Generating High-Intensity Ultrashort Optical Pulses

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THIS LECTURE is about how light interacts with matter and how the interaction changes when the power of the light gets very high. When the power of the light is low, the interactions are linear. That is, the response of the interaction varies linearly with the power of the light. If you double the power of the light impinging on the material, you will absorb twice as much power. At the time of my PhD thesis, scientists were investigating nonlinear interactions with media. With nonlinear absorption, when the incident light power is doubled the absorption rate is more than doubled. My PhD research project was to study a highly nonlinear experiment and to do the experiment I needed first to develop a very intense laser. This is the reason that I developed Chirped Pulse Amplification (CPA) along with my PhD supervisor, Prof. Gérard Mourou. With the new intense CPA laser system, we were able to show that the interactions were not the nonlinear interactions that we were expecting. We had to rethink how intense light interacted with matter, and the development of CPA helped usher in a new field of study that was emerging called high intensity laser physics.

The interaction of light with matter has been studied over the centuries. Scientists wondered if light was made up of particles or whether it could be a wave. Experimental observations showed evidence of both explanations of light. The fact that a tree casts a well-defined shadow led people to think light had to be made of particles travelling in straight

lines. If the path of a light particle went through the tree, it was simply blocked by the tree, resulting in the shadow. On the other hand, wave-like phenomena were also observed. When light passes through a small aperture there are fringes on the edge of the resulting light pattern that can only be explained using wave theory.

In the mid-19th century, theorist James Clerk Maxwell combined the equations resulting from various experimental studies on time varying electric and magnetic fields. There were four equations in total coupling electric and magnetic fields. To make the four equations mathematically consistent, Maxwell had to add one more term concerning time varying electric fields inducing a magnetic field. This last piece of the puzzle could not be experimentally observed with mid-19th century technology. By combining the four complete mathematical equations, Maxwell was able to show theoretically that time varying electric and magnetic fields travelled as waves. These electro-magnetic waves travelled at the speed of light. He then theorized that since light travels at the speed of light, it must be an electro-magnetic wave. By the end of the 19th century Heinrich Hertz had experimentally confirmed that time varying electric fields did indeed travel as waves. Because of the success of Maxwell's equations leading to the wave equation describing the time varying electro-magnetic waves, scientists were led to believe that light must be a wave.

By the end of the 19th century, scientists such as Hertz were carrying out experiments on ejecting electrons from material by shining light on the material. If light was indeed a wave, the brighter the light, the faster the electrons should be travelling when they leave the material. These experimental observations would be analogous to watching stones be being thrown up on a beach by a water wave. A small ripple in the water will not move a stone very much, but when the waves get big, the stones can move quickly and travel further away from the water. The power of a wave is related to the amplitude of the wave.

The experiments with light ejecting electrons used different colours of light. The colour of light is given by the wavelength of the light, which is the distance between the crests of the wave. Of the colours that we can see with our eyes, red has the longest wavelength of about 0.7 micrometers (one micrometer is one millionth of a meter) and the shortest wavelengths of light that we can see are violet light with wavelength around 0.4 micrometers. When the scientists shone red light on the material, no electrons were ejected no matter how powerful the red light was made. With green light, electrons came off the material but at low speed. When the power was increased, more electrons were ejected but always at the low speed. With violet light, the electron speed was higher than with green light, but again the speed did not increase with increased light power. The

number of electrons ejected increased with light power. These experiments flew in the face of the theory that light was a wave.

In 1905, Albert Einstein was able to explain this effect. Of all the physics theories that Albert Einstein discovered, it is his work on this phenomenon known as the photo-electric effect that Einstein was awarded his Nobel Prize for. From these experimental observations of light causing electrons to be ejected from materials, Einstein figured out that light is quantized in its energy. There is a minimum energy unit of light that we now call the photon. A photon is a wave-like particle. Einstein realized that the energy of a photon is given by the wavelength of the light. The total energy in a light pulse is then given by the energy of a single photon multiplied by the number of photons.

To understand why the photon picture of light explains the experimental observations, I will use an analogy with gravitational energy because it's harder for us to feel the energy of light. We know from everyday experience that if we drop a ball to the ground, the ball picks up speed as it falls. The ball would be moving faster when it hits the ground if dropped from a higher position above the ground. We will imagine playing basketball with a child's basketball net. The photons will be the basketball players trying to drop the ball through the net and we will determine the speed the ball has when it enters the net. The speed of the ball through the net is analogous to the speed of the electron as it is ejected from the material by the photons.

