# Bright terahertz sources

The performance of terahertz sources has been significantly improved in recent years, and the superiority of terahertz radiation is being demonstrated in various fields. Xi-Cheng Zhang discusses the past, present and future of terahertz science.

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Xi-Cheng Zhang from the University of Rochester and Huazhong University of Science and Technology, who has been active in the field of THz science since its early days, is excited about future applications of THz technology.

### What was terahertz science like in the early days?

When I first became involved in terahertz (THz) research in the late 1980s at Columbia University, only three groups in the USA were actively investigating THz pulses produced from ultrashort laser pulses: the group at IBM led by Daniel Grischkowsky, that at Bell Laboratories led by Martin Nuss and that at Columbia University led by David Auston. As there was no established experimental technique for generating or detecting broadband THz waves, we had to fabricate optical components and develop a THz measurement system. We tried generating THz waves using a photoconductive antenna (sometimes referred to as an Auston switch) and also by employing electro-optic rectification. During my time at Auston's laboratory, I was curious whether THz radiation has the ability to 'see through' optically opaque materials. I first observed pulsed THz emission from an unbiased semiconductor wafer using femtosecond laser excitation. In a search for new THz-emitting materials, I investigated many different materials, including dielectrics, metals, tissue paper, fabrics and wood — basically anything I could lay my hands on (even my fingers!). At that time, most of us used photoconductive dipole antennas to detect THz waves.

### What were the milestones in the development of THz sources?

There were two milestones. The first one was the demonstration of THz pulses generated from short laser pulses in the visible or near-infrared wavelength range. This work was pioneered by Gerard Mourou, David Auston and Daniel Grischkowsky in the late 1980s and early 1990s. The second breakthrough was the development of the THz quantum cascade laser. Federico Capasso's group demonstrated infrared lasing from a quantum cascade laser in 1997, and then Alessandro Tredicucci's group obtained THz lasing from a quantum cascade laser in 2002. Soon after that, Qing Hu of Massachusetts Institute of Technology fabricated a clever, more reliable THz quantum cascade laser. This invention opened the door for industrial applications and led to many advances in research and development.

### What is likely to be the next milestone?

The development of high-intensity THz sources could well be the third milestone. THz fields with high peak powers can be generated by a tilted optical wavefront in $LiNbO_3$ or by using dual-colour laser mixing to produce a laser plasma in a gas. This opens up new opportunities to study basic THz science. We are currently unable to predict what happens under high-intensity THz illumination; this has generated a lot of excitement and speculation. For example, THz imaging is currently based on linear effects, but there is great interest about how nonlinear effects induced by THz radiation could be exploited in THz imaging. If nonlinear THz imaging could provide useful information that is unobtainable by conventional THz imaging, the use of high-intensity THz radiation would boost nonlinear THz spectroscopy. To generate THz radiation with high field strengths of the order of 100 kV $cm^{-1}$ or higher, it is currently necessary to either apply for beam time at national synchrotron facilities (such as those at Argonne and Brookhaven) or purchase a commercially available, but very expensive, amplified laser system, which only a few groups can afford. Thus, a true milestone would be realizing a significant reduction in the cost of fibre lasers, which are the most expensive components in amplified laser systems, or developing a more accessible laser system for producing high-intensity THz radiation.

### What special features does THz imaging offer?

THz imaging can be considered to be complementary to X-ray and infrared imaging. For certain materials, THz radiation provides superior imaging capability to X-rays or infrared radiation. For example, for low-contrast materials such as low-density structures and thermal insulating layers, THz radiation offers higher amplitude and phase contrast ratios than X-rays. Furthermore, THz radiation offers greater penetration for some optically opaque materials such as paper, plastics and fabric. Consequently, many body scanners at airports now employ millimetre-wave imaging, and the frequency of radiation used in such scanners is being extended to the sub-THz and THz regions. Although the THz range has a narrower bandwidth than infrared light, certain materials (for example, crystals and microcrystals) have molecular resonances and/or phonon resonances. For example, the explosive RDX can be identified with 100% certainty from the THz spectrum.

**What are some emerging industrial applications of THz radiation?**
Perhaps the most promising industrial application is non-destructive evaluation for quality control and defect inspection. THz radiation can penetrate materials that are opaque at visible and infrared wavelengths, and it gives a higher spatial resolution than microwave radiation, making it uniquely suitable for a variety of imaging applications ranging from industrial quality control, to biomedical applications to security applications. Approximately 300 companies have contacted me regarding this application, and over 80% of those companies expressed a need for a means of performing non-destructive evaluation.

**What are some future opportunities for THz science?**
Some industrial THz systems can be used for homeland security and quality control applications, whereas THz communication systems offer unprecedented bandwidth for secure, ultrahigh-definition wireless video. THz sensing systems are attractive for environmental studies and space science, and THz imaging medical systems can be used for diagnosing and treating certain cancers and other diseases. THz/extreme-ultraviolet tabletop systems can be used for dynamic imaging on the molecular level. Asia and Europe have poured significant funding into THz science and technology, and have formed several major national programs or international centres. Examples of facilities include an X-ray–THz synchronized source and a nonlinear THz spectrometer that employs an intense THz source. A novel concept is combining THz photonic, electronic and plasmonic technologies. We need to develop multiscale THz photonic, electronic and plasmonic devices that can be used in novel THz systems to realize orders of magnitude improvement in performance at a fraction of the cost of existing systems. The validation of such systems for medical, security and industrial applications is on the horizon.

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