

Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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Week – 04

Lecture - 16

Introduction to Lasers

In today's lecture, we are going to look at just a very brief summary of the introduction to laser physics. So this material is taken from Laura Corner at the Cockcroft Institute for Accelerator Science, Liverpool, and the CERN Accelerator School. So let's get started. So we are going to, these are some of the reference materials where you can see the different things that, for example, lasers and principles of lasers, et cetera. So we will cover what a laser is, the basic laser physics, and the different types of laser systems.

Introduction to Laser Physics

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CERN Accelerator School
High Gradient Wakefield Accelerators

Sesimbra, Portugal, March 2019

Outline

- What is a laser?
- Basic laser physics
- Different types of laser systems.
- High power lasers

Suggested reading:

- 'Lasers', A.E. Siegman, University Science Books
- 'Principles of Lasers', O. Svelto, Springer
- 'Laser Physics', S. Hooker & C. Webb, Oxford University Press
- 'Optical Electronics in Modern Communications', A. Yariv, Oxford University Press

So laser is the acronym for Light Amplification by the Stimulated Emission of Radiation. You can see that it is light amplification by stimulated emission of radiation. We'll see what that means. We are all familiar with lasers, from light emitted by laser pointers to eye surgeries where lasers are used. And the materials that we are going to cover later, like BIV, LDV, and PDPA, all use lasers in one way or another.

So it is almost mission-critical to have lasers as part of your suite of measurements. And that is where we come from. Laser has many other utilities as well, which you already know. Even the supermarket scanners are made of lasers.

The slide features the University of Liverpool logo on the top left and The Cockcroft Institute logo on the top right. The title 'LASER' is centered at the top. Below the title, the acronym is expanded: 'Light Amplification by Stimulated Emission of Radiation'. Two images are shown: on the left, a photograph of a complex laser system with various components and light paths; on the right, a collection of colorful laser pointers (pink, purple, green, orange, red) scattered on a surface. At the bottom of the slide, the text 'CERN High Gradient Accelerator School, Sesimbra Portugal, March 2019' and the number '3' are visible.

So what makes the laser so special is that when you actually have a simple light source, like, for example, an incandescent bulb, it gives out beams, you know, beams that come out like this.

Not only that, the lights are typically very incoherent and are not monochromatic. So, in other words, when a bulb actually emits something, it is very different from what we expect; for example, your normal room light will be very different. When you actually have a laser, it produces what we call a directional beam. This is the beam is in all possible direction. It produces a directional beam.

If you compare the spectrum, you will find that a normal light, incandescent light, will have intensity across a multitude of wavelengths. It is not a monochromatic source at all. So it is given by some kind of spectrum. So, at each wavelength, it will have some intensity of irradiation. And that is what is typically plotted here.

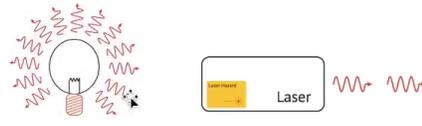
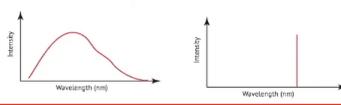
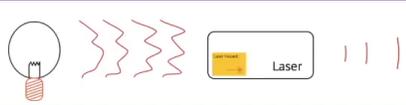
This is a cartoon. Whereas if you have a laser, you will see that all this becomes a narrow line. This is, of course, what seems like a line actually has a little bit of width associated with it. But for all practical purposes, the line width of this particular laser is much, much narrower than what we have experienced with, say, white light or incandescent light. Okay, this, however, does remember to have a little bit of width.

That means there is a little bit of a range of wavelengths that is here as well. So it looks like it is lasing at a single wavelength. So nothing is exactly at a single wavelength. There is a little bit of a wavelength change, even in the case of a laser. And on top of that, as we already said, the laser is coherent.

Spatially and temporally, they are coherent. Whereas a normal light source, as we know, we have already covered what spatial and temporal coherence are. The coherence is actually destroyed in a light source. They are typically on the order of femtoseconds, the temporal coherence. So this is of no use.

We need lasers, and you can maintain the phase and all those things over very large distances as well. And over a longer period of time, almost on the order of a second. So few features are that it is directional, it is almost monochromatic, and they are coherent. This is what makes the laser so special.