As depicted in Figure 1, a red photon has the longest wavelength and so has the smallest energy. It is like a child sized basketball player. A red photon playing basketball, no matter how they try, even on their tippy-toes cannot reach the net to drop their electron through. And no matter how many of these child-sized photons there are, electrons are never going to get through the basketball net. This is equivalent to no electrons coming off the material when irradiated by red light at any power.

Figure 1. Energy of photons is depicted as height. Of the visible colours, red photons have the least energy, violet photons the greatest energy, with green photons in between. The height of the ball held up by the photon, compared to the height of the basketball net is equivalent to the comparison of photon energy with the energy that holds the electrons to the atoms.

Now if you have a green light, that's like an adult sized photon, playing with a child's basketball net and they can dunk the electron through the net, but only barely. They're only standing slightly taller than the basketball net and so when they drop their ball through it has only picked up a small speed before reaching the net.

But the violet photon is like a pro basketball player. They're the very tall photons. Their height is well above the net and when they drop their electron through the net, the electron has a lot more speed. But it wouldn't matter how many of these violet photons there were, they would all be dropping electrons at the same speed through the net. There would be more electrons coming through the net.

Usually when people study the photoelectric effect, it is about the study of quantum mechanics, but that's not what I want to concentrate on for this lecture. What the experiment and theory of the photo-electric effect tells us is about how light interacts with matter. It is always one photon interacting with one atom at a time. If that photon has enough energy, more than the energy that the atom is holding onto its electron, it can send that electron on its way. The kinetic energy of the electron is given by the difference in the energy of the photon and the energy the atom was using to hold onto the electron. As the power of the light is increased, it means that there are more photons in the pulse and so more photons are available to interact with more atoms, but always one photon meeting one atom at a time.

And that's how we understood how light interacted with matter through the beginning of the 20th century. And then along came Maria Goeppert Mayer, the second woman to be awarded a Nobel Prize in physics. Her Nobel Prize work was about nuclear shell structure, but I will discuss the work she did for her PhD in 1930 and published in 1931[1]. I cited that 1931 paper in my own PhD thesis.

Maria Goeppert Mayer started a whole new area of physics known now as multiphoton physics. She worked out the quantum mechanical theory of an atom simultaneously absorbing two photons to leave the atom in an excited electronic state. In order for light to be linearly absorbed, the energy of the photon must match the energy of the atomic energy between the ground state and the excited state. For the case of two photon absorption that Goeppert Mayer solved, the addition of the energies of the two photons must equal the energy difference of the atomic states. Of all possible two photon processes, absorption is the most likely because it uses a resonant interaction. This is the same idea as pushing a child on a swing. To make the swing go higher you only push one time each period or in other words only when the swing has reached its maximum height. If you pushed at other times, it would disrupt the swinging motion rather than increase the swinging motion to greater heights.

If instead of absorption, we consider the process of multiphoton ionization, two little red photons would be simultaneously absorbed and the combined energy of the two red photons would be the same energy as a violet photon of twice the energy. The two red photons would cause an electron to be ejected as if it was irradiated by a single violet photon.

Goeppert Mayer had theoretically predicted multi-photon absorption, but no one had observed the effect experimentally. In fact, no one would see a multi-photon effect for another 30 years. It was Peter Franken's group at the University of Michigan that were the first to see a multiphoton effect. They were not investigating multiphoton absorption but rather a nonlinear optical process known as second harmonic generation [2]. To clarify, multiphoton physics refers to the study of the medium undergoing a multiphoton process and nonlinear optics is the study of the resulting light from a multiphoton process. Harmonic generation is not a resonant process, but one where an atom will simultaneously absorb the energy of two photons but then quickly release the energy. The energy will be released as a single photon having twice the energy. The photon having twice the energy of the input photons is known as the second harmonic. Since the photon energy is doubled, the wavelength is halved. Using an optical spectrometer that could measure both the red optical signal as well as the generated violet light, the Franken group measured a very small signal in the violet when they had a very powerful red light.

Second harmonic generation was then first observed in 1961, which begs the question of why it took 30 years to see any type of multiphoton effect similar to what Maria Goeppert Meyer had predicted in 1931. What was special about 1961 was that in 1960, the laser was first demonstrated.

Because this is a Nobel lecture, I want to honour all of the people that have been awarded Nobel Prizes for developments that led to the invention of the laser. Nicolay Basov, Alexander Prokhorov and Charles Townes were honoured for developing the maser. The maser was the precursor of the laser and the m is for microwave rather than light in lasers. Technologically it was easier to make a maser than a laser. Masers were first demonstrated in the 1950s. Art Schawlow was then awarded a Nobel Prize for laser spectroscopy, but he had done a lot of the pioneering work on converting maser technology to the optical wavelengths.

