where the complexity of scattering requires the highest possible degree of control. There is a need for dedicated hardware that may now be worth developing, given the bright prospects of the field. One can already cite recent efforts towards merging an SLM and a camera into a single device[10], or developing thin endoscopes made of multimode fibres that can carry both light and ultrasound[11].

The second aspect is fundamental: it is necessary to better understand the complex physics of light propagation in tissues beyond a full multiple scattering regime model, where mesoscopic theory provides a suitable description but also comes with a rather pessimistic view. Indeed, in the first few millimetres of tissue, ballistic photons disappear, but light has not yet fully undergone isotropic multiple scattering: in this regime, the multiscale nature of tissue heterogeneity is paramount to accurately describe light scattering. We thus expect other interesting effects to be revealed, and in turn bring new opportunities for more efficient imaging approaches. For instance, unexpected spatial or polarization correlations of scattered light were recently reported in the literature[12,13].

Finally, computational optics concepts (such as phase retrieval, compressive sensing and light field imaging) have proved extremely useful to better analyse the information carried by scattered light (in neuroscience[14], for example), or to significantly improve imaging speed, depth and resolution[15]. It is likely that computational methods will become an inescapable tool in deep optical microscopy techniques, efficiently complementing a purely physical approach.

To conclude, it is important to note that going deeper is by no means an incremental progress over existing achievements in optical microscopy. As an illustration, present optogenetics techniques give access, in rodents, to only a fraction of the cortex thickness. Being able to monitor and optically control brain activity through the whole cortex, and possibly through the skull[16], would represent a revolution in neuroscience. While the specific applications that will result from new imaging techniques are difficult to predict, the next decade is expected to bring deeper insight into biomedical optics. ❐

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Extreme terahertz science

Xi Cheng Zhang, Alexander Shkurinov and Yan Zhang

In the future, sources of intense terahertz radiation will open up an era of extreme terahertz science featuring nonlinear light–matter interactions and applications in spectroscopy and imaging.

The far-infrared region of the electromagnetic spectrum (0.3–10 THz), known as the THz frequency band, is a spectral window with rich scientific opportunities, but is, at present, served by limited technology. The region has long been considered the last remaining scientific gap in the electromagnetic spectrum, which is underdeveloped but ripe for exploitation.

This field shows great promise for a variety of reasons. First, many molecules have structural absorption resonances at these frequencies, making THz spectroscopy a unique tool for investigating matter. Second, the THz range constitutes the ultimate limit of operation for high-frequency electronics. Third, the oscillation period of THz waves corresponds to the timescale of elementary chemical reactions, weak collective

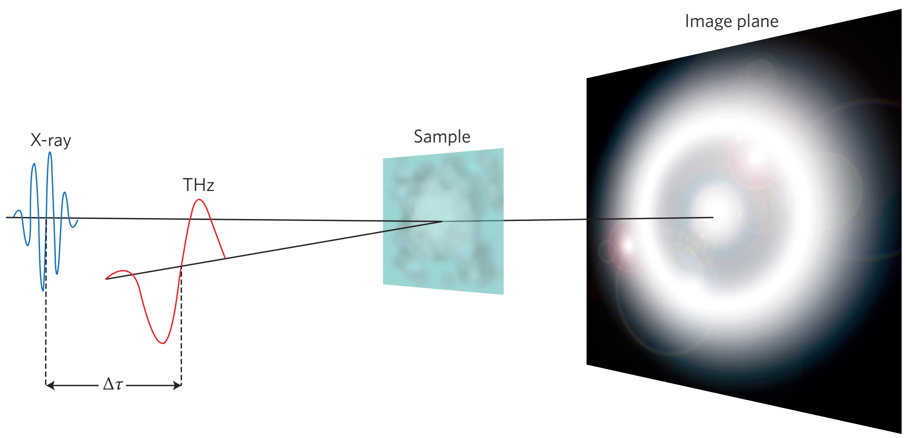

Figure 1 | Conceptual illustration of a pump–probe experiment employing a THz pump and an X-ray probe for time-resolved nanoscale imaging. The idea is to use the THz pulse as a pump to modify the atomic structure of a target and then capture an image of the atomic structure by X-ray scattering. $\Delta\tau$ is the timing between the X-ray pulse and the THz pulse.

excitations in solids, relaxation time of phonons and free-carrier collision time. As a result, THz science has the opportunity to enable technology that directly impacts our lives, from industrial quality control, to national security and environmental studies, and to medical diagnostics and treatment.