UNIVERSITY OF LIVERPOOL **What makes lasers special?** The Cockcroft Institute of Accelerator Science and Technology

- They produce a directional beam. 
- They have a narrow spectrum (or bandwidth). 
- They are coherent. 

Slide courtesy Prof. S. Hooker CERN High Gradient Accelerator School, Sesimbra Portugal, March 2019 4

Basically, in order to understand lasers, you have to understand a little bit of quantum mechanics.

And basically, you know, it comes from the two-level system description that was advocated by Albert Einstein. What Einstein did was identify three ways in which atoms and molecules can exchange energy with a radiation field. This we will also cover when we actually give our lectures on DDLS. A tunable diode laser-based absorption spectroscopy. This we have already covered in detail in our statistical thermodynamics course.

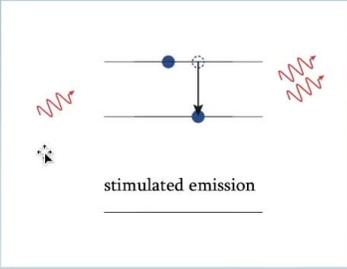
So this is just a little bit of a heads-up about what is coming. So the first one is what we call absorption, or basically, you know, stimulated absorption. What happens is that, you know, when a photon of a particular color and the correct energy is incident on a two-level system—this is a two-level system, this is level one, this is level two—what happens is that the electrons can actually absorb this energy and can go to the next higher energy level. You know, that is what it's called. So let me just stack this up a little bit because I think this is what absorption is all about.

So that you can see properly. So when we talk about absorption, this is what it is. So this is n equal to one; this is n equal to two. So what happens is that when a photon, which is $h\nu$, impinges on this particular system, the electron from the lower energy level is promoted

to the higher energy level. So this is called absorption or stimulated emission.

Einstein model

- Einstein identified 3 ways in which atoms exchange energy with a radiation field
- Absorption
- Spontaneous emission
- Stimulated emission
- Rate of absorption/stimulated emission dependent on no of photons & number of atoms in lower/upper state.
 - ▶ photon needs to have correct energy
 - ▶ the number of photons can be *amplified*



Albert Einstein

Slide courtesy Prof. S. Hooker CERN High Gradient Accelerator School, Sesimbra Portugal, March 2019 5

Okay, now in what happens, this is when electromagnetic radiation actually impinges on the system. That means this is basically electromagnetic radiation interacting with matter, a light interaction with matter. This is what happens. Now there can be another case in which you have what is called spontaneous emission. In this, there is no electromagnetic radiation that is necessary.

So the electrons that are in the higher energy levels are basically unstable. So they have a very short lifespan, typically on the order of 10^{-8} to 10^{-10} to the power of minus seven also sometimes. So it's about 100 nanoseconds that the electron spends in a higher energy level where it is unstable. So it comes back to the lower ground state and releases a photon of the same color or the same energy as the one that impinged on it.

So this has a particular requirement for photons. So it gives out photons of a particular energy only. So this comes from this level to that level. So this is called spontaneous emission; it does not require interaction with radiation per se. This actually requires interaction with electromagnetic radiation, which promotes the electron from the lower level to the higher level.

There is a third process called stimulated emission. Now, what is stimulated emission? In stimulated emission, what happens is that there is already an electron at the higher energy level. A photon comes, or a proton comes and bumps this electron from that level to the ground level because, remember, this was already unstable here. It just requires a little push. Now what happens is that two photons get emitted; these photons are coherent, and

they actually have the same phase.

They are emitted in the same direction, so this is what is called stimulated emission. You give one photon, and you get two photons out of the system, which are coherent to begin with. Okay, remember the word coherent. In the case of spontaneous emission, if you have multiple systems that are undergoing this spontaneous emission, the direction of the photons will be all around. But why does spontaneous emission occur? This is due to the vacuum perturbations present in the system.

That means the electron is basically residing in a very unstable position. Imagine this is like a stone at the top of a mountain. So any small push in either direction would actually land the particle or the stone on the ground. So these small perturbations, which are always inherent in the system, are what make the electron undergo spontaneous emission, even in the absence of stimulated emission. And the lifetime of the electron, therefore, is about 100 nanoseconds or so, very unstable.

But the emissions that are created are multidirectional. As a result of that, you cannot really, you know, use it for any meaningful purpose; you can use it for other purposes, for something which is for emission spectroscopy, but not in this particular case, whereas stimulated emission means the photons that are produced are basically coherent, and they basically knock the electron off, so you therefore get two photons coming out of it. The stimulated emission is basically the ES and E of the laser. All right, so as you can understand now, these three processes—absorption, spontaneous emission, and stimulated emission—are the ways in which atoms exchange energy when they are interacting with a radiation field or not. The rate of absorption or stimulated emission is dependent on the number of photons and the number of atoms in the upper and lower states.

These upper and lower states actually determine the number of photons that are impinging on the system; that is what actually determines the number of photons. Also, the photon needs to have the correct energy. It needs to have the energy of $h\nu$, so that means it needs to have the correct color. Okay, if it does not have the correct color, then what will happen is that it is not going to promote, you know, in the case of, for example, in the case of. Absorption would not be able to promote the electron from the lower to the upper energy level, and it is also not going to be able to knock off the electron from the upper level; you won't have two photons of exactly the same color, so the photons need to have the correct energy, and the number of photons can actually be amplified.

So you just having the photons of the wrong color and having a lot of them essentially do not do anything to the system. You need to have the photon of the correct frequency because without that, which means the correct color, you cannot promote absorption or

stimulated emission. So this is one of the prime things that you should keep in mind. And you can have millions of those photons; it absolutely will not do anything to the system. All right? So in the laser, the basic idea is that you want a lot of stimulated emission.

Einstein model

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- Einstein identified 3 ways in which atoms exchange energy with a radiation field
- Absorption

stimulated emission

absorption

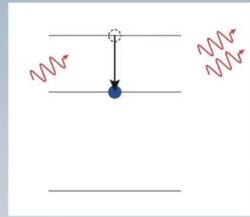
spontaneous emission

the number of photons can be amplified

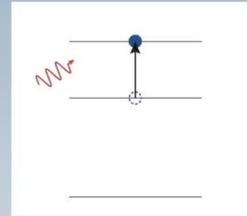
Slide courtesy Prof. S. Hooker CERN High Gradient Accelerator School

That means you want to have this avalanche of coherent photons coming in a particular direction. We actually want lots of this, but you do not want a lot of absorption. Because when a light is impinging, you have a probability of this as well as that. Now, because it is dependent on the number of electrons in the two states, you see, if you have, say, more electrons here in the ground state than in the excited state, what will happen is that you will have more absorption. Because the probability of this photon interacting with an electron and promoting it to an upper energy level is much higher than that of the photon actually knocking an electron from the upper energy level to the lower energy level.

Because this level already has a lesser number of electrons to begin with. A system in thermal equilibrium will have an arrangement in which the ground state will have the most electrons, and then there will be progressively fewer electrons in the upper energy states, so the chances of stimulated absorption will be much greater than stimulated emission. But in essence, for lasing to happen, you want more stimulated emission because that's where the photons come out as a coherent beam. They are lockstepped with each other, but you do not want a whole lot of stimulated absorption because that is not your prime thing. Because once it goes up, it has only 100 nanoseconds before it comes back, giving out radiation in all possible directions, which we cannot use.



We want lots of this....



... but not much of this

Hence we need a **population inversion**,
i.e. more atoms in the upper level than in the lower level.

So in essence, what you need is more electrons in the upper energy level than in the lower energy level. In other words, you need what we call a population inversion. That is a greater number of atoms in the upper level than in the lower level. This does not practically happen because, you know, for a system that is in thermal equilibrium, this is basically $\frac{N_2}{N_1}$.

This is both written as N_2 . So, this is the population graph that you normally see. You see, the greatest number of electrons will be at the ground state, and progressively it is like a well. It's like an exponential function that you can see. In thermal equilibrium, this is what will happen. But what you want is basically to create an inversion state.

That means you want to repopulate a particular state so that the number of electrons in that particular state is greater than the corresponding ground state. Then what will happen is that if you have the correct photon impinging on this particular system, the chances of stimulated emission will be much greater than stimulated absorption or absorption in general. So this is what we emphasized here because the probability will otherwise be greater for this to happen than for that to happen. So if you populate and create a population inversion, the chances of a photon knocking an electron from the upper to the lower energy level are much higher. Therefore, the probability of stimulated emission will be much higher than that of absorption.

And this is exactly what is shown here: that normally the states are like this, but you need to create an inversion. That means you need to artificially increase the population to a higher energy level than the corresponding lower energy level. Because otherwise, a system in thermal equilibrium will not have this. So you basically need to pump energy into the medium, which is called a gain medium, where the electrons are actually residing,

to achieve such an inversion. So that means you need to add energy to achieve this because you need to promote a few electrons from the lower energy levels to the higher energy levels.

And by the laws of thermodynamics, you need to add energy to achieve that population inversion, which is rather unusual to begin with.



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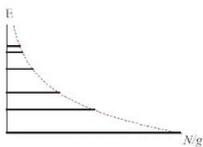
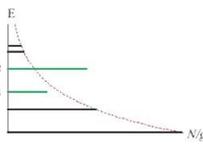
Population Inversion



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Population inversion

A population inversion is unusual:

In thermal equilibrium

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} \exp\left(-\frac{\Delta E}{kT}\right)$$

and hence population inversion not possible in this case.

Need to pump (add energy to) the gain medium to get an inversion

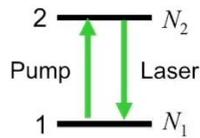
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Now, so this is the pump mechanism. So you have N_1 and N_2 . N_1 is the number of electrons, for example, at the ground level.

N_2 is the number of electrons in the upper level. The way you are saying electrons, it can be molecules; it can be other things as well. So, by the green upward line, you are basically pumping electrons from the lower energy level to the higher energy level, and then the photons that are impinging are going to knock them off, and you are going to have the lasing. So the rate of population change is proportional to the population density multiplied by the pumping rate. So, the absorption and emission are equally likely. What we can do, the best we can do, is basically that N_2 can be made equal to N_1 .

So there is no population inversion if we use a two-level system. So, a two-level system is the maximum thing that you can do. So, the two-level system is no good because you cannot achieve a population inversion.



Rate of change of population \propto population density \times pumping rate

Absorption & stimulated emission equally likely

Best we can do is $N_2 = N_1$ - no population inversion in 2 level laser

Hence, we go to three- and four-level systems. What happens in a three-level system, for example, is that you basically use a pump that makes the electrons go from state one, or ground state one, to ground level two or level three.

So there is an intermediate that is closer to 3. There is an intermediate level that has an energy E_2 and a population, the number of particles N_2 . So what will happen is that in this particular location, the state is very short-lived. So this will go down to this metastable level using a very fast and radiation-less transition, more like heat rather than a radiation. And then here at level two, what you have is a metastable state where the electrons are somewhat stable for up to milliseconds.

So this acts like a hold place. This is like a hold where the electrons will be in a metastable state. So that is rather important because this is what a three-level laser system actually does. So it pumps and puts it to E_3 . There is a fast radiationless transition to E_2 . And from E_2 to E_1 , it's slow, and this is what the lasing function is all about.

So, you cannot achieve a population inversion in two-level systems. So the lasers are broadly categorized as three- or four-level systems. So now, in a three-level system, N_2 is greater than N_1 . So one is thermally populated.

So we need to raise the population from one to three. So that is what is done by using the pumping mechanism. Remember, this is a metastable state to begin with. All right. So basically, it acts as a buffer or a hold where the electrons are populated, and then they have this on the order of milliseconds before they actually undergo a slow transition to the ground level. You can also do the same thing with, you know, four-level laser systems as well.

Here also, there are two buffers now. So you again have the pump that takes it from one

to four. Then you have a fast radiation-less transition to three. And from three to two, you have a slow laser transition. And then from two to one, you have a fast radiationless transition. So this is basically that there are two hold places, two metastable levels, and the lasing happens only for photons that match this particular energy transition.

Only this, not this one and four, but rather two and three. And here it is, of course, between one and two. So this pumping mechanism is not necessarily monochromatic. So pumping need not be monochromatic. We sometimes use a flash lamp.

And some lasers also have a broad emission range. That can also happen. But it is not white light per se; it has a slightly wider frequency band or wavelength band. Let's look at it this way: again, this is the four-level system.