But I want to give credit to Theodore Maiman. There was a race on at the end of the 1950s and into 1960 to see who would be the first person to demonstrate the laser. Ted Maiman won the race [3]. He was working at Hughes Aircraft.

The laser was born in 1960 and that's why Peter Franken's group could see a nonlinear optical effect. Why did laser light lead to observations of nonlinear optics? Regular light sources such as the sun or a light bulb emit photons of every colour, which is why the light appears white. The

photons go off in all directions. They also don't communicate with each other. They emit at random times. Because the photons are emitted at random times, the crests of some waves overlap troughs of other waves and the waves cancel each other out. The overall amplitude of the combined waves then is not that high. In other words, the density of photons is low. On the other hand, a laser emits a beam of light where all the photons travel in one direction. The light from a laser will also only have one colour. The photons in the laser communicate with each other so that the photons are emitted in a way to have all the crests of the waves of each photon line up together. The waves of each of the photons add together, making themselves into a giant wave and a giant wave means the density of photons is very high.

So now we need to discuss why the higher density of photons leads to the observation of multiphoton interactions. The density of the photons is given by the total number of photons in a given volume. For a light beam, two dimensions of the volume are given by the area of the beam. The beam area can be reduced by focusing the beam with a lens. The shorter the focal length of the lens, the smaller the beam diameter. The smallest beam diameter is limited to the dimension of the wavelength. For light, these wavelengths are on the order of 1 micron. The third dimension of the volume of light is given by the length of the pulse. The pulse length can be given by a spatial dimension, l, or the temporal length of the pulse τ. The two lengths are related by the speed of light, c such that, $l = c\tau$. The shortest pulses to date are on the order of two wavelengths although pulses this short have yet to be amplified in a laser amplifier.

In a linear interaction, one photon interacts with one atom at time. The rate of interaction is given by the probability of finding a photon in the interaction volume of the atom. The interaction volume differs from the actual size of the atom. The interaction volume is given by what is known as the cross-sectional area of the atom. The easier it is for the atom to interact with the light, the larger is this area, but it is about the area of the atom, which has dimensions of 0.1nm squared. This area is more than one hundred million times smaller than the focused spot area of the light. The third dimension of the interaction volume is given by the interaction time. The interaction time increases as the photon energy approaches the energy of the electronic state of the atom. If the photon is absorbed in the interaction, the process is a resonant process and the interaction time can be quite long, such as microseconds. This time scale corresponds to a length, l, of 300 m so that the interaction volume can be large. With linear interactions, the probability of finding a single photon in the interaction volume increases linearly with photon density.

To see a second order nonlinear process such as the Franken group observed, there must be a non-negligible probability of finding two pho-

tons in the interaction volume. Unlike two-photon absorption, second harmonic generation is a non-resonant process and so the time scale of the process is quite short and the interaction volume is the cross-sectional area of the atom and a length of a few microns. With regular light, the photon density is too small to have an observable chance to see the effect. The Franken group used a laser that had 3 J of energy with a 1 ms time duration pulse. With this 300W of laser power focused into the medium, the efficiency of the frequency doubling process was 10^{-7} or one violet photon for every 10 million red photons [3].

By the time I was working on my PhD in the 1980s, scientists were working on higher order nonlinear harmonic generation. The goal of the work was to generate coherent radiation equivalent to laser radiation, but out in the ultraviolet and possibly beyond that to the extreme ultraviolet. My supervisor Gérard Mourou gave me a paper [4] written by Stephen Harris of Stanford University to read and consider whether I could experimentally show the type of effects that Harris had considered theoretically. Harris had determined various transitions in atoms and ions that would have resonances for high order even harmonics. There are reasons of symmetry that do not allow even numbers of photons to be absorbed in isotropic, homogeneous media such as any gas medium so the even number of photons could not be absorbed with this multi-photon resonance. The even harmonic would also not be generated. By finding resonances for high order even harmonics, this would allow the next higher odd harmonic to have a better chance of being generated than the lower orders, which would not experience any resonant enhancement.

I determined that twice ionized nickel would have a resonance with the 8^{th} harmonic of the radiation from a particular type of laser that we had in our research group, a Nd:YAG laser. My original thesis project was then to generate the 9^{th} harmonic of the 1-micron radiation from this laser. There are many reasons that I won't go into here, but I never did accomplish these experiments. To try and do a ninth order nonlinear optical experiment, I didn't just need a pulsed laser. I needed a high intensity laser. This is why I was the student who worked with Gérard to develop Chirped Pulse Amplification.

