Ultrafast Optics and Spectroscopy
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Lecture - 20
Construction of Ultrafast Laser

Welcome to module 6 of the course Ultrafast Optics and Spectroscopy. In this module we will learn how to Construct Ultrafast Laser.

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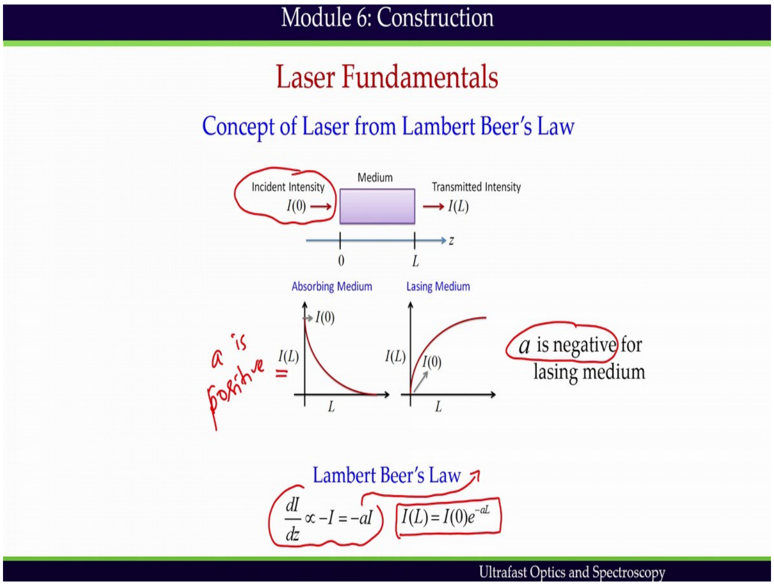

We will begin with Lambert Beer's law which connects the absorption of light to the properties of materials through which light is travelling. According to this law absorption is observed as a decrease of the number of photons in the beam while transmitting in the medium.

In linear optical regime, the decrease of intensity in z direction is proportional to the intensity. This is the beer Lambert's law and here a is proportionality constant which is also called absorption coefficient. After integrating this equation we get an exponential function, which suggest that intensity of the beam incident beam will decrease as a function of L.

If a is positive and that is called absorption. The idea of laser comes when a for the medium becomes negative. In that case what will happen? Light amplifiers its intensity as it propagates through the medium and that is nothing, but laser.

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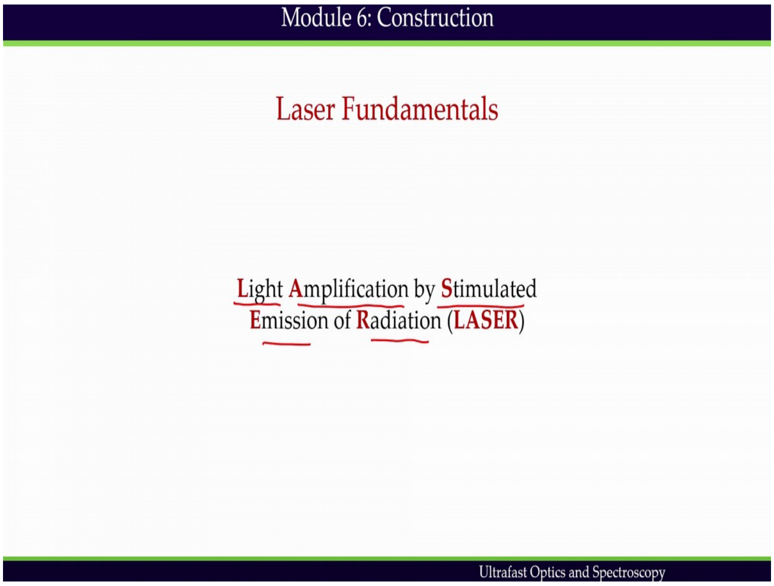

The name laser originates from an acronym of light amplification by stimulated emission of radiation. As the name suggest amplification of light is achieved based on the stimulated emission process. What is stimulated emission?

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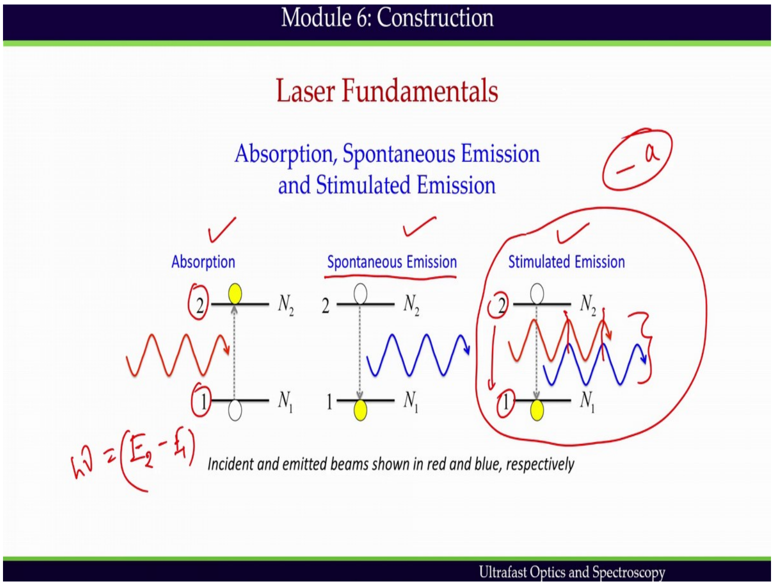

In 1917 Einstein identified three independent processes which contribute to the electronic transition between two states absorption, spontaneous emission and stimulated emission. Each process is associated with an Einstein coefficient which is a measure of the probability of the respective transition. Absorption is a process by which a molecule or an atom is excited from lower state 1, 2 higher state 2 by absorbing a photon with an energy E 2 minus E 1 induced by incident electromagnetic radiation.

So, spontaneous emission is the process by which an electrically excited electronically excited molecule or atom spontaneously decays from upper state to the lower state. So, spontaneous emission is not induced by any external electromagnetic field. On the contrary stimulated emission is the process by which an electronically excited molecular atom jumps from upper state 2 to lower state 1 induced by incident electromagnetic radiation.

Thus technically absorption destroys an incident photon while stimulated emission provides or produces an additional photon. Further more in stimulated emission emitted electromagnetic wave and incident wave these 2 waves stay in phase this is indicative of staying in phase. This is why stimulated emission is coherent forming a unified hole as spontaneous emission is incoherent.

Emission occurs in all direction and with random phase consequently, the incident radiation is amplified in stimulated emission. So, we need stimulated emission always for the amplification or negative a in Beers Lambert’s law. This is the physical basis of light amplification in lasers more specifically. This is the idea behind negative absorption coefficient in the Beer Lambert’s law.

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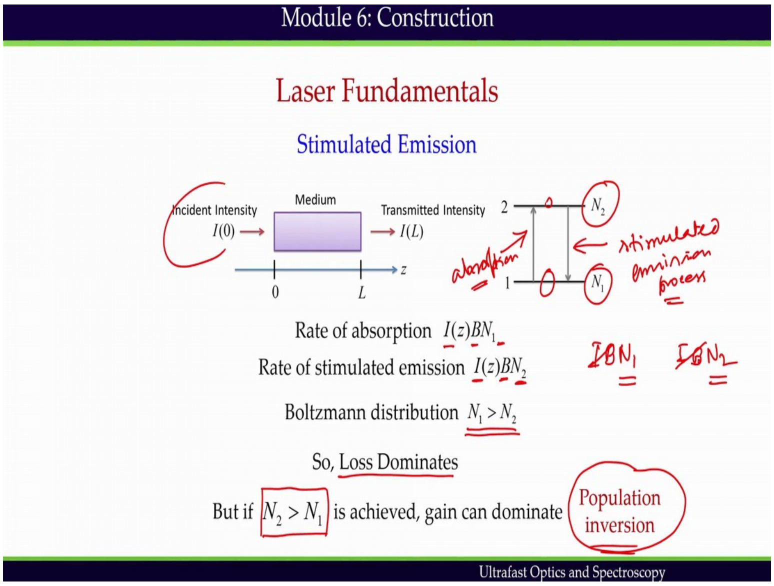

Quiet unfortunately condition to achieve stimulated emission is not thermodynamically favored. Considered a light beam with incident intensity I naught propagating along a laser medium consider 2 energy levels 1 and 2 populated N 1 is the population for the first state, N 2 is the populated; N 2 is the population of the second state now the rate of absorption this is absorption process and this is stimulation emission process.

