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ANIKA BANK

“Delving into the fundamentals of nature is almost akin to a religious experience”

Albert Stolow uses ultrafast laser technology to make “movies” showing how electrons rearrange themselves around atoms and how molecules are formed. His research is paving the way for a whole new field of laser material processing — and seeing this progress gives him a profound sense of serenity.

You say you take a dynamic view of nature. What do you mean by that? We are living in unusual times. We tend to forget that just 100 or so years ago, we had no idea about the fundamental structure of molecules, steels or pharmaceutical drugs. Quantum mechanics, X-ray diffraction and spectroscopy completely transformed our view of nature and we began to understand the fundamental relations between structure and function. The DNA molecule is a prime example: it wasn’t until we discovered its double helix structure that we understood how it functions. There are many other examples and these structure-function relationships carried us to where we are today in science and technology. But it is a static picture and therefore incomplete. Nature isn’t static, it is also dynamic. What do you mean by that? We must differentiate between a structure and a process. If the required function involves something dynamic, something changing, then a purely static, structural perspective will not suffice. Imagine designing an aircraft, for example. This cannot be done without understanding what happens when it’s in motion. The same holds true on a molecular level. To understand fundamental material or molecular processes, we first have to accept that they are dynamic. This is especially true for processes involving the interaction of light with matter. Photosynthesis, the basis of life on Earth, involves ultrafast transformations occurring on a femtosecond time scale (10^{-15} of a second), a tremendously dynamic process.

» **“Nature is dynamic. Our job in the 21st century will be to discover the relations between dynamics and function.”**

Right, but what does that have to do with shape or geometry? Let me give you another example: the rod cells of your retina contain a molecule called retinal, which acts as a kind of antenna for light. In simple terms, when a photon strikes a retinal, it changes shape from bent to straight. This causes a mechanical stress on the rod cell membrane, leading to a change in electrical conductivity. The result is a tiny current, a nerve signal, that tells your brain: I see something. Vision relies on this ultrafast change in molecular geometry. If it were too slow, the system would just relax and there would be no current and, therefore, no vision. Since we cannot tell how fast something goes just from its structure, in the 21st century we will need to develop a new paradigm, a dynamics-function perspective of nature. Would I be right in thinking that we'll be using laser pulses to do that? Absolutely. Only laser pulses are fast enough to observe atomic and molecular processes on their natural time scales. In addition, matter is ultimately held together by electric forces. And light is of course an electromagnetic field. Lasers also allow us to apply strong electric forces to matter in highly precise and controlled manners. This is why we use ultrafast laser technology. How can you do that? Everything we do is related to the interactions of light with matter. There are basically three key aspects of ultrashort laser pulses: time, phase and intensity. The most obvious one is time: ultrashort pulses allow researchers to observe the fastest processes in nature. We developed a technique of time-resolved photoemission spectroscopy here in Ottawa. Put simply, we use a femtosecond laser pulse to excite a material or molecule into a non-equilibrium state. We then use a second laser pulse, delayed with respect to the first, to suddenly kick out an electron. We can learn a lot about how electrons, vibrations, heat, etc. flow on ultrafast time scales by observing these emitted electron distributions as a function of time. The second aspect is phase: we developed a new type of quantum control called dynamic Stark control, using specially phase-shaped, strong ultrafast laser pulses – a method that controls material processes without any net absorption of light. It works by taking advantage of the effect of the laser's electric field – the Stark effect. This is a whole new way of using lasers to control material responses. We're still at an early stage, but I think it has a lot of potential. And finally, we have intensity. With modern, high-power lasers, we can create electric fields that are stronger than those which hold matter together, a new regime of light-matter interaction. We're basically using light as a tool to make carefully controlled changes to matter on a molecular level. Finally, we use low-energy ultrashort pulses in microscopy, allowing us to do real-time imaging of cells, tissues, materials, etc. in a chemical-specific yet completely label-free (i.e. no added stains or dyes) manner. This gives you a rough idea of the different ways in which we use and apply ultrafast laser technology. But are you really just observing? Aren't you actually interfering in the processes you want to observe with your photons? Right, obviously we can never see what goes on without the light. As we know, quantum mechanics is a theory of measurement and the first lesson is that observation always changes the process: there is no glass wall between us and the universe! However, this physics is very well understood and all of the key advances in science and technology over the past century are based on it. We also must use quantum theory and electromagnetic theory to understand our experiments. What kind of lasers do you use? Ultrafast laser physics is currently undergoing something of a technological revolution prompted by new powerful Yb:YAG disk lasers. Unlike conventional Ti:sapphire lasers, Yb:YAG disk lasers produce femtosecond pulses that are freely scalable in terms of their repetition rate and energy. We're currently working with the world leader, TRUMPF Scientific Lasers, to build a unique high-power laser system here in Ottawa. One of the main outcomes will be a tabletop ultrafast X-ray source. This new system will enable us to conduct basic and applied research into laser material processing.

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What contribution does your research make to the world? Well, in the short term, we are developing new types of nonlinear microscopy which we hope anyone will be able to buy and use for their imaging research. In the medium term, a new understanding of ultrafast light-matter interactions will lead to new forms of laser material processing. Just think of all the new materials that are being created with unusual mechanical, electrical and thermal properties and often heterogeneous structures such as composites and laminates. How will people drill, cut or finish such materials? I believe that the only way we'll be able to process these materials of the future will be with ultrashort pulse lasers. And, looking even further ahead, we believe that our research will contribute to the understanding of how molecular systems can transport charge so efficiently and coherently: this relates to the future of solar energy conversion and molecular-scale electronics. Where do you get your motivation for what you do? All humans have looked up at the starry sky and asked: Why are we here? Deep inside us we have a powerful need to find meaning. Obviously, we might never find the answers. Nevertheless, we have entered into a long dialogue with nature. Contributing to this dialogue is what motivates many researchers, myself included! How does it feel to move so close to the very fundamentals of nature? I will happily admit that it can be hard to understand nature. We simply need to believe that there is a logical order, a rationality, even if we don't yet understand it. And when, on rare occasions, you do manage to put a few pieces of the puzzle together, it feels like a revelation: for some it is almost akin to a religious experience. I get a profound sense of serenity in those moments. Does that happen often? No, unfortunately not. Most of the time I'm just confused!

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Professor Albert Stolow is the Canada Research Chair in Molecular Photonics at the University of Ottawa and a member of the National Research Council of Canada’s Molecular Photonics group. He is a Fellow of both the Optical Society of America and the American Physical Society. Together with his research group, he uses ultrafast lasers to observe the fastest processes in nature: the motion of atoms and electrons and the response of matter to laser fields. Stolow has won several awards, including the 2017 Earle K. Plyler Prize from the American Physical Society and the Canadian Queen Elizabeth II Diamond Jubilee Medal.

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