VIEW FROM... TERANANO 2011

Terahertz nano-exploration

Amalgamating the interdisciplinary domains of nanotechnology and terahertz technology, particularly the field of terahertz science in nanomaterials and nanodevices, seems to be where the terahertz research community is now heading.

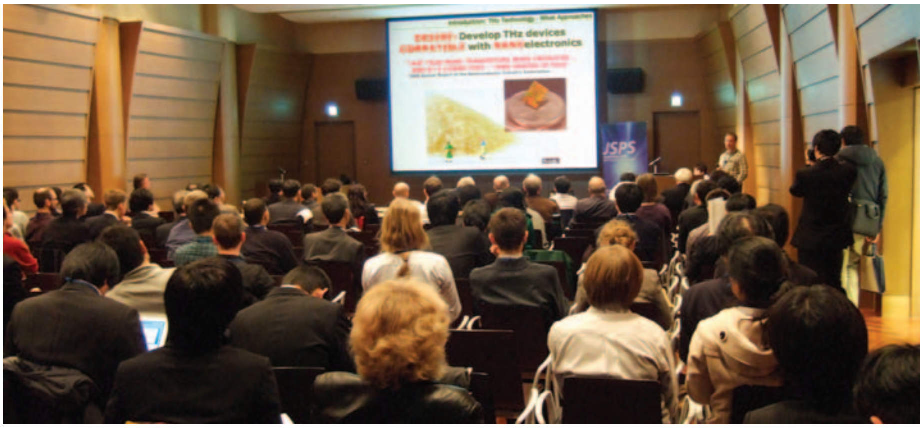
Noriaki Horiuchi

Research into coherent light sources and detectors for the terahertz (THz) frequency regime (0.1–100 THz) has seen a flurry of activity in recent years, primarily in an attempt to bridge the gap between optical and microwave wavelengths. THz waves have a wide range of potential applications, including THz time-domain spectroscopy and tomography, surveillance and security, and high-altitude communications.

Although narrowing the THz gap remains one of the primary goals, the research community has also begun using THz waves to investigate the optical and electