Once uniformity over a large area has been obtained and the carbon nanotube doping has been optimized for either a particular infrared wavelength or a range of infrared wavelengths, there will be great promise for the use of this technology throughout a wide range of applications, including medical diagnostics and surveillance. ❐

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ATTOSECOND PHOTONICS

Extreme ultraviolet catastrophes

Extreme ultraviolet attosecond pulses, which emerge from the interaction of atoms with intense laser fields, play a central role in modern ultrafast science and the exploration of electron behaviour. Recent work now shows that catastrophe theory can help optimize the properties of these pulses.

Eleftherios Goulielmakis

The bright patterns of light often seen in the bottom of a tea cup or in a pool on a sunny day are typical examples of optical caustics. However, despite their ubiquitous nature, the most elementary theory of light propagation — ray optics — fails to describe these beautiful shapes. Caustics correspond to regions where several geometrical rays bunch together to form discontinuities at which the light intensity diverges. Catastrophe theory, under the guise of catastrophe optics[1], can treat these discontinuities by introducing smooth analytical functions called catastrophes. Selecting the catastrophe most suited to describe an optical caustic negates the introduction of complicated diffraction-based concepts while retaining the simplicity and intuitiveness pertaining to geometrical optics.

Caustics are not limited to optical phenomena. Catastrophe theory has been recently employed to study caustics in electronics[2], astrophysics[3] and other exciting areas of modern science. Now, writing in *Nature Photonics*, Raz and colleagues[4] describe the role of caustics in high-order harmonic generation (HHG), the key process for the production of attosecond (10^{-18} s) extreme ultraviolet (EUV) pulses. They demonstrate that catastrophe theory can conveniently describe the caustics that form in high-harmonic spectra and provide a new route for optimizing the properties of attosecond pulses.

Attosecond science uses intense, controlled optical fields of light and EUV attosecond pulses to explore electron dynamics in atoms, molecules and solids. Intense fields provide adjustable forces to drive the motion of electrons with a precision equal to a fraction of an optical cycle. Attosecond EUV pulses, on the other hand, can trigger or trace electron dynamics in the valence and inner electronic shells of atoms or molecules at a resolution approaching the atomic unit of time (~24 as). Both of these tools have played a key role in the advancement of ultrafast science to the attosecond regime[5].

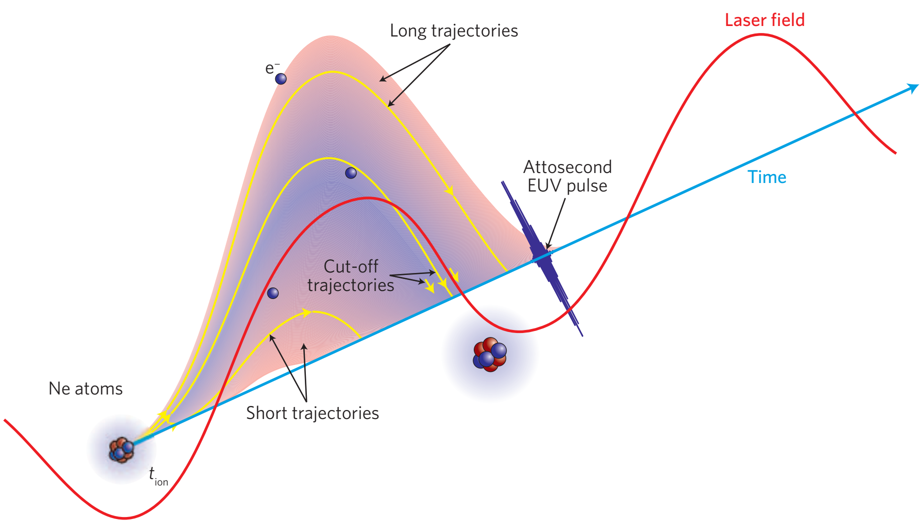

Figure 1 | Caustics in HHG. The coalescence of long and of short electron trajectories (yellow) near the cut-off energy (purple region) gives rise to spectral caustics that can be treated by catastrophe theory.

