Laser: Fundamentals and Applications
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Lecture – 22
Mode - locking (contd.)

Hello and welcome back today's second day of the fifth week. So, we were discussing about active mode locking. So, very quickly recap. So, what we started with that active mode locking can be done using several things and one of them is the acousto optic devices.

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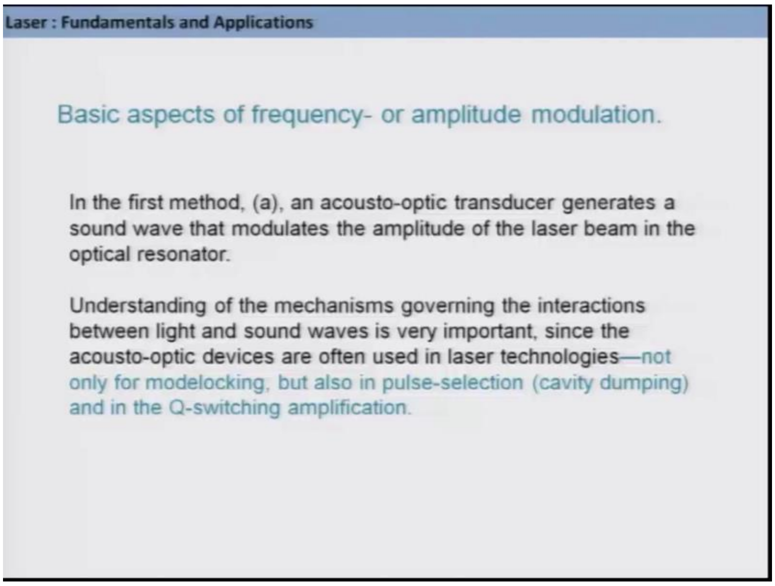

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Basic aspects of frequency- or amplitude modulation.

In the first method, (a), an acousto-optic transducer generates a sound wave that modulates the amplitude of the laser beam in the optical resonator.

Understanding of the mechanisms governing the interactions between light and sound waves is very important, since the acousto-optic devices are often used in laser technologies—not only for modelocking, but also in pulse-selection (cavity dumping) and in the Q-switching amplification.

So, what we said in the previous classes that this acousto optic transducers, they can generate sound wave that can modulate the altitude of laser beam in the optical resonator. And we realized that since this acousto optic device uses a sound wave and that plays a major role in modulating the, you know amplitude of the you know light wave we need to understand the interaction between this sound and light wave.

So, we took an example of a glass of water and taking a acousto optic transducer, which sayings the sound wave through the glass. So, what will happen? Then the sound wave will you know change the, you know it will go through compression and deletion and it will propagate through it. So, if the transducer is here and the glass of water is here then the wave will propagate downwards. And in the meantime if you have a laser light you know or any light for that matter, if it goes through the glass of water in this reaction then the frequencies of the light will also be shifted by some definite amounts.

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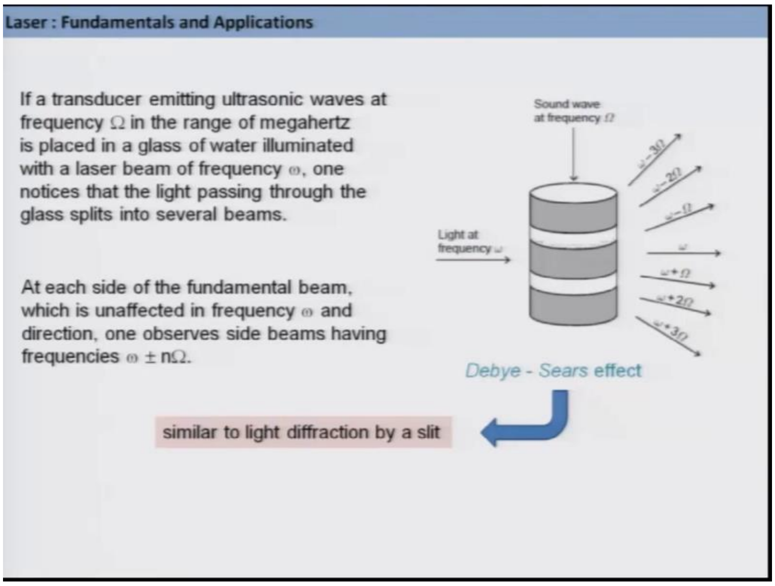

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If a transducer emitting ultrasonic waves at frequency Ω in the range of megahertz is placed in a glass of water illuminated with a laser beam of frequency ω, one notices that the light passing through the glass splits into several beams.

At each side of the fundamental beam, which is unaffected in frequency ω and direction, one observes side beams having frequencies ω ± nΩ.

similar to light diffraction by a slit

So, we said that this effect is known as Debye Sears effect and this Debye Sears effect is analogous to a diffraction except for the fact that in case of like diffraction you know by a slit does not change the frequency of light, it just modulus the intensities.

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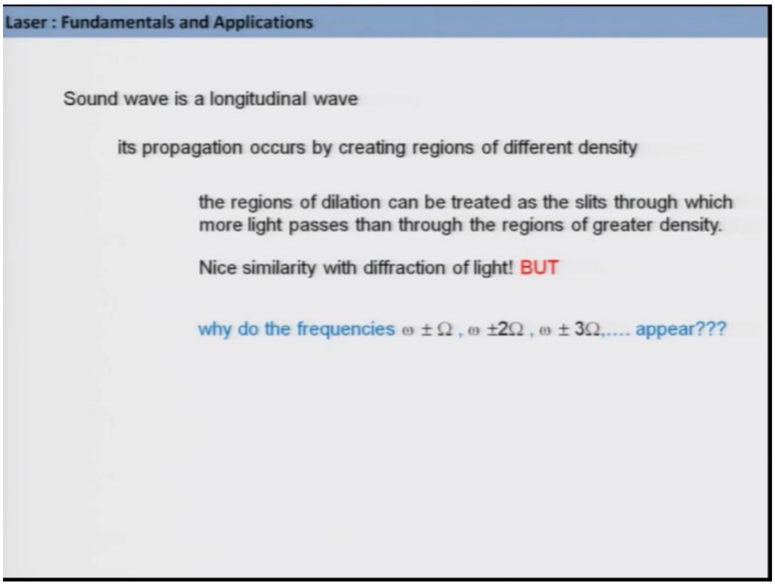

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Sound wave is a longitudinal wave

its propagation occurs by creating regions of different density

the regions of dilation can be treated as the slits through which more light passes than through the regions of greater density.

Nice similarity with diffraction of light! BUT

why do the frequencies ω ± Ω , ω ±2Ω , ω ± 3Ω,.... appear???

Now, we raise the question here that fine, we understand that this is very much analogues to like diffraction by a slit, but then why you know do we have you know have this frequencies like you know omega plus minus capital omega and omega plus minus capital 2 capital omega and so on.

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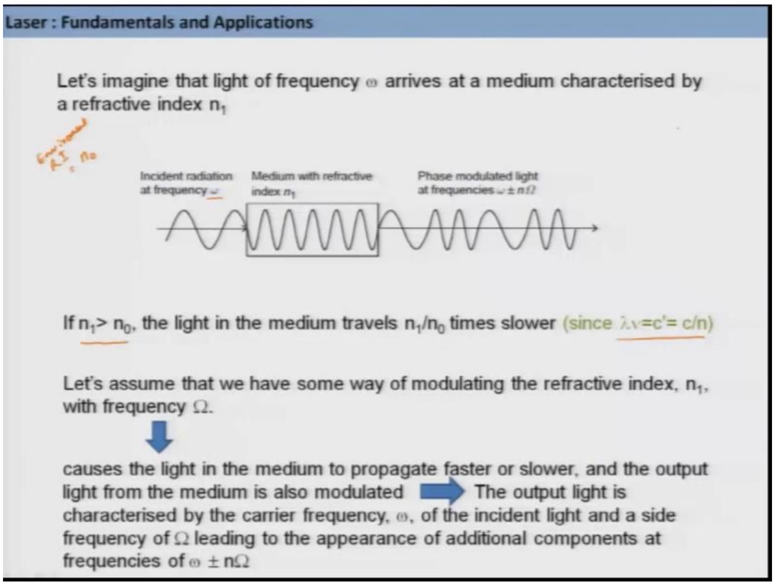

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Let's imagine that light of frequency ω arrives at a medium characterised by a refractive index n_1

If $n_1 > n_0$, the light in the medium travels n_1/n_0 times slower (since $\lambda\nu = c' = c/n$)

Let's assume that we have some way of modulating the refractive index, n_1, with frequency Ω.

⬇

causes the light in the medium to propagate faster or slower, and the output light from the medium is also modulated ➡ The output light is characterised by the carrier frequency, ω, of the incident light and a side frequency of Ω leading to the appearance of additional components at frequencies of $\omega \pm n\Omega$

So, we were here trying to answer this question. So, what we did we you know did hypothetically experiment where we took an active medium, which has a frequency refractive index value say n 1. So, what we did we took an active medium with a refractive index n 1, which is higher than the refractive index of the environment which is given as n 0. So, the environment refractive index is given by, environment R I is given by n 0.

Now, I have an incident radiation which is coming with a frequency small omega. If n 1 is greater than n 0 then the light of the medium will travel slower, how much slower is n by n 0 time slower. Why? That we already know, knowing trouble you know our relation between the frequency and velocity of light we can say that and how it is governed by the refractive index of light.