As discussed previously, nonlinear interactions are dependent not on the total energy in the laser pulse, but rather the energy density. To generate the highest order nonlinearities, you want the highest energy density, which is energy per unit volume. Because we are discussing light waves, we more often refer to the intensity, which is the energy per unit area per unit time. The area of the beam is fixed by the focusing element and the wavelength of the light. The energy per unit time is the power of the light. To increase this power, you have two choices, increase the energy or

decrease the time duration. Ideally, to maximize the intensity, you want both high energy and short pulses.

At the time of my PhD project, inside the Laboratory for Laser Energetics (LLE) at the University of Rochester, where I was working on the experiments for my thesis, both high energy lasers and short pulse lasers existed. Within Gérard's research group there were several short pulse laser systems. During the 1980s, the shortest pulses were created with dye lasers. Dye lasers had very large gain bandwidths that could support short pulses. I will discuss later the connection between short pulses and large spectral bandwidths. The dye lasers at LLE operated with pulses as short as 100 femtoseconds (fs). The 100 fs pulses stretch over a distance of only 30 microns. Compare this length to a 1 second pulse of light, which would stretch over two thirds of the distance from the earth to the moon, 300,000 km. Dye lasers have high gain, which means the lasing medium can be quite short to achieve the maximum power stored in the lasing medium. It is this characteristic of high gain, that makes dye lasers poor energy storage lasers. To store the maximum energy, the gain medium must stay in the excited state for a long time. To be a high gain medium, the opposite is true. The atoms must want to give up the energy in the excited state to allow for gain by stimulated emission. Dye lasers are therefore always low energy lasers with a maximum energy of about 1mJ. The maximum power of the dye laser was then 1 mJ per 100 fs or 10 GW. On the other hand, there was a high energy laser system known as the Omega laser at LLE. The main research goal at LLE is laser fusion, which is a process based on the total laser energy that can be applied to the fuel target. The Omega laser could deliver one kJ of energy, but the laser pulses had to be longer than 1 ns to not damage the laser rods. The gain medium of the Omega system was Nd doped glass. The energy of the glass laser was a million times greater than the dye system, but the pulse duration was 10,000 times longer. The power in the pulses was higher and reached a TW or a million MW.

The gain bandwidth of the Nd:glass laser is large enough to support amplifying pulses as short as 1 ps. The pulse duration was limited by the nonlinear optical effect of self-focussing. Self-focusing is a different nonlinearity than already discussed. At low power, the light is transmitted through the medium at a lower speed than light travels in vacuum. The difference in speed is determined by the index of refraction of the medium. At low power, the refractive index is given just by the material itself. When the intensity gets sufficiently high, the interaction changes such that the index of refraction changes instantaneously with light intensity. A laser beam is more intense in the centre of the beam compared to the edges. At high intensities then, the light in the centre of the beam travels slower than the light at the edges. This causes the light beam to start

to focus in on itself, which causes the beam to get smaller and more intense. This is then a runaway process where the beam finally collapses to a small enough size that the intensity is large enough to damage the material.

Scientists want the high peak power at the output of the laser system so they can study the various nonlinear processes, but the lasers themselves are damaged by the nonlinear processes if the power gets too high inside the gain medium. This was the problem that had to be overcome. High intensity laser pulses had to be generated without destroying the laser medium itself. The solution was CPA.

The CPA idea is beautiful in its simplicity as depicted in Figure 2. Start with a short pulse from an oscillator and then stretch it to be long enough to not allow nonlinear interactions in the lasing medium. Amplify the stretched pulses. After amplification the long, high energy pulse can be compressed back to its short pulse duration creating the high-power pulse at the output of the system.

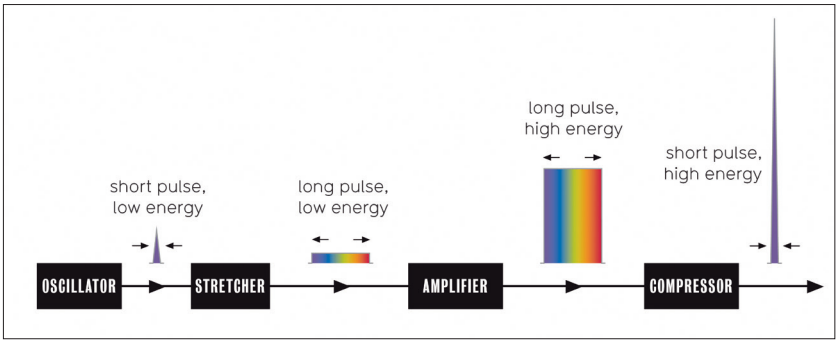

Figure 2. Schematic of chirped pulse amplification, showing that the power remains low in the amplifier because of the stretcher, but the power is very high at the output of the pulse compressor.

