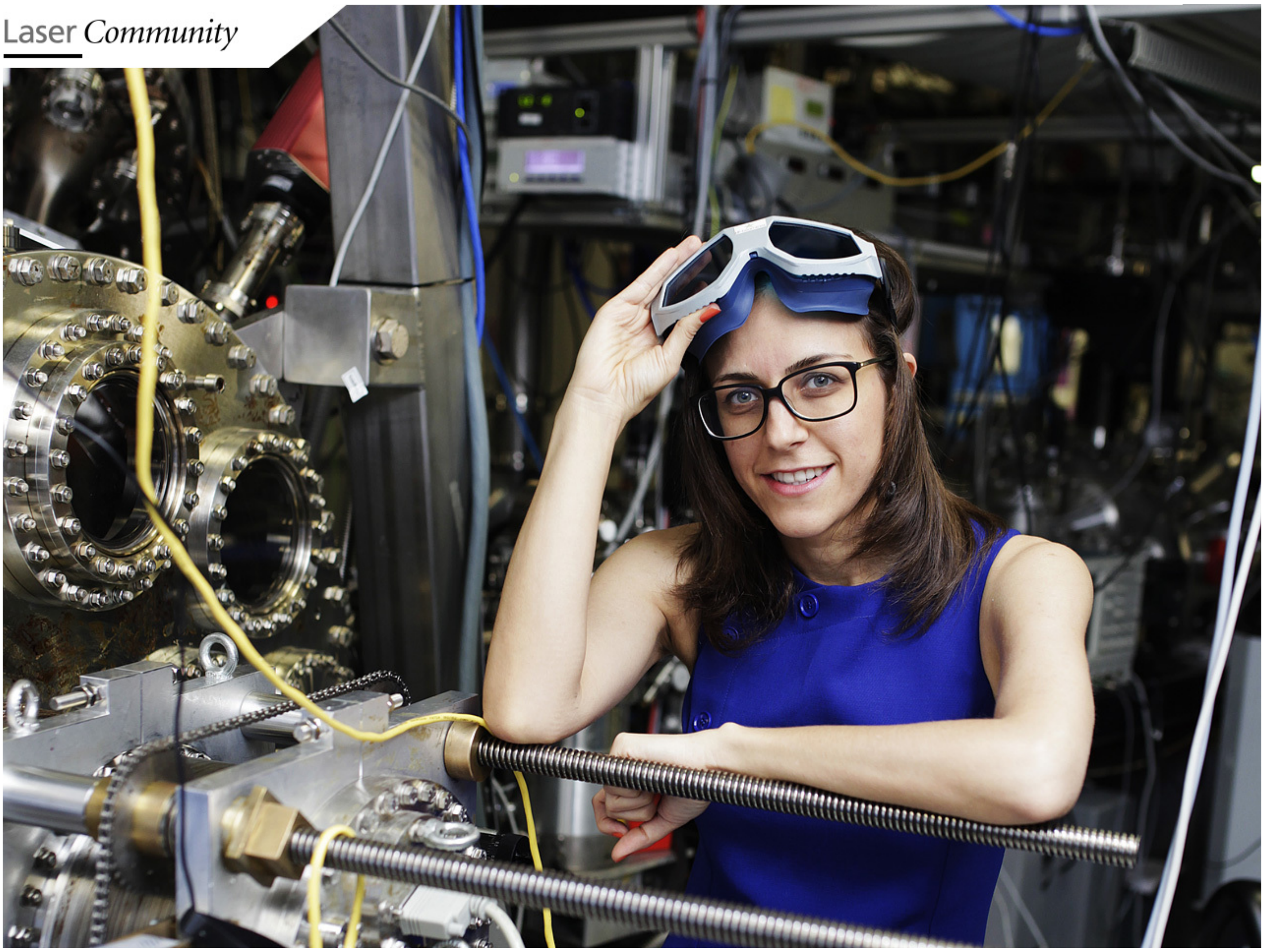


2016-04-01

“WE MAKE LASER PULSES STRONGER, FASTER, AND SHORTER”

Physicists, doctors, chemists – all are waiting for shorter and higher energy laser pulses. The research of Dr. Hanieh Fattahi shows how it is done.

You speak of the “third generation of femtosecond technology”. What does that mean?

