n_e$$

$$\Delta n = (n_o - n_e) - \frac{n_o^3}{2} r_{63} \frac{V}{d}$$

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Now, now you have without electric field and x dash equal to n_o n_z equal to this. So, because now these are the two polarizations which are now coming into play, it is not y because y is now the direction of propagation of light perpendicular to that y direction y prime direction y dash direction is the $n_{x'}$ polarization and $n_{z'}$ dashed the refractive indices of the polarization.

So, polarization parallel to x y plane sees refractive index n_o that is why it is n_o and it is n_e now with the field you have seen that it is because of this external field E_z , your $n_{x'}$

dash is modified with this incorporation of this quantity which has come from the a diagonalization or the axes rotation of the crystal. So, you get n_x dash which is the new principal axes refractive index is equal to this, but n_z dash it remains n_z n_e extraordinary light refractive index. So, it does not undergo any change therefore, the birefringence in this case is n_o minus n_e , which is the which is the birefringence in absence of even if we do not apply any voltage the two lights you will see the birefringence which is equal to this.

Because one is now this time along z axis, you are a refractive index in by the polarization will be n_e and along your x axis the refractive index x dash axis refractive index n_o will be n_o . So, this is in absence of any field this is a fixed birefringence, which gives you that the different kind of in a quarter wave plate half wave plate by adjusting the length of this birefringence in interaction, and this is the part which is because of the voltage. So, this is voltage dependent birefringence and this is a fixed one and this requires the compensation ok.

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Induced birefringence

After travelling a length l in the crystal

- ✓ the emergent field component along x' direction:

$$E_{x'}(y' = l) = \frac{A}{\sqrt{2}} e^{i(\omega t - k_0 n_o l + \frac{1}{2} k_0 n_o^3 r_{63} E_z l)}$$
- ✓ the emergent field component along z direction:

$$E_z(y' = l) = \frac{A}{\sqrt{2}} e^{i(\omega t - k_0 n_e l)}$$

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So, after travelling a length l in the crystal the emerging field component along the x direction will be equal to y dash equal to l at this point, A by root 2 because you have taken halfway through. So, this is coming because of the 45 degree inclination of the polarization with the z and x axis, and this we have seen that this is the fixed phase of

this light and ωt is the time dependent phase, whereas this is the phase which is proportional to the external field.

So, this part of the phase: which has come into play because of the application of the external voltage. The emergent field component along the z axis z direction then will be equal to this because in this case there is no voltage dependent of phase which is coming to play may recall that this z dash does not involve any voltage dependent phase. So, it is only because of the x dependent phase that the change in the phase that is the birefringence sees change in the birefringence sees only accounted for the presence of this quantity is term which involves the external voltage.

So, it is an external voltage dependent birefringence, that involves that his only due the x dash polarized light not because of the z polarized light n does not undergo any change. So, that is pretty useful that now E x dashed has this phase E z at the output of the crystal has this phase, this is the fixed phase which is which is carried by the z polarized light along the length of the length. So, when at the output of the crystal it has this phase. So, these are the two phases of the two polar orthogonal polarized light. So, now, we will have to take the superposition of this along the pass axis of the analyzer

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Phase retardation

After travelling a length l in the crystal

- ✓ the phase retardation between 2 linearly polarized light:

$$\gamma = k_0 \left\{ (n_0 - n_e)l - \frac{1}{2} n_0^3 r_{63} E_z l \right\}$$

$$= k_0 \left\{ (n_0 - n_e)l - \frac{1}{2} n_0^3 r_{63} \frac{V}{d} l \right\}$$

- ✓ hence the phase shift induced by the applied voltage is:

$$\gamma = k_0 \frac{1}{2} n_0^3 r_{63} \frac{l}{d} V$$

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So, the phase retardation between the two linearly polarized light will be gamma is equal to this just difference of these two phases, these two phases if I take the different ωt ωt cancels this will give you $k_0 n_0$ minus n_e difference of n_0 and n_e into l and

this will be staying back as it is. And this is the only voltage dependent phase field dependent phase birefringent.

So, I get this phase which is equal to this as I mentioned this is a fixed phase which is staying back just because of the refractive indices or ordinary and extraordinary light, without any electric field and this is the phase. So, hence the phase shift induced by the applied voltage is this. This is the phase shift only this quantity this is not changing is the base phase this is a fixed phase d c phase this is the phase which is oscillating if you changing with the voltage.

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Half-voltage

The phase shift introduced in absence of applied field:

$$\Delta\phi = k_0(n_o - n_e)l$$

In this case modulator half-wave voltage is defined by:

$$k_0(n_o - n_e)l + \pi = k_0 \left\{ (n_o - n_e)l - \frac{1}{2} n_o^3 r_{63} \frac{V}{d} l \right\}$$

$$\pi = \frac{2\pi}{\lambda} \frac{1}{2} n_o^3 r_{63} \frac{l}{d} V_\pi$$

So half-wave voltage is $V_\pi = \frac{\lambda}{n_o^3 r_{63}} \left(\frac{d}{l} \right)$

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Therefore the phase shift introduced in absence of the applied voltage is this quantity, which is the fixed phase I have already discussed about this; this does not play any role in the modulation it is only the constant phase that is staying. Now in the case of modulator half voltage in this case, will be defined as the sum of this 2 pi and this because anyway this is not playing. So, switching should be done only because of this voltage. So, you can write that pi equal to this. So, half voltage in this case will be equal to an anyway this V by d has come for this electric field E z.

So, V by d because this is a transverse mode of operation, and V by d this represents the electric field. So, electric field into l the length of interaction of the two travel of the two polarized light. So, that gives you the phase of the light that is. So, therefore, you get V pi the half voltage in this case which is equal to lambda by n o r 63 and is proportional to

the width of the crystal and also the length of the inversely proportional to the length of the crystal. We have seen we have given some special observation on this that how this d/l can drastically change the half voltage that the performance of the modulator very good by suitably designing this will you will see that mode.

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Half-voltage

In the transverse configuration

The half-voltage is

- ✓ Not independent of modulator length l
- ✓ But depends on width-length ratio d/l
- ✓ Choosing a small geometrical factor d/l

Half-voltage can be **reduced** reasonably

- ✓ Operation at linear region by **external bias** (voltage bias or **optical**) is the same as of **longitudinal configuration**

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So, in the transverse configuration the half voltage is not independent of the modulator l , but it depends on the width to length ratio d/l . So, if we choose this factor this we have seen the d/l this factor if you choose appropriately then the half voltage can be reduced drastically. So, operation at linear region for that purpose you require again the modulator to operate to bias at the 50 percent operating point that is the same as one has to do in the case of longitudinal configuration. The same way that you have to insert a half wave plate a quarter wave plate to create a phase difference of $\pi/2$ between the two polarized light. So, that the phase difference the base phase can be cancelled.

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Commercial EO modulator

Transverse electro-optic modulators

- ✓ Are commercially available (highly deuterated KDP)
- ✓ Operate with only low driving voltage ($V_{\pi} = 275$ V)
- ✓ Cylindrical: 2.5 mm diameter
- ✓ Useful bandwidth 0-100 MHz



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Commercial electro optic modulator this is taken from this site, they this is an amplitude modulator electro optic crystal is in KDP these are commercially available, but usually they are highly deuterated and operated with only low driving voltage that is about 275 volt. You can see that the very drastic improvement we started with some kilovolt of switching voltage, but this time it has only 100s 200s of voltage the design is cylindrical of diameter this and the useful bandwidth is this. So, this is the one which are available in the open in the market commercially available, and used in the in the signal processing in the laboratory and in communications light wave communication modulation system.

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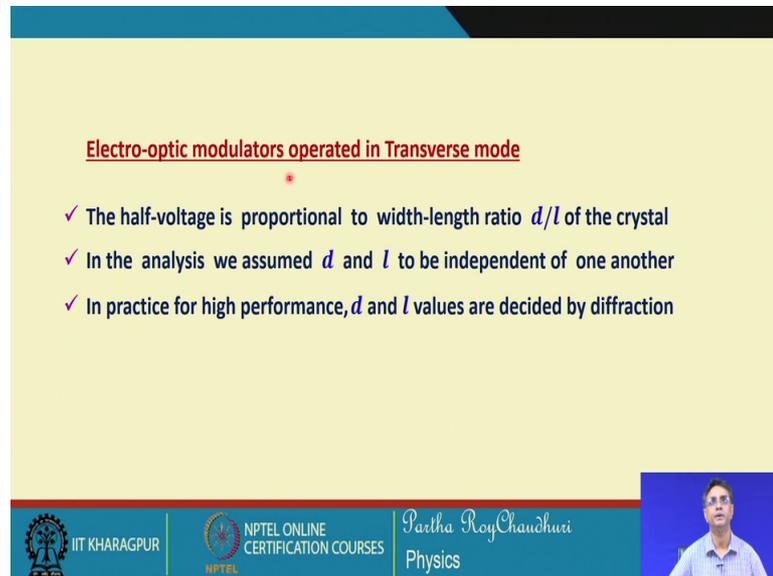
Modulator design

Geometrical consideration

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Now, we will look at this important aspect of this design of the modulator in terms of the geometrical parameters dimensions.