So, we can write down that rate of absorption is going to be product of intensity probability of that transition and population. Similarly rate of stimulated emission will depend on intensity, probability, this B is Einstein coefficient which represents the probability of that respective transition and the population. Here we note that it is the same probability which is acting for absorption as well as stimulated emission. They are the same process, but there is starting state starting energy state and ending energy states are different.

To amplify light intensity now which is called act of lasing, the rate of stimulated emission has to overcome the rate of absorption. Gain or loss of intensity does depends on the magnitude of N 1 and N 2 because we have to find out what is the relationship we have between IB N 1 and IB N 2 and depending on which means that depending on N 1 and N 2 magnitudes, we will be able to find out which rate is dominating.

Normally under normal thermodynamic equilibrium in which Boltzmann population distribution is obeyed N 1 is always going to be N 2, N 1 is always going to be greater than N 2 and therefore, there will be a loss mostly absorption in the medium. So, lost dominates which means that incident beam intensity will decrease as it propagates through the medium. However, if N 2 greater than N 1 this condition is achieved in order to have this condition achieved stimulated emission must exceed the loss.

And this is a condition which is called population inversion, inverted population. Normal population distribution is always going to be higher population in the ground state than upper exited state. But in order to achieve act of lasing I need to have inverted population and this is called population inversion. Which features and negative temperature in Boltzmann distribution. As long as there are more atoms or molecules in the upper level then in the lower level stimulated emission can dominate. The first emitted photon will stimulate the emission of another photon, then 2 photons subsequently stimulate the emission of more photons and so, on. Does cascade of photons grows resulting in the amplification of emitted light.

Spontaneous emission also emits photons, but they are incoherent emitting in all direction with random phase. Now, there is an important question here, how do we achieve population inversion?

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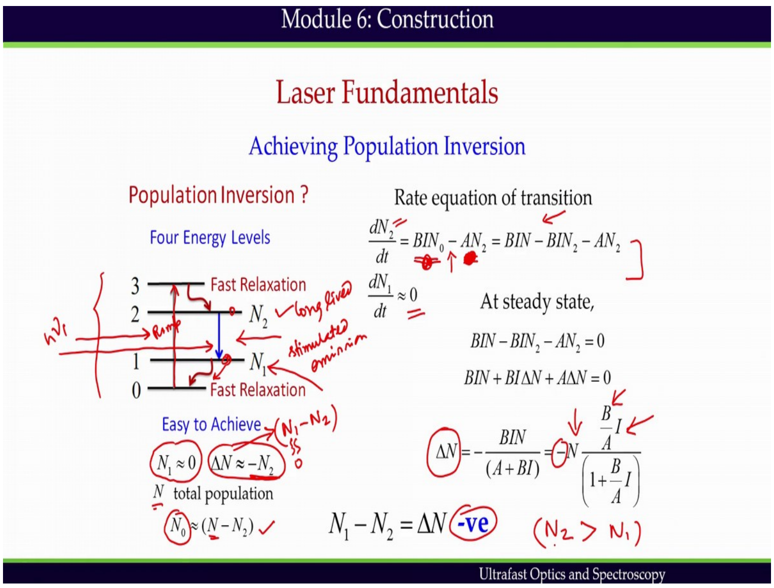

In order to achieve population inversion we need more than 2 energy levels we cannot deal with only 2 energy levels. We need system, which will exhibits many energy levels let us take an example of four level system which is shown here in this lights.

In this case pump beam transfers the population from 0 to 3, this is a pump beam I am using is transforming population from 0 to 3 with the help of pump. Now, this 3 population is rapidly decaying to 2 level 2 and this level 2 is long lived excited state. Stimulated emission then occurs from level 2 to level 1 this emission is stimulated emission.