Attosecond EUV pulses are generated when a strong laser field — one comparable in strength to the field that binds an electron to its nucleus — is used to drive electron oscillations in atoms or molecules. The generation process is qualitatively described by a semiclassical approach known as the three-step model[6]. In the first step, the electric field of the laser can overcome the atomic barrier, which allows an electron to escape (ionize) through quantum tunnelling. In the second step, the field accelerates the freed electron away from its parent ion. In the final step, a change in field direction reunites the electron with the ion, and its excess energy is released as radiation (Fig. 1). Typically, this radiation comprises photons with energies in the range of tens to hundreds of electronvolts, which corresponds to emission in EUV part of the electromagnetic spectrum. Because recombination between the returning electron and the parent ion occurs within a small fraction of an optical cycle, the emitted bursts of radiation are extremely short — typically in the range of tens to hundreds of attoseconds. Multicycle laser pulses drive electrons to recombine with their parent ions every half optical cycle and thus give rise to attosecond pulse trains[7] that are manifested by discrete spectra at harmonic frequencies of the driving pulse. Few-cycle pulses, on the other hand, confine the above HHG process to a fraction of an optical field cycle and permit the emission of isolated attosecond pulses[8]. These pulses are manifested by the emission of continuous spectra, rather than discrete spectra in the EUV regime.

The quantum character of electron tunnelling dictates that an atom is most likely to ionize when the laser electric field is at a maximum, given that the atomic potential is mostly suppressed at that point. Tunnelling can still occur at other instances, although with lower probability. The exact instance of ionization (t_{ion}) defines not only the classical trajectory that an electron is destined to follow, but also the energy that it accumulates and releases upon recollision with its parent ion. A classical model must simulate thousands of electron trajectories (Fig. 1), each of them associated with different ionization moments, in order to reproduce high-harmonic spectra. These trajectories are classified as either short, for those that arrive early after ionization, or long, for those that arrive later (Fig. 1). The short and long trajectories coalesce close to the maximum emitted energy (purple region of Fig. 1), which is also known as the cut-off energy. The spectral intensity of the emitted light, using the classical description, also diverges.

Raz *et al.* describe an analogy between electron trajectories coalescing at the same final energy and geometrical rays coalescing at the same spot to form optical caustics[4]. They explore the principles of catastrophe theory for describing HHG in a spectral region where electron trajectories coalesce to give rise to 'spectral caustics' (such as the cut-off) without invoking complex and computationally demanding quantum-mechanical calculations.

To explore how caustics are manifested in HHG, Raz *et al.* used femtosecond laser pulses to generate high-order harmonics in a neon gas jet and recorded the emitted spectra using an EUV spectrometer. Although this simple situation is sufficient for a qualitative description, it offers little room to explore caustics in HHG because the emitted spectra depend only on t_{ion}. To add more control parameters, Raz *et al.* considered a more modular scheme in which HHG is driven by two pulses of different wavelengths: one centred at 800 nm and the other frequency-doubled to a wavelength of 400 nm. HHG by the superposition of such two-colour pulses has recently been shown to result in multiple electron trajectories and thus provides great opportunity for controlling EUV emission control[9]. This scheme therefore offers fertile ground for exploring spectral caustics. By selecting the appropriate catastrophe — the swallowtail catastrophe — Raz *et al.* were able to predict with reasonable accuracy how the detailed spectral shape of the recorded EUV radiation would change depending on various tunable parameters, such as the relative phase between the two fields. More importantly, they demonstrated spectral enhancements of up to an order of magnitude (which they refer to as spectra focusing) with considerable accuracy. Their technique was also able to cope with large variations in the pressure of the neon gas sample, which is well-known to have a significant effect on the HHG process.

The extent to which attosecond science will be influenced by this deeper understanding and control over spectral caustics in HHG, together with the use of catastrophe theory to interpret the relevant phenomena, will undoubtedly be explored in the years to come. The capability of this technique to predict local enhancements in the emitted spectra, in lieu of complex quantum mechanical calculations, provides a new way to tune the properties of attosecond pulses effectively and easily. As for the technologies required to generate the predicted pulses, although conventional pulse-shaping methods[10] are unlikely to be applied soon in this demanding spectral range, the recent technology of light field synthesis[11], which operates over superoctave bandwidths, does promise such control. In the future, catastrophes may be used to predict the optimal field waveforms of light, the synthesis and applications of which may lead to exciting new experiments in attosecond science and open up new routes to the quantum control of matter at extreme frequencies and time scales. ❐

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INTEGRATION

Fibres embrace optoelectronics

The demonstration of an in-fibre semiconductor photodetector with gigahertz bandwidth bodes well for the future development of hybrid fibre optoelectronics.

Markus A. Schmidt

Optical networks and optical signal processing form the basis of modern telecommunications and have enabled the proliferation of the internet around the globe. This impressive achievement relies technologically on two key building blocks. The first is the development of planar photonic on-chip devices, whose micrometre and even nanometre dimensions have enabled the integration of modulators, small-scale switches and photodetectors[1] on semiconductor chips. Planar fabrication technology has been extensively developed in recent years, and the vision of achieving all-optical control on a single chip is now close to realization. The second type of device that forms the backbone of modern telecommunications is the silica glass optical fibre. This fibre is essential to network systems because of its ability to