The CPA concept works best for lasing medium that can support short pulses because of a very large gain bandwidth and also support high energy because they are a good energy storage medium. The best compromise between these two criteria is titanium doped sapphire, which was being discovered at the same time as CPA was being developed [5]. Most CPA lasers today use Ti:sapphire as the lasing medium both for the oscillator and the amplifiers. However, in the mid 1980s the short laser pulses came from dye lasers that had wavelengths of 0.6 μm and the large energy storage lasers were Nd:glass operating at wavelengths of 1.0 μm, so it was not possible to simply stretch the short dye laser pulses and amplify them in the high energy glass amplifiers.

To demonstrate the CPA concept we used a mode-locked Nd:YAG laser, which could generate pulses with durations of about 100 ps at the same 1μm wavelength as Nd:glass amplifiers. As we wanted pulse durations shorter than 100 ps, we first had to use optical fiber pulse compression techniques that were being developed at that time [6]. In order to generate short pulses, you need large spectral bandwidths. If you have a single wavelength, the wave goes on forever. If you add a wave that has a slightly different wavelength to the first wave, such that at one time, which we will call t = 0, both waves crest, then at a later time the two waves will add up to zero because one will be at a peak when the other is at a trough. As shown in Figure 3, if you keep adding waves with different wavelengths so that they all peak at t = 0, then when the waves all add together, only at t = 0 do they all add constructively. At all other times there is some amount of destructive interference, that is, there are peaks and troughs adding together to make zero. The more wavelengths you can add, the shorter the pulse becomes. This is why there is an inverse relationship between spectral bandwidth and minimum possible temporal duration. The laser process that ensures all the wavelengths are adding so that all the crests add together at one time in order to produce a short pulse is known as mode-locking. The Nd:YAG laser used mode-locking to produce the ~ 100ps pulses.

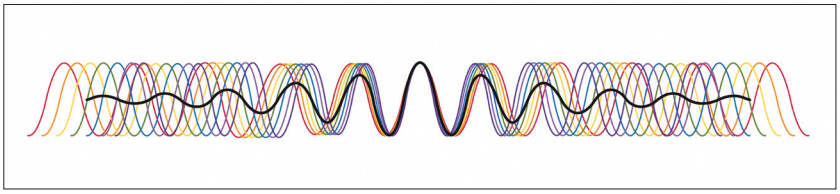

Figure 3. Demonstration of adding different wavelengths in a controlled manner leading to shorter pulses.

Fiber pulse compression uses a nonlinear optical technique known as self-phase modulation (SPM) to generate more spectral bandwidth. It is the same nonlinearity that leads to self-focusing in the bulk media, but rather than the intensity varying spatially across the beam, the intensity varies temporally over the pulse duration. In an optical fiber, the beam is guided and so the beam continues to travel as a plane wave down the fiber. The beam area is very small in the fiber, leading to the intensity of the light being high and remaining high over the long lengths of the fiber. The laser pulse has a time varying intensity. The index of refraction changes with intensity at these high intensities, causing the peak of the pulse to move slower than the leading and trailing edges of the pulse.

Because the light at the peak of the pulse moves slower than the leading edge, as the pulse propagates, the distance between the leading edge and the peak lengthens. The number of phase fronts remains constant and so the phase fronts must have greater distance between them. This longer distance between phase fronts is a longer wavelength than the original wavelength. At the same time, the peak is getting closer to the trailing edge of the pulse with propagation, and so the crests of the waves are being pushed together to create shorter wavelengths. The pulse duration does not change because of SPM, as the beginning and end of the pulse both continue to propagate at the low intensity speed. If the newly generated colours can be timed together rather than the red at the front and the blue at the back, the extra bandwidth would allow a shorter pulse duration. This retiming of the colours is known as pulse compression.

Propagation in the fiber not only creates new colours by the nonlinear interaction SPM, but these colours disperse along the fiber because the ordinary refractive index is wavelength dependent. The reddest of the colours travel fastest, leaving the bluest colours to trail at the rear of the pulse. The dispersion leads to the pulse durations becoming longer with propagation. By 1984, scientists had shown that the best pulse compression occurred when the fiber length was sufficient to not only create the needed extra spectral bandwidth, but that the pulse had stretched sufficiently so that the colours spread out in such a way that the frequency of the light changed almost linearly with time throughout the pulse [6]. The frequency sweep through the pulse is known as a chirp, in the same way that a bird's chirp has its sound frequency change in time. We could have called the technique stretched pulse amplification, but chirped pulse amplification sounded better.

It was already known by 1969 that a pair of parallel gratings could compress a linearly chirped pulse back down to its minimum pulse duration by completely eliminating the chirp [7]. The work on fiber optic pulse compression then gave us the path forward to demonstrate CPA. We would generate the needed spectrum and stretch the pulse in an optical fiber. This stretched pulse was then amplified in a Nd:glass amplifier and a pair of parallel gratings compressed the pulses to deliver short, energetic pulses at the output [8].

The Mourou group had a mode-locked Nd:YAG laser to pump a short pulse dye laser. Dye lasers needed green colour pumps, which was achieved by generating the second harmonic of the 1μm beam from the Nd:YAG laser. The beam intensity was sufficient to convert about 10% of the power to green light, but that left 90% of the infrared beam wasted. It was this wasted beam that I used for the input to the original CPA laser. It is lucky that we needed to use a long fiber for the spectral enhancement and pulse stretching as there was no room in the dye laser lab for me to

build the CPA system. We were able to string the fiber in the ceiling down to another lab at the other end of the building where we had the space to build the system.

We used 1.4 kilometers of specialty optical fiber from Corning Inc. This fiber had a 9 μm core and so was single mode for the 1 μm light from the Nd:YAG laser. Corning had donated 2.5 km of fiber to us for this project. Unfortunately, only one end was available on the spool and so I had to unwind and rewind the fiber onto a different spool and I damaged the fiber during this process and was left with two pieces of optical fiber. I used the longer piece which was 1.4 km in length. The 2 W, Nd:YAG laser beam was focused into the fiber. At this power, the spectral bandwidth was increased to 4 nm Full Width Half Maximum (FWHM). The pulse duration increased to 300 ps at the output of the fiber.

To amplify the pulses a regenerative amplifier was built. This type of amplifier uses a cavity similar to an oscillator, but the focusing is weaker in the amplifier compared to an oscillator allowing a larger beam diameter in the gain medium. The oscillator must start with one spontaneously emitted photon. This photon then stimulates another and the then the two become four. This is exponential gain and how all lasers start. However, the gain must reach the saturation level where the gain becomes linear. Otherwise the amplification is very inefficient. As shown in Figure 4, if you consider one single pass through an amplifier with low input signal, then at the input side of the gain medium, there are insufficient photons to de-excite the atoms, leaving most of the energy behind in the gain medium. In order to extract that energy, the input to each amplifier stage must be at the saturation level. Each type of laser gain medium has its own saturation level and it is related to the energy storage. Nd:glass amplifiers have a large saturation energy of ~ 5 J/cm2. In oscillators and regenerative amplifiers, the pulses make multiple passes through the gain

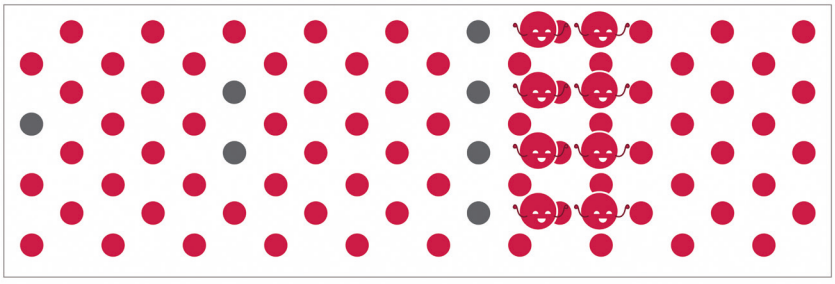

Figure 4. Demonstration of low signal gain being energy inefficient. The figure shows the output photon number of 8 having started with one photon at the input. The stimulated emission has left only 7 of the atoms de-excited and almost all the atoms still in the excited state. This energy would be wasted.

medium such that they reach the saturation level by the final pass through the gain medium. To keep increasing the energy of the pulses, the size of the beam must keep increasing so that at the output of each amplification stage, the energy per unit area remains the same. In our case the pulse energy was increased almost a million times, from a few nJ to about 2 mJ. The repetition rate was decreased from 80 MHz to 10 Hz.

