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From Femtoseconds to Attoseconds

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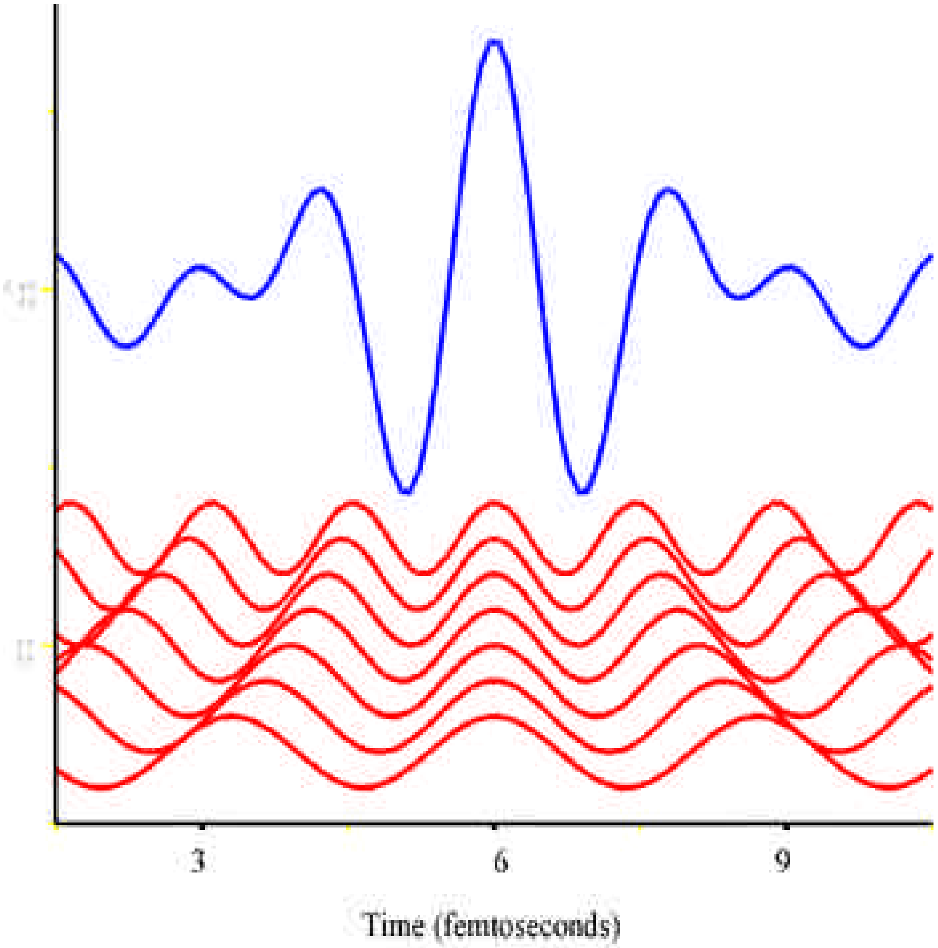
If you were asked to draw an accurate representation of a pulse of laser light that lasts 4.5/1,000,000,000,000,000 of a second (4.5 femtoseconds), how would you do it? Where would you start?

Can’t even imagine such a timeframe? Considering it’s the shortest laser light pulse that has ever been produced, who could blame you. Maybe it will help to think of it this way: the duration of this light pulse “is to a minute as a minute is to the age of the universe.” Very short.

Still having trouble? Then consider the illustration below, which represents a 4.5-femtosecond pulse. It shows two aspects of light. In the first, that light is a wave (the red lines). In the second, a short pulse is the total of waves of different wavelengths (the blue line). The ticks on the horizontal axis are 3 femtoseconds apart.



Now that you've indulged us with your powers of imagination, we'll get to the point. What can we do with something so infinitesimally short? The possibilities are virtually unlimited and carry with them great potential for all aspects of our lives. In fact, once we learn how to harness that light pulse's power, we can use it for applications as diverse as increasing the speed and capacity of our telecommunications-delivery systems, and introducing new tools for non-invasive diagnostics and "bloodless" surgery.

Small but mighty — the power of concentration

Despite popular belief and images in the media of the extraordinary power of lasers, scientists are quite aware that individual laser pulses have very little energy. If you think of the impact of a fly landing on a human arm, you'll have a fairly accurate comparison of the kind of energy that comes from a single laser.

However, when the same light pulse is compressed to a femtosecond's duration, the pulse ends up containing hundreds of gigawatts and takes on new power. The result? It can easily exceed the total power produced in all of Canada during that same femtosecond. But we can go even further. If we focus those hundreds of gigawatts of power on a target only 1/100 the diameter of a human hair, the energy coming from the light pulse is astronomically intensified. Figuratively speaking, you'd end up with an inferno. At least that's what should happen. At this point, the science is so new that no one in the world has much experience with such high concentrations of power. And as scientists continue to study it, they keep making new discoveries.

At low intensities — holding molecules in pockets of light

Before we continue on our investigation of the energy in light pulses, we'll need some background on the nature and composition of molecules.

A molecule is made up of many electrons whizzing around a set of heavy ions. The electrons are held in place by the attraction between their negative charge and the positive charge of their heavy ions. The electrons, in turn, help glue the ions together, making the molecule. It's a tight and amicable relationship. But if you focus a laser light directly on a molecule, it "pushes" both the positive ions and the negative electrons, trying to move them in opposite directions. Since the electrons are not as massive as the ions, they give in first.

What happens next can best be visualized by thinking of the molecule as a ball. The moving electrons allow the laser beam to grasp the ball much the same way that you would grasp a ball in your hand. (Interestingly, if the light is strong enough it will distort the molecule, just as you can deform a soft NERF® ball by squeezing it.) Once you grasp the ball in your hand, the ball must follow every move your hand makes. Similarly, if we grasp a molecule in a light pulse, we can move the light pulse, and the molecule must follow. Imagine how, during a baseball game, a pitcher twists his fingers as he throws a ball—to put a spin on it. If we do the same to a molecule by "twisting" the light pulse, the molecule will also spin.

Although this is a new area of research, at the National Research Council (NRC) we have already shown that laser beams can move molecules, and that we can focus molecules just as we focus light with a lens. We have also shown that you can spin a molecule—sometimes so fast that the molecule breaks into pieces.

At intermediate intensities — even shorter pulses

We've just expended a considerable amount of energy demonstrating that femtoseconds are very short. No arguments there. But now it's time to consider something that's even shorter: attoseconds. In fact, attoseconds are 1,000 times shorter than femtoseconds.

Scientists will soon be able to make 100-attosecond light pulses. The technology to do this requires light pulses of higher intensity than those needed to hold a molecule. They should be just high enough so that the force of the laser on the electrons overcomes the force holding an electron in an atom or molecule.

As we pull a single electron free, it is buffeted by the light wave. To get a good picture of what happens next, let us consider a lifeboat launched from a ship in stormy seas. As it swings free of the ship, it rocks in the waves. Unless the ship's crew is very careful, the lifeboat might collide with the parent ship. In this way, the electron can also collide with the ion that it just left. In the ensuing violent collision, the electron can emit light—leaving the analogue of the lifeboat shattered.
We are able to control the electron-ion collision so well that it can be restricted to only a single 100-attosecond time interval. This means that scientists are close to achieving the goal of producing 100-attosecond light pulses. And when that's possible, a whole new world of possibilities will open up.

At higher intensities: photographing chemical reactions

Every high school science student knows that, in a chemical reaction, the atoms in a molecule rearrange themselves. Although we're sure it happens, it's not visible to the naked eye. Imagine the possibilities, however, if we could actually photograph the chemical reaction. How could it be done? In labs all around the world, the investigation has been underway for quite some time. Scientists have been working on the challenge of observing chemical reactions in real time for some 15 years now, and have made considerable progress. In fact, the 1999 Nobel Prize in chemistry, which went to Dr. Ahmed H. Zewail, recognized his significant contribution to this area of investigation.

But obstacles remain and we still have a long way to go. For example, we can't use the visible light that normal photography uses because the wavelength of ordinary light is too large. We have considered using X-rays, but X-rays are difficult to manipulate and we're just now learning how to make short bursts of X-rays.

At the National Research Council, we believe that we can come close to producing an actual photograph, at least for small molecules. It would require light of higher intensity than we needed to create attosecond pulses. And while these pulses don't have to be of the "inferno" variety, they have to be powerful enough to pull a large number of the molecule's electrons free from their ions, thereby breaking the bond that holds the atoms of the molecule together.

The opportunity to accomplish this lies with the ions, whose charges naturally repel each other. When attosecond pulses are used to remove a large number of the electrons, the remaining ions are all positively charged. They explode apart like a firecracker. Therefore, if we want to “see” how the molecule was shaped just before we triggered the explosion, we would need only to catch all of the fragments and determine where they came from, and then reassemble them pictorially, using computer graphics. Need a better mental picture of how this would work? Imagine a film that depicts a car filled with explosives. When the explosives are detonated, the roof of the car flies up, the doors to each side, the headlights forward. If we caught each piece, we could deduce the basic shape of the car just before it exploded.

Approaching the highest intensity: relativity

For scientists, one of the most exciting prospects of all is the possibility of bringing relativity right into the laboratory where we can study and exploit it whenever we wish. The lasers for doing this are small enough to fit on a dining room table and they are sure to get smaller.

Therefore, if scientists are creative enough to find important applications, we may someday benefit from appliances in our homes, or devices in our hospitals, that rely on relativity. Even scientists are amazed that we can now imagine exploiting in daily life such seemingly obscure and remote concepts as Albert Einstein’s famous equation $E=mc^2$, which established exciting new theories about light and gravity.

Let me explain how relativity is being tamed. Einstein stated that it is impossible for any object to exceed the speed of light because, as the object (no matter how large or small) approaches that speed, it is held back by an ever-increasing mass. We know that light pushes on electrons, and intense light pushes on them very hard. At only about 1/10,000 of the maximum light intensity that we can technically reach, any electron caught in the light is accelerated first one way, then the other way, as the light wave oscillates. During each 1/2 period of the light wave, the electron is accelerated from rest to very close to the velocity of light, then returns to rest. The process takes only about 1.5 femtoseconds.

It is too early to know if we will find something important enough to warrant bringing relativity into our homes. Since I cannot provide a practical application of relativity yet, let me instead introduce you to an early spin-off of this area of science.

Application — writing waveguides

Over the past two decades, we have learned that laser technology continues to get better and better—whether it’s applied to laser pointers, your CD player, or the supermarket checkout machine. This is equally true for femtosecond lasers. They will eventually become pocket-size devices, which means they will likely be used in many applications.

One practical application of this that we are studying at the NRC is emerging from an area of applied research that involves photonic integration. How does it work? Imagine that we focus light into a transparent material—a window glass, for example. Away from the point of focus, the laser light enters the glass just like sunlight. Only near the focus (inside the glass) does the light become so intense that it pulls electrons free from the material, in the same way it pulls them free of a molecule. There is not, however, very much energy in the pulse and there are a large number of molecules in the solid, so very soon the pulse runs out of steam. Although it begins violently, the pulse soon "wimps out." And because it wimps out, it does not damage the glass. Instead, the pulse gently modifies the glass.

We soon discover that, if we move the laser beam after each shot, we can actually draw inside glass (almost like a pen draws on a piece of paper). If we move continuously, we draw a continuous line. We can guide light along this line, just as we guide electricity along a copper wire, or light along a fibre-optic waveguide. Just as in the 1960s scientists developed the technology that allowed many electronic devices to be integrated onto the surface of a single silicon chip, today's new technology for writing inside transparent materials will be one of the important tools of photonic integration. For the first time, we would be able to write optical circuits in 3-D.

My view of the future

It is often said that the heyday of science was in the early part of the 20th Century when so many fundamental theories were discovered. These theories described the mechanics of nature's building blocks: atoms, molecules, solids. However, although theory at that time flourished, actual "experiment" had a long way to go.

In my opinion, experiment is now catching up. Scanning tunneling microscopes have made individual atoms visible to us. Femtosecond lasers have given us a tool to harness forces that are as strong as those that hold matter together. Not only that, we can now control these forces with incredible precision. These tools give us "tweezers of light" to reach into the microworld, where we will be able to manipulate atoms and molecules at will and clear a path that will lead us to incredible breakthroughs in numerous areas. With such significant breakthroughs within our grasp, I truly believe that the present time is just as exciting and important to "experiment" as the 1920s were to theory.