The main issues holding back the future development of THz science and technology are (1) the lack of intense THz sources and sensitive THz detectors; (2) the lack of commercial optical components and instrumentation operating in this wavelength range; and (3) strong water vapour absorption that prohibits sensing and imaging of water-rich targets as well as limiting the range of THz wave propagation for remote applications.

Following the steady evolution of THz science and technology since the late 1980s, the next exciting frontier will possibly be the era of extreme THz science, where strong THz field–matter interactions can be investigated and nonlinear THz spectroscopy and imaging explored. However, for these opportunities to be fully realized will require the development of suitably bright, efficient THz sources.

Short-pulse, energetic lasers are commonly used to generate intense broadband THz pulses via interaction with a suitable target. In addition to well-established methods for THz wave generation, such as photoconductive antennae and optical rectification, new approaches include the use of tilted wavefronts in the nonlinear material $LiNbO_3$ and the use of new organic crystals with giant electro-optical coefficients, as well as dual-colour-laser-excited plasma and coherent transition radiation (Table 1). Importantly, these schemes are now able to generate THz fields with peak strengths exceeding MV cm^{-1}. For example, a focused optical pulse with >1 mJ pulse energy and <100 fs pulse duration in gas can create a plasma that emits intense (>MV cm^{-1}), highly directional (<6°) and ultrabroadband (10% bandwidth from 0.1 to 10 THz) THz waves. Even broader continuous spectral bandwidths from 0.1 to 20–100 THz can be obtained with ultrashort, sub-10-fs laser excitation[1].

The availability of such intense pulses in the THz frequency region will enable strong field–matter interactions and investigation of a wide range of scientific phenomena[2]. Potential research topics include THz field-induced lattice distortion, molecular alignment, resonant and non-resonant control, as well as transient bandgap dynamics[3]. For example, at a field strength of 1 MV cm^{-1}, a variety of intense THz field–matter interactions can be explored including molecular vibration, rotation and spin precession. Intense THz pulses can open new avenues for understanding a variety of interesting phenomena, including exploring giant nonlinearity in the THz frequency range, high-harmonic generation of THz waves, determination of the THz nonlinear responses of novel metamaterials and control of THz wave-induced fluorescence for remote sensing (Box 1).

The THz community is certainly taking the development of intense THz sources and extreme THz science seriously and is organizing itself to support research in the area. In 2015, at a meeting in Moscow, the International Consortium of THz Photonics and Optoelectronics was established with 71 partners from 15 countries[4], and exploration of extreme THz science is one of the high-priority tasks of the consortium. Furthermore, a two-day US Army Research Office THz workshop on ‘Bright THz Source and Nonlinear THz Field–Matter Interaction’ in Rochester, USA in June 2016 brought together 17 leading researchers from 8 countries to share their views, achievements and plans about the future direction of research on intense THz sources.

Several international laser development plans are in place for developing sources of extreme THz waves. The Advanced Laser Light Source (ALLS), located near Montreal, Canada plans to make a major upgrade of its laser facility by developing

Table 1 | Methods for intense THz wave generation.

Method	Reported THz field (MV cm^{-1})	Photon energy conversion efficiency	Central frequency (THz)	Bandwidth (THz)
Photoconductive antenna	<1	10^{-6}	~2	~5
Dual-colour-laser-excited air plasma[5]	8	10^{-4}	~2	>50
Optical rectification[6]	83	$2–3\times10^{-2}$	~4	~5
Tilted wavefront in $LiNbO_3$ (ref. 7)	1	10^{-3}	~0.8	~2
Short electron bunch radiation[8]	200	10^{-4}	-	>10
Free-electron laser	2	10^{-3}	3	~10

Box 1 | Future opportunities for THz science.

Metamaterials for nonlinear THz processes. Metamaterials are artificially engineered materials that can control the amplitude, phase and polarization of an electromagnetic wave. Such materials can be designed to have a nonlinear susceptibility that can be as large as 10^{-16} m^2 V^{-1}, which far exceeds that of thin films and bulk materials. They thus provide a new quasi-phase-matching capability for nonlinear processes and it is expected that this technology can provide an efficient approach for strong THz generation and frequency conversion[9].

THz quantum sensing and imaging. It is possible for a visible photon to generate a pair of entangled photons (a THz photon and a visible photon) through a nonlinear optical process. These photon pairs can then be employed for applications such as ghost imaging. In this scheme, the THz photon illuminates a target/sample but is not detected by any detector, whereas the entangled (or correlated) visible photon is detected by a detector but it does not interact with the target[10]. The THz spectroscopic or imaging data can be obtained by interpreting the visible photon’s data. The approach benefits from the high detection sensitivity of visible photons but it is challenging to experimentally realize the required degree of entanglement between visible and THz photons.

Time-resolved molecular-level imaging. Multidimensional spectroscopic characterization of a complex target material with a nanometre-scale spatial structure is challenging. Coherent diffractive imaging using synchronized THz pump and extreme-ultraviolet or X-ray probe pulses offers a promising solution, as shown in Fig. 1.

a unique system operating at 500 Hz and delivering sub-30-fs pulses at 3 μm with 75 mJ per pulse. In the future, this laser should be able to provide 30 MV cm^{-1} THz peak field from laser-induced plasma by using dual-colour excitation. Furthermore, this laser system will offer a synchronized THz-pump–X-ray-probe capability, where high-brightness, ultrashort, soft X-ray pulses are fully synchronized to the THz pulses (Fig. 1). The Laboratory of Laser Energetics at the University of Rochester, New York is also developing a new near-to-mid-infrared wavelength laser, with goals to provide pulses of 30 fs duration with an energy of 3 J (in 3–5 years) and 30 J pulse energy (in 10 years) at a repetition rate of 1 kHz. One of the main goals for this laser is to produce extremely bright THz pulses for exploring THz science, in particular nonlinear THz field–matter interactions under extreme conditions. The future of THz science is certainly bright. ❐

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Quantum optics, what next?

J. Ignacio Cirac and H. Jeff Kimble

Quantum optics is a well-established field that spans from fundamental physics to quantum information science. In the coming decade, areas including computation, communication and metrology are all likely to experience scientific and technological advances supported by this far-reaching research field.

Quantum optics originated in the 1950s from the quest to understand fundamental phenomena in the interaction between light and matter, most importantly for masers and lasers. Despite the success of quantum electrodynamics (QED), there was no adequate quantum framework to describe even simple experiments with light. With the development of theories for open quantum systems and quantum coherence in the 1960s[1,2], a much broader understanding of the diverse and even bizarre possibilities for the behaviour of light in a quantum regime emerged.

New concepts such as antibunched light, parametric downconversion[3] and squeezing guided landmark experimental efforts in the quantum optics community that demonstrated the fascinating operational consequences of quantum light in the laboratory through the 1970s and 1980s, including measurements with precision beyond standard quantum limits. Entanglement, a most intriguing feature of quantum physics, was the subject of great interest and was successfully generated between beams of light, atoms and photons, as well as arrays of atoms.

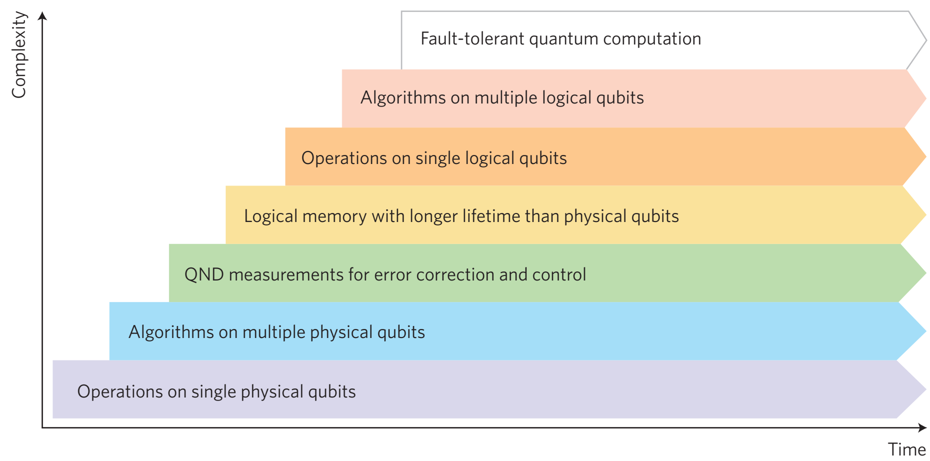

Figure 1 | A roadmap to quantum computing. A quantum computer is composed of qubits undergoing quantum operations. To scale-up the computations, it is necessary to perform error correction that encodes logical qubits in several physical qubits and is tolerant to noise. Figure reproduced with permission from ref. 7, AAAS.

A bridge across disciplines

Despite their fundamental nature, the concepts and tools born from quantum optics have led to new and powerful capabilities in many other fields. In microscopy, for instance, photon statistics can be used to identify unambiguously the presence of single quantum emitters such as single molecules in chemistry and biology. In metrology, atomic clocks take advantage of entanglement to reach unprecedented levels of accuracy[4,5]. Owing to the intimate connection between theoretical and experimental advances, quantum optics has also had a strong and continuing impact on the establishment and development of quantum information science (QIS), which emerged in the 1990s. A principal thrust of QIS is to harness quantum