The self-focusing nonlinearity limits the maximum pulse intensity or energy density. The saturation energy of the gain medium determines the maximum energy per unit area. From these two limits, you can determine the minimum pulse duration that can be amplified without causing self-focusing. To achieve the maximum possible energy from a Nd:glass laser, the pulse should be stretched to 1 ns. As we only achieved 300 ps with our 1.4 km fiber, we did not extract the maximum energy from the regenerative amplifier.

The final step in CPA is the pulse compression. We used a pair of parallel gratings and a roof top prism. Gratings cause the colours to diffract at different angles as depicted in Figure 5. If you look at the path of the red beam, you will see that it has the longest path to the output of the compressor, whereas the blue wavelength beam has the shortest path. After diffracting off the pair of gratings, the colours will be along a line perpendicular to the beam path. Because we want to have a circular beam at the output of the compressor, this line of colours is reflected by the roof prism back through the pair of gratings. In this way all the colours come back together into one circular beam, but the path length difference between the reddest and bluest colours has been doubled.

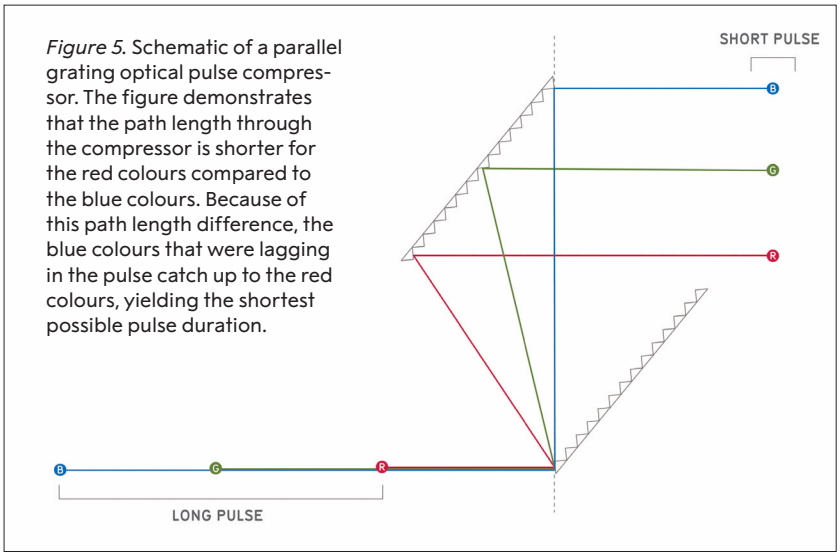

Figure 5. Schematic of a parallel grating optical pulse compressor. The figure demonstrates that the path length through the compressor is shorter for the red colours compared to the blue colours. Because of this path length difference, the blue colours that were lagging in the pulse catch up to the red colours, yielding the shortest possible pulse duration.

By placing the two gratings a certain distance apart, you can have the opposite dispersion than the fiber dispersion. That is, the colours that were stretched out over 300 ps can now be compressed to the minimum duration allowed by the spectral bandwidth. As I pointed out, even with the best fiber pulse compression, the chirp after the fiber is not perfectly linear. The opposite dispersion of the pair of gratings is also not perfectly linear, and so the pulse duration does not compress completely to the bandwidth-imposed limit. The compressor was set up with the stretched oscillator pulses, as we had the type of pulse duration measurement device, known as an autocorrelator, that could operate at the high repetition rate of the oscillator. We compressed the pulses to 1.5 ps.

To measure the amplified and compressed pulses at the 10 Hz repetition rate, I needed to use a streak camera. My colleague Steve Williamson had such an instrument and together we measured the pulse duration to be 2 ps. This was the limit of temporal resolution of the streak camera, but it showed that the amplification process had not changed the chirp, as the compressed pulse duration was ~ 2 ps before and after amplification.

This first CPA laser system delivered 1 GW power pulses, with 2 mJ of energy in 2 ps duration. At Rochester, along with Patrick Maine, we continued to develop CPA lasers to deliver TW laser power from a laser system that could sit on one optical table, which we referred to as a table top terawatt or T-cubed laser [9]. It was with the TW system that I completed my PhD research.

Rather than study high order harmonic generation for my PhD, we decided to study multi-photon ionization. This is an extension of the perturbative treatment worked out by Goeppert Mayer for the case of two photon absorption. Again, using gravitational energy as an analogy for the electromagnetic energy, an electron in an atom sits down in a well. The height difference to the top of the well from where the electron sits is known as the ionization potential. In order to ionize by a multiphoton process, the atom needs to absorb the energy of enough photons so the total absorbed energy is greater than the ionization energy. With a multi-photon process, the ionization rate would vary with the light intensity to the power given by the number of photons required to exceed the ionization energy threshold. We used various noble gases, with Xenon being the easiest to ionize. With xenon, it would take 11 photons to ionize the atoms with 1 μm photons so we expected to see the ionization rate vary to the eleventh power of intensity. This was not the case. With our infrared photons and ultrahigh laser intensity of 10^{15} W/cm^2, we were no longer in the multi-photon regime. We had such a large photon density that the light energy could once again be thought of as a giant wave.

At high intensities, rather than the electron getting enough kinetic energy to jump out of the potential well, the potential well is distorted by

the interaction with the light wave as demonstrated in Figure 6. The well is bent over by the wave at the frequency of the light. The well is tipped one direction for half the period of light and then the other direction for the second half of the period of the light. The electron then is no longer contained by the well, for a brief moment of time. The longer the wavelength, the longer the time duration that the potential well is bent allowing a longer time for the electron to escape. Quantum mechanics also allows the electron to tunnel through a barrier and so the potential does not need to be completely tipped, but our work with long wavelengths in the infrared and the very high intensity showed that the electrons did simply ionize over the barrier [10]. These ionization studies [11] helped usher in a new field of study, high intensity laser physics.

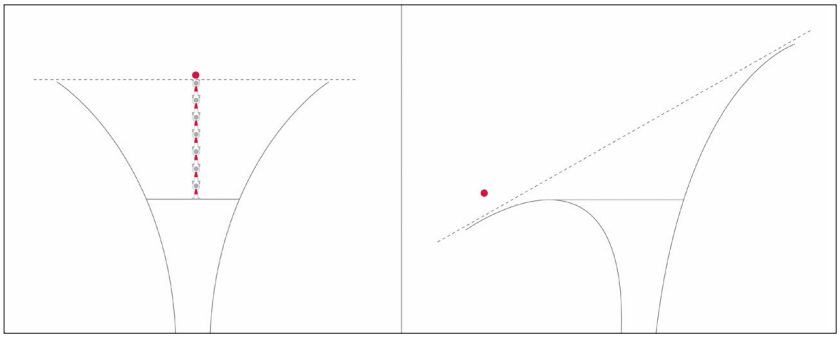

Figure 6. On the left panel, the perturbative effect of multi-photon ionization is depicted. The electron gets sufficient energy from simultaneous absorption of multiple photons to escape from the potential well. On the right panel, the process of over-the-barrier ionization is shown. The interaction with the high intensity light wave bends the potential energy wall over. If the light power is sufficiently strong, the well is bent as low as the electron energy level and the electron is free to escape for the duration of the half period of the wave.

Whereas some physical processes are a result of the total energy that can be applied, other processes occur because of the force applied per unit time. A mechanical example is the use of a hammer. If you simply push on a nail, it is difficult to move the nail, but if you hit the nail quickly with the hammer, the nail moves easily. This is why I like to say that I built a laser hammer when I built the CPA. The laser hammer has led to new types of laser machining. Unlike the thermal machining processes carried out by long pulse or continuous wave lasers, which depend on the total energy deposited to the material, short pulse laser machining leads to very precise cutting and drilling. This is because there is very little heat delivered to the material. Any heat spreads through the material, melting

and deforming the material. If you can have a very short pulse, material can be cut with very low energy and so very little heat. This short pulse, low energy machining results then in very clean cuts and the drilling of very small holes. The machining is a result of the material being ablated or in other words ripped apart. The ablation is a result of the electrons being ripped off the atoms by the high intensity laser ionization process. Because this type of machining does not depend on depositing the energy in the material, it can machine transparent material such as glass or the cornea in the eye. The light is then not absorbed by the material and the laser ablation of material occurs only at the focal point. The machining can therefore be done inside the transparent material. It is because of this machining precision, that CPA lasers have found applications in machining and in particular machining the corneal flap for laser eye surgery.

The laser ushered in a new field of experimental study in nonlinear optics and multi-photon atomic processes. The development of CPA furthered our understanding of the interaction processes, which not only include exciting the electrons' kinetic energy but also the distortion of the potential energy. The new field of high intensity laser physics has pushed new technologies to be developed that lead to shorter pulse durations or higher powers or both. These new technologies continue to lead us to a new understanding of how light and matter interact.

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