So, it means that in order to use this four level system, I need a pump which will have higher frequency higher h nu 1 this is pump and another beam which will induce this stimulated emission having lower frequency, the energy gap is low. So, there are 2 beams I need in order to activate or in order to use this four level system and this N 1 state is very short lived and that is why the population in N 1 states rapidly decays to 0 state.

So, under this condition one can approximately write down that N 1 is almost 0 no population is sustained in N 1 state. And delta N which is defined by N 1 minus N 2 population difference between 1 and 2 states can be expressed as negative N 2 because N 1 is approximated as 0. N is the total population that is why we can write down that population in the 0 state is going to be total population minus N 2 N 2 population is staying here.

We have to write down the rate equations the first rate equation is how the population doing in the N 2 state, which will depend on how we are pumping that is BIN naught and how the spontaneous emission going on from N 2 state. This is negative sign because spontaneous emission this part will decrease the population and this part will increase the population and that is why it is positive. Finally, we can plug this expression in this equations.

On the other hand change your population of N 1 remains 0 that we have assumed that N 1 state is very short lived that is why no population is sustain there. And at steady state this 2 rate should be equal that is a simple kinetic theory and after doing little bit of basic mathematics, we get an expression for delta N. Look at this expression N is positive total number of molecules B and A are Einstein coefficients which is also positive, intensity is also positive everything is positive that is why delta N becomes negative.

When delta N becomes negative it means that I have achieved population inversion which means that N 2 population is going to be greater than N 1 population and that is the condition which is required for getting population inversion.

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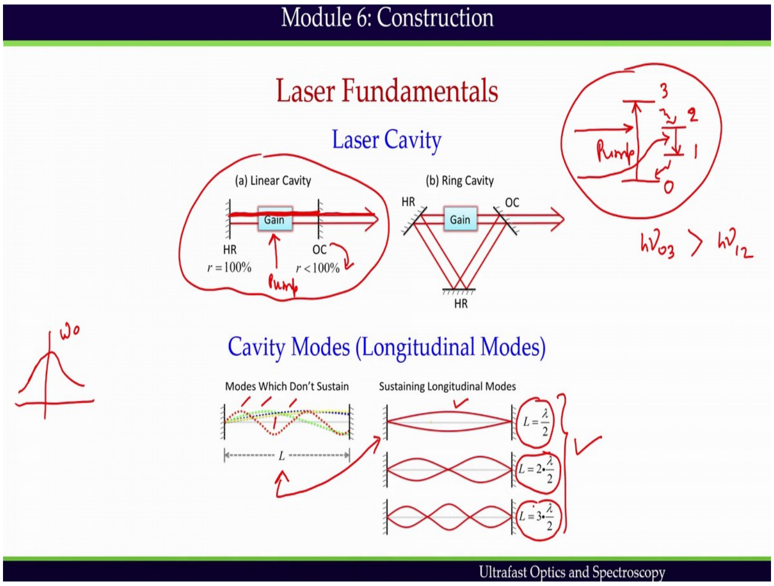

So, we have already seen that to achieve population inversion we need a medium with four level system. Furthermore we have also understood that we need to pump the active medium to achieve population inversion.

So, I repeat this idea one more time, I have a four level system I have to excite and create a population in the upper state with pump, I need a pump beam then with the lower frequency I need another beam to stimulate this. So, pump will create the population inversion and another beam we need to stimulate the stimulated emission. It is quite clear from this figure of four level system that the pump beam does not induce stimulated emission.

We can recheck this one this is your 0, this is your 3, this is your 2, this is your 1 that is the way you have defined previously we see that hυ 0 3 energy gap is different from hυ 1 2 gap. Here 03 gap corresponds to pump photon energy and 12 gap corresponds to photon energy which will be stimulate which will stimulate mediums emission. With this understanding we shall go back to the Lamberts Beers law which states that intensity of the emitted beam grows amplification achieved exponentially with the length of active medium. This suggest that longer the active material higher the laser intensity. In order to fulfill this requirement active medium is enclosed in an optical cavity like the one which is shown here, this cavity is composed of 2 mirrors. So, that emitted beam is amplified each time it passes through the gain medium.

