Professor Winful

Part 1 (UNIT 3)

(1) As you've been told, I'm a Professor of Electrical Engineering and Computer

(2) Science here at the University. My specialty is optics (writing on the board).

(3) Optics, which is the study of light. Now you might ask, What is light? That's a

(4) very difficult question to answer, but most of you probably can say "Well, I

(5) can't define light, but I know it when I see it". Probably true, right? We're

(6) sitting here, we are surrounded by light. We have light coming from these

(7) bulbs. Okay. In my pocket there is another kind of light. I have this thing which

(8) is a laser, it's a laser pointer. Uh you probably can't see the dot right now

(9) because it's too bright in the room here. But there's a little red dot over there,

(10) okay. That's coming from this laser, okay. Most of my work deals with laser

(11) light. The study of laser light. How laser light travels. What you can do with it

(12) and so today I'm going to tell you a little bit about how a laser works. And

(13) also some of the principles that govern the control and manipulation of light.

(14) We will talk about certain concepts that you need to know if you're going to

(15) work with light. Some of you may already know this stuff and so it will be

(16) elementary, which is good. You should never underestimate the pleasure of

(17) hearing something you already know. Now for those who don't know this

(18) stuff, maybe you'll be enlightened along the way. Okay. So I mentioned the

(19) laser. So first let me tell you what the laser is. Laser actually is an acronym.

(20) So let's write down laser (writing). It stands for something. It stands for light.

What else? Don’t be shy. What wh-what does the ‘A’ stand for? You-you on the right, right! It’s light amplification – am-pli-fi-cation. And then light amplification by and this ‘S’ stands for stimulated, stim-u-late-d (writing). The ‘E’ is for emission of. And ‘R’ is for radiation, ra-di-a-tion (writing). Okay. So the laser stands for light amplification by stimulated emission of radiation. Now I’ll explain some of these words for you. Light is kind of difficult to explain. We can only describe some of its properties. I could tell you that light is a form of electromagnetic radiation, but that doesn’t leave you any wiser than you were before, okay. So we’re going to skip and go onto some of the other concepts like amplification and stimulated emission. Okay, to describe amplification and stimulated emission, we need to know a little bit about where light comes from. Now let’s go back to your elementary days in high school when you first took science. You learned about atoms and you probably learned that an atom. Okay, so here we’re gonna talk about atoms. An atom consists of a dense nucleus nucleus made up of protons and neutrons. And it’s surrounded by electrons. Okay, so we have electrons spinning around the nucleus. I should – they are quite far from the nucleus, this is just a cartoon, okay. These distances are not accurate, but it’s an electron. And there are other electrons by there. Many of them spinnin’ around the nucleus. Rather like planets spinnin’ around the sun. Now this is not a terribly accurate picture, okay. A correct picture of atoms requires the use of quantum mechanics. But we’re not going to do any of that, okay. Alright, so imagine an atom, it has electrons whizzin’ around the nucleus.