Most of the time we do not include the refractive index part in our equation, but to be correct one must use the refractive index whenever we are talking about of propagation of light through any medium. Now if we can somehow modulate the refractive index of the medium n 1. So, I can change it to n 1, n 1 prime, n 1 double prime and so on by some way, we do not know how, but if we can do that with particular frequency say capital omega, then that will cause the light in the medium to propagate either faster or slower. Because we have earlier said that due to this device here say effect takes place than the you know incident frequency will be shifted by you know integer multiple of the you know frequency capital omega.

In both the direction; it can have downward shift as we as it can have upward shift; that means, frequency can decrease or increase. So, the result is the modulation of the you know output light and this output light is characterized by the frequency omega; small omega and the site band frequencies which is governed by the capital omega. So, we will have several frequencies appearing in the spectrum and they will look something like this which is on your screen.

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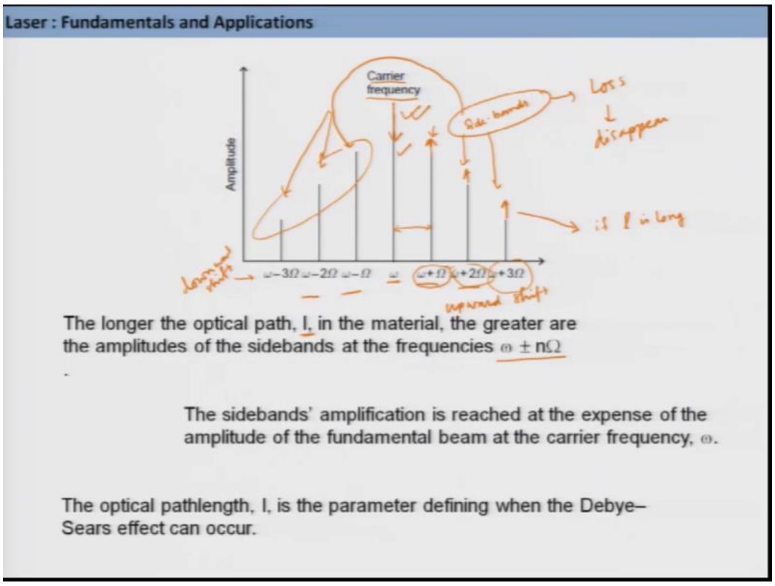

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The longer the optical path, l, in the material, the greater are the amplitudes of the sidebands at the frequencies $\omega \pm n\Omega$

The sidebands' amplification is reached at the expense of the amplitude of the fundamental beam at the carrier frequency, ω.

The optical pathlength, l, is the parameter defining when the Debye–Sears effect can occur.

So, the central part this omega is my incident frequency and this frequency is being modulated by this amount, this amount or in this side. So, this is the you know upward shift and this are the downward shift; so this guys. So, these are called side bands because they were not there earlier. So, this is my main band that is also known as the carrier frequency and these side bands are created.

So, now just imagine at this point, if I can have this distance exactly same as the distance between two neighboring modes. When I talk about this distance, this is in frequency domain alright. So, if I can do this one then you know this particular frequency is nothing, but the frequency of the next mode and next to next mode and then so on. So, this will create a situation and this will happen for any given omega right. So, if I choose a omega anywhere then the corresponding side bands will match to the neighbouring modes. If I change the omega somewhere else and again for that one also I will have this side bands which will match to the neighbouring modes. So, in other word all the modes are now coupled and they have a you know definite correlation with each other. And for the time being if I just can say that if I somehow you know minimize this side bands, if I can say make huge losses to these side bands.

So, if we can make huge losses of the side bands then this will disappear right. So, this guy will disappear and same will happen for these guys also. So, only thing which will remain is this frequency and that will be magnified because that will have the gain and we know that when the gain becomes non linear then I will have a chance of laser output and we already have learnt that we can play with the width of the pulse that is created at this particular frequency by you know choosing the system which has a say large number of modes within the spectral bandwidth. So, in that case I will have you know a selective pulse moving back and forth in the cavity and that has a very short pulse with and that is what our aim is.

So, there are few important things to consider. The most important thing here is the length of this active medium. So, in other word the optical path through which the light is travelling right. So, it said that the longer the optical path which we designate by, l here in the material meaning active medium the greater or the amplitudes of the side bands at the frequencies omega plus n capital omega. So, if my active medium length, so in the previous slide as we shown here, so if this is my l and if l is longer then what will happen?

So, here if l is long so, if l is long the side band intensities will grow, this will grow in intensity right; if l is long. Now if side band grows; that means, they are growing you know from something. So, what happens is they take this you know intensity from the carrier frequency. So, essentially this will go down. So, this will go down and this guys will go up which is exactly the opposite of what you want right. So, yeah; so here we mention it explicitly that side bands amplification is reached at the expense of the amplitude of the fundamental beam at the carrier frequency omega and that is what we do not want. So, the optical path length l is the parameter defining when Debye Sears effect can occur. So, this involves lot of detail right, now we are not going into the detail of that one, but let us take it that this optical path length can control you know the occurrence of Debye Sears effect; that means, whether we will be able to create this side bands at a particular frequency gaps which is defined by this omega plus minus n capital omega; got it.

And then we can get a chance to have a proper mode locking if it fulfils, could the condition that this omega is equal to the delta nu, the gap between the two modes. Now knowing this that this optical path length is very very crucial; then we can have two different situations.

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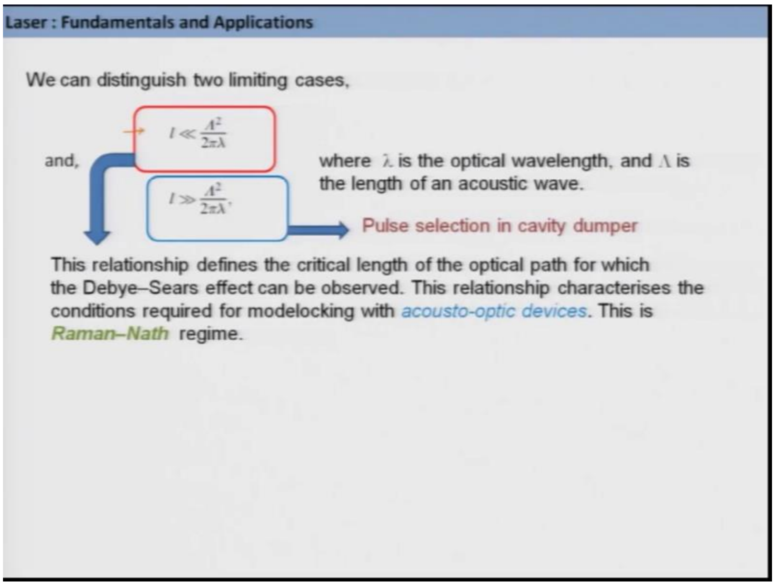

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We can distinguish two limiting cases,

$$l \ll \frac{\Lambda^2}{2\pi\lambda}$$

and,

$$l \gg \frac{\Lambda^2}{2\pi\lambda},$$

where λ is the optical wavelength, and Λ is the length of an acoustic wave.

Pulse selection in cavity dumper

This relationship defines the critical length of the optical path for which the Debye–Sears effect can be observed. This relationship characterises the conditions required for modelocking with *acousto-optic devices*. This is *Raman–Nath* regime.

And then two limiting cases essentially; one is this one, where the optical path length is you know far less than the quantity given by capital lambda square by 2 pi lambda and the other limiting case can be the optical path length is much much much greater than capital lambda square by 2 pi lambda. We are not bothered about how did we come to this conclusion because that is not a part of this particular course curriculum, but we will just look at these two you know values that can be obtained.

So, in these two cases, the capital lambda refers to the length of the acoustic wave and small lambda as we know it is the optical wavelength. So, the first case that is l much much less than the right hand side, this particular relationship it defines a critical length of the optical path for which this Debye Sears effect can be observed. And this relationship also characterizes the condition that is required for mode locking using acousto optic device. And just for you information this is known as Raman Nath regime where optical path length is much much less than lambda square by 2 pi small lambda right.

So, this particular relationship is of importance to us; now we should also know what the second relation being for us. So, when the optical path length is much larger; it is not to difficult for you to understand at this point if you have understood the previous classes. If suppose the optical path length is such that it causes the shifting of the carrier frequency by certain amount which is equal to the cavity round trip. Cavity round trip is quite large correct.

So, if it is that much then what will happen? I can have a situation where I can select one pulse in the cavity and dump everything else and essentially we can use it for cavity dumping. If you can you know if you look back the, you know case where we did the cavity dumping you will be able to relate this.

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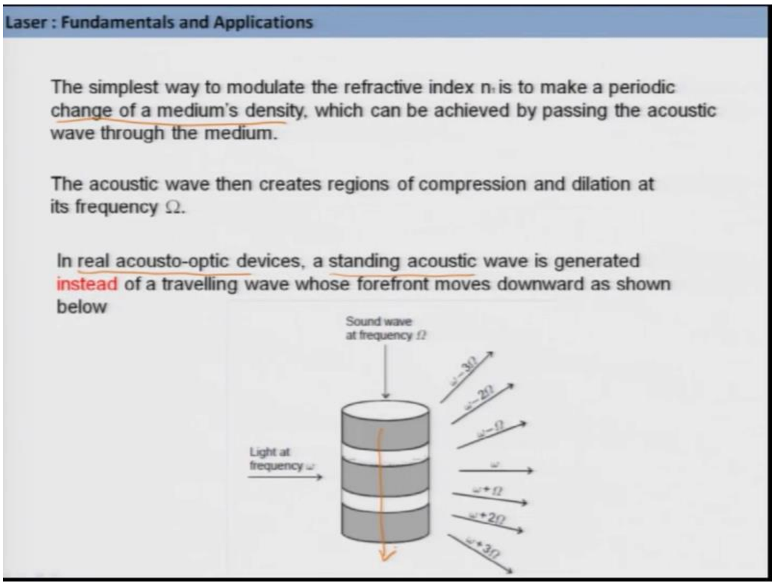

