Modern Optics

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Lecture - 36
Electro-optic Modulators and Devices (Contd.)

So, we were discussing the Electro-optics of Anisotropic Crystals and we were discussing this KDP crystal, the properties of this KDP crystal.

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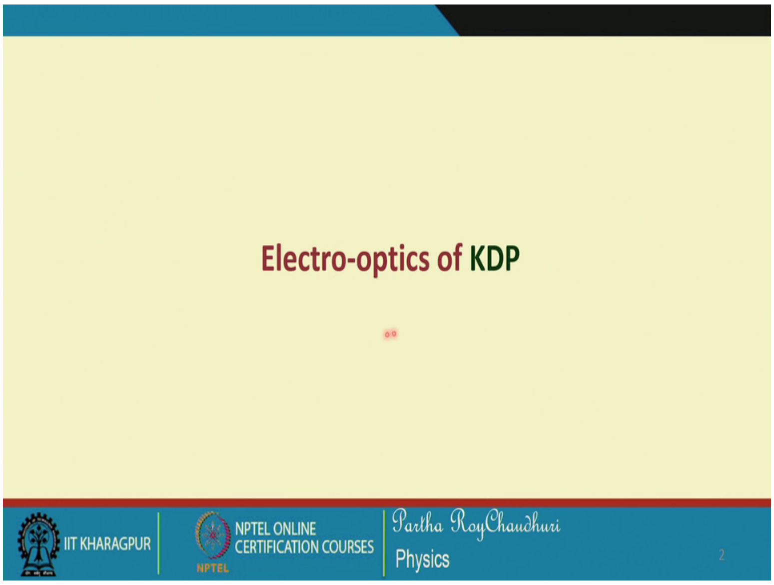

And we will now see the configuration of this KDP crystal and how this amplitude and phase can be modulated.

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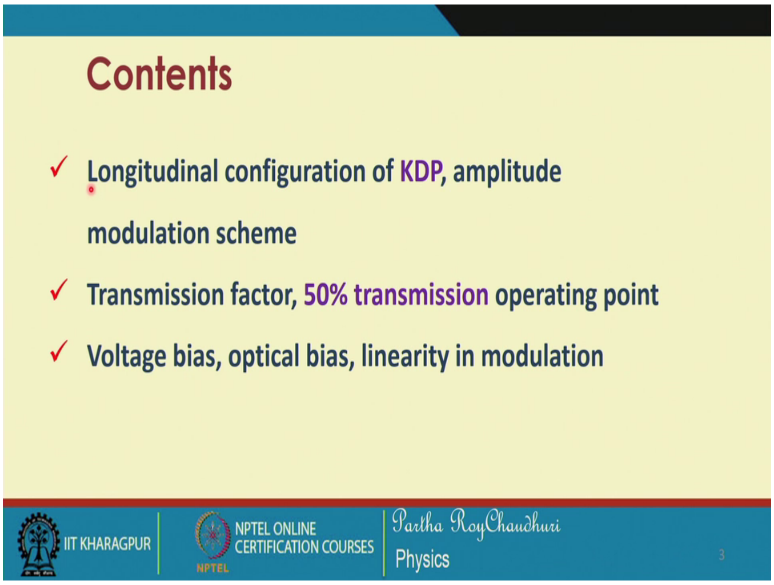

So and then we also work out that how this biasing that will be required for this modulator. So, that it should be linearly proportional to the input other the modulating frequency and the modulator frequency.

So, this longitudinal configuration of KDP that we will discuss and under this modulation amplitude modulation scheme. Then we will see that the modulator has to be biased for 50 percent transmission operating point, then this we will see that this biasing can be achieved by a voltage bias or by giving optical bias this will be no applying a voltage bias we will see that it will be a costly thing cost some affair whereas, biasing by using this optical bias optical method will be easier and simpler and with all known and existing optics we can do this. Then we can look at the modulation scheme that is we can see that this in modulation is now linearly proportional the phase modulation.

So, we will also see look at the basic algebra involved with this modulation scheme.

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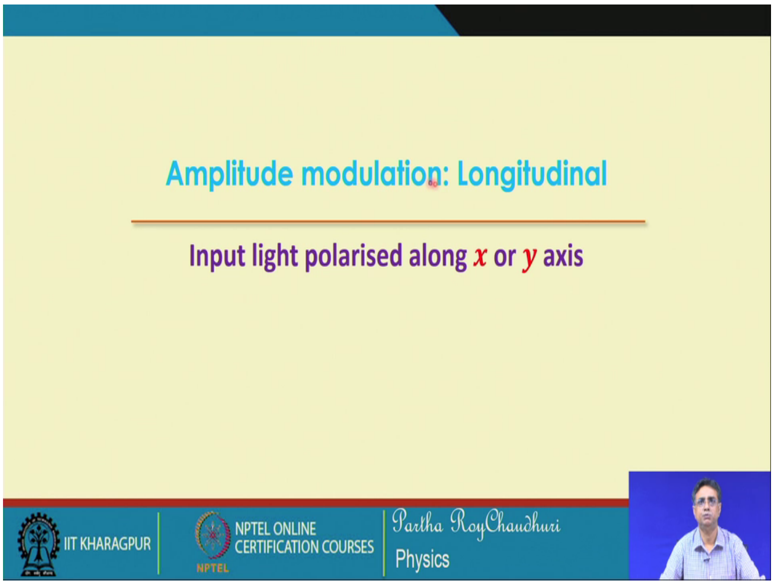

So, the amplitude modulation in the longitudinal mode of operation it requires this we have seen earlier and we have learnt very well that this input light has to be polarised along x or y axis any of the any of the two Eigen polarization. So, that when you apply the voltage the modulator crystal will be induced to have x dash and y dash these two Eigen access and where the refractive induces will be different and this if you apply an input polarization which is along x this x will be split into x prime and y prime. This x prime and y prime which are orthogonal polarizations they will be carrying different phases and because of the voltage dependent refractive induces. So, this then these two will develop the delay which will be modulated and at the output if you put a cross polarizer this modulator output will be amplitude modulate.

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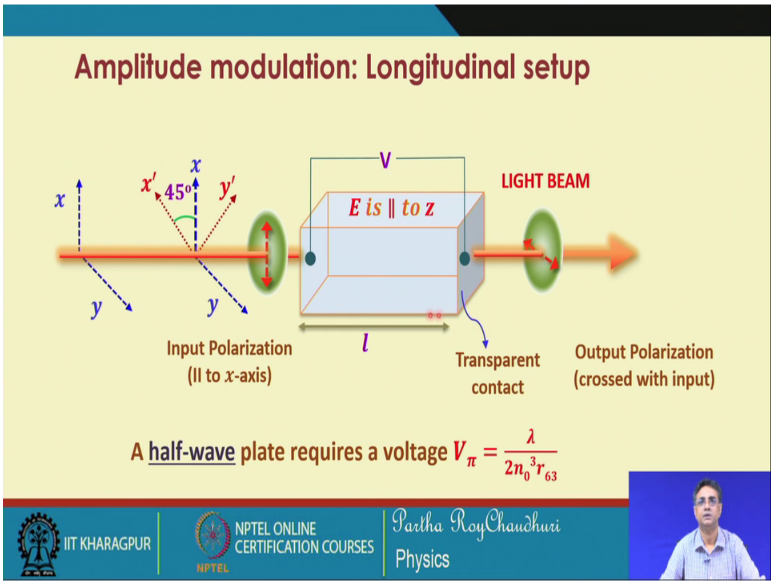

So, this you have this basic set up. once again it is very interesting to note that issuing if you have the input polarization which is along the old principal axes system. Old by saying old principal axes system I mean that when there is no applied voltage to the crystal and if I launch light so without in absence of any external field electric field in terms of any external voltage, in the crystal will have its Eigen axis which is principal axes which is one of the axis is x another one is y, but the moment we apply a voltage then this will be having principal axes new principal axes which are x dash and y dash. Now, I lunch light input which is polarised along the old principle axes old x axis or it could be along old y axis as well.

Let us suppose that I apply this input polarization this will be split into two parts x dash and y dash which will be travel all along the length of the crystal and because these two polarizations orthogonal polarizations which are the new principal axes in the principal axes system they will see different refractive induces will calculate that. And these two different refractive induces will travel with different velocities there will be a phase delay. So, that if I place you know a an analyser which is at 90 degree with the input one then the output beam will be output polarization will be modulated out.

So, a half wave a half wave plate. So, when you want to have a phase difference of pi that requires a voltage half voltage V pi which is equal to this we have seen. And the configuration it remains the same as you have seen in the case of the isotropic material also.

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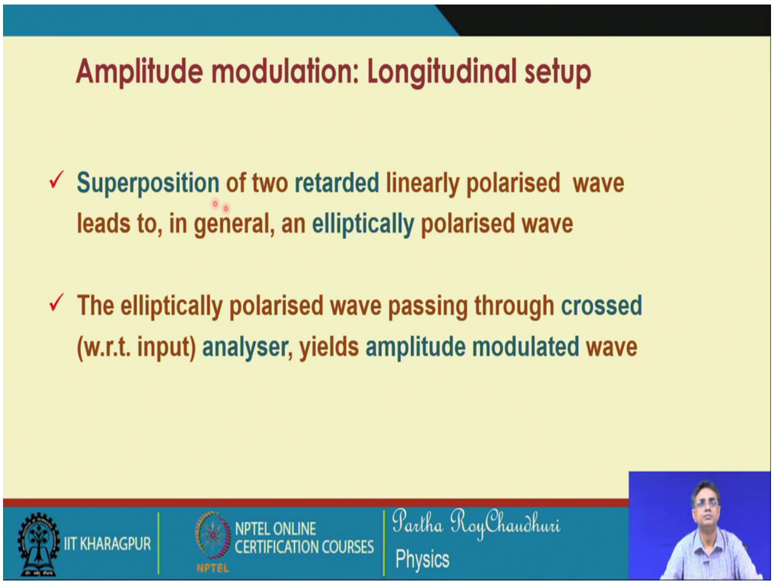

Now, this superposition of the two retarded linearly polarized wave leads to in general and elliptically polarised light. So, if you have an elliptically polarised light and I place a polarizer analyser a cross position with the input polarizer then it yields the this is the thumb rule it is the wave the modulators amplitude modulating system for light it works with the with a with a pair of crossed modulator crossed polarizer and analysers.

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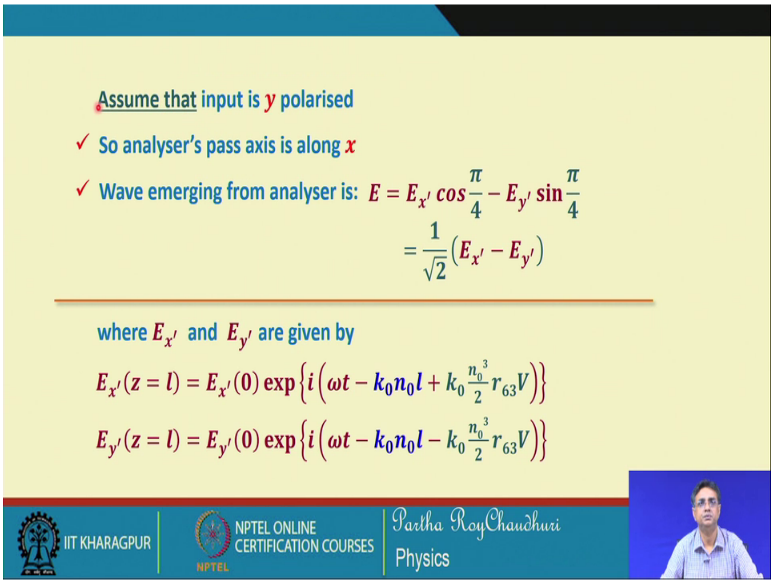

So, let us assume that the input light is y polarized. In this configuration let us assume that the input light is instead of x it could be y polarised as well and everything will remain same phase difference and all. So, we assume that the light is in input light is y polarised. So, the analysers pass axis is along x because it has to be crossed with this. So, if the polariser is along polarisers, polarisers pass axis is along the old y axis then the analysers pass axis will be along the old x axis that is what is the requirement.

So, the wave which will be emerging from the analyser so it has we have an input which is y polarised and you will get an output through along the x polarization, along the x polarization. If this y polarization is exciting this x polarization then only you will get an output so, the wave emerging from the analyser will have E equal to this because the moment you have this input we will be split into two parts, E x dash and E y dash, but they are at 45 degree with y polarization as a result this will be equal to E x dash by root 2 and this will be equal to E y dash by under root 2. So, these two are the components of the amplitudes which will be travelling through the crystal. So and by saying this we consider that the amplitudes are at the output of the crystal.

Now, at z equal to at z equal to 0 I have this input which is y polarised and at z equal to l, I have this output immediately after the crystal then there is no activity electro-optic effect in the free space. So, whether I place the analyser very close to the crystal or little away from this still we considered the effective length z equal to l of the crystal E dash E x dash z equal to l at this distance after the immediately after the crystal this will be a function of E x 0 the input polarization and then this light has undergone a phase change because of the electro-optic effect which is voltage dependent phase change.

So, this is k 0 n 0 l because we have seen you remember that it is equal to n 0 minus n 0 cube by 2 r 63 V that is the refractive index seen by this x polarised light and this is n 0 plus n cube by 2 r 63 V this will be the refractive index which is not V it should be V by l its. So, will be the refractive index in by the y polarized light when passing through the crystal. So, this two polarization polarised lights E x dash and E y dash will have this space at the output of the crystal this includes this phase k 0 n 0 l which is the phase carried by this x polarised light x prime polarised light in absence of any external field. So, this is the fixed phase which is carried by both the x and y polarized light. So, this is the amount of fixed phase which is carried, but this is the phase which is proportional to the external voltage.

So, these are the two voltage, one is added up one is subtracted depending on the magnitude of the coefficients r 63 for KDP and also the direction of the voltage. So, we have these two output electric field, the polarization of the electric field.

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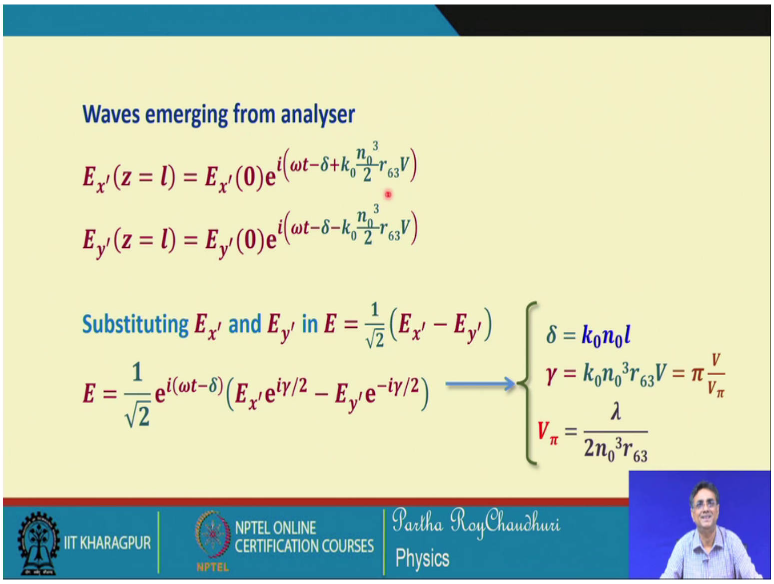

Now, we can write this in terms of this. So, e to the power of, e to the power of omega t minus delta I call this fixed phase which is in absence of any field this is a phase carried by the both the polarizations which is equal for both of them. And if there is no voltage you can see that both of them will have the same phase and there is no delay because V equal to 0, V equal to 0. So, they will be the same. So, these are the two electric field components along x dash and y dash.

Now, in this E x dash and E y dash if I substitute this value which we have calculated here that because it is half wave through x half wave through y, so it has equal amplitude for x prime and y prime therefore, if I substitute for E dash, E x dash and E y dash then we can write this equation in terms of this. So, E x dash by root 2 this is E y dash by root 2. So, that is equal to E and then we can write this we can write this is equal to the difference. So, in this equation in this equation E equal to this, I put E x dash equal to this and E y dash is equal to this.

So, if I put these two values in this equation then I can write E equal to this you can see this is very straight forward and very simple delta is the fixed phase whereas, this gamma is the phase which is proportional to the voltage for each of the polarization and this can also be represented in terms of the V pi. Because you have a straight relationship you have seen that V and V pi can be related. So, V pi is equal to this. So, if you just substitute in place of these quantities for this crystal with r 63 as the coefficient I can write this V pi equal to this which will give me this gamma are the phase in terms of this. So, this pi, V pi they are all fixed quantities. So, the phase gamma is proportional to V therefore, I can write this equation in this term that is very straightforward.

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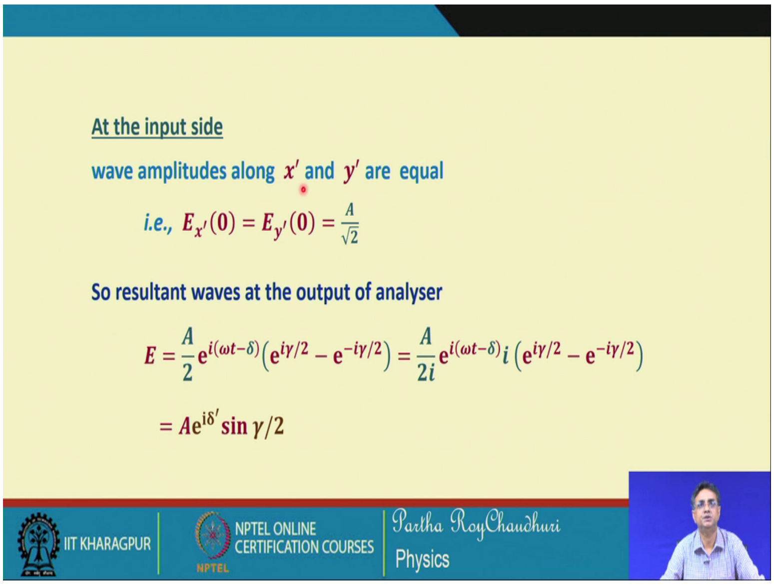

So, wave amplitudes along x dash and y dash the equal at the input side that is at z equal to 0 just at the input end of the crystal at that is z equal to 0 both of them are A by under root 2, that is E by under root 2 whatever wave we want to write. So, the resultant waves at the output of the analyser is this. So, this was the input this is the output.

The intention of writing in this form is that we can translate the output in terms of the input we can write this equation. So, this is A by 2, A by 2 for both of them and then because this now we multiply the numerator and denominator by i, this i and the complex entity. So, which will give you that is e to the power of i gamma by 2 minus e to the power of minus i gamma by 2 divided by 2 I which is the sin function. So, I get e to the power of i delta dash which is just to replace this fixed phase time dependent of course, omega t minus delta this is the fixed phase. So, I replace this entire quantity i omega t minus delta by i delta dash and this is for this sin gamma. So, you have a very straight relationship reduced relationship for the output electric field in terms of the phase difference and the amplitude which is the input amplitude.

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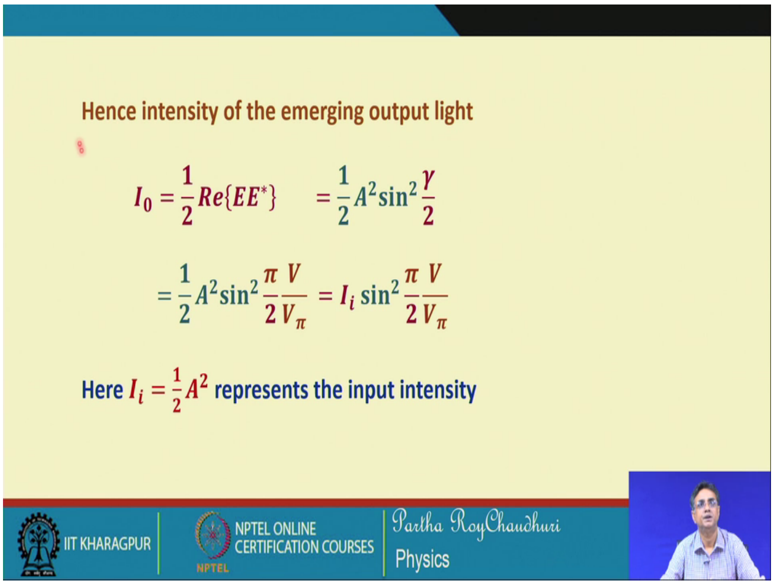

Therefore you can write the intensity of the emerging light output basically we are looking for the intensity modulation. So, it is the intensity I 0 that comes from the real part of EE star and half of that time average. So, half of A square sin square gamma by 2. So, this is your input intensity.

Now, this gamma we can replace by using this factor gamma equal to V pi by V pi. So, we have just use that V pi by V pi and there is a factor of two so that comes here therefore, you can write this input intensity i naught in terms you can write this output intensity i naught in terms of the input intensity and this sin square of the phase factor. As a result you can write because this input in intensity I have used this half a square which represent the input intensity. So, I have this relationship I 0 equal to i input sin square of V pi by twice V pi.

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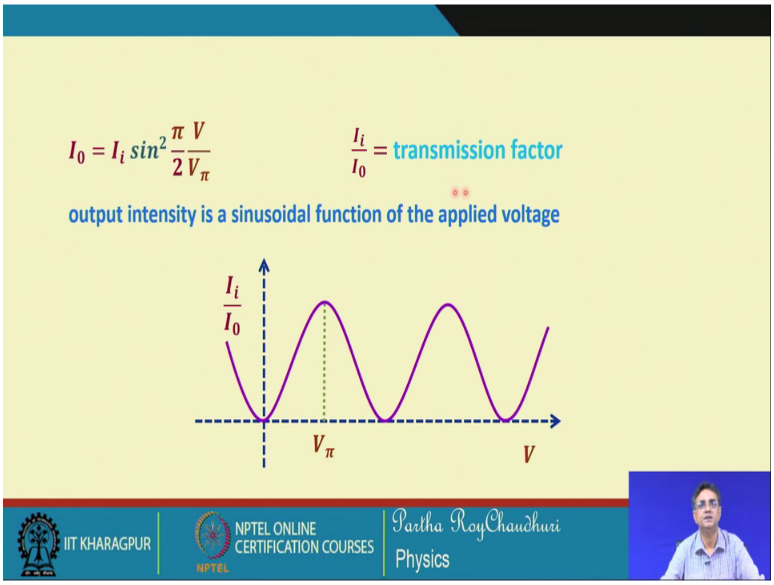

Now, if you plot this because this I by I naught this is the transmission factor how much factor of the input light is transmitted to the output. So, this output intensity is sinusoidal function of the applied voltage sinusoidal function of the applied voltage. So, I by I naught will be like this because it is a sin square function. I think this should be I naught this should be I naught by I i. So, it is it is the other way because in flip. So, this will be I naught by I 0, I output by I input. So, that will be the transmission factor because when this is equal to 0 V equal to 0 then I 0 will be 0, yeah. So, this is this is wrong this will be other way, ok.

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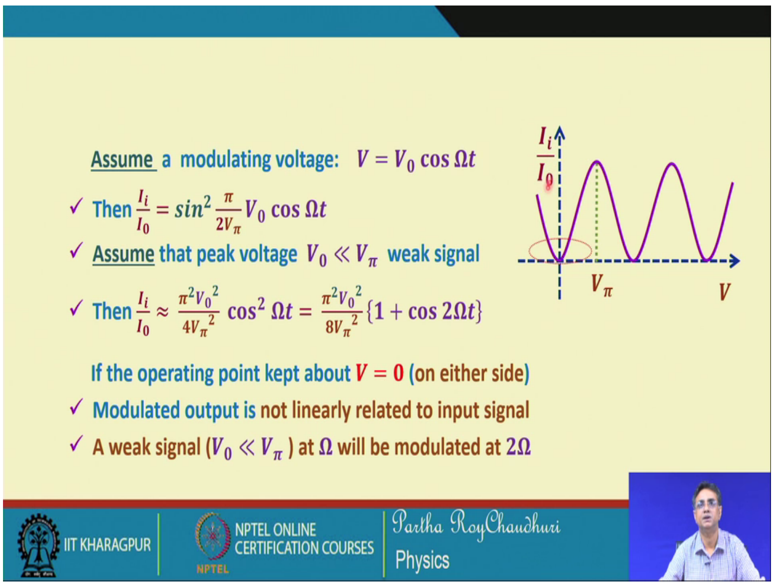

Here also the same thing has carried over. So, I naught by I, I naught by I, I naught by I this should be I naught by I. So, this will be equal to sin square of this voltage. So, then I naught by I 0 equal to this and pi square.

So, you can write this if we assume a voltage which is V equal to V 0 cosine omega t, if I assume a sinusoidal voltage which is the modulating voltage of the for the external field that is being applied to the crystal then I can write this transmission factor as this because it is a sin square function of V pi by twice V pi. So, assuming this peak voltage this look at this graph assuming this peak voltage this one V pi is much more than the modulating voltage which is very small we are trying to restrict ourselves within a within a small modulating voltage. V 0 the peak value of the modulating voltage is much less than this. In that case this transmission factor will be proportional to this, because this quantity sin square of a small quantity. So, it becomes this only.

And this cosine square this is very straight forward as a result you can write this equation because it is a cosine square of omega t I can write this equation, if I divide by multiply and divide by 2 then it can be written as 1 plus cosine 2 omega t. The notable part of this result is that the transmission factor through this transmission factor we can find that the modulation is with a frequency which is double the input frequency because you have given an input frequency which is omega, but you get an output which is twice omega.

So, if the operating point is kept about V equal to 0 at this point then the input that is modulating voltage it can go on either side of the 0 with this and this plus V to minus V it can go to platform whereas, V to minus V, as a result this will be modulated twice. So, modulated output is not linearly proportional to the input, but for this weak signal under this weak signal condition then you will get that omega will be modulated at twice omega.

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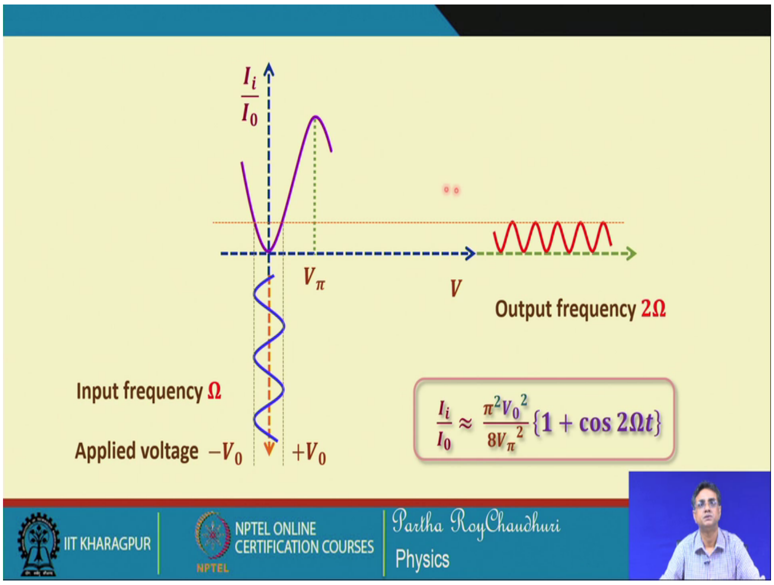

So, you get a modulation frequency which is double the input, ok. So, now, look at this input frequency omega, is this. So, it is that a frequency omega, but you get the output frequency which is which is double the input frequency.

It becomes at a faster rate this is because your voltage this modulating voltage is on either side of V 0 that is it ranges from minus V to plus V. Very straightforward to understand that if it is only on one side that is on the plus side or minus side then we do not get it. So, we will it try to look at this situation and whether we can get some improvement. So, the applied voltage is from minus V 0 to plus V 0 so it modulates in this way. Whereas, the output voltage is always positive, but the output transmission factor is always positive, but it is double the at a rate which is double the frequency of the input.

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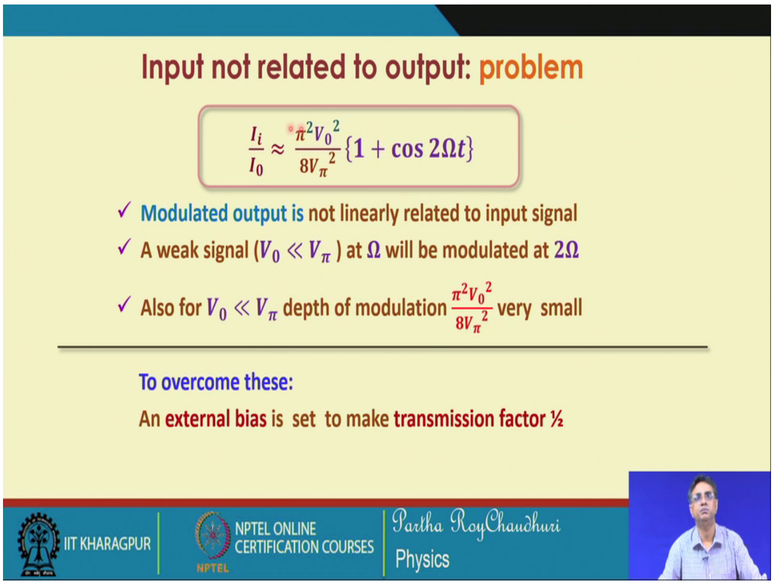

So, there is this is the problem, so this problem can be overcome by using some external bias to the system to make the transmission factor 50 percent. So, this modulated output is now not linearly related to the input these are the outcomes and a weak signal at omega will be modulated at twice omega. For the peak voltage modulating of the modulating signal which is much less than the half voltage the depth of modulation frequency from here, the depth of modulation will be given by this quantity which is also very small the depth of modulation.

Now, to overcome these problems we will see that if we can set the operating point at 50 percent that is half the transmission factor is half that is I naught by I will be equal to half. In that case what happened? So, small signal a small change in the voltage is proportional to the changes in the in the transmissivity.

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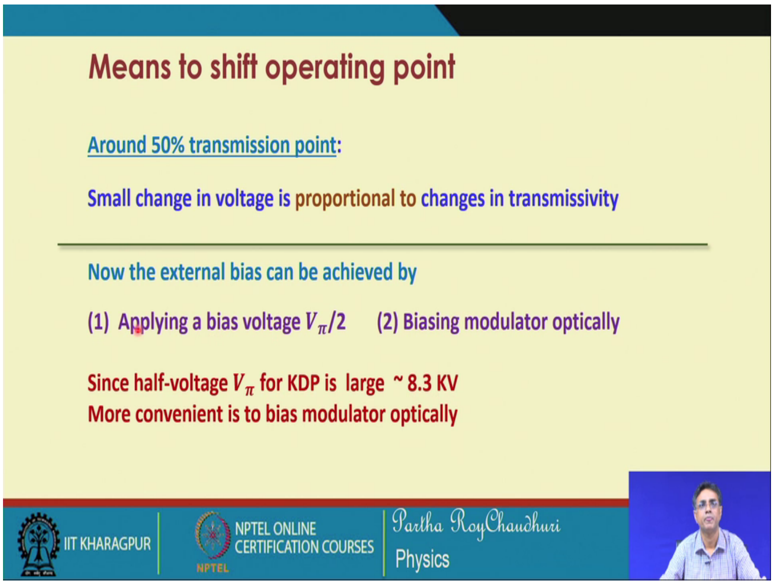

Now, the external bias that is I just need to shift the operating point from this region that is minus V 0 to plus V 0 to somewhere here somewhere here. So, that it is stick within only plus side or within the minus side.

So, to do that I have to shift the operating point and this can be done by applying a bias by voltage that is V pi by 2 so that the operating, so this point if you add half of this V pi by 2. So, it will come to this point because this is 0 this is V pi half wave through is this. So, this will be around this point it has to be modulated, around this point around this point it has to be modulated. So, to do that you have to apply additional voltage additional fixed bias that is a steady DC voltage in excess of in addition to the modulating voltage so that you can shift the operating point from here to here.

So, but you have seen that for KDP this V pi is of the order of sum 8 kilo volt which is very large. Now, additionally you have to put another 4 kilo volt. So, all together it becomes about 12 to 13 kilo volt which is not desired and which is very cost sum compared to the other possible option that is by biasing the modulator optically, because anyway I need to shift the operating point from this is 0 to V pi by 2 at this position I have to shift the operating point of the modulator.

So, this optical biasing is more convenient because we just have to insert one more optical element at the right configuration. So, that operating point can we shifted we will understand how it can be done.

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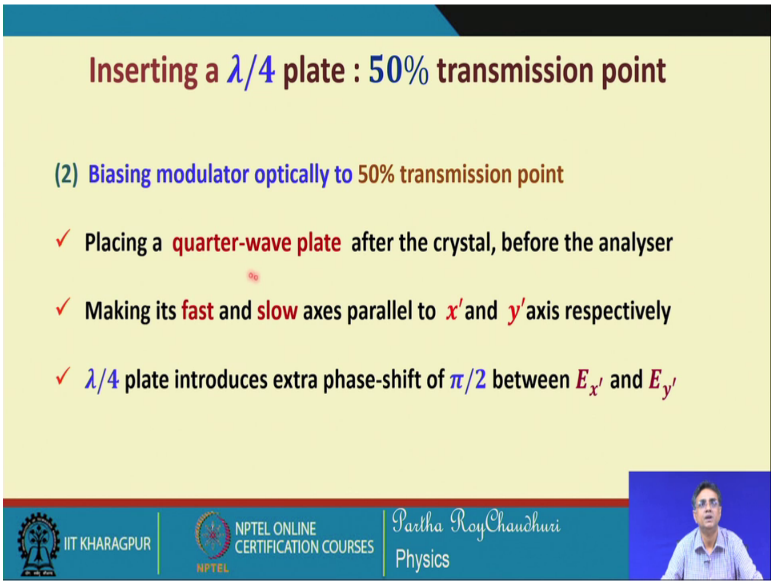

So, a biasing of the modulator to 50 percent transmission these are the requirement, so inserting a lambda by 4 plate how it works. So, because if you put a lambda by 4 plate then there will be an additional phase of pi by 2 which will be introduced and if there is a phase additional phase of pi by 2 that is introduced then the operating point will be automatically shifted. So, making its fast and slow axes parallel to this, I then the lambda by 4 plate introduces this which will be actually existing cancelling the fixed phase that is appearing there.

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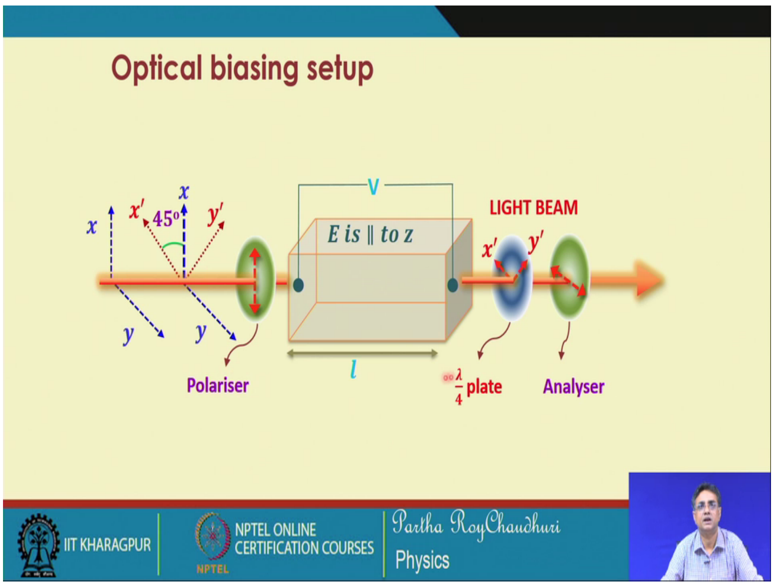

So, this is the configuration for optical bias we will have to put add additional compensator lambda by 4 plate which will compensate the phase which is carried by these two lights in excess of the phase that is due to the applied voltage.

