Nanobiophotonics: Touching Our Daily Life

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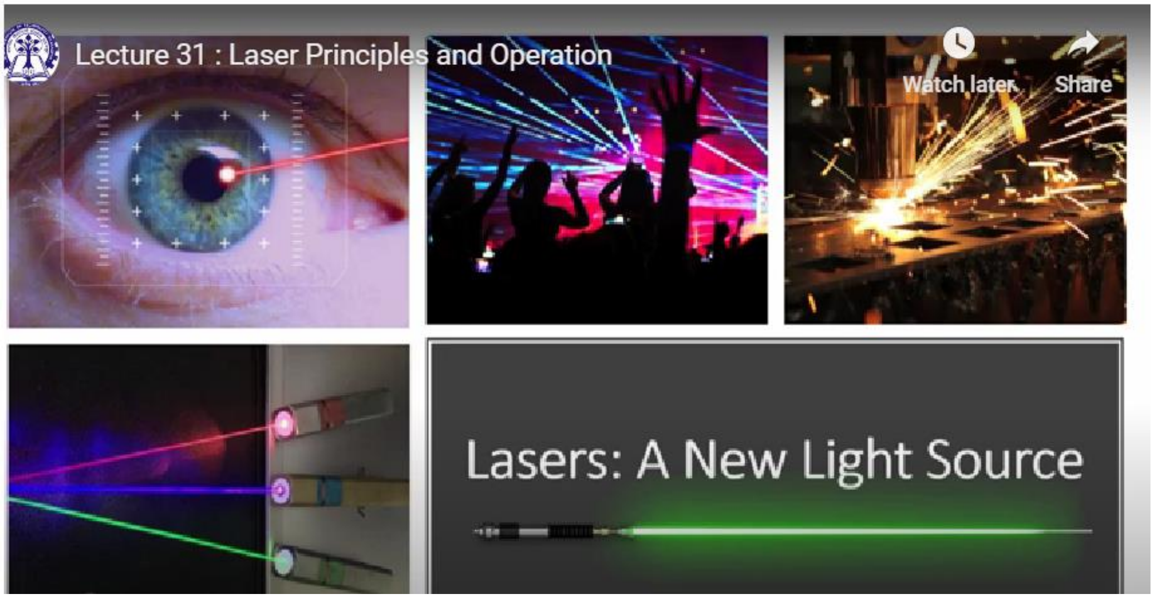
Lecture No. 31

Laser Principles and Operation

So, there is a question for you, who is the inventor of laser? You know laser is considered one of the top 10 inventions of the last century, which has taken human beings to a civilizational quantum leap. So, who invented laser? You all know greatest inventors and their great inventions James Watt, ah steam engine, Thomas Alphere Disson, light bulb so on and so forth. So, who exactly invented laser? All of you have had used lasers, many of you have not used steam engine, but ah in general knowledge question why nobody asks who invented laser? The answer is it is complicated. You cannot pinpoint one particular person and claim that this is the person who has invented laser. Several several different people all over the world work together and all of them contributed in creating this particular light fantastic. Today in module number 7, I am going to discuss laser for biophotonics.

And in today's lecture today's specific lecture, we will be discussing the very very basic of what lasers are, how they work and ah how can you utilize them. Specifically, how lasers like it has contributed and revolutionized several different fields from communication to military to ah on chip making to ah laser welding in fact, your ah laser pointers. How in the in this particular module we will see laser could very well be utilized in medicine specifically for biophotonics. So, in today's lecture I am going to discuss specifically about how laser works.

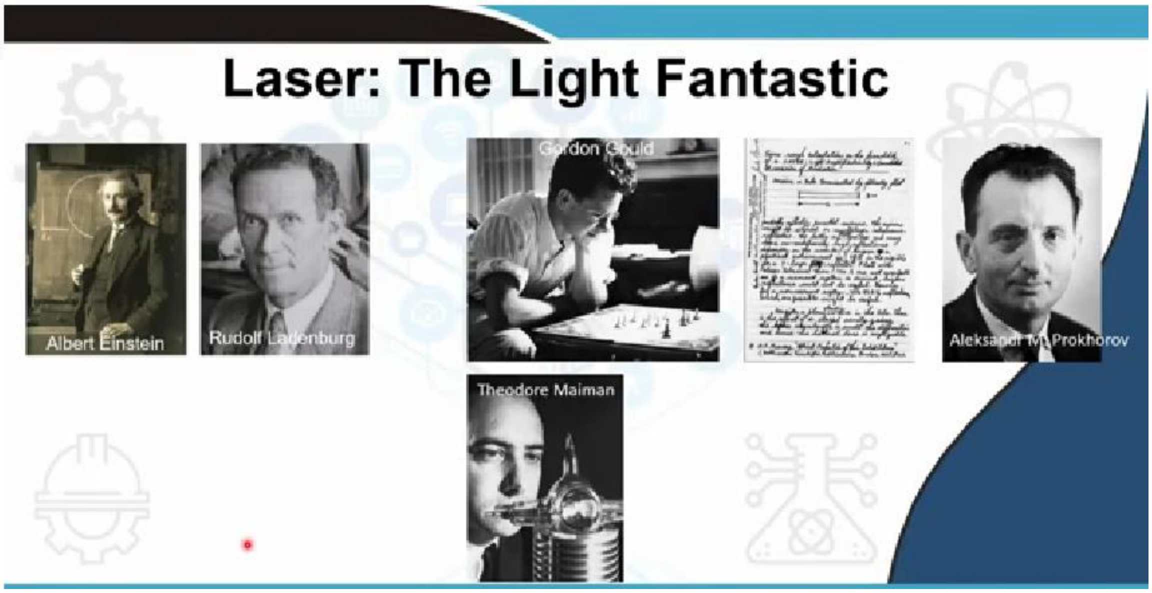
Do not worry I will not bore you with ah tremendous amount of jargon or mathematical calculations. I need it this laser topic will be focused for people from medical or biological science background ah so that they could understand the operating principles behind laser rather than solve mathematical equation. I would like this lecture to be typically specifically catering towards those people who are from a medical or life science backgrounds right.



So, let us start you know laser is ubiquitous it is everywhere around us. In medical field we are using it in ah laser eye surgery all of you have probably heard of LASIK cataract operations ah several other type of operations as we will see in our ah coming lectures laser is used.

Many of you must have visited the discotheque where laser light show entertainment shows takes place laser based will ah welding and cutting takes place which which which cuts precisely at a very small scale level. Of course, you have the ubiquitous laser pointer these days it is available ah very cheaply in the market and you probably have seen or particularly used it in ah while giving presentation while giving lectures. Apart from this of course, laser has several other applications as I was mentioning communication military application ah so on and so forth. So, much so that laser is being considered one of the top 10 inventions of not just last century, but of humanity in general right laser-based communication has converted it. And those of you who know what actually this is may the force be with you right.

So, what exactly is laser first and foremost is it is a coherent light source remember coherence coherence means that the photons photons are ah particles of light we are at the end of the day studying bio nanophotonics ah each photon or each wave that comes out of the laser light source maintains perfect coherent relationship with each other. They are either phase matched or they have at the same time they have specific wavelength specific frequency specific energy they could be focused in a very very tight spot light diverges lasers are generally generally non-divergent they are usually monochromatic. So, you will have one energy one wavelength one frequency and depending on how intensities the losses to a large extent can also be controlled as compared to a normal normal ah light bulb or a light source.



So, what how exactly this came into effect what exactly transpired ah so that laser per say was invented. So, how this all started well like everything else in modern physics it started with Albert Einstein and Rudolf Landenburg.

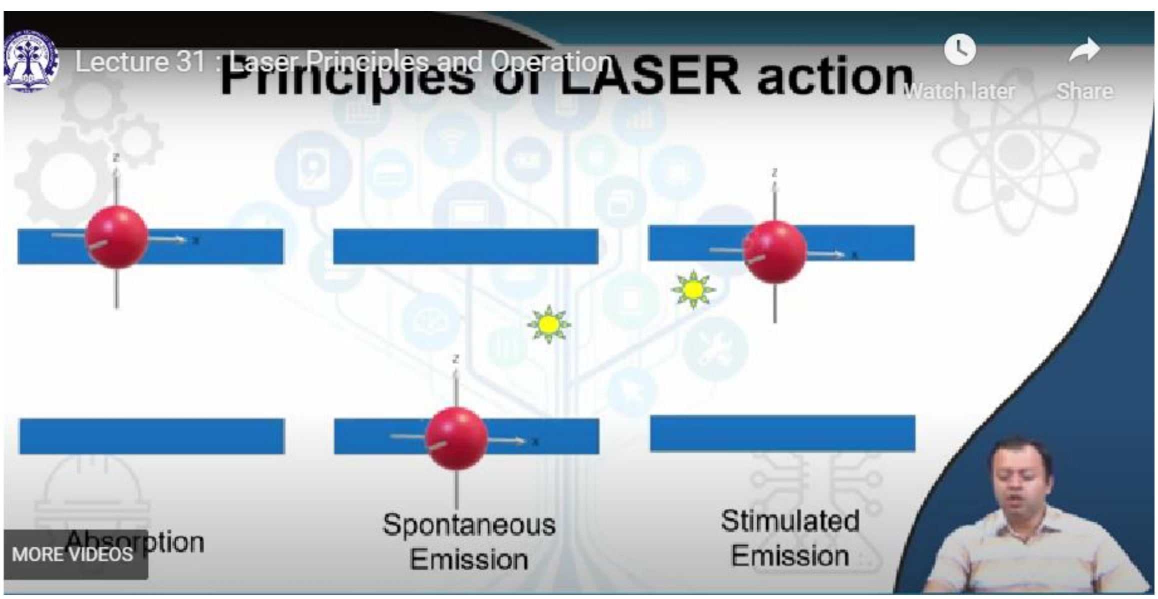
Rudolf Landenburg was one of the first German scientist one of the first German scientist who left Germany in the early 19th century because of the coming of Nazi party into power he was Jewish and he left and went to America and he helped in the relocation of several German Jewish scientists to America where they ah worked either together or simultaneously different universities in developing different ah concepts of physics which we all study. So, Rudolf Landenburg came up with this ah notion of negative absorption you know absorption photon comes electron absorbs and goes to a higher energy state the photon is consumed. So, the consumption or eating of the photon is called ah absorption Rudolf Landenburg came up with the term of negative absorption in which upon interaction with a photon upon interaction of electron with a photon the electron does not consume the photon, but emit another photon right. Albert Einstein modified it and came up with the idea of stimulated emission stimulated emission is just exactly that in which an electron upon interaction with a photon emit another photon. Now, we absolutely absolutely certain what I am talking about right we have discussed previously spontaneous emission electron consumes light electron consumes photon goes from lower level to higher level right after staying in higher level for a period of time 10 nanosecond, 1 nanosecond, 1 attosecond, 1 picosecond it returns back it returns back while emitting a photon out that is spontaneous the process is run random what time it will come back you do not know from 0 to 10 to the power ah minus 9 second some some some time it will come right 10 to the power minus minus 9 second is almost 0, but not 0 from 0 to this time any any any time it will return back it is spontaneous it is random you have no control over this.

This is stimulated this is negative absorption here while the electron is at top level while the electron is in high energy state it is interacting with another photon it is interacting with another photon this interaction this interaction results in the electron to drop down emitting another photon. Meaning this will only happen with underlining on the term only this will only only happen when the electron is interacting with another photon electron will emit a photon only when it is interacting with another photon if you switch off the photon if the light is switched off it will not emit it can emit randomly at a different period of time, but you will not be controlling it. So, that is another type of emission which Albert Einstein ah said had stimulated emission you are stimulating it you know stimulations you give some external conditions this external condition result in this emission previous was spontaneous emission spontaneous by itself you talk about this person is very spontaneous by himself or by herself the person starts singing or dancing or so, spontaneous emission your work is done you have taught that electron is emitting photon. Stimulated emission when an external condition needs to be matched needs to be fulfilled you are asking you are pressurizing that person to sing yeah that is the overall difference. So, anyways these were all theoretical calculations these were all theoretical calculations and people were thinking ok new type of emission have had been discovered we have fluorescence we have phosphorescence most of them are spontaneous emission right, but now we have another type of emission which is stimulated emission which is also theoretically possible, but ah have you seen it or have you actually prepared a material which shows stimulated emission where have you actually seen stimulated emission.

So, it was not there till these gentleman were ah working actively only after world war II when technology was ah you know growing by leaps and bounds mostly because of the cold war the Americans were afraid of what new technology the ah Soviets will discover Soviets will invent Soviets were ah afraid what new technology Americans were discover will discovered. So, they were each ah spending huge amount of money in science and development and you know about space race between Soviet space space mission and NASA and who won the final space race and what not. So, it was not just in space, but every other field of technology driven science. So, basically engineering large number of people were trying to see if a device working on spontaneous emission could actually be utilized actually be created actually be developed. While many people were discussing this PhD student in New York ah Gordon Gould came up with an idea that yes spontaneous emission could actually be done and it could be done using two sets of mirrors resonator basically something that captures the photon and resonated like a ping pong ball like a tennis ball.