So, I need a pump beam to create the population. So, pump will create the population and then will start stimulated emission at lower frequency and that will go back and forth within this cavity and in the end this output coupler will give me the laser output. Mirrors together make up the laser cavity resonator and maybe can be flat mirror or curved one. The cavity is aligned so, that light reflects back and forth again and again and passing along the same path every time.

Part of the light passes through them partially transmissive output coupler. So, the reflectivity of this output coupler this is a mirror is less than 100 percent and this forms the output laser beam which can be used for the experiment. In closed cavity different standing wave patterns are formed inside the cavity which exhibits nodes at both ends like the one which is shown here and that is characteristic of any cavity which is trying to trap electromagnetic wave.

Considering 2 plane parallel mirrors. This figure illustrates different longitudinal modes of the cavity a longitudinal mode of a laser cavity is a particular standing wave pattern formed by waves confined in the cavity. The longitudinal modes correspond to the wavelengths of different colors which are reinforced by the constructive interference after many reflections from the cavities reflecting surfaces.

The longitudinal modes correspond to the wavelengths of different colors which are reinforced by the constructive interference after many reflections from the cavities reflecting surface. So, longitudinal modes are nothing, but the frequency components. We have been saying that an ultra fast pulse having a number of frequency components and what are the frequency components which are present in the cavity which will which the cavity will allow to sustain this frequency components are called longitudinal modes.

If we compare this 2 figures, then we find that this particular wavelength or the frequency component can sustain in the cavity, but other frequency components like the one this red one, then green one, blue one, this yellow one all of them they cannot sustain in the cavity due to destructive interference they will die. So, a longitudinal mode pattern has its nodes locally a longitudinal mode pattern has its nodes located axially along the length of the cavity.

The longest wavelength which can sustain in the planner parallel cavity of length L is lambda by 2 equals L. Next one is going to be 2 multiplied by lambda by 2 equals L, next one 3 multiplied by lambda by 2 and so, on.

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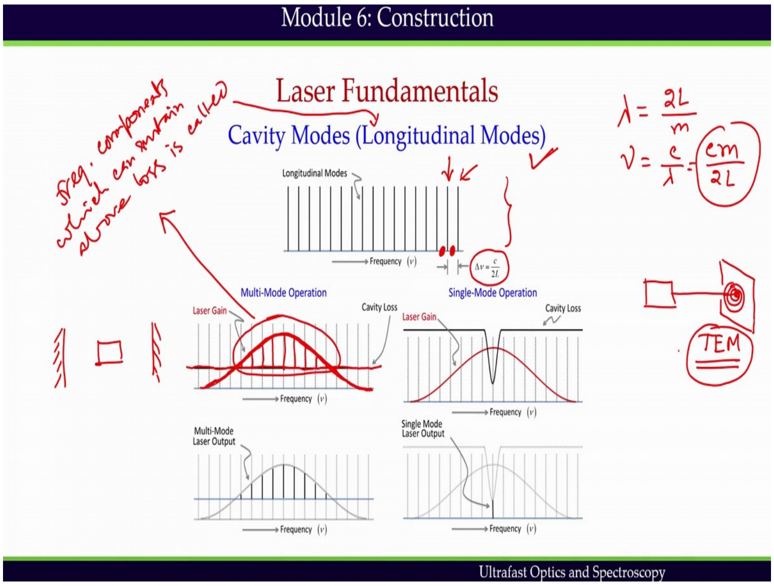

Does wavelengths which can sustain in the cavity can be expressed as lambda equals 2 L by m or in other words the frequencies which can sustain is can be expressed as c m by 2 L. For 2 consecutive modes if we consider this mode and this mode. So, this is a plot of the modes which can sustain in the cavity, we see that they are discrete wavelength components. There is no frequency which can sustain in this regime there is no frequency which can sustain in this regime.