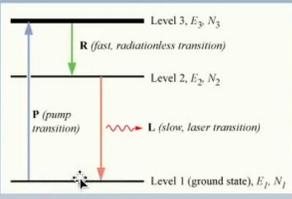


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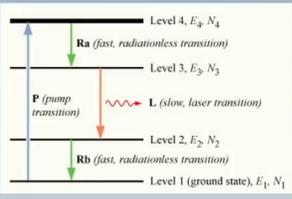
3 and 4 level lasers



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Level 3, E_3, N_3
R (fast, radiationless transition)
 Level 2, E_2, N_2
P (pump transition) *L* (slow, laser transition)
 Level 1 (ground state), E_1, N_1



Level 4, E_4, N_4
Ra (fast, radiationless transition)
 Level 3, E_3, N_3
P (pump transition) *L* (slow, laser transition)
 Level 2, E_2, N_2
Rb (fast, radiationless transition)
 Level 1 (ground state), E_1, N_1

- Can't get a population inversion in 2 level system.
- So lasers broadly categorised as 3 or 4 level systems.
- 3 level - $N_2 > N_1 - 1$ thermally populated so need raise lots of population from 1 – 3
- 4 level - $N_2 = 0$, so any population in 3 is an inversion – less pump, more efficient!
- Not necessarily monochromatic:
- Some lasers have broad emission range (although not white light!)

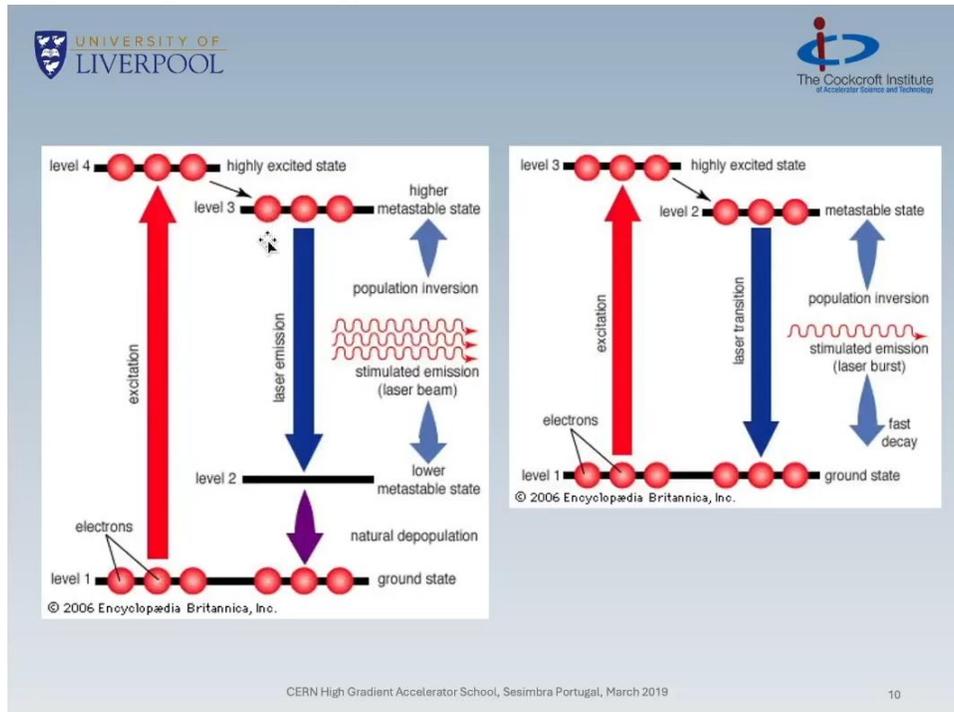
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So at four, this is highly excited. It goes to this metastable state. And then you have the laser emissions. And this is the population inversion. And this goes to a lower metastable state. And this is the stimulated emission. We need photons that basically match the energy of these two levels from three to two.

Then you have these coherent photons that come out of it, in the same phase and in the same direction. And then you actually have from a lower beta stable state all the way up to the ground state by using the non-radiative decay processes. The same thing happens here. You know, this is the population inversion that you have. And then you have the fast decay due to stimulated emission, which is like a laser burst.

This is more used for bursting purposes. This is used more for beam purposes. OK, those are semantics and additional details. But those are also done if you want to get energy throughout the day or something like that. Okay, or at any time if you want it to lace, this

will give you energy in short bursts, so to say.



All right, so all laser oscillators are opposed to amplifiers. To make a laser, you need a gain medium, which is the medium in which these transitions are taking place. There can be gas, solid state, or liquid, which provides the laser transition. It needs to have a pump. A source of energy that is needed to create the population inversion is usually another light source, for example, a flash lamp or a laser, or it can be an electric current that is used as a source of energy.

To create the population inversion, you need to have a source of energy. A flash lamp is the most commonly used. You need a cavity because, in this cavity, you need to recirculate the photons to stimulate emission or the lasing transition. So the photons are basically made to go inside this cavity round and round so that they can knock off more and more photons. And so often, mirrors guide these cavities, et cetera.

So there is a lasing threshold. So when the gain, that is, the number of photons emitted in one round trip through the cavity, exceeds the loss due to absorption and due to mirrors, we will see the construction. And when that lasing threshold is reached, when the gain exceeds it, you have a lasing threshold. The gain should exceed the loss. Otherwise, you have a decay of photons rather than amplification. And whether you want the laser to emit light all the time, like continuous wave lasers or pulsed lasers, the lasers can operate in femtoseconds to nanoseconds.

- All laser oscillators (as opposed to amplifiers) have 3 parts:
- **Gain medium** – gas, solid state, liquid – what provides the lasing transition.
- **Pump** – source of energy to create population inversion – usually another light source e.g. flashlamp or another laser, can be electrical discharge or current.
- **Cavity** – need to recirculate photons to stimulate emission on lasing transition – often mirrors around gain medium, can be medium itself.
- Lasing threshold – when gain (no. photons emitted in round trip) exceeds loss (number lost to absorption, through mirrors etc.).
- Do you want laser light all the time (continuous wave, cw) or pulsed? Pulses can be from femtoseconds - nanoseconds
- And that's it!

So there are all kinds of lasers available. If you look at just a cavity that has a reflector on one side, this is a 100% reflector. And then there is a partial reflector on the other side, which allows the laser beam to go through. And this is the amplifying cavity. What you do is provide the energy input by pumping, and then the photons are basically emitted, so the photons knock off more photons in this amplifying cavity in such a way that there is a population of photons of the same kind and the same coherence. So what happens is that you pump from the medium to the upper level, the photon decays spontaneously, so a photon happens spontaneously, and then it stimulates more emission.

Because it is knocking off all the loose electrons that are in this gain medium, as well as all the electrons that are in that upper energy state. Now, if the number of photons emitted in each round trip through this cavity, because the photons are then reflected, exceeds the losses because the mirrors are never really, you know, absolutely 100% reflective. So they will absorb a little bit, and there can be other losses as well. So if this is one round trip, you should have a greater number of photons.

That means your number of photons should go on increasing. So only one of the mirrors will allow a small amount of light to pass through. This is what is called the laser output. So, the laser output is controlled by the gain of the medium. That means that the number of photons you are getting and what the modes of the cavity are, whether transverse or longitudinal, because the photons get knocked off in all possible directions. You can control which modes by controlling the length and the dimensions of the cavity to basically pre-populate, okay?

Cavity

- Pump gain medium to upper level
- A photon decays spontaneously & stimulates more emission
- The photons bounce back and forth along the cavity – if the number of photons emitted each round trip exceeds losses (mirrors etc.) laser is above threshold
- One of the mirrors allows a small amount of this light out – laser output!
- Laser output controlled by gain of medium and longitudinal & transverse modes of cavity

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So the gas lasers are usually electrically pumped, have a wide range of wavelengths, and have a low gain.

Liquid lasers use complex organic dyes. They are tunable also, so that means you can change the wavelength of lasing by changing the dye, essentially, because the medium actually controls which wavelength will come out of it—okay, the red versus blue versus green, et cetera. Solid-state lasers are the largest class of lasers. The lasing is usually iron-doped in a crystalline host, such as Nd:YAG laser, Ti:sapphire laser, fiber laser, and semiconductor diode lasers. So they have a very complex system. The gas lasers, helium-neon lasers, are the most common, at 632 nanometers, okay? Here you can see how it's done, okay? So this is the laser board tube.

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Types of laser

- **Gas lasers:**
 - Usually electrically pumped
 - Wide range of wavelengths
 - Low gain
- **Liquid lasers**
 - Solution of complex organic dyes
 - Widely tunable
- **Solid state lasers**
 - Widest class of laser systems
 - Lasing ion doped in crystalline host - Nd:YAG, Ti:sapp
 - Ion in glass - Nd:glass
 - Fibre lasers – Er, Yb in glass
 - Semiconductor diode lasers

But you don't get every colour! Dependent on lasing transition

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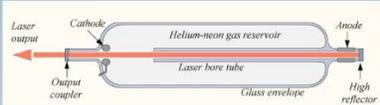
Then you have the UV excimer laser. And then you have the pumps for the chemical reaction. Then you also have CO₂ lasers. This is used for industrial and medical applications, not necessarily for flow diagnostics. This was sometimes used, but NDAG is the most common source of lasers that are used.

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Gas lasers

- Probably widest range of wavelengths – uv to infrared.
- Helium neon – HeNe red (632.8nm) gas laser.
- Pumped by electrical discharge.




- uv excimer lasers – 100 – 300nm
- Photolithography
- Pumps for chemical reactions
- Poisonous gases – chlorine, fluorine




- CO₂ lasers (10.6µm).
- Industrial & medical applications.
- Research on increasing peak power at BNL.

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This is, for example, the liquid laser. You can get whatever light you want. This is very important when you actually deal with it. The dye lasers are actually very good when you

are dealing with laser-induced processes.

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Liquid lasers

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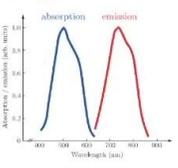


- Less common, usually organic dyes – Rhodamine 6G
- Can get orange/yellow, hard to get with other gain media.
- Often carcinogenic materials.

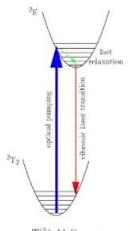
The solid-state laser is the most widely used laser. You have TI-SAPPHIRE. NDIAG is the most commonly used one. You also have semiconductor lasers, and we will also see semiconductor diode lasers in our EDLS presentation. And the pumping mechanism is usually flash lamps, specifically broadband flash lamps. Other lasers use fiber optics and also electricity in the case of semiconductor diodes. And this is TI Sapphire laser. This is a very important laser in the sense that it has a bandwidth of 300 nanometers and very short pulses.

This is basically the two energy levels that are shown. It's a little more complicated than what we have been taught over here. And it is commercially available in petawatts. This is the workhorse of much scientific research. Again, it is very good for combustion diagnostics.

Ti:sapphire

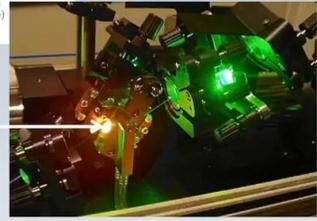


- Simple spectrum: Only single 3d electron
- Four-level laser
- $\tau_2 = 3.8 \mu s$, $\tau_1 = 100 ps$
- Largest bandwidth of any laser
– allows generation of pulses as short as 5fs



Ti³⁺:Al₂O₃ (Ti:sapphire)

- Hugely important laser
- Bandwidth! – 300nm
- Shortest pulses.
- Absorbs at 500nm – pump with green laser.
- Commercially available petawatt (PW) Ti:sapp lasers
- Workhorse of science research

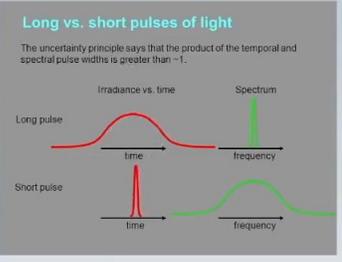


Ti:sapp crystal

So, in other words, we can also have high-power lasers, where you can have long pulses and short pulses, and stuff like that.

You can have a mixture of laser systems. So basically, whatever wavelength you want these days, we can have a laser that is catered to that.

- 100s TW & PW lasers - laser plasma wakefield acceleration, laser ion acceleration
- Usually Ti:sapp (fs), sometimes Nd doped systems
- How do you make a PW laser without damaging it?
- Chirped Pulse Amplification (CPA). (Also useful for winning Nobel prizes).
- But need to know something about ultrashort pulses to know how this works.



- Fourier synthesis of short pulse requires many frequency components - spectrum!
- When all components have no phase difference pulse is shortest it can be for a given spectrum.
- Pulse is Fourier transform limited (FTL).

In other words, this is the story of lasers. Remember, it always works on these three principles, which are absorption, spontaneous emission, and stimulated emission. We need stimulated emission, and this is achieved using a population inversion mechanism.