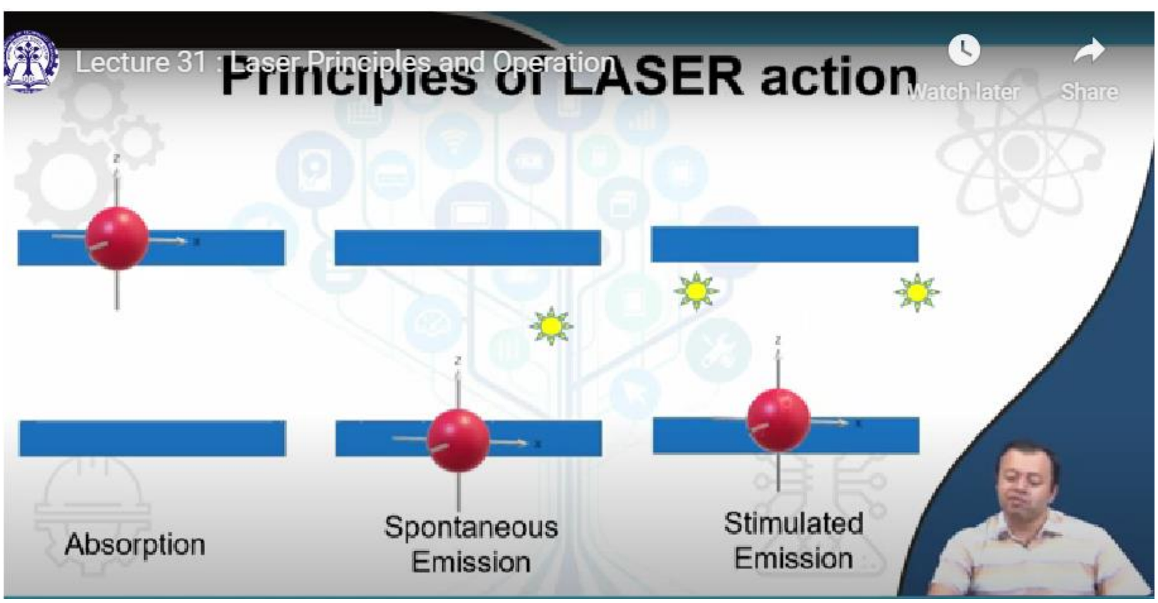
So, the light is captured between these are two mirrors these two mirrors it will be resonating inside and something of that could be created to make a proper working device which we which he used the term I do not think he used the term at because at that time they were talking about microwave is a microwave amplified by stimulated emission similarly infrared emitted by stimulated emission amplified by stimulated emission. I think he came up with similar terms I am not sure whether laser was coined by Gordon Gould or not, but anyway he came up with the idea that any photon which falls in these two mirrors will bounce off and the overall result could create something like a light amplification light will get amplified stimulated emission will be created. However ah he did not patented the idea he simply notarized it and then was a huge litigation ah people from ah New Jersey I think ah Bell laboratories used his idea and they were fighting legally who discovered this first while the idea the device was still not being made the idea because many people saw that idea and decided yes it is a workable idea by following this idea by following this blueprint people can do it ah. Theodore Meiman ah and I think west coast made the first ruby based laser that was the first laser I think something around 1968 69 something of that, but I am bad with dates. So, ah ask my wife so figure that out which date.

So, Theodore Meiman in west coast made a ruby based laser while he was doing it Alexander Prokhorov and rest the Soviet scientist were also doing their independent research and they demonstrated something in Moscow, but only ah to select few public officials not everybody. So, there is a fight between all of these people technically who actually contributed or who actually created laser people have got Nobel prize in utilizing laser or understanding laser, but there is not one single inventor of laser light.



So, let us get straight into it what exactly are the principles of laser action. So, you all know absorption there is an electron at a lower level you send or ah you send a particular frequency of light this particular frequency of light has to match the band gap the gap between valence band and conduction band the valence between homo and lumo upon consuming this particular photon the electron will go up this is absorption simple absorption the light is consumed the light is eaten up. After staying in this upper level after certain time the electron will decide to return back while emitting the photon that it has consumed.

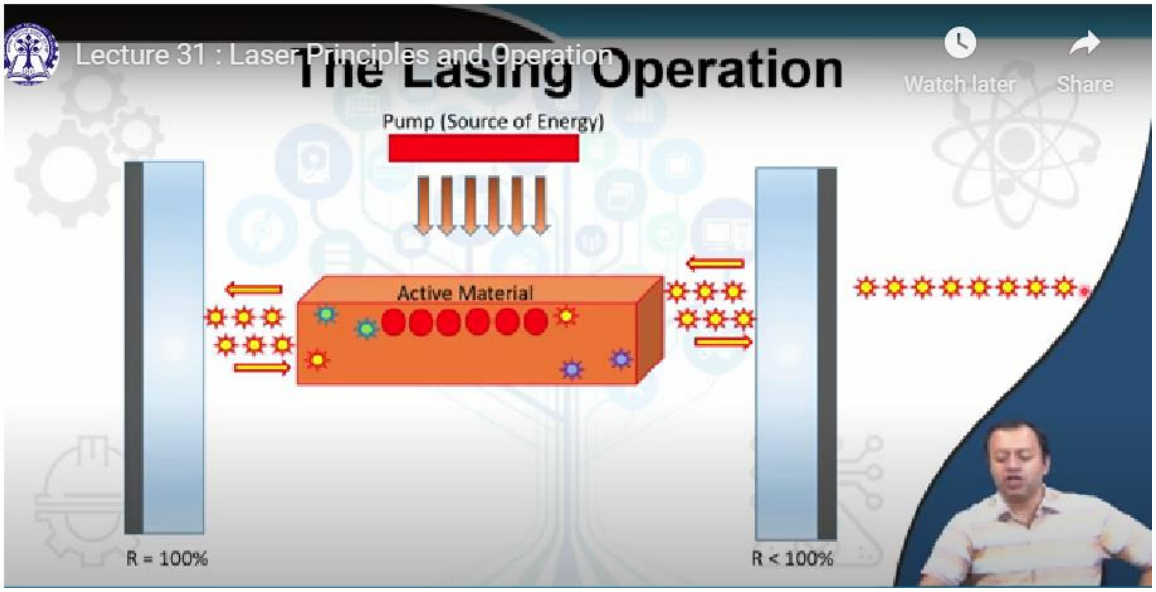
Now, in spontaneous emission there is a loss because this part is very thick we have discussed this this part is very thick, but suppose suppose this is a normal semiconductor like a silicon or anything like that where silicon would not happen because silicon would not emit photon, but say a direct band gap semiconductor the same photon that it has absorbed will more or less be emitted absorption is eating spontaneous emission is excretion yeah you will never forget one is eating one is taking it out. Stimulated emission stimulated emission is that when while the electron is still up while the electron is still up in the upper level it has not returned it has not returned at this particular position you are subjected it to another photon. The fundamental principle that you have to maintain is that this photon will be of exactly same energy of this band gap meaning this photon will have the exact same energy of what the electron is presently there should not be any difference between the energy of the this photon and energy of the electron if this is higher then this will go further up if this is lower this will have very little effect, but if this energy and this energy matches what will happen when two energies are matching side by side there will be no change in energy right if your temperature if you take a body with temperature 23 degree Celsius and another body with 23 degree Celsius temperature you you attach them together you you you stick them together do you think there will be a flow of temperature will one become 0 and one become 46 degree if you have current flows because there is a voltage difference yes if there is a same voltage into this side and that side will current flow.



