How did Bengtsson *et al.* manipulate the phase-matching condition to redirect FID radiation? Since the propagation direction of light is determined by the plane formed by atoms oscillating in phase, the redirection of FID radiation can be achieved through the phase shift of the oscillating atoms, which depends on the spatial position of the atoms. One can shift the phase of a Lorentz oscillator by changing its spring constant for a short time. In the case of real atoms, Bengtsson *et al.* used the AC-Stark shift[7] (also known as the Autler–Townes effect) of the energy levels of atoms induced by IR ultrashort laser pulses[8,9]. When the FID lifetime (which is longer than a few hundred femtoseconds in the case of Bengtsson and colleagues' work) is longer than the duration of the IR pulses, the phase shift accumulated is $\Delta\varphi = \int \Delta E(t')/\hbar dt'$ (ref. 8), where ΔE is the intensity-dependent level shift, t' is time and $\hbar$ is the reduced Planck constant. Thanks to the recent development of attosecond time-resolved spectroscopy, this phase shift was recently observed in the frequency domain by observing the changes of spectral profiles between Lorentz and Fano types[8,9].

Bengtsson *et al.* exploited the possibility to control the phase shift $\Delta\varphi$ through not only the temporal but also the spatial profile of the IR pulses. If the ensemble of atoms pre-excited by the high-harmonic pulses is irradiated by an off-axis IR pulse (Fig. 1b), the amount of the phase shift depends on the distance from the axis of the IR beam, enabling the wavefront of the FID to be tailored. In this way, Bengtsson *et al.* successfully deflected the part of the FID arriving after the control pulse from the pump beam axis. The redirection angle and timing can be controlled at will by the intensity and delay, respectively, of the IR pulse.

Bengtsson *et al.* further extended this optical phase modulation technique to the XUV spectral range at 28.8 eV. Since the photon energy is higher than the ionization potential of any atom, the $3s^1 3p^5 np$ series of autoionizing states in Ar with shorter lifetimes than bound excited states were excited to induce FID. The researchers successfully redirected the 28.8-eV photons with an efficiency of more than 70%. In the visible region, an acousto-optic (AO) modulator is often used for the beam deflection with a typical efficiency of ~70%. However, for the XUV region, solid crystals for the AO modulation are not usually available and, therefore, it has not been feasible to control the phase and amplitude of XUV light. Now, the comparable efficiency of deflection in the XUV region is promising for the phase control of XUV light by IR or visible light.

One potential application of this approach is the isolation of attosecond pulses. The truncation of FID in the XUV region (XFID) to form attosecond pulses has been proposed[10]. However, the truncated pulses are still concentric to the XUV pump pulses. With the sequential application of the first IR pulse for deflection of XFID and of the second IR pulse for truncation of the XFID, interacting with one another in gas media, it should be possible to generate isolated attosecond pulses. Although XUV light had not been considered tractable in optical manipulation, the high efficiency of the phase manipulation demonstrated by Bengtsson *et al.* shows that XUV light will have various applications, for example, in quantum control, ultrafast science and telecommunications. ❐

Taro Sekikawa is in the Department of Applied Physics, Graduate School of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo 060-8628, Japan. Kenichi L. Ishikawa is in the Department of Nuclear Engineering and Management, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.
e-mail: sekikawa@eng.hokudai.ac.jp; ishiken@n.t.u-tokyo.ac.jp

References

1. McPherson, A. *et al. J. Opt. Soc. Am. B* **4,** 595–601 (1987).
2. Ferray, M. *et al. J. Phys. B* **21,** L31–L36 (1988).
3. Ishikawa, T. *et al. Nat. Photon.* **6,** 540–544 (2012).
4. Bengtsson, S. *et al. Nat. Photon.* **11,** 252–258 (2017).
5. Hahn, E. L. *Phys. Rev.* **77,** 297–298 (1950).
6. Brewer, R. G. & Shoemaker, R. L. *Phys. Rev. A* **6,** 2001–2007 (1972).
7. Delone, N. B. & Krainov, V. P. *Phys. Usp.* **42,** 669–687 (1999).
8. Ott, C. *et al. Science* **340,** 716–720 (2013).
9. Kaldun, A. *et al. Science* **354,** 738–741 (2016).
10. Mashiko, H. *et al. Nat. Commun.* **5,** 5599 (2014).

NONLINEAR OPTICS

Attosecond nanophotonics

Combining attosecond science and nanophotonics potentially offers a route to enhance control over light–matter interactions at the nanoscale and provide a promising platform for information processing.

Giulio Vampa, Hanieh Fattahi, Jelena Vučković and Ferenc Krausz

New insights gained into microscopic ultrafast dynamics in recent years are largely due to advances in attosecond science and technology, which provide access to petahertz frequencies for the measurement[1,2] and control[3] of the electric field of light. In parallel to the progress in this area, the realization of devices that confine light into nanoscopic volumes[4] has been made possible thanks to improved optical design and nanofabrication techniques. Although attosecond science and nanophotonics have both independently reached a considerable level of maturity, synergies between the two have so far remained largely unexplored. Here, we propose and discuss how nanophotonics can further advance attosecond technology and, conversely, how the sensitivity of attosecond-scale methods to electric-field oscillations can benefit research into nanophotonics devices.

Up until recently, pump–probe femtosecond spectroscopy measured the effect of a pump pulse on the envelope of a delayed probe pulse, leaving effects occurring in response to the oscillating electric field unresolved.

Things began to change in 2001 when, through an extremely nonlinear frequency conversion method — known as high-harmonic generation — the first coherent extreme-ultraviolet pulses with sub-femtosecond (attosecond) duration were generated[1]. If synchronized with a visible pulse, scanning one relative to the other — a technique known as attosecond streaking[1] — allows the measurement of the light's electric field at petahertz frequencies. To reach this milestone, researchers synthesized light pulses that lasted just a few optical cycles in duration,

and today further developments have made it possible to generate half-cycle pulses[3,5].

It was later realized that the electrons' dynamics in the gas medium responsible for the high-harmonic generation provide an intrinsic attosecond gate that can be used instead of the attosecond pulses to measure the oscillating electric field of visible light[2]. Resolving the oscillating electric field of visible light meanwhile provides access to the full nonlinear polarization response of matter with ramifications for the advancement of electronic signal processing to higher clock rates, ultimately up to optical frequencies[6].

As we have gained access to new regimes in the temporal properties of light, we have also learnt how to confine light tightly to increasingly small volumes so that it can interact strongly and efficiently with matter. Over the past few decades, the field of nanophotonics has primarily focused on the use of periodic media (such as photonic crystals and metamaterials) and of nanometallic structures to control the propagation and localization of light (see ref. 4 for a review). In particular, the employed structures are generally designed by tuning a limited number of parameters without guarantee that these are optimal for a given application. Alternatively, one can explore the design space towards the optimal choice of parameters following a trajectory determined by physical constraints[7]. Such a 'guided' design process can be referred to as inverse design for nanophotonics, since the input is the desired device behaviour, footprint and fabrication constraints, if any, whereas the output delivers the structure parameters and the corresponding field patterns. Nanophotonic devices designed with this approach include compact and efficient dielectric wavelength splitters, routers, hubs and mode converters (see ref. 7 for a review).

This ability to control and manipulate light has great relevance to ultrafast photonics when one recalls that synchronization of all the wavelengths of a broadband laser source is necessary to synthesize few-optical-cycle pulses and light transients. In free space, this task is traditionally performed with chirped mirrors, made of a stack of Bragg reflectors where each wavelength penetrates the mirror at different depths to compensate the delay between the colours of the incident pulse. This operation can potentially be performed on-chip (Fig. 1) with nanophotonic devices that are optimized for desired output transient optical fields, rather than for frequency selection as in ref. 7. These operations would require processing of octave-spanning bandwidth that could either be injected from a suitable source in free space, or integrated in the chip itself[8].