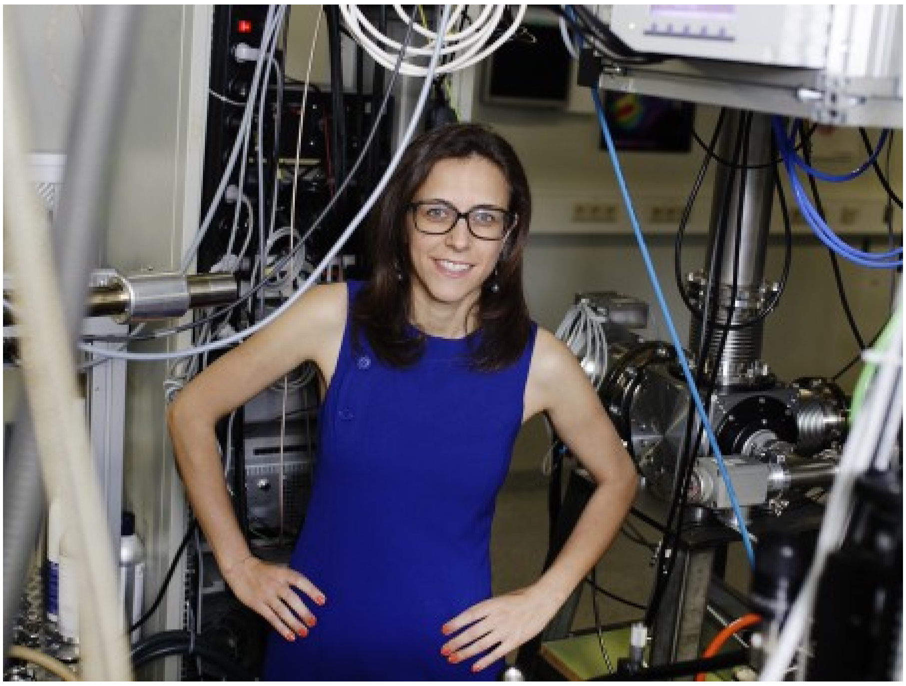
The first generation of femtosecond pulses came from dye lasers, which could produce different frequencies. But although they yielded ultra-short pulses, it was not possible to increase either the pulse energy or the average power – in other words, the repetition rate. Next came titanium-sapphire-based laser technology.

Here you had to choose whether you wanted to crank up the pulse energy or the repetition rate. Doing both at the same time doesn’t work, because it causes the crystal to overheat. In the third generation, it is now possible to create many very short pulses with high pulse energy and also a high repetition rate.

How does it work?

The third generation is based on OPCPA – short for optical parametric chirped-pulse amplification. This technology is not new: such systems have been around since the 1970s. To really get the most out of OPCPA, however, you need one heck of a pump source: scalable and stable.

Happily, one exists in the form of TRUMPF's turn-key ytterbium:YAG thin disk laser. This laser reliably generates pulses with durations of 900 femtoseconds and is freely scalable in terms of repetition rate and energy. We amplify the pulses from this high-power disk laser and make them another 1,000 times shorter with coherent synthesis.



Hanieh Fattahi studied biophysics at Sharif University of Technology in Tehran and has been a researcher at the Laboratory for Attosecond Physics at the Max Planck Institute of Quantum Optics in Munich since 2008. (Photo: Simon Koy)

In my dissertation, I show how it is possible to attain the following parameters: ultra-short pulses with durations of one field cycle, peak pulse power in the terawatt range, average power in hundreds Watt range and a repetition rate between 500 and 1000 Hertz. This wasn't possible before.

Please tell us how you do it!

You need a very broad color spectrum to do it. The more frequency components you combine in a pulse, the shorter it becomes. For a pulse with low energy, that is really easy. And if you want to amplify it, you can simply use an OPCPA. However, physical limits come into play: in a single OPCPA crystal, you can amplify only a few frequencies simultaneously.

So I designed an amplifier setup to get round this limitation: I split the laser pulse into various frequency components and send each one through a separate amplifier. It's a kind of multi-channel OPCPA system if you like. In this way, I obtain various high-energy ultra-short pulses of different frequencies. Then I recombine them coherently in the time dimension: that is, I synchronize them using a waveform synthesizer.