So, if this energy is exactly that of this energy the electron will not go up however the electron will be knocked out will be knocked out from its state and it will return back to its ground state vomiting vomiting out the energy that it has consumed before. So, this photon is simply send not it to be absorbed because it has already absorbed this photon it has already absorbed this photon when it has come up it has already absorbed this photon when it has come up it cannot absorb anymore it cannot absorb anymore if the frequency if the energy if the wavelength is exactly same this photon is simply given to knock it out think about it in billiards or in carom this photon has only one work this is there to knock out knock out the electron which was in the top place it will knock out vomit the photon it has consumed before it is eating this is excretion this is vomiting you will never forget this if you remember this analogy eat excrete vomit right this is vomiting out.

So, you see this photon is not consumed. So, this photon exists as it is it is simply there to knock something over you have seen in billiard or in carom one coin or one billiard ball is used to knock another out it exists it is not consumed it is not destroyed instead it is producing one more. So, the total is two photon previously there was one photon which you have somehow figured out from external source, but this has not been destroyed this stays as it is this has generated another photon this has generated another photon combination of these two photon combination of these two photon will go on knocking out several of these electrons which were in other ah energy level higher energy levels and will the population of photon will simply increase the original photon is not consumed keep in mind the original photon is not consumed it is simply given to knock something out it is given to knock the electron out as soon as the electron gets knocked out it vomit it vomit the photon of the exact same energy that is what it has consumed that is what it has consumed. So, this photon and this photon are exactly same energy they will go on knocking out other electrons which exist in same conditions. So, they will keep on generating more and more photon no absorption is taking place.

So, what is happening if you give one photon input two photon output so on and so forth how does that work is that not amplification and is that not amplification stimulated emission. So, that is what the acronym stands for light amplified by stimulated emission of radiation that is it. So, that is overall the principle of laser you have to create something you have to create a system where the photon is given simply to knock out high energy electrons existing at high energy states condition the photon has to be of the exact same energy that the electron has previously consumed and gone up it cannot be any mismatch.



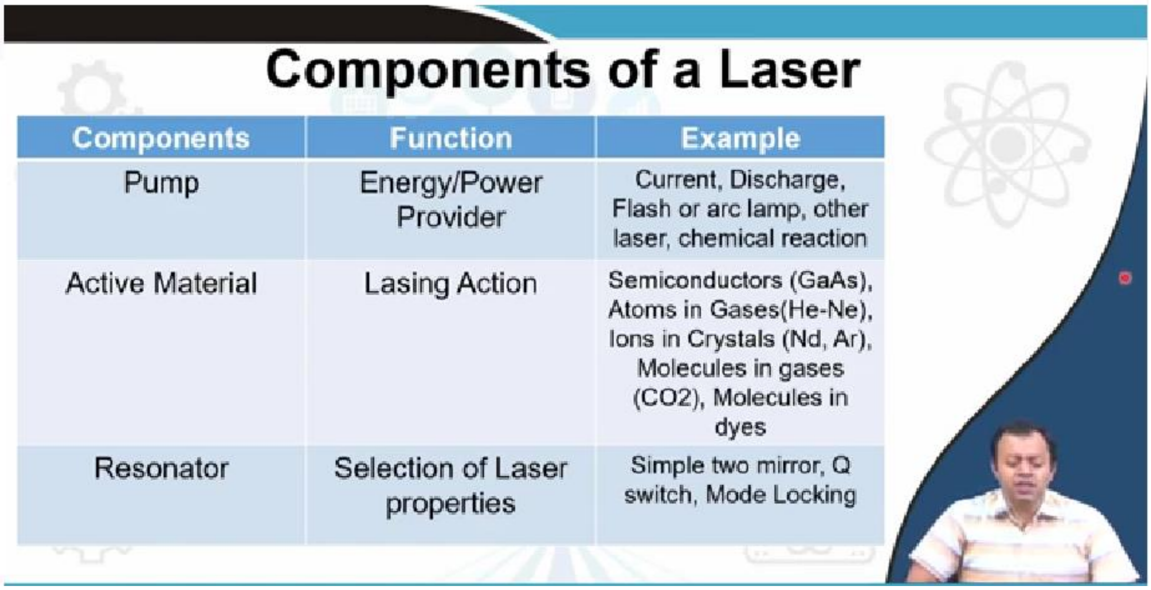
So, how does laser operates all you need is an active material active material is material which has band gap which basically more or less everything except probably metals because here in metals you tell me what happens in the band gap of metals electronics engineers will be chuckling, but ah figure it out why metals are not I will not be giving you all the answers active materials in many material which has discrete energy levels which could be populated and depopulated. So, active materials suppose at the ground at the 0th position ground condition have all the electrons in the ground state right you use a pump a source of energy and you use two mirror.

So, this active material is put inside two mirrors I have purposefully not put the mirror here and here, but the mirror you can consider it as spherical mirror or mirror a cavity the entire active material is covered is surrounded by two mirror for simplicity do not think there is empty space here these are also covered by mirror, but for simplicity two mirrors this mirror has a reflectivity of 100 percent this mirror has a reflectivity less than 100 percent 90 percent 99 percent 95 percent meaning whatever light falls into this mirror it reflects back whatever light falls into this mirror 90 percent of it 98 percent of it is reflected back some percent can also transmit out also transmit out. So, three things are required for laser an active material any material that has any material that has band gap lower energy level higher energy level you have a source of energy an external source of energy external source of energy can be voltage source battery it could be electric current it could be some kind of a chemical reaction it could be heat it could be laser light from other source so on and so forth any energy source as long as it produces enough energy for the electrons to consume and go from lower level to upper level as long as the band gap is covered as long as the band gap is bridge. So, what happens the pump source of energy just like your water pump that pulls out water from ground underground to the to the tank which is situated at the top of your apartment. So, pump is giving energy so that electrons which are at a ground level goes upstairs go to a higher energy level ok. What happen then well when they return back they start emitting spontaneous photons spontaneously they will sometimes some of them will stay some of them will return back as they return back they will emit different types of photons spontaneous emission spontaneous emission.

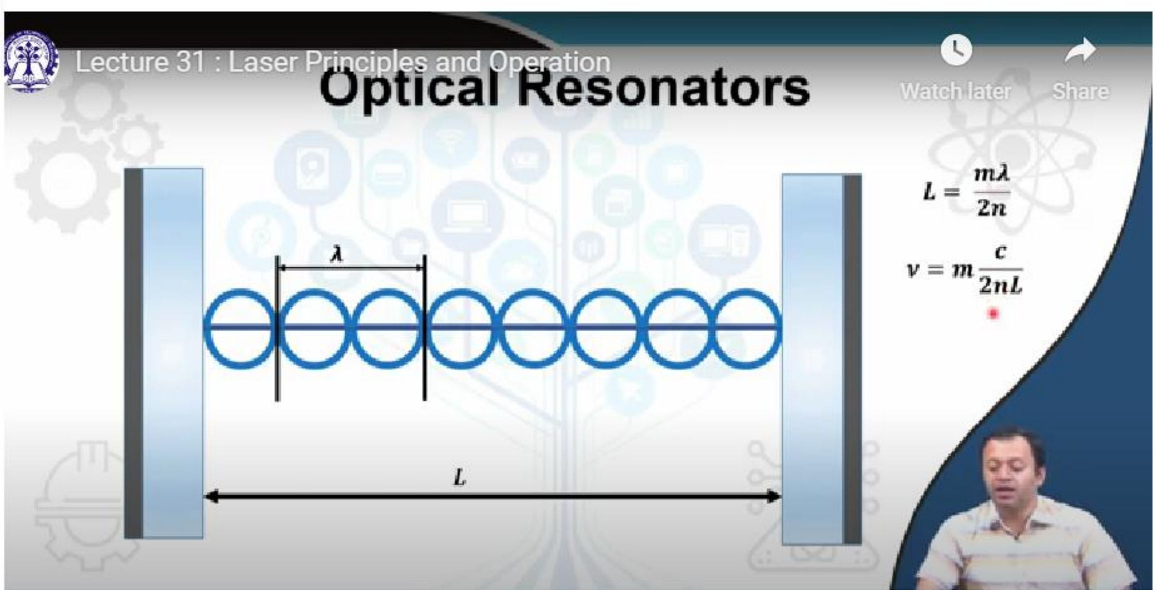
So, in the first case as the pump was given as the pump was given there was absorption after absorption spontaneous emission took place spontaneous emission took place at random time all of these electrons which has gone up will not simultaneously be coming down some come now some come later it is a random process a large number of different energies was produced different wavelengths can be produced from the pump. So, the electrons can go not only from 0 level to ah level 1 it can go to level 4 level 6 level 10 and they can all return back at different time emitting different types of photons and different energy etcetera. So, these photons will go out of the active material assuming the active material is light emitting material that has to be the conditions etcetera it has to ah emit photons ah. So, they will ah go out of the active material they will fall on to the ah cavity fall on to the mirror. Now the mirror is actually a resonator here you need to understand the mirror is a resonator I have a slide to tell you exactly what it does, but the length of the mirror allows allows only a particular photon to stay how it interferes it produces interference pattern different type of light wavelength comes out of it all because this is a mirror this is a mirror they interfere they overlap on one another the light is coming out and there it is returning back it is interfering among each other only those survive which has positive interference which has 100 percent positive interference only those electrons ah photons will survive into the cavity inside the resonator which is a whole number of the length of the distance between them.

I will tell you this mirror acts as a filter it allows only one type of photon to exist this mirror this cavity this ping pong ball type mirror allows only one type of photon to survive only one frequency one energy one type. Since it is a mirror all other mirror cavity all other photons are simply destroyed one type of photon survives and that is fed back into the system back into the active material the active material initially produces spontaneous emission spontaneous emission produces large number of different type of photons of these different type of photons only one type of photon is chosen rest of the photons are simply killed off simply killed off I will show you how I will show you how, but for the time being assume all the other photons are simply killed off one photon survives that photon returns back into the active material that photon is your input photon that goes back into the active material. Here in the active material it will find still some electron which are at the upper state has not returned back has not returned back it returns back simultaneously there could be some who are still in the upper state what will this photon do it will knock out one of those electrons which are still in its upper state and this upper state will be knocked down by emitting another extra photon like I showed in the previous slide this will again be feed back into the system and a chain reaction will keep on happening I told you previously this has less than 100% reflection whatever light falls into this mirror everything is fed back whatever light falls into this mirror 90% of this is fed back 90% of this is reflected 10% or 8% or 5% or 2% is transmitted out the transmitted out single frequency coherent one type of photon is your laser it is that simple that diabolically simple three thing you are required active material something that has electrons at a lower level can go to upper level and while returning back can produce light if it produces heat or produces vibration it would not work active material is such that pump any energy source. So in laser all three things happen all three things happens absorption pump gives you energy electron goes up then the electron depending on them sometimes coming out going down start emitting random photons of these random photons one is selected rest of them is cut off rest of them is absorbed rest of them is destroyed that one photon that comes back is reflected back into the system while it is back into the system there are still some electrons still in the upper level you pump one more time you pump one more time does not matter you pump several times does not matter there will still be electron in the upper level. So this photon that has existed that has made to be alive inside the system inside the mirror system returns back returns back and knocks this electron down resulting in creation of similar type of another two photon it comes out it again get reflected back into the system you have pumped again the electrons are up those specific electrons matching that of the band gap of this photon energy is knocked out more photons are produced chain so on and so forth the chain reaction goes on of this chain reaction of specific set is taken out.

Same energy same frequency same wavelength very coherent this is it this is exactly lasing operation this is nothing more complicated than that and that is why it is considered one of the top inventions of human kind this is this diabolically simple there is nothing more complicated than that.



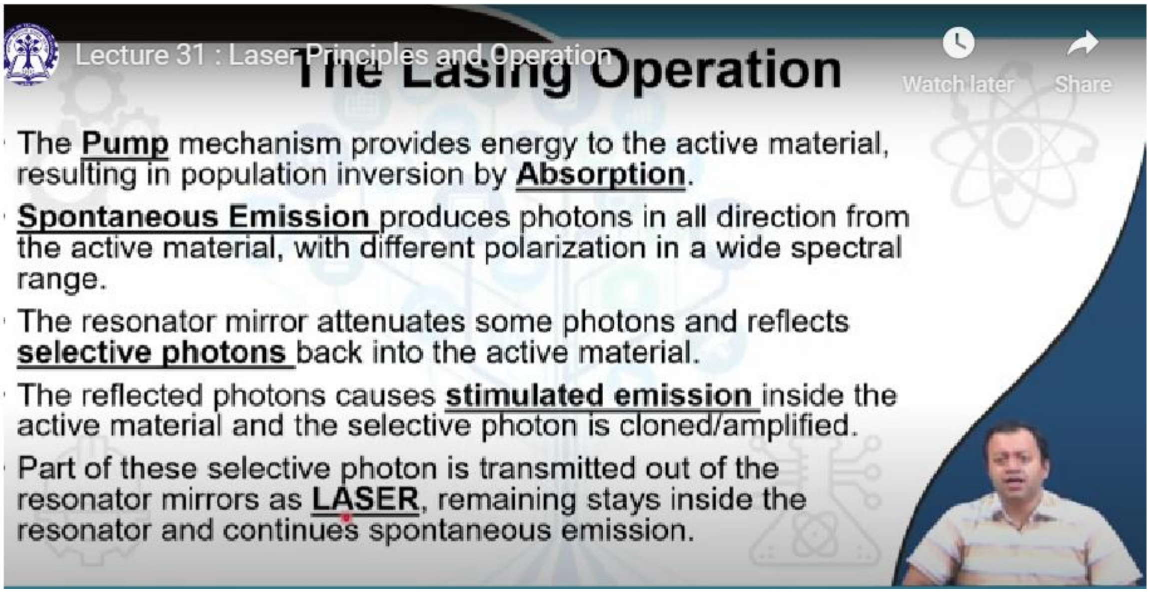
So all three things pump active material or resonator resonator selects the laser properties simple two mirror q switch mode locking you do not need to worry too much about them just simple two mirror for the timing will do lasing action is any semiconductor direct band gap semiconductor atomic gases remember the it not necessarily always that electron needs to go from lower level to upper level as I showed you molecules or atoms can also go from lower level to upper level as long as there is a band gap between them and as long as while the atom returns back to the original state it emits a particular photon be it a low energy photon infrared or mid infrared or something like that energy could be current discharge flash.



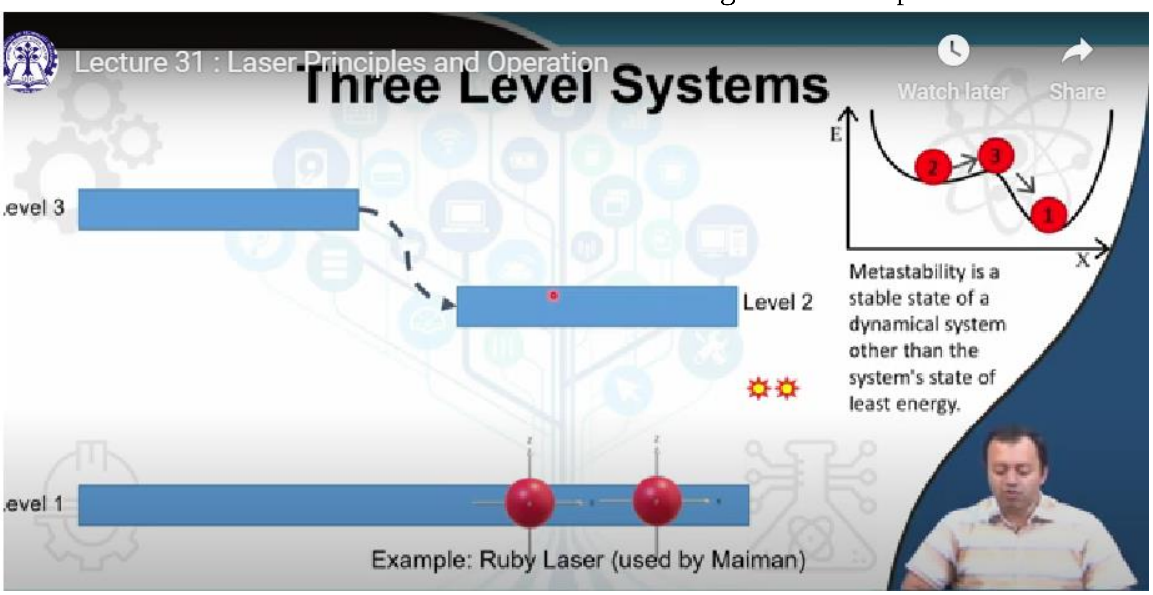
Now let us come to the question optical resonator what exactly are optical resonator optical resonators allows only whole wavelength to come through. So, the lambda the frequency the energy of a of of of a photon which survives into the system which survives into the system has to follow this particular law. So, m is the mode considered as one n is the refractive index of the medium between lambda by 2.

So, the length of the cavity the length of the distance between the two mirror has to be the length l is equal to lambda by 2 m can be considered as 1 mode 1 n can be considered refractive index as 1. So, meaning if you are trying to get say a green light of 500 nanometer first and foremost you have to figure out certain active material that has band gap one of the several band gap within 500 nanometer range. Secondly you have to put that active material in a cavity in a mirror arrangement in a resonator with length 500 nanometer by 2 which is how much which is how much. Now tell me why nanotechnology is important and why only this was available after the advent of nanotechnology after IC design has come. What it means that optical so whatever electro whatever photon is generated here they interfere with each other right they will generate they will hit this mirror they will return back they will hit this mirror they will return back they will overlap they will interfere among each other.

Depending on their phases either they will interfere destructively or they will interfere constructively. The condition here is in order to have constructive interference L has to be lambda by 2 L has to be lambda by 2 or the frequencies m c and L c is speed of light n is again refractive index m is the mode mode simply means there are 500 1000 1500 these are the different types of modes do not worry about that for the time being considered m to be 1. So, so this length has to be lambda by 2 length has to be lambda by 2 meaning in order to have constructive interference in order to have constructive interference all other photons are simply destroyed only that photon will survive that can have a full circle full circle resonance when it is interfering with each other and that depends on the overall length. You can control this you have the active device which we have figured out what is its band gap you have a pump that is it will work right.

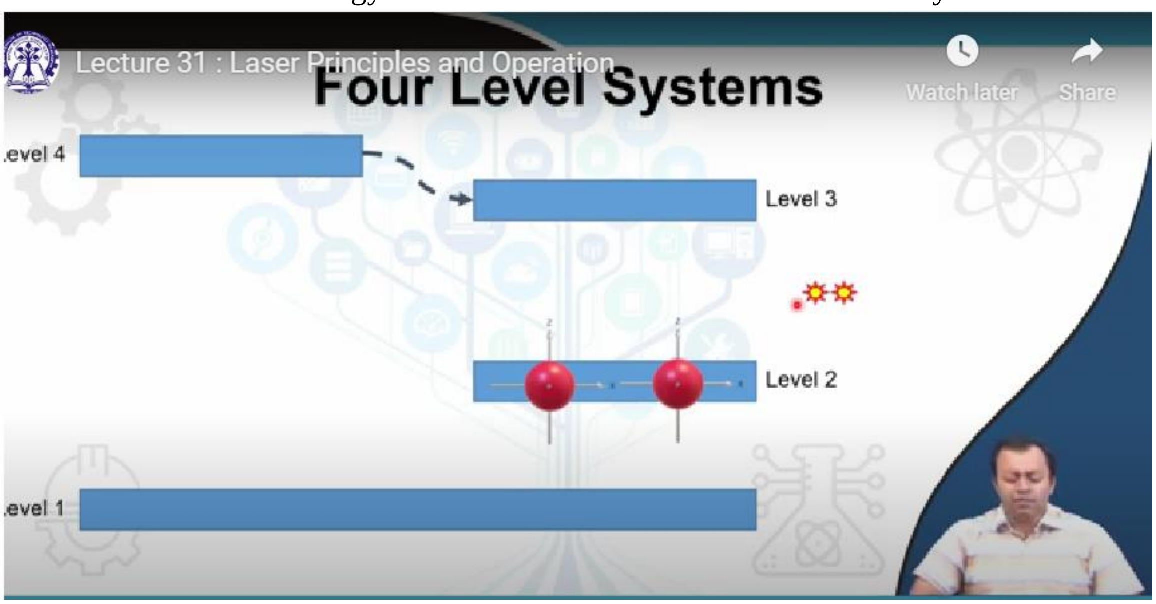


So, the lasing operation simply requires a pump mechanism that provides absorption spontaneous emission produces photons in all direction in the active material the resonator mirror attenuates eats up some photons and reflect selective photons back into the active material the reflected photon cause stimulated emission and part of the selective photon is transmitted out and that is lesser that is it nothing more complicated than that.

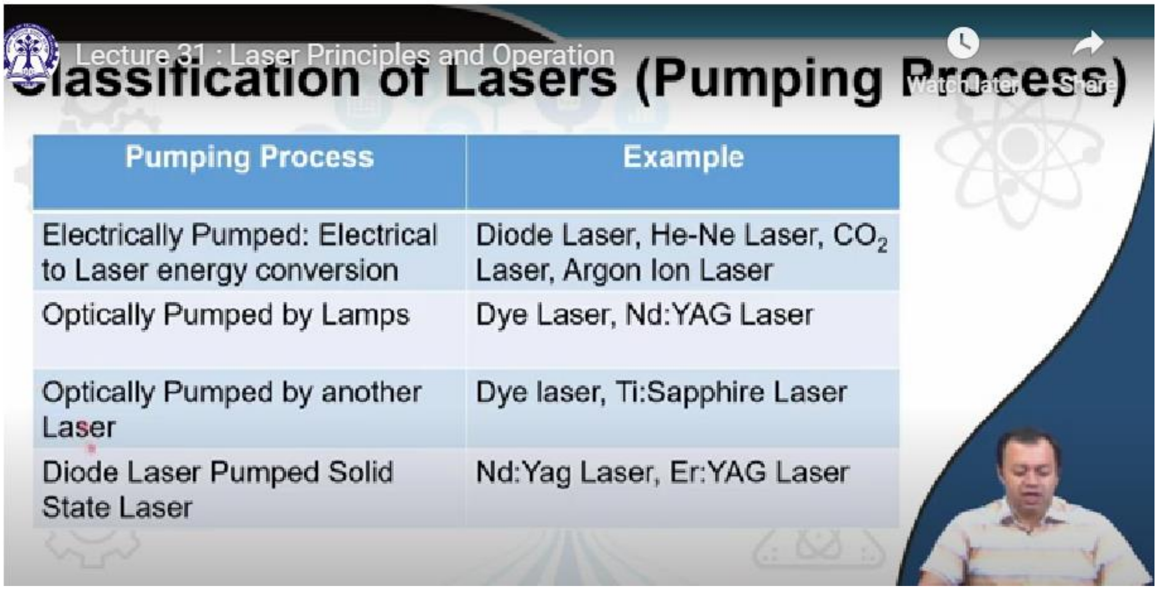


We need to understand one more thing here and that is that the two level system lower level and upper level is very unstable yeah it is very unstable because as soon as electron goes up it can come down as you know less than few nanosecond. So, it is better if we create a three-level system a three-level system is in where there is a defect state in between remember phosphorescence. So, this level 2 this level 2 is below level 3, but greater than level 1. So, it is I think it goes first here stays there and then return back that gives you enough time for the reflected photon to hit this to hit this rather than hitting here because this is unstable. You have a meta stable state you have a defect state in between level 1 and level 3 level 2 which gives you some more amount of time some more amount of time for the reflected light to produce stimulated emission because in first case it may so happen that by the time your stimulated emission has return your reflected light has returned back all the electron has come down.

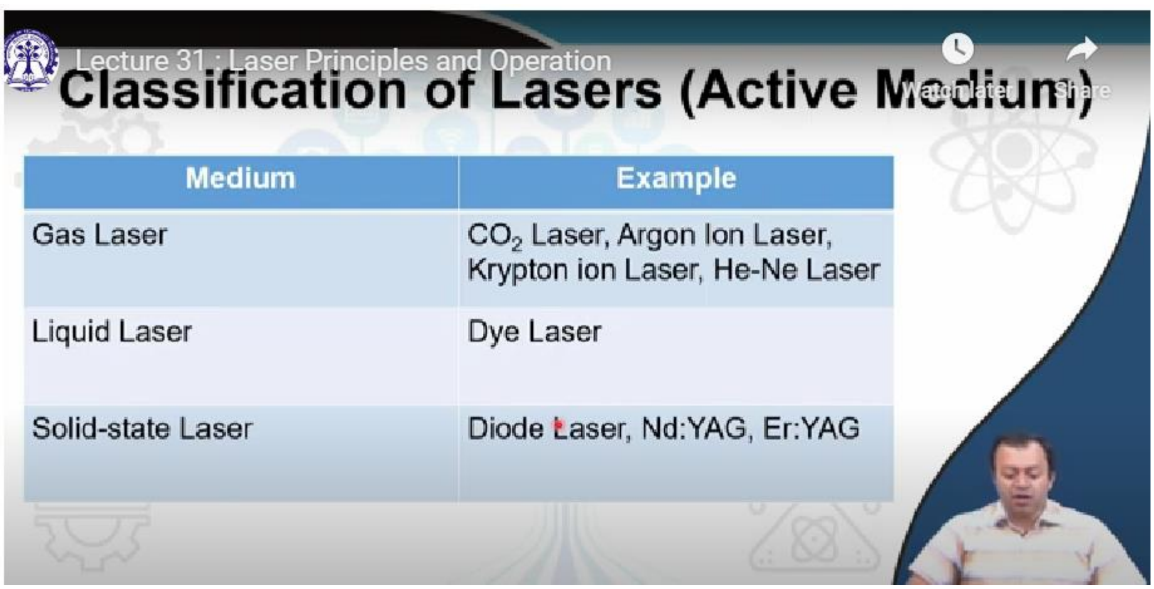
Yes you pump again and again, but that is time consuming cost wise you want to make it smaller. So, this is basically a meta stable state meta stable is a stable state. So, although 2 is less than 1, but ah 2 is higher than 1, but it is still at lower energy state than level 3 is a stable state of dynamical system other than the systems state of least energy. So, level 2 is meta stable it is lower than level 3 and higher than level 1 and this is an intermediate step this step is used as a staging ground a defect state where electrons after pump can return back and stay for a longer time than few nanoseconds. This is the example of the ruby laser used by Maimon ruby naturally occurring ah precious stone semi precious stone it has large number of defects defect state produces this intermediate quantum state intermediate energy state and they exist.



Of course, 4 level systems are also there 4 level systems are the one that you create these days artificially and they are the one which causes the laser to form it goes from level 3 to level 2 and the difference between level 3 and level 2 is your laser light. Meaning the electron do not need to return back to level 1 there is no requirement for the electron to return back to ground state as long as it is returning from a higher energy level to lower energy level can level 5 and level 4 or level 6 and level 10 cause for ah laser theoretically yes, but practically no because those states as you know are very very unstable. If you have produced some kind of stability in between 2 levels level 4 and level 1 you got yourself a laser there are thousands of ah mathematical equations to solve this, but my idea here is to give you simply simply some sort of an overall understanding of how laser works. So, it returns back to its original state helium neon or yttrium aluminium garland garnet yttrium aluminium garnet neodymium these are the cases of 4 level lasers.

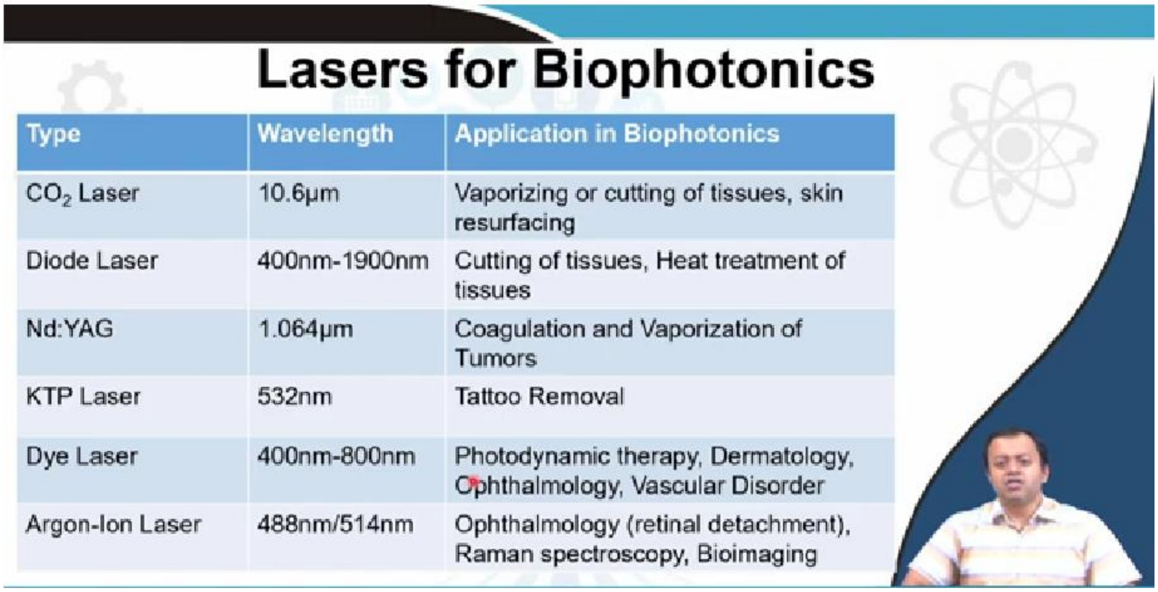


So, lasers can be classified according to their pumping processes different types of pumping process optically pumped diode laser pumped electrically pumped and these are its example you can read it at your own leisure



there is classification of lasers according to different type of active medium carbon dioxide laser argon ion laser ah liquid lasers are dye lasers all different types of lasers have been produced even they produce laser from one single atom as long as they are discrete energy states.

Metals it is difficult, but not impossible and you need to have material that that has the capacity to emit photon it cannot be indirect it is very difficult to produce energy ah light out of silicon though we are hearing about this thing called silicene though the practical applications needs to be accepted.

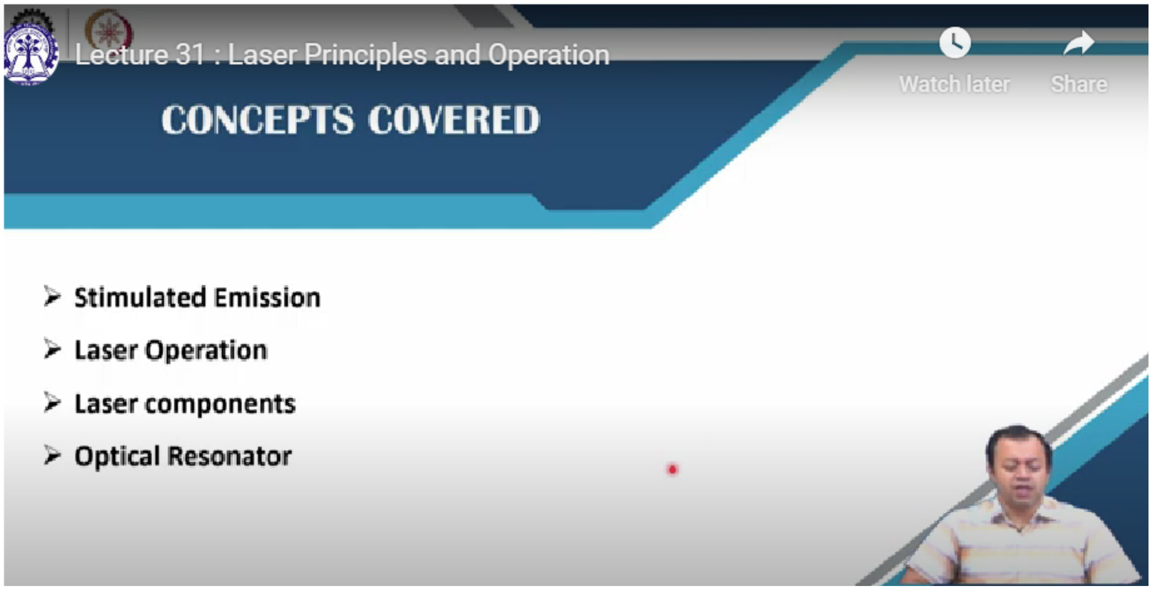


Lasers for Biophotonics

Type	Wavelength	Application in Biophotonics
CO_2 Laser	10.6μm	Vaporizing or cutting of tissues, skin resurfacing
Diode Laser	400nm-1900nm	Cutting of tissues, Heat treatment of tissues
Nd:YAG	1.064μm	Coagulation and Vaporization of Tumors
KTP Laser	532nm	Tattoo Removal
Dye Laser	400nm-800nm	Photodynamic therapy, Dermatology, Ophthalmology, Vascular Disorder
Argon-Ion Laser	488nm/514nm	Ophthalmology (retinal detachment), Raman spectroscopy, Bioimaging

Where are lasers applied in biophotonics this I have to tell before I conclude that laser is one of the most prominent light sources used in medical field specifically when it comes to biophotonics. Almost all the various medical diagnostic systems from MRI to CAT scan to your laser scanning confocal microscope to everything have some something of a laser source that utilizes either the main process or a subsidiary process that is quite important. And you utilize it for various processes CO_2 laser was used for a long period of time in eye ah operations skin resurfacing these days diode lasers are used for you know laser-based operation cutting etcetera. Time yag is used for vaporization of tumor similarly tattoo removal is used by KTP laser dye laser used for photodynamic therapy will be reading a bit of photodynamic therapy.

These days argon ion laser 488 nanometer is used for ah ophthalmology eye operation previously CO 2 laser have had been used, but ophthalmology these days use argon ion lasers. So, lasers have had fantastic applications in biophotonics. So, we will be concerned more about that rather than finding out the theory or mathematical equations with lasers. If you are interested either drop me a mail or ah go for some particular physics class where this is a subject not a chapter of 30 minutes laser is a particular course module.



So, these are the concepts that we covered these days and these are my references please

go through them if you want to know bit more about laser and I will see you in the next class. Thank you.