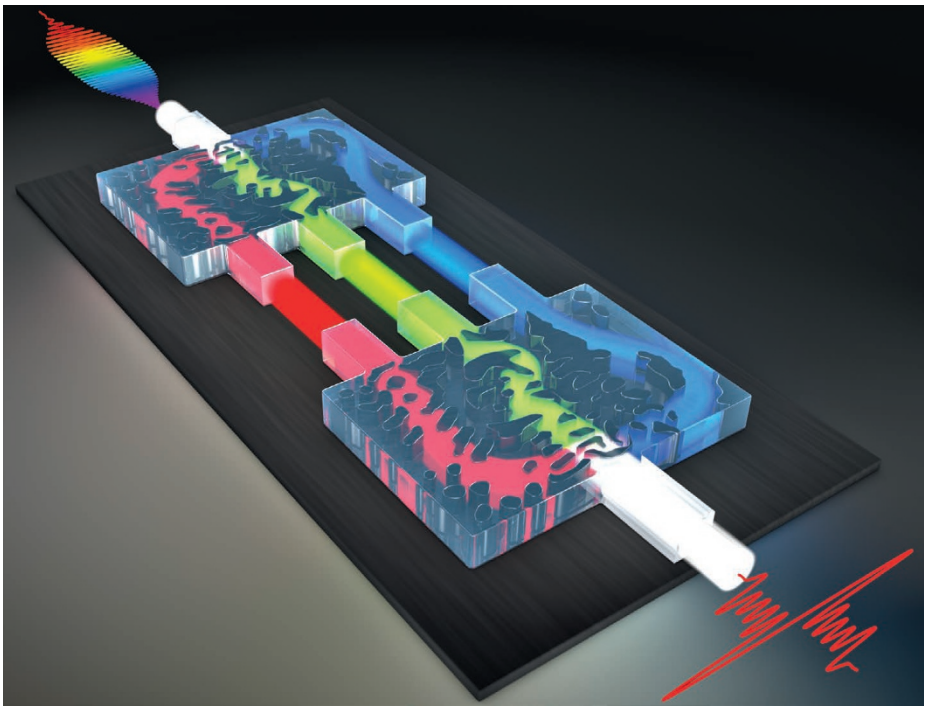

Figure 1 | On-chip ultrafast photonics. Nanophotonic devices can be designed to introduce controlled delays between different wavelengths of broadband laser pulses, akin to the role of bulk, chirped gratings in free space. This capability potentially allows controlled, ultrafast optical waveforms to be obtained at the output.

The ability to generate customizable light waveforms on integrated microscale chips could open new perspectives for signal processing with petahertz bandwidth. Indeed, bits could be encoded on the amplitude of consecutive engineered half cycles of these light transients. Additionally, controlled electric fields with customized temporal structure could play a role in the burgeoning area of metatronics at light frequencies, where integration or differentiation operations could be performed with an unprecedented bandwidth on-chip[9].

Notably, the precise control of the spectral phase of the electric field can be exploited to optimize optical nonlinear processes. For example, the maximum achievable photon energy in high-harmonic generation is optimal for an electric field that increases linearly in time and that is offset from zero[10]. Such fields can be synthesized by controlling the delay between a fundamental laser frequency, its first few harmonics and a longer-wavelength field.

As high harmonics have been recently generated in bulk solids[11], one could also imagine in the future novel devices that embed nanoscale high-harmonic sources. For example, these devices could synthesize the shortest and most intense pulse at the output channel, where harmonic generation from the material itself can take place. By positioning the output close to a sample, near-field imaging with attosecond temporal resolution could be achieved.

It is well known that adding a perturbing field to a strong driver of high harmonics imposes a clear spectral and spatial signature on the high harmonics, as is the case for the generation of even-order harmonics[12] or for a deflection of the high-harmonic beam[2]. In both cases, this signature is a measure of the spatial distribution of the perturbing field. Fields in nanophotonic devices propagate in space along predetermined paths. Following the observation of high-harmonic generation from semiconductors (including silicon[12]), it seems plausible to generate high harmonics from these devices. When the considered device is 'off', an image of the harmonic beam provides information about the structure of the device itself — emission happens only in the presence of material. When the device is 'on' and light propagates through it, the emission process is altered and results, for example, in the formation of even harmonics. An image of these even harmonics would then capture the instantaneous distribution of the electric field within the device[13].

Controlling the electric field of light makes it possible to tune the interaction

between light and nanoscale systems. For example, light can couple strongly to quantum dot emitters embedded in nanocavities — forming a light–dot quasiparticle called a 'polariton'[4]. The Rabi frequency of quantum dot emitters strongly depends on the position of the dot relative to the electric field maximum. Therefore, varying the field profile with high accuracy in such nanostructures would help tune the emitter–field interaction. Measuring the emitted high harmonics would allow to control the field profile, thereby guiding the optimization of the interaction. Possible perturbations induced by the emitter on the field profile can be measured as well. Such perturbations are expected due to the strong nature of the light–dot coupling.

There are other ways that attosecond technology can address issues in nanophotonics. For example, silicon photonic devices — such as electronic circuits — ought to be precisely characterized in both the spectral bandwidth and spectral phase. For this purpose, one can measure the input and output electric field of a visible or infrared pulse with coherent detection methods, to fully characterize the response of the device, in both amplitude and phase.

Attosecond science and nanophotonics have been largely evolving independently of each other. However, we believe that these rapidly growing fields can mutually benefit each other's development. Measuring and controlling the oscillating field of light at petahertz frequencies provides precious insight into nonlinear light–matter interactions at the nanoscale. Conversely, by synthesizing the shortest pulse at the output of a device it may become possible to confine extreme optical nonlinearities, such as high-harmonic generation, in nanoscopic volumes. The combination of nanophotonics and attosecond techniques will allow for the manipulation of optical fields at nanometre–attosecond scales — a crucial capability towards electron-based signal processing at higher speed and ultimately at optical frequencies. ❐

Giulio Vampa is at the University of Ottawa, Ottawa, Ontario K1N 6N5, Canada and at the PULSE Institute, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA. Hanieh Fattahi and Ferenc Krausz are at the Max-Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany and the Department für Physik, Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany.