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The simplest way to modulate the refractive index n_1 is to make a periodic change of a medium's density, which can be achieved by passing the acoustic wave through the medium.

The acoustic wave then creates regions of compression and dilation at its frequency Ω.

In real acousto-optic devices, a standing acoustic wave is generated instead of a travelling wave whose forefront moves downward as shown below

Now, so all this things we you know came up to using the simple idea that by instance if we can modulate the refractive index. And we did know how to do that right, but we assume that there is something I can use that and you know modulate the refractive index of the medium which we took as n 1. So, how to do that? So the simplest way to modulate the refractive index n 1 is to make periodic change of a mediums density which can be achieved by passing acoustic wave, sound wave.

Of course, you expected this one because we started with this acousto optic devices. So, you know we are developing this, we are making a transition in a way like we know that acousto optic device will be used. Now how acousto optic will actually do the job of mode locking? So, we you know broking to separate parts one, where we you know show what acousto optic device does; it sends sound way. Now again; if we need to modulate the frequency, what we need to do? We need to modulate the refractive index and if I can modulate the refractive what happens? Now let us connect the acousto optic device and this refractive index modulation. So, it is true that acousto optic modulator can modulate the refractive index of the medium. Now once it does the acousto optic wave creates regions of compression and dilation at the frequency capital omega. Capital omega is the optical sorry is the acoustic frequency.

So, I showed you an image earlier a picture like this where we took this glass of water and then send the sound wave. So, sound wave propagates downward right. Now in actual acousto optic devices, the real acousto optic devices instead of this you know moving sound wave they generate standing waves. So, they generate standing acoustic wave, which is totally different from this picture where you know this wave propagates downward. Now if such standing wave is formed and if I vary the frequency how does it look like?

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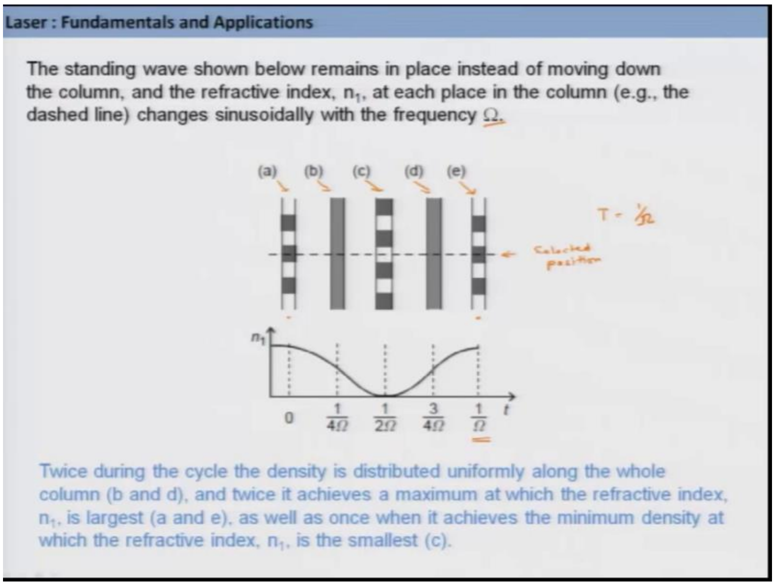

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The standing wave shown below remains in place instead of moving down the column, and the refractive index, n_1, at each place in the column (e.g., the dashed line) changes sinusoidally with the frequency Ω.

Twice during the cycle the density is distributed uniformly along the whole column (b and d), and twice it achieves a maximum at which the refractive index, n_1, is largest (a and e), as well as once when it achieves the minimum density at which the refractive index, n_1, is the smallest (c).

So, here we have given five different situation for the same type of column through which acoustic wave is being sent and essentially that is forming the acoustic standing wave. So, we have given situations a to e; you can see that you know there are different modes are possible. And a to e essentially covers from time 0 to the full period time which is given by 1 upon omega.

So, in these cases we have taken in different different intervals and you can see that the refractive index n 1, effective matrix of the active medium at you know each place in this column at different different times, changes in a sinusoidal fashion with the acoustic wave frequency capital omega right. So, if you choose any particular position of the column say we have chosen this position which is given by this dash line. So, this is our selected position to look at this effect. So, if I select this one, what do I see? So, what I see is twice that is in case of column b. So, these are little bit shifted.

So, you can easily correlate this refers to this one. So, for b and d, the density is uniformly distributed over the column. On the other hand for case a and e, you have the maximum refractive index. So, this colors are you know essentially the intensity of this color is in the (Refer Time: 20:08) is giving you the amount of refractive index or the you know value of the refractive index. So, darker it is higher the value and lighter it is lower the value. So, if you look at along this line the selected position you will see that this is varying. So, it is darkest to you know ah little faded and then totally you know like I say giving merely the lowest value and then again it goes up. So, twice the maxima occurs so at these two places within a time period and here it is the minima.

So, this is the smallest at 1 by 2 omega, the value of refractive index n 1 is slowest. So, there by varying the you know omega you can actually change the refractive index. Moreover you can change it a in a vary systematic manner in a periodic manner, why? Because you can see that nature of the curve of n 1 against this 1 upon n omega that is essentially in terms of T, capital T; the period is sinusoidal in nature which is the periodic function correct. So, remember just few minutes back we say that requirement to get this mode locking is the creation of a periodic variation of the refractive index of the medium so that I can modulate the light wave alright.

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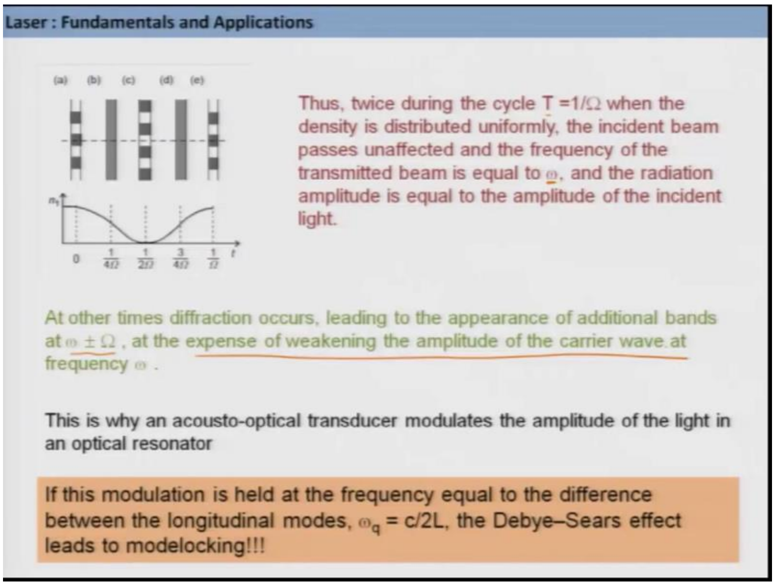

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Thus, twice during the cycle $T = 1/\Omega$ when the density is distributed uniformly, the incident beam passes unaffected and the frequency of the transmitted beam is equal to ω, and the radiation amplitude is equal to the amplitude of the incident light.

At other times diffraction occurs, leading to the appearance of additional bands at $\omega \pm \Omega$, at the expense of weakening the amplitude of the carrier wave at frequency ω.

This is why an acousto-optical transducer modulates the amplitude of the light in an optical resonator

If this modulation is held at the frequency equal to the difference between the longitudinal modes, $\omega_q = c/2L$, the Debye–Sears effect leads to modelocking!!!

So, I have put this picture once again, so that we can you know see where we discuss. Now, we can see from this picture that twice during the cycle capital T which I have already mentioned when the density is distributed uniformly, what will happen to the light wave? Nothing will happen to the light wave; the light wave we will pass through unchanged. So, the outgoing light will have the same frequency as the incident one. So, if it starts with small omega, the output also will be small omega and the amplitude we will remain the same. So, no change when it is uniformly the refractive index is uniformly distributed.

Now, at any other given time what will happen? We will achieve diffraction. So, essentially Debye Sears effect which will leads to the appearance of this additional side bands at omega plus minus capital omega. And this will happen at the expense of the weakening of the amplitude of the carrier wave at frequency small omega. We have already seen that nothing new. So, this is the reason why an acousto optic transducer modulates the amplitude of the light in within an optical resonator. So, if this modulation can be held at a frequency equal to the difference between the longitudinal modes which we defined in the previous classes, small omega subscript q which is equal to c by 2 L, we have been dealing with this one for long time. So, we know this one.

We will achieve Debye Sears effect not only Debye Sears effect will happen, but we will achieve the mode locking and that is the condition. I should be able to vary the diffractive index, so that I can modulate the amplitude and create the Debye Sears effect, so that the frequencies are shifted by certain amount. And if I can control this amount of shifting such that they are equal to the gap between two successive longitudinal modes of the cavity; I got mode locking.

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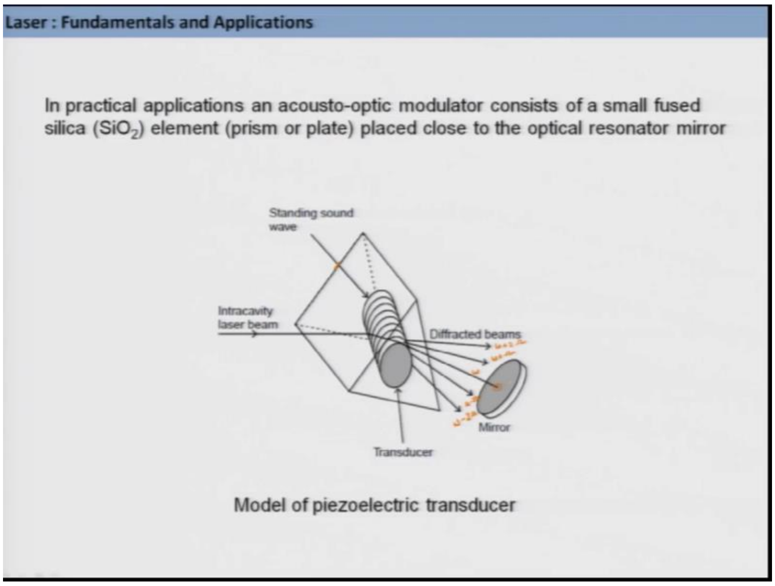

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In practical applications an acousto-optic modulator consists of a small fused silica (SiO_2) element (prism or plate) placed close to the optical resonator mirror

Model of piezoelectric transducer

Now, how do you do that practically? So, you need to use an acousto optic modulator. So, this acousto optic modulator generally can be as I said in one of the previous classes it can be like fused silica and this is one of the most used systems. So, if you take small prism of fused silica or small window of fused silica and place it extremely close to the optical resonator mirror then, what will happen that is shown in this picture given here.

So, this, the sound wave is given. So, this acousto optic modulator is attached right here. So, this gives the sound wave and the sound wave will modify the refractive index of the medium. So, depending on the frequency of the acoustic wave you will create the Debye Sears effect and for a definite frequency, you will see this kind of thing where this guy is just omega and this is like omega plus omega, this is omega plus 2 omega and so on and this is omega minus capital omega, omega minus 2 capital omega and this is. So, by now you probably have understood, what we are going to achieve. Now they are being diffracted correct. So, one beam which is unchanged in the frequency is following you here on the mirror, what will happen?

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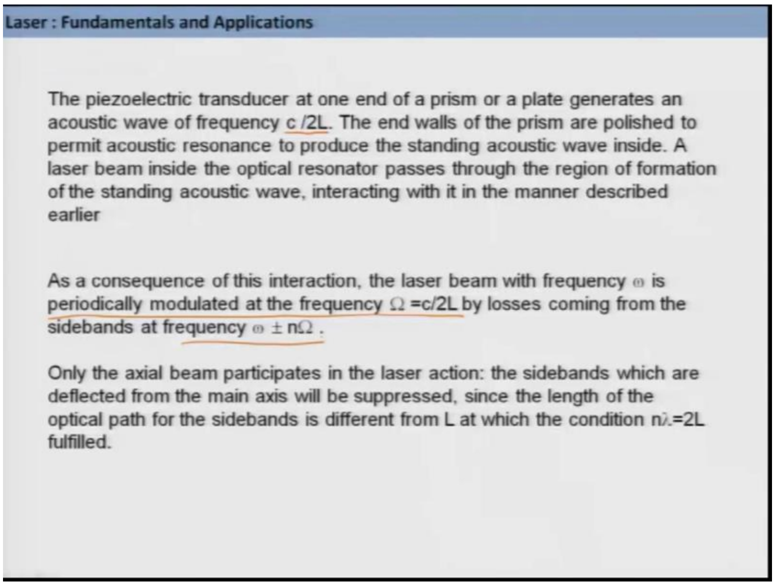

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The piezoelectric transducer at one end of a prism or a plate generates an acoustic wave of frequency $c/2L$. The end walls of the prism are polished to permit acoustic resonance to produce the standing acoustic wave inside. A laser beam inside the optical resonator passes through the region of formation of the standing acoustic wave, interacting with it in the manner described earlier

As a consequence of this interaction, the laser beam with frequency ω is periodically modulated at the frequency $\Omega = c/2L$ by losses coming from the sidebands at frequency $\omega \pm n\Omega$.

Only the axial beam participates in the laser action: the sidebands which are deflected from the main axis will be suppressed, since the length of the optical path for the sidebands is different from L at which the condition $n\lambda = 2L$ fulfilled.

This particular frequency small omega which we are selecting, that will be amplified. So, we have you know written down here explicitly that the piezoelectric transducer at one of the end of a prism generates acoustic wave at a frequency capital omega and if I choose the frequency capital omega to be equal to c by 2 L where c is the (Refer Time: 27:02) light, L is the length of the cavity. The end walls of the prisms you know it is a practical concerned that the end wall of the prisms are polished to permit acoustic resonance which is needed for you know practical reasons to produce the standing acoustic wave. A laser beam inside the optical resonator passes through the region of formation of the standing acoustic wave as we shown in the previous slide like this. So, this is my essentially the beam which is coming from the active medium and that will interact with this standing acoustic wave.

As a consequence of this interaction of the laser light coming from the active medium and the acoustic sound wave passing through that prism or glass plate made up of fused silica and attached to a acoustic modulator. The laser beam with the frequency omega is periodically modulated at the frequency this, we know that. So, this will happen at the expense of the sidebands; why? Because if you notice the previous picture here. So, this guy is the axial guy because this is passing through this you know axis of the cavity. So, you know the cavities formed in such a way that you know this beam is the axial beam for you know goes in the way along the axis of the cavity . So, only this axial beam participates in the laser action and other beams are not going into the cavity active medium back again.

So, it will go out of the you know mirror. So, I will incur losses for the side bands and that is what exactly we want. We want to lose this sidebands and we want to you know amplify the axial band at small omega. So, the side bands which are deflected from the main axis will be suppressed; since the length of the optical path of the side bands is different from capital L. Of course, you have to follow the standing wave condition of the optical cavity right. So, if you know these sidebands are not supported by the cavity then also I will have the losses. So, in that case this axial one, axial beam will form the you know laser output.

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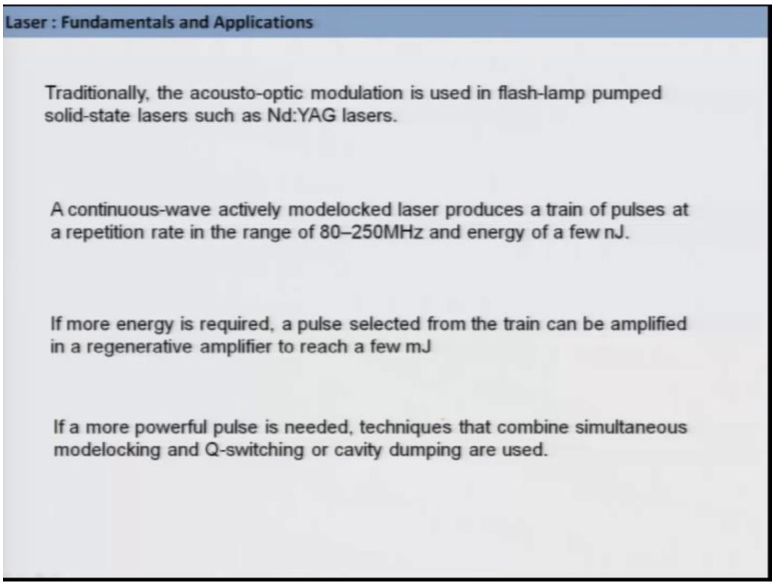

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Traditionally, the acousto-optic modulation is used in flash-lamp pumped solid-state lasers such as Nd:YAG lasers.

A continuous-wave actively modelocked laser produces a train of pulses at a repetition rate in the range of 80–250MHz and energy of a few nJ.

If more energy is required, a pulse selected from the train can be amplified in a regenerative amplifier to reach a few mJ

If a more powerful pulse is needed, techniques that combine simultaneous modelocking and Q-switching or cavity dumping are used.

And this is one pulse because this has been chosen in such a way that the you know every round trip, one light output will come out.

Again it will go back and come back to this output coupler, one pulse is going out and this pulse is extremely narrow. So, this is how the active mode locking involving the acousto optic modulator is done. Now traditionally the acousto optic modulation is used in flash lamp pumped solid state laser such as Nd YAG lasers. Any continuous wave laser can be actively mode locked and that can produce pulses in the you know having energy of few nano joule and it may have a repetition rate of say 100 to 250 megahertz at max.

If someone needs more energy what you need to do? You can you know select a pulse from the train and you can amplify it further by something called regenerative amplifier which we are not going to discuss during this course. If someone is interested you can go through the you know books that have suggested. If you want to even further increase the power you can you know combine a Q switching or cavity dumping through this mode lock laser and you know this cavity dumping or Q switching that can give high power. So, if you can combine mode locked laser with a Q switching and cavity dumping technique you can end up getting higher energy output. So, we will stop here today and in the following class we will start learning about other type of mode locking procedures.

Thank you very much.