For two consecutive modes where m equals 1 they differ by 1 delta nu is going to be c by 2 L. This relationship states that laser is only allowed to work at certain discrete frequency is given by cm by 2 L. A frequency domain view of basic operation of a laser cavity is pictured schematically in this figure. The resonator loss is taken as frequency independent while the gain is assumed to feature band pass, spectral response a Gaussian emission spectrum of the gain medium.

Let us say I have a medium which shows this spectrum which emits in this regime and this medium is placed in a cavity. In that case all the frequency components present in this emission from the source will not sustain only the portion which will sustain here these are the portion which will sustain. And it will sustain above the loss the medium emission will be observed by the cavity as well.

So, everything which is staying above the laws will sustain and these are the discrete frequency components which can be sustained in the cavity. And this frequency component which can sustain above laws is called longitudinal modes. Here you can remind our self that there is another mode we have discussed that is called transverse electromagnetic mode. When we have a source a laser beam propagating like this way and we place a piece of paper, in the cross sectional section we have seen a spatial distribution of the intensity, that is called TEM mode Transverse Electromagnetic mode and this one is longitudinal modes. So, longitudinal modes are the frequency components which can sustain in the cavity above the laws and TEM mode is the special intensity distribution of the laser.

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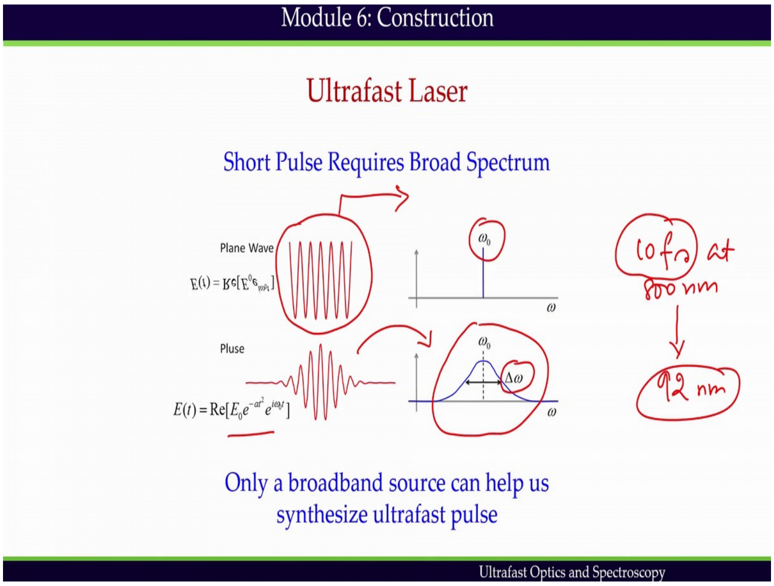

And electromagnetic wave propagation can completely be described using Maxwell's equations which give solution for propagating electromagnetic plane wave and we have seen that. So, if we take a plane wave and if we Fourier transform it, we get a single frequency omega naught.

On the other hand the time evolution of a pulse for an example of Gaussian pulse if we Fourier transform it, then we get another Gaussian envelope in frequency domain having with delta omega which suggests that frequency content of a pulse is larger than the unique frequency of a monochromatic plane wave. Therefore, in order to produce light pulses including ultra fast pulse it is necessary to use a broadband source which can produce this many frequency components.

For an example a Gaussian 10 femtosecond pulse at 800 nano meter center wavelength you have to produce this 10 femtosecond pulse at 800 center wave length I need 92 nano meter bandwidth requirement of large bandwidth to synthesize ultrafast pulse is an important realization.