Jelena Vučković is at Stanford University, Ginzton Laboratory, Stanford, California 94305-4088, USA.
e-mail: gvampa@stanford.edu; hanieh.fattahi@mpq.mpg.de; ferenc.krausz@mpq.mpg.de; jela@stanford.edu

References

1. Krausz, F. & Ivanov, M. *Rev. Mod. Phys.* **81,** 163–234 (2009).
2. Kim, K. T. *et al. Nat. Photon.* **7,** 958–962 (2013).
3. Wirth, A. *et al. Science* **334,** 195–200 (2011).
4. Fabre, C., Sandoghdar, V., Treps, N. & Cugliandolo, L. F. (eds) *Quantum Optics and Nanophotonics* (Lecture Notes of the Les Houches 101st School of Physics, August 2013, Oxford Univ. Press, in the press).
5. Fattahi, H. *et al. Optica* **1,** 45–63 (2014).
6. Sommer, A. *et al. Nature* **534,** 86–90 (2016).
7. Piggott, A. Y., Lu, J. & Vučković, J. *Laser Focus World* **52,** 24–27 (2016).
8. Moss, D. J., Morandotti, R., Gaeta, A. L. & Lipson, M. *Nat. Photon.* **7,** 597–607 (2013).
9. Sun, Y., Edwards, B., Alù, A. & Engheta, N. *Nat. Mater.* **11,** 208–212 (2012).
10. Chipperfield, L. E. *et al. Phys. Rev. Lett.* **102,** 063003 (2009).
11. Ghimire, S. *et al. Nat. Phys.* **7,** 138–141 (2011).
12. Vampa, G. *et al.* Preprint at http://arXiv.org/abs/1605.06345 (2016).
13. Vampa, G., Corkum, P. & Brabec, T. Apparatus and method for tunable generation of coherent radiation. US patent 20,160,149,371 (2016).

Additional information

This work summarizes the ideas that emerged during the workshop 'New regimes for nonlinear optics' held during the 2016 Conference on Lasers and Electro-Optics (CLEO) in San Jose, California, and organized by the Optical Society of America (OSA) technical group on Short Wavelength Sources & Attosecond/High Field Physics.

OPTICAL PHYSICS

Anisotropy enables unusual waves

It has been revealed that simple anisotropic optical waveguides and the vectorial nature of electromagnetic waves can support a variety of bound states in the continuum akin to those introduced in quantum mechanics almost a century ago.

Yuri Kivshar and Mikhail Rybin

One of the most important problems in photonics is to spatially confine light. Conventional approaches typically involve the use of optical waveguides such as fibres. Recently, an approach based on a century-old concept of bound states in the continuum (BICs) has attracted a lot of attention in photonics[1] as an alternative means to achieve very large quality factors and to tune the system into the so-called supercavity regime[2]. Several approaches to realize BICs have been suggested for waves in electronic, electromagnetic, acoustic and even fluidic systems.

Writing in *Nature Photonics*, Gomis-Bresco and colleagues suggest exploiting both anisotropic materials and the vectorial nature of electromagnetic fields to realize two types of BIC in rather simple waveguiding structures[3]. In particular, the anisotropy-induced BICs are shown to form in tunable angular propagation directions; their polarization may be pure transverse electric (TE), pure transverse magnetic (TM) or full vector, with tunable polarization-hybridity; and they are the only possible bound states of the system. The idea is revealed in the simplest geometry, but the concept is general and holds for more complex structures and different materials.

The concept of BICs was introduced in quantum mechanics in the form of unusual states of electron waves by von Neumann and Wigner[4], who discovered that certain potentials could support spatially localized states of electrons with positive energies. In photonics, there is no direct analogy to quantum-mechanical negative potentials, but formally classical guided modes can be considered as BICs protected by the momentum conservation law, since electromagnetic waves are allowed to propagate at arbitrary frequencies. In addition, a leaky mode can be converted to a BIC at certain conditions[1]. However, a mode that is transformed into a BIC should demonstrate a dramatic increase in the quality factor (Q-factor) that mathematically should tend to infinity in the BIC regime when one of the parameters is varied[2]. This is in sharp contrast to conventional resonances and conventional guided modes for which the Q-factor does not change substantially. In the case of the BIC modes, the Q-factor increases due to destructive interference between two leaky modes that may completely cancel each other out for