Now each of these orbits has a different amount of energy. So we can associate each orbit with a different energy level. Okay. An electron in the innermost orbit is considered to be in its ground state. Okay so we talk about the energy levels. The lowest energy level is a ground state. And then you have higher energy levels, higher states, okay. So they are not necessarily equally spaced, okay. So we have all these. We'll call them upper energy levels. Now suppose we have an electron that for some reason we've been able to excite from the ground state to an upper state. There are many ways you can excite electrons from a ground state to an upper state. You can hit them with a pulse of light. You can send a strong electrical pulse. Even heating upper material can promote electrons to more excited states. So let's imagine that somehow we've promoted an electron from the ground state to an upper state. Well that's level is actually not very stable. It's like ya know if I put a piece of chalk on the edge of uh this table. It just fell, right? It falls to the ground. The ground is like a stable energy level, it's a ground state. Up here we have an excited state and so if an electron is in the excited state it wants to drop down to the ground state. That process where an electron drops down to a ground state. Okay so an electron and now it's gonna drop down to the ground state. It can happen spontaneously. I don't need to do anything to the electron. It will just fall just like the piece of chalk just fell without me pushing it. Okay. When it drops the ground state it emits light, it emits a photon. Okay, a photon is a particle of light. And so the electron drops to the ground state and it emits a photon. This process happens spontaneously so we call this emission of the photon spontaneous emission (writing) Spontaneous emission is the light or the radiation that comes out of an atom when an electron drops down spontaneously from one higher level to a lower level. Okay, emittin’ a photon of light. Well, this photon that comes out has a particular color. Okay, now that we’ve started to talk about photons, it’s necessary to say a bit more about the na- about light and the words we use to describe light. Okay. You can think of light as a stream of particles of photons. So it has different nature ya know it in some ways it can act like particles. Photons are like little particles or it can act as a wave like waves. You’re all familiar with waves, like water waves you drop a pebble in a pond and you see waves spreadin’ away from the point where you dropped the pebble. Well light is a kind of wave. Now to describe a wave okay. Let’s draw one. This is a wave. Something that oscillates in a regular fashion. Now as a there are words that we use to describe the nature of a wave. One of them is the wavelength which we’ll describe with the Greek symbol lambda. So lambda is the wavelength of the light. Now the wavelength is what determines the color of the light that we are seein’. So for example, this laser that I showed you puts out red light, okay. Now if you read the label on this it will tell you what the wavelength of that light is. The wavelength being the separation between two peeks or two valleys of the wave of light. So for example for this laser the wavelength. Uh for example lambda here is. Okay it ranges from 620 nanometers to 680 nanometers, okay. As a range of wavelengths are contained in here. What’s a nanometer? (student answers). Ten to the minus nine, okay. So a nanometer is 10 to the minus nine of a meter. Which is very short. Okay, it's one billionth of a meter. And that is the wavelength of this reddish lookin' light that we see. Okay. Now back to this emission process. The wavelength of the light that comes out when spontaneous emission occurs is related to the separation of energy between the upper state and the ground state. So the wavelength is determined by the energy level separation. Determined by energy separation. Okay. When an electron drops down spontaneously, the wavelength that the light that comes out has a small- a range of wavelengths associate with it. Okay because i-i-imagine in the typical material you have many many billions, uh, lots and lots of atoms, lots of electrons and all of these are emitted spontaneously. So you can get a broad range of colors as a result of all these electrons emitting spontaneously. The typical light bulb that we have here operates on spontaneous emission, okay. Alright. And