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Electro-optic modulators operated in Transverse mode

- ✓ The half-voltage is proportional to width-length ratio d/l of the crystal
- ✓ In the analysis we assumed d and l to be independent of one another
- ✓ In practice for high performance, d and l values are decided by diffraction

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You see that electro optic modulators can be operated in the transverse mode when the half voltage is proportional to d/l ; the key point of this discussion for this designing, which will give a very high most very big for improvement in the performance of the modulator; d by l this ratio can be suitably adjusted of course, it has to be reduced, can be suitably adjusted to bring down the half voltage. In the analysis we assume the d and l to be independent of one another.

So, all throughout our discussion we have not talked about d and l we took we assume some value of d or we just kept it as it is. But if there is a relation between d and l when you look at the design of the modulator, that is that will be limited by the diffraction the this will come from the relationship will come for optimum performance of course, come from the diffraction of the light beam within the crystal. So, that part we are now going to discuss, and this is very useful in terms of this modulator design and can be applied for such crystal modulator designing.

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Minimum value of d is determined by the diffraction of the beam and will correspond to the case at which the beam just passes through the crystal

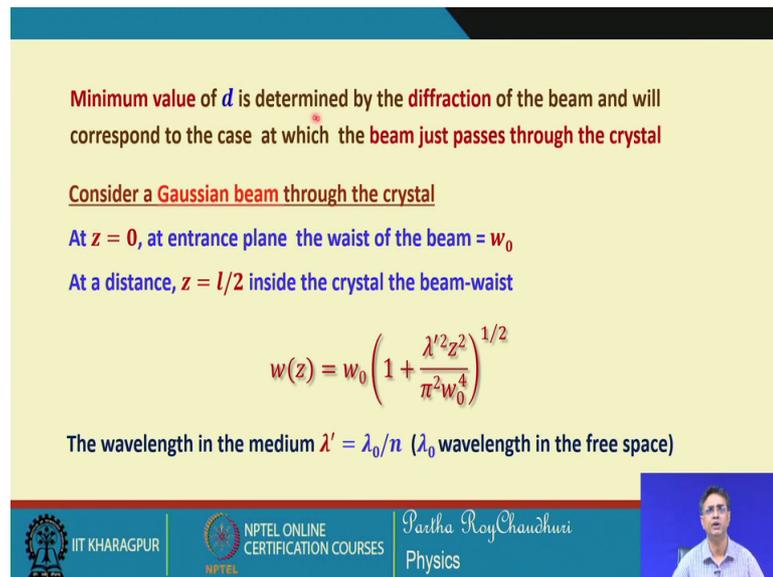
Consider a Gaussian beam through the crystal

At $z = 0$, at entrance plane the waist of the beam = w_0

At a distance, $z = l/2$ inside the crystal the beam-waist

$$w(z) = w_0 \left(1 + \frac{\lambda'^2 z^2}{\pi^2 w_0^4} \right)^{1/2}$$

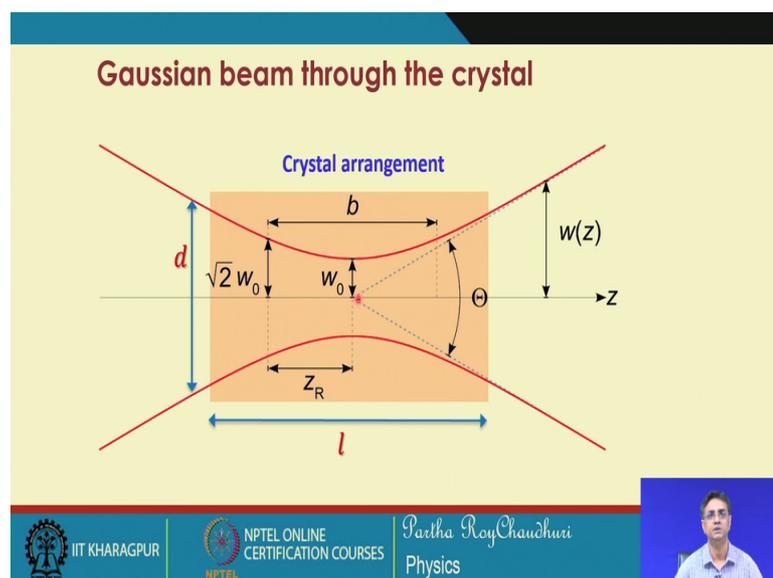
The wavelength in the medium $\lambda' = \lambda_0/n$ (λ_0 wavelength in the free space)



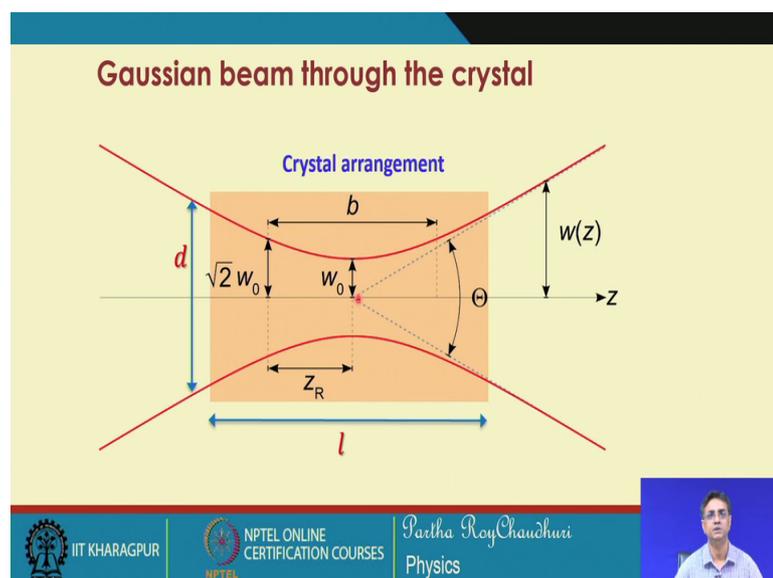
So, the minimum value of d is determined from the diffraction of the beam within the crystal, you will see that configuration. So, let us considered a Gaussian beam through the crystal usually laser lights are sort of Gaussian beam. So, at z equal to 0 it is not at z equal to 0 is actually it is at the at the centre of the of the beam, where the beam size is the minimum that is what we call the beam waist that is the spot size which is equal w_0 and at a distance z_0 within the crystal. So, they are related how the, this is the diffraction of the Gaussian beam. So, the spot size at a distance let me see that the figure.

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Gaussian beam through the crystal



The diagram illustrates a Gaussian beam passing through a crystal of length l and thickness d . The beam waist w_0 is located at the center of the crystal, at a distance z_R from the entrance plane. The beam radius at the entrance and exit is $w(z)$. The angle of divergence is θ . The crystal arrangement is shown with the beam waist w_0 at the center, and the beam radius at the entrance and exit is $w(z)$. The distance from the waist to the entrance plane is z_R . The total length of the crystal is l . The thickness of the crystal is d . The beam radius at the entrance plane is $\sqrt{2} w_0$.



This you have this beam waist here which is W_0 , and as you move away from this the beam diverges. So, at any point which is z distance away from this waist of the beam then this is your W_z . So, this W of z the spot size at a distance z from the waist and the spot size at this point w they are related by this equation this is simply from the diffraction of a Gaussian beam. So, this expression can be very quickly derived from z x. So, and this is the this is the notation that that we have used λ dash is for λ_0 by n your λ dash is the free space because the wave is travelling within the crystal.

So, the wavelength will be different and so, now, because you do not want that the light should be out from the crystal, but you can maximize the light within the crystal. So, that is the design. So, the most part of the light which is traveling through the crystal within the crystal and you can also and also that the because you have to apply a voltage in the transverse direction you will not allow unnecessarily the width to be more. So, that you lose a part of the width which is not being occupied by the beam; that means, the beam size and the widths should be just hand them out just it should be hitting each other and there is no extra width because putting an extra width you will just require more voltage, to get the same amount of width. So, that is the philosophy of this designing.

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So, $w(z = l/2) = w_0 \left(1 + \frac{\lambda^2 l^2}{4\pi^2 w_0^4} \right)^{1/2}$

Then, $d = 2w = 2w_0 \left(1 + \frac{\lambda^2 l^2}{4\pi^2 w_0^4} \right)^{1/2}$

For a minimum d , $\frac{d(d)}{dw_0} = 0$

$$0 = 2 \left(1 + \frac{\lambda^2 l^2}{4\pi^2 w_0^4} \right)^{1/2} + 2 \frac{1}{2} w_0 \left(1 + \frac{\lambda^2 l^2}{4\pi^2 w_0^4} \right)^{-1/2} \frac{\lambda^2 l^2}{4\pi^2} \left(\frac{-4}{w_0^5} \right)$$

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So, by doing that what we can see that when z equal to l by 2 that is half the distance of this is your l . So, half the distance at l equal to and this is z equal to 0 where the beam is the minimum size waist at z equal to 0 the width and the beam size there should be equal.

So, d is equal to l by 2 this is you just plug in this expression z equal to l by 2 . So, you will get this value very straight forward and very simple. So, then d because now twice the w look at this I have called w at l by 2 twice of this will be the. So, that is the requirement; so, d equal to twice of w equal to $2 w_0$ and this quantity. Now I have to minimize this value of d for this d w , because this is the thing which is given this spot size at the beam waist, but this is a function of the distance of the travel that is because of the divergence. So, this is with respect to this spot size how much divergence I can allow so, that it will just encroach this width of the modulator d . So, that is the philosophy if I do that if I do that then d d d w is equal to 0 this is the minimization of d .

So, putting this left hand side that is this equal to 0 , I just differentiate this quantity which will lead to this is again a very basic differentiation which will lead to this expression and if I use this expression we can find out because from here from here will get the value of w_0 in terms of λ dash l . So, that this λ dash l these values are going to decide what will be the w_0 so, that you get this minimum value of d . So, to get the minimum value of d , what will be the value of w_0 that I find out from this algebra which is equal to here w_0 under root of λ prime l by twice π .

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This gives, $w_0 = \sqrt{\frac{\lambda' l}{2\pi}}$ and $d = 2 \sqrt{\frac{\lambda' l}{\pi}}$ (critical exact value)

In practical modulator, a safety factor ' s ' is introduced

$d = 2 \cdot s \cdot \sqrt{\frac{\lambda' l}{\pi}}$ where $3 < s < 6$

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So, this is the quantity this should be the beam waist. So, beam waist and the length of the crystal of course, the wavelength is there, beam waist and the length of the crystal they are related in this way. And if I know that then I also know because this value I can

plug in to this expression now that I know the value of w_0 I know the value of w_0 . So, this value of w_0 which will come from here will be plugged into this expression which will intern give me the value of d . So, this d value is the optimum value the exact critical value we can give some more you know tolerance to this because if you just put it then there is a chance of, it requires a very very high precision alignment and should be extremely stable that is also the second requirement, but if you give a small tolerance to this. So, this is the exact critical analytical value of d that is required when the l is given. So, d and l they are now geometrically related through the Gaussian beam refraction optic.

Now, in practice there will be a tolerance just now what I said that if it is exactly this value in terms of this, then it will be a very alignment critical operation and also it has to be extremely stable because otherwise any small fluctuations in the positioning will miss out the beam outside the crystal. So, there is a small tolerance, this factor is tolerance factor is between 3 to 6 for practical design, this is all experimental values which are found out and so, in that case there is a factor s which gets into this $2s$. And so, this is the this is a design for this. Now, will see after having this design that is when this d and l values are related through this parameter, then what is the half voltage.

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KDP geometry: transverse

TYPICAL VALUES

- Length of the crystal = 2 cm
- Operated with a red-laser source (0.6328 μm)
- Refractive index of KDP (n_0) = 1.512
- Safety factor, $s = 3$ (typically in the range of 3-6)
- A minimum value of d is

$$d = 2 \cdot s \cdot \sqrt{\frac{\lambda_0 l}{n_0 \pi}} = 2 \cdot 3 \cdot \sqrt{\frac{0.6328 \times 10^{-6} \times 2 \times 10^{-2}}{3.14 \times 1.512}}$$

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You can see very interesting that let us assume a typical crystal length of 2 centimeter which will decide the value of d through this calculation through this calculation this will

decide the value s we have taken three, because it can be well within 3 to 6. So, if you take the minimum value of 3 then this is the value of d . Now, a laser operated at this length helium neon gas laser at this operating wavelength I assume that wavelength λ_0 , refractive index of this KDP ordinary refractive index 1.512 you should assume these are the values that if we are use in this expression I can calculate the value of d which will be some fraction of millimeter.

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A minimum value of d is

$$d = 2.3 \sqrt{\frac{0.6328 \times 10^{-6} \times 2 \times 10^{-2}}{3 \cdot 14 \times 1.512}} = 0.038 \text{ mm}$$

The corresponding half-voltage is

$$V_{\pi} = \left(\frac{\lambda}{2r_{63}n_0^3} \right) \left(\frac{d}{l} \right) = \left(\frac{0.6328 \times 10^{-6}}{2 \times 10.5 \times 10^{-12} \times (1.512)^3} \right) \left(\frac{0.038}{2 \times 10^{-2}} \right)$$

$$\approx 314 \text{ V}$$

(compare with 8.3 kV in longitudinal arrangement $\sim 1/25^{\text{th}}$ times)

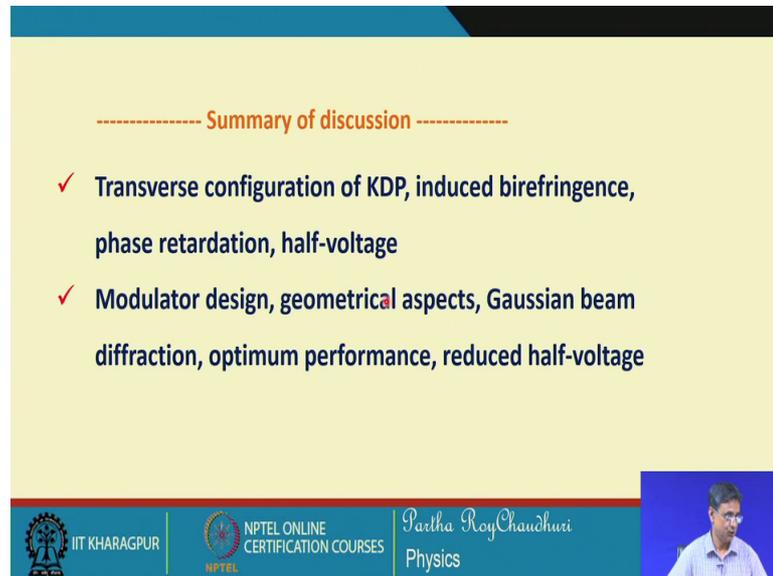
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So, d on this calculation it gives you 0.038 millimeter, which is a very thin width of the crystal; so, now if I use this d value in the V_{π} that is your half voltage, that λ is 2 centimeter you have already assume that l equal to 2 centimeter which has given me a d value which is 0.038 millimeter. Of course, you have already included the tolerance factor 3 otherwise you could have been 3 times less, even if you round it up to point 0.04 millimeter 1 100th of a millimeter, which is very thin.

In that case for 2 centimeter of crystal with a thin width you get that the after this I will get a an operating V_{π} which is about 300 and which is the line voltage 314 volt, which is not drastically very small you can see this is about 1 upon 25 times less than the V voltage which was required in the case of longitudinal mode of operation. So, there has been a tremendous improvement from kilo volt to volt some tens of kilo volt to some hundreds of volt there has been a tremendous improvement in the in the switching voltage just by taking the geometrical consideration of this design this is how l and d are

related through the spot size at the waist that is w_0 . So, this design is very useful for this crystal modulator designing and then you see that this half voltage has been reduced drastically.

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----- Summary of discussion -----

- ✓ Transverse configuration of KDP, induced birefringence, phase retardation, half-voltage
- ✓ Modulator design, geometrical aspects, Gaussian beam diffraction, optimum performance, reduced half-voltage

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So, this is how we have understood that you can actually have the freedom of designing the crystal. In the case of transverse configuration when you evaluate this induced birefringence then phase retardation we end up with the half voltage which is which is large reasonably.

But once you incorporate these geometrical aspects of the modulator in terms of the length and width of the modulator such that, most part of the light beam which is traveling through the crystal is utilized by the modulator by the electric field also, you do not allow any excess of width such that unnecessarily the voltage requirement becomes more in order to get the same electric field. We also discuss this Gaussian beam diffraction result for getting the optimum performance, and we saw that the reduced half voltage which is of the order of some 300 volt we will continue with this discussion.

Thank you very much.