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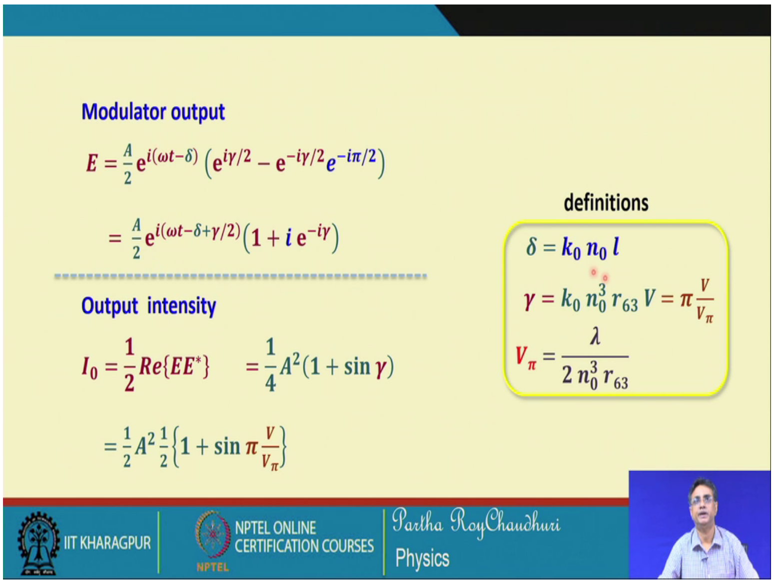

So, let us look at this basic you know calculation mathematics which gives is this clarity that E equal to a by 2, e to the power of pi omega t and now with the introduction of insertion of this quarter wave plate I have this additional phase which can be attached to any of the any of the polarization. So, we can write this equation in this form. So, this is 1 plus ie to the power of i delta.

Now, if you take the output intensity that is I 0 equal to half real part of EE star then you can write this equation in this form A square by 4 which is half of A square, half of this quantity you can see this, but this is your input light, this is your input polarization. So, I 0 equal to I i input into half of this quantity. And this is the definition which we have already used k 0 n 0 l that is to represent the fixed phase in absence of any electric field which is correct because of the travel length l of the two polarized lights, gamma is the phase which is induced because of the voltage and V pi is the switching voltage.

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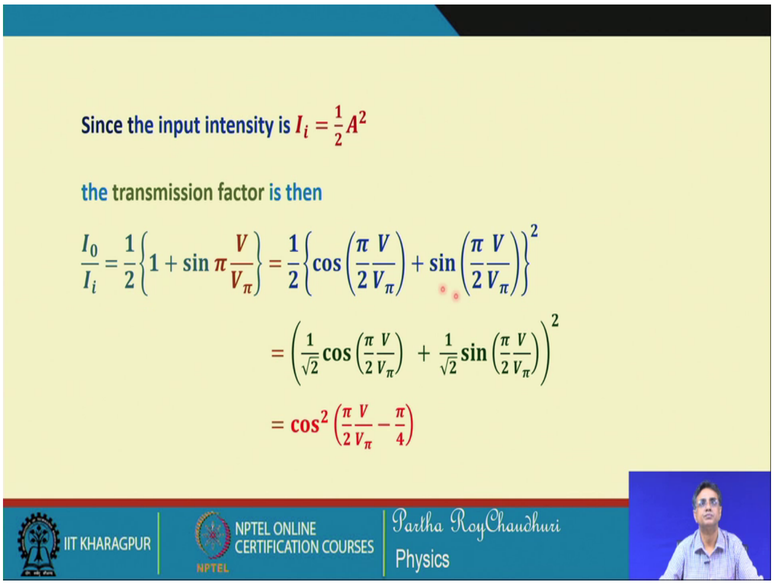

Therefore at the and since the input intense intensity is I i equal to this quantity we can write this equation I 0 by I i which is the this is correctly written how output by input that is the transmission factor. So, I o by I i this transmission factor is equal to this and this because if I write this in terms of the cosine that is sin of 2 theta 1 plus sin of 2 theta.

So, this gives you that it can be written in terms of this one means sin square let us call this is equal to theta, this is equal to 2 theta then this will be sin square theta plus cosine square theta plus 2 sin theta cosine theta. So, you can put the entire thing in the bracket with square and that gives you that each of these quantities 1 by root 2. So, you can write in this form one by because half you can take inside.

And once you take this is a simple way of understanding to looking to look at the calculation 1 by root 2 is nothing but pi by 4 cosine pi by 4 or sin pi by 4. So, if I replace we attach this sin and cosine pi by 4 to this you can represent this in terms of this wave. Here we have used 1 by root 2 equal to cosine pi by 4. So, cosine pi by 4 cosine of this theta plus sin pi by 4 sin of this theta put together it gives you that cosine square of this. So, beautiful you can see that this transmission factor is now a cosine square function of this quantity.

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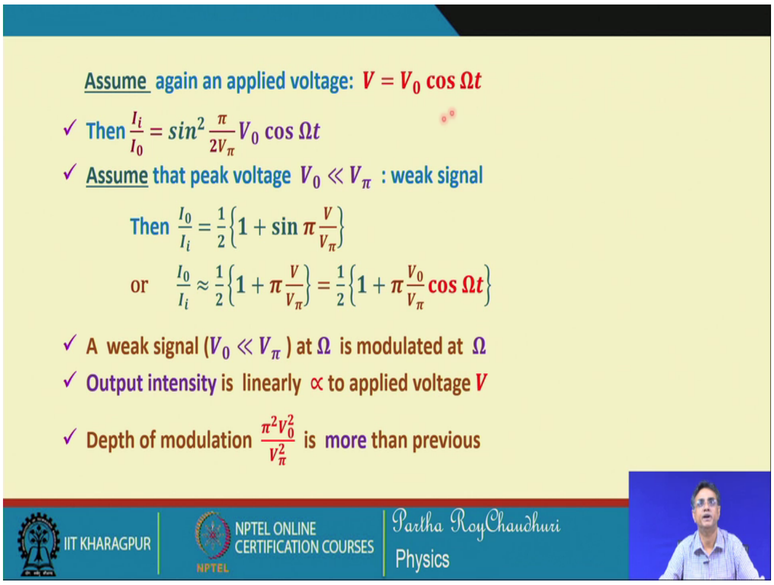

As a result you can see that this, now if I apply the modulating voltage V equal to V 0 cosine omega t and you still assume that this V 0 peak voltage that is the range of modulation the with the peak to peak this voltage is very small compared to V pi, V pi is quite large you know that these of the order of kilo volt. So, it is very small very small then this can be because this cosine square factor you can write in terms of this quantity and then you can write once again I o by I i equal to this. So, this is again once again this is around this should be I 0 by I i output by input will be the transmission factor.

Here also this is correct I 0 by I i. So, half 1 plus sin pi V by V pi then I 0 by I i you can write by doing this because these quantities and you a very small. So, sin of theta can be replaced by can be well approximated by using this theta. So, that gives you this is the interesting outcome of this optical biasing for just giving and additional bias so that for a weak signal which is equal to this output beam is linearly proportional to this voltage, because you have an input which is which has a frequency of omega and you also have the frequency which is omega and both of them are now cosine functions. It is very interesting so that means, it gives you a linearized output. So, this as an one to one relationship the depth of modulation in this case will come from here will come from here, so which is pi square V 0 square by V pi square. So, that is the depth of modulation which is because in the earlier occasion it was 8 at the denominator. So, this is 8 hold more, this is 8 times more this depth of modulation.

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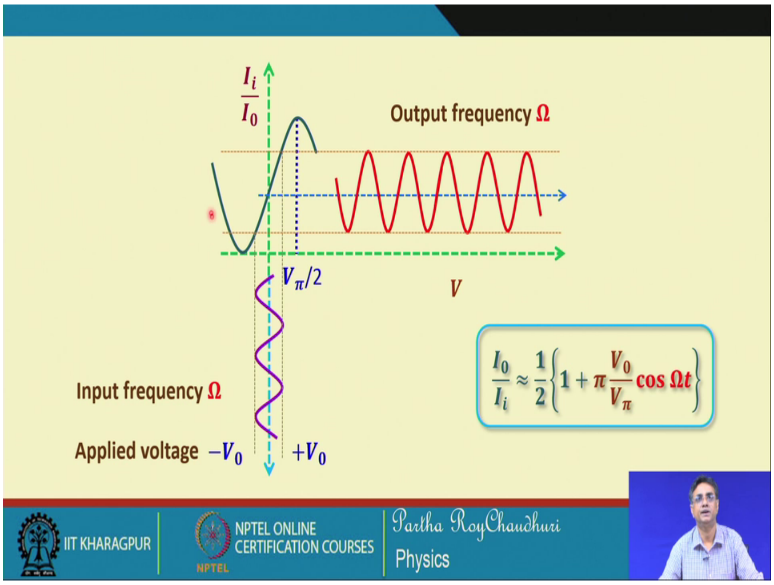

And if you look at the output waveform, so, because now earlier we were here at this point the output frequency will be low.

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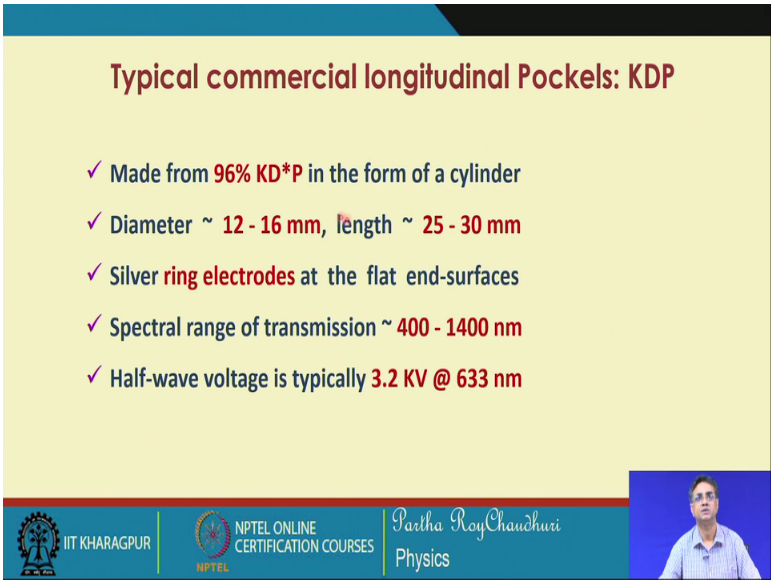

So, a commercial typical commercial longitudinal Pockel of crystals KDP which are made from this in the form of a cylinder then diameters are 12 to 16 millimeter these are the typical numbers for commercial KDP crystal modulators. You have a silver ring electrodes at the flat surfaces and the spectral range is within 400 to 1400 nanometer half wave voltage is typically 3.2 voltage at this helium neon laser wavelength. So, these are the specifications for commercially available KDP crystal modulator and this is a you know a very effective way of doing modulation by putting this optical bias.

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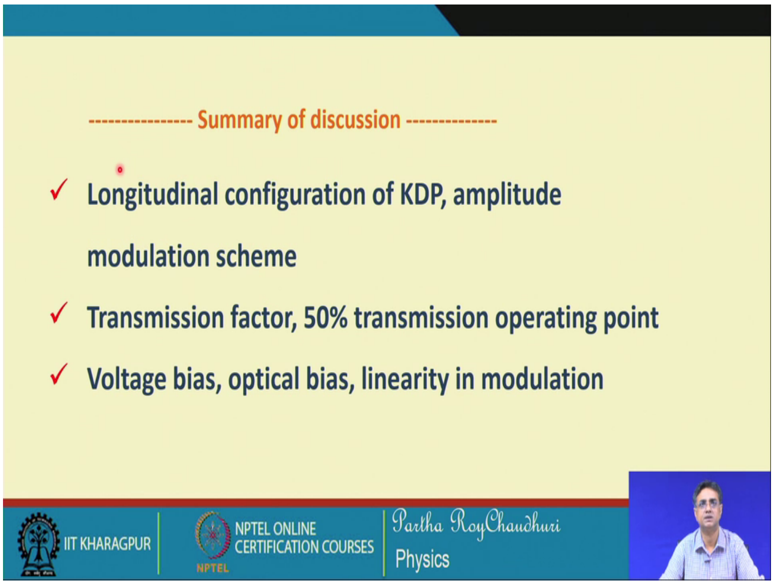

So, in this discussion we considered this longitudinal configuration of KDP and then we discussed how this amplitude modulation scheme can be implemented. Then we found that the linearity can be achieved within the input and output of the modulation by putting by shifting the operating point to a position where the transmission factor is 50 percent of the operating point. So, for that requirement is voltage bias or it could be optical bias that we discuss that putting by putting an optical bias this linearization in the modulation is much easier to implement and to this crystals are commercially available and very useful in the optical modulation scheme.

Thank you very much.