one key feature is that the photons emitted by different atoms spontaneously have nothing to do with each other they are different one from the other. Okay, in spontaneous emission the photons that come out have different directions, slightly different wavelengths, and their properties are not identical. Okay, so in spontaneous emission, the different photons emitted and I'm gonna use a word "correlation". The different photons emitted are not correlated with each other. Okay. So that's one feature of light. Now let's talk about stimulated emission because that's a principle on which the laser works. Stimulated emission is quite different from spontaneous emission and this is how stimulated emission works. Stimulated emission. Well in stimulated emission suppose you have an atom here, electron in the upper state, for ground state and another one here. Okay, say we have a whole bunch of them. Suppose this atom emits a photon spontaneously. Okay so it goes down thereby emittin' a photon. Well Einstein showed that this photon that's been emitted can trigger another atom to emit. It can stimulate another atom to emit a photon. So this photon comes along and is go- it can knock down this electron to the ground state. In other words it it can stimulate this other electron to emit. Okay, so photon comes along and forces this one to emit. Going down to the ground state. Well, the photon that's emitted in response to this one is going to be identical to the photon that caused the emission. So the photon that's coming out by stimulated emission is going to be alike in all respects to this photon that caused it to emit. Okay and so we started out with one photon, it comes in here causes stimulated emission, so we get the new photon that's travelin' along plus the old one that caused the emission, okay. It doesn't go away, it's there. So it comes in, knocks down an electron, creates another photon which is identical. It's its twin, okay. So, suppose these come along and no one of them triggers or stimulates another electron to emit. Well, how many are we gonna have then? How many identical photons will we have? Three! Okay, so this one is also stimulated to emit, so we're gonna have these old two photons going along plus a third one that's emitted. Okay, so in stimulated emission the photon that's emitted is identical in every respect to the photon that caused the emission. We say that the photons are correlated. In stimulated emission, (writing) ah, correlated and this gives a certain property to the laser light. Which is obtained from stimulated emission. Because of this correlation, the laser light is coherent. Coherent. And I will explain in a little bit what coherence really means. Laser light is coherent as opposed to the light from spontaneous sources like these light bulbs which is incoherent. Okay, so we have coherent versus incoherent (writing). Now incoherent is like say if all of you started talking at the same time in different languages. And uh at the top of your voices. Someone walks in here and doesn't know what's going on, it's just babble, right? Because if you call start talking the same language, saying the same thing. Well, someone out there will hear very loud and uh totally coherent output coming from this room. And that's how you create uh a choir or a symphony, an orchestra. Okay everybody played together. Okay, now we've seen stimulated emission. Along the way we've also seen something. What what is it that you can see here that's related to the words in laser? We started out with one photon, we're going on let's say this one is also stimulated to emit and now we have all identical ones going along. What does this imply? Amplification. Amplification. We started with one, now we have four. If we keep going we'll have five, six…more and more. And since the typical material has ten to the thirty or more atoms, pretty soon we'll have a uh pretty hefty number of photons which are all identical. So what we've seen here is amplification of radiation (writing). Okay, so we’ve covered these words here. We’ve seen stimulated emission, how it creates photons that are correlated with one another and therefore leads to coherence, light or radiation. And we’ve seen amplification, okay. How successive photons can trigger the emission by other uh atoms. So you get all these, okay. So, that’s really th-the guts of a laser. That the physical principle on which laser operation is founded. Now feedback.

Professor Winful

Part 2 (UNIT 3)

(166) In addition to having amplification, we also need something called

(167) feedback. You probably heard feedback. Does anyone have an idea of

(168) what feedback means? In some sense uh. Have any idea of what

(169) feedback…is? Either in real life. What? (student answers) To show the

(170) reaction, okay alright. I think what you say is that a sudden reaction can

(171) affect something back again, you know. Alright let let's let's say, let me give

(172) some examples that you might have encountered. Uh you might

(173) sometimes hear someone speaking into a microphone and there's a loud

(174) speaker. And if he brings the microphone too close to the loudspeaker, you

(174) hear this very annoying sound BEAP! Very, very annoying. That's

(175) feedback. And feedback happens when let's say you have this microphone.

(176) Somebody is speaking into a microphone here (writing) microphone. So

(177) you're speaking into it. And the signal from microphone goes to an amplifier

(178) amplifier. Which boosts up the sound and then it goes to a loud speaker.

(179) Let's draw a loud speaker. So loud speaker. Well usually you want this

(180) microphone to only pick up you know the words that you say. Ya know,

(181) you're over here you are talking. Draw a mouth over here (laughs). So

(182) talking into a loud speaker, it picks up your sound, amplifies it, and the

(183) audience hears it through the loud speaker. Now if the microphone gets too

(184) close to the loud speaker, the amplified sound that's coming from the loud

(185) speaker can be picked up by the microphone, okay. So it's fed back to the

microphone. And that is further amplified. It goes to the loud speaker. Fed back more, amplified. I mean, eventually you can see that it can get very loud, very annoying. And what happens is that you get oscillations. It’s called ah-ci-lations. Okay, so if you have feedback in an amplifier like this, you can get oscillations. The same with the laser. The laser is actually a light oscillator. It’s an oscillator of light. And the way you get feedback in a laser is to use mirrors. So in a laser, feedback is provided by mirrors (writing). Feedback provided by mirrors. Okay, so suppose this is a amplifier. And I’ll say a little bit about how we create the amplifying material. Okay, so we have some material in here which can amplify light. Now we need feedback and the feedback we’re going to put mirrors. Usually in lasers the mirrors are curved mirrors like this. So it’s a mirror (writing) and put another mirror over here (writing). Mirror. Mirror. And I’m gonna draw a box around this material (lots of drawing). A box of atoms. Okay so mirrors are providing feedback. So suppose we start out with just a single photon is getting amplified. It gets over here, now we have four. Well these four photons hit the mirror and they get reflected. So they come back this way. Well they come back. And now a slight uh detail. If these photons coming back are going to cause more stimulated emission, you would like the electrons to be back up somehow in the upper level. You don’t want them to have been sitting down in the ground state because they wouldn’t emit. Okay the way you get them back in the upper state is by. I use the technical term it’s called pumping. Pump-ing. It’s different from ya know it’s not uh a bicycle pump or anything like that. It’s pumping is the process in which you elevate electrons to an upper level so that they can emit. So let’s say you have a ground state. Uh you provide a pump. This pump can take several different forms. This pump can be some other light. It can be electrical. It can be a stream of electrons hitting these atoms, to pump them up to an upper level. Okay, and then they can tr-trickle down and they can emit and get stimulated emission. So the pump is what puts them back out in the upper state. So okay back to this thing. We assume that the me- the laser. Material has been pumped. These photons comin’ back can then cause more stimulated emission. And so these four will become five, six, seven, eight, nine, ten by the time they get over here, okay. And then back again. So feedback causes the intensity to build up. Very, very strongly, okay. Now of course you don’t want the light to just stay inside the laser otherwise it’s not very useful. You want it to come out, okay. The way it comes out is that these mirrors are not one hundred percent reflected, okay. So the mirror reflectivity is less than a hundred percent. Reflectivity. Well usually we have one mirror that’s very highly reflective. Let’s say 100% okay. So let’s say but that’s why this laser I have here, light is only comin’ out of one end instead of both ends. One of the mirrors is very very highly reflective, about 100%. The other one might be mm maybe only ninety something percent reflective. Okay say 90% 80%. Which means that in every round trip, 20% of the light comes out, okay. And so that is our laser beam. We call this mirror out here the output coupling mirror. Output Coupling mirror. The other one you can call the high reflector. Okay, so this already tells you something. If I’m only coupling out 20%. Okay so if the reflectivity is twenty per- uh 80%, I’m only coupling out 20%. It must mean that there is still an enormous amount of light energy still inside the laser. And in fact there are some experiments that we do in our labs where because we need a certain level of intensity, we actually place the material that we are going to work with the material that we want to use lasers to interact with, we place inside the laser cavity, where the intensity is higher, okay. But anyway these are the basic principles of the laser. Another thing that might be useful for you to know is why the laser light is so directional, you know. Why it’s essentially a straight beam, very narrow beam. Well the directionality comes from a couple of things. One is the fact that these mirrors actually have a focusing effect on light so that the light beam inside a cavity actually looks like that. It’s very narrow here and it it j-uh spreads out a bit. Out here it’s still spreading, but it’s not spreadin’ as much as ya know an ordinary light bulbs. Also, and this is a bit more sophisticated, uh. This cavity this these feedat feedback mirrors select only certain wavelengths. Certain wavelengths inside the cavity that satisfy so-called oscillation condition are selected by the cavity. So this is for extra credit. Okay so, the laser cavity mirrors (writing) select only certain wavelengths. Those wavelengths are wavelengths that satisfy the round trip oscillation condition (writing). Roundtrip oscillation condition. Now this will make sense only to those of you who know a little bit about phase. Phase meaning phase not f-a-c-e but p-h-a-s-e. Phase. Well maybe I'll take some time and tell you what phase is. Um. Phase. Let's look at a wave and draw it. As let this be time and this is some intensity or amplitude of the wave. Amplitude. You know I can start my wave at T=0. Okay and like this. Or I could have a wave that at T=0 is going negative. Okay, th-th- this axis here up here is positive, down here it's negative, okay? I could have a wave that starts out going negative like that. Okay and then becomes positive. Now visually you can see that these two waves are out of phase, meaning that when one is up the other is down. When this one is down, this one is up. They are out of phase. Well what happens when you try to add two waves that are out of phase? What's gonna happen? (student answers). They counteract. And in fact they can cancel each other out. Okay, you can imagine if this if this amplitude has plus one and this amplitude over here has minus one. When I add these two waves together, they're gonna cancel. And in fact they'll cancel everywhere. So phase is a very important property of a wave. On the other hand if they're in phase, then one I add them together they're going to constructively interfere, okay. They'll they're gonna add up coherently. Okay so two examples. If I add up two out of phase waves, this plus this. When you add them what you get is zero everywhere. So amplitude is zero. It's like you add one plus one and you get zero. On the other hand as I indicated, if they are in phase. Like this one and well I'll use the same picture I'll just redraw this one so that the two are in phase. When I add them together I'll get a doubling of the amplitude. So instead of this being one, now it’s going to be two. So okay. So how does that relate to this? If we are following the light waves bouncing back and forth inside a cavity, you would like all these waves to add up in phase. After every roundtrip, in one roundtrip they should add up in phase with the waves that are there already. Rather then out of phase. Okay now whether these waves arrive in phase or out of phase depends on the wavelength, okay. And so this cavity here th-these two mirrors because they are spaced a certain distance apart, okay. Imagine that mirrors are spaced a distance L apart. Only those wavelengths such that in one round trip, the waves add up in phase are going to enjoy maximum amplification, okay. And they’ll grow coherently. So that’s what gives you an oscillation condition. So in one round trip trip, the waves must add up in phase. And since only certain wave lengths satisfy that condition, only those wave lengths will be selected by the laser cavity. And that’s why the laser light is so pure, okay. It has a very narrow band of frequencies, of colors associated with it. Okay, any questions? Oh it’s all just absolutely clear. Well uh in the couple of minutes left let me mention a few applications of the laser (erasing the board). Lasers. Well one of the most important applications of lasers is to communications. Uh communications. And in particular communications through optical fibers. So uh optical fibers or fiber optics. An optical fiber is a very thin strand of glass um that can guide light for thousands and thousands of kilometers. So an optical fiber looks like that it’s it’s a round. Very thin, it’s thinner than a strand of hair, okay. And inside the strand of glass, a light wave can be guided can travel for thousands of kilometers without spreadin'. Now in free space, even a thin laser beam, will spread when it travels many kilometers. It can start out about a milometer wide. After it's traveled a thousand kilometers, it could be a meter wide. And that's not good because if it's that wide, the intensity is less. An optical fiber can trap the light inside and it can travel for millions of miles without spreadin'. And so you can send information on this light wave and it can go essentially forever. Uh you can send massive amounts of information on the lightwave. And the way you send information on the lightwave. Well, think about having a code that says okay if I flip on. Let me turn down the light a bit so you can see the laser. Let's see center room, nope. Alright so now where's the spot. Okay, the spot is right here. So suppose I have a code. If I flip it on either have a three flashes it means something or five flashes it means something else. Now I'm only flashing this as fast as my finger can move this. In a real optical communications system, these flashes are occurring at rates of a billion times per second, okay. So you can send your information on the light wave nearby flashin' this laser billions of times. And those bits travel along and it's very fast, can send massive amounts of information. So that's one very important application. Another important application is for medical uh medical applications. Um any medical applications. We use the fact that the laser light is very, very intense. The light is so intense that it can burn. You can use it to cut. You can do surgery with it. You can do eye surgery. And that because it’s so coherent that you can focus into a very small spot with a lot of energy into a small space and you can cut flesh, you can do surgery. You can also cut metal, okay. Alright so those are two important applications. Other applications are for example to holography. You’ve all seen holograms. These days all credit cards have little holograms on them. They are made using lasers and they give you a three dimensional image. And holography is based on the interference of light waves. They create these patterns, these uh they capture the entire image in a standing wave, okay. Uh holographies and the application. Can someone mention another application of lasers? (student answers) Hm? Weapon! Ah! Laser weapons, yes! That is true. Star Wars. Yeah, laser weapons. Any others? Can you use them for like things like measuring-measuring distances? Uh waz that? (student answers). Telemetry. Yes, exactly. Yeah, you can use for telemetry. You can use it for uh let’s see what other things. Ah you can go to a Kroger, the a grocery shop. They can scan your your produce. And that’s uh there’s a laser in there that using the laser scanner. It’s using CD’s you know compact discs, etc. So lasers essentially impact every aspect of our lives right now. And they all it’s all based on fairly simple principle, but we can make it much more complicated if you really want to understand the details of the physics behind lasers. Okay, so I guess I’ll stop now. And thank you for your attention.