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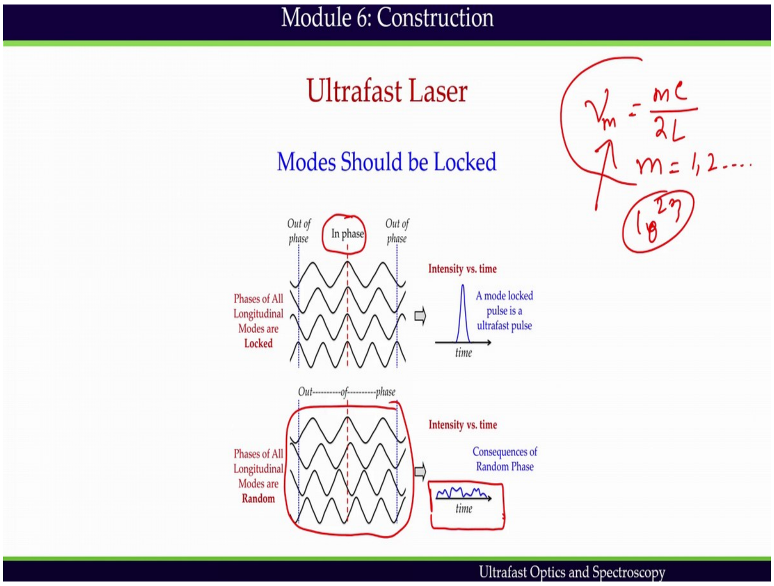

But when we place a broadband source in cavity the laser cavity will allow oscillation of discrete resonance frequencies given by the equation 2 L previously c was q was represented by a m.

So, we can use the same thing m here also and m is an integer, c is speed of light and L is the optical path length cavity and these are the called longitudinal modes. So, we said that we need this longitudinal modes and we need many such longitudinal modes. Let us say we have Avogadro numbers of longitudinal modes which could sustain in the cavity this; however, does not mean that we have produced ultra fast pulse.

So, having this all these modes 10 to the power 23 number of modes does not mean that we will have we have already produced the ultra fast pulse. The phase relationship between the different modes decide whether we can synthesize ultrafast pulse or not which means that let us say I have many such frequency components and those frequency components has to be in phase. And if we cannot maintain a constant phase relationship among frequency components, then will have destructive interference like the one which is shown here and in the end intensity of that system will fluctuate in time. That is why modes which can sustain they should be in phase and then locked.

This is an important requirement to produce ultrafast pulse. Having many frequency components is not the only necessary condition to get ultrafast pulse first we have to get many frequency components and then all the modes should be locked. If phases are not locked instantaneous intensity will show fluctuations on the other hand if the modes are having constant phase difference, the laser is set to be laser is set to operate in mode lock regime.

The purpose of locking the modes is to organize the competition between modes in such a way that the relative phases stay constant which results in ultrafast pulse. In general stimulated emission in a laser cavity creates coherent laser modes; however, due to different factors modes do not stay in phase all the time. In order to create ultra fast pulse we need to achieve mode locking. How do we achieve mode locking?

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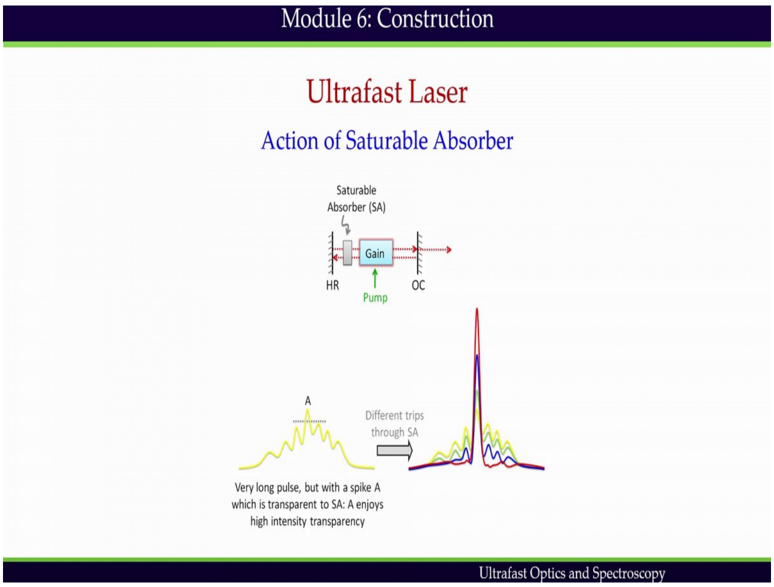

The simple answer is to use saturable absorber. We will stop here and we will continue the subject in the next class.