How attosecond flashes are generated:

Attosecond pulses are obtained by focusing highly energized femtosecond pulses into a non-linear medium, such as a beam of inert gas. The laser pulses' strong electrical field exceeds the atomic binding energy and accelerates electrons away from the nucleus of the atom. As a result, the electrons reach speeds of several tens of thousands of kilometers per second.

But in the next half-oscillation of the laser pulse – the electrons could travel only a few nanometers meanwhile – they are already forced back again toward the nucleus of the atom. A recollision can occur. When this happens, the electrons emit the full amount of energy they had gained through the laser field in the form of an attosecond pulse.

The higher the intensity of the femtosecond laser pulse, the higher the harmonics and the shorter and more energetic the attosecond pulses.

And what is the result?

A sub-cycle pulse with a spectral bandwidth of several octaves. Potentially it works with unlimited numbers of frequency components. In this way, we can compress the duration of laser pulses down as far as 500 attoseconds. So we actually can obtain attosecond pulses directly from the OPCPA and the ytterbium:YAG thin disk laser! A nice side effect of this method is the high conversion efficiency of 30 percent. In other amplifier systems, 20 percent is more the norm.

What is the goal of your research?

We want to use these bunched and amplified laser pulses to indirectly generate attosecond pulses that are much shorter again. To do this, we focus the pulses into an inert gas beam and accelerate the electrons of the gas atoms. As the electrons fall back to their ground state, they emit an attosecond pulse.

The maximum photon energy that we have got out of a non-linear medium – the inert gas in this case – so far is 200 electron volts. However, with the third generation of femtosecond technology, we will massively increase the photon energy; hopefully up to a size of over a thousand electron volts. Kiloelectron volts in the lab – that's the dream of every high energy physicist!

What are the shorter attosecond pulses good for? What can you do with them?

It opens us all kinds of possibilities! For example, we will use the method to construct the most precise, highest resolution microscope in the world so that we can observe electrons moving through space. And that's not all: the attosecond pulses will act as a sort of camera shutter, enabling us to film the movements of electrons.

You can imagine it as follows: the faster an event is, the faster the shutter has to work. If you try to photograph a car that is moving faster than the aperture of your camera closes, the image blurs. Electrons are ridiculously fast. Only attosecond pulses come into question as camera shutters here.

The big goal is to film a four-dimensional video of the movement of the electrons in matter – the three spatial dimensions plus time. There have already been very successful attempts to make the movements of electrons in gas visible. But for solids, where electrons are bonded very tightly, we are reliant on higher photon energies in the kiloelectron volt range. You see, most things in the world are solids. So it is important to know what is happening there.

Aside from the new knowledge it brings, what uses could an electron video have?

Electrons play a major role in our lives. For example, so many things in our world depend on electronics, which is based on the movement of electrons: namely, electrical current. Electrons are matter and therefore have a defined speed that cannot be increased indefinitely. By contrast, light is much faster than electrons.

> *I want to have the opportunity one day to look inside an atom. I love the idea of peering down that deeply!*

It is hugely important to understand the interplay between light and matter, because one day people could be able to use this interaction to build optical transistors. These transistors could then open and close at unbelievable speeds, which would enable superfast computing operations. The possibilities this would open up are absolutely limitless.

When will these things become a reality?

Kiloelectron volt photons will arrive in the next two years, I think, while a system for recording electron images will be ready in around four or five years. As for optical transistors, I would not like to make any concrete predictions.

What motivates you?

I want to have the opportunity one day to look inside an atom. I love the idea of peering down that deeply! Over the past few years, I was completely caught up with laser development. In the laboratory sometimes I felt like a magician! I was able to create any frequency I wanted. Ytterbium:YAG laser light is infrared: you cannot see it. But then you convert it into various frequencies in the lab by using nonlinear optics and suddenly millions of beautiful colors become visible – out of nothing!

Or only seemingly out of nothing, as of course there is something there; it is just that you could not see it before. There are so many things that are there but which we cannot see. And that is precisely why I want to make the movement of electrons visible. You know, around 95 percent of the day-to-day life of a researcher is pretty unglamorous stuff: setting up lasers, fixing defective components. But the other five percent, when everything works and you make progress – those times are so wonderful that they make it all worthwhile. That is what I live and work for!

Learn more about the research on the attosecond physics at the Max Planck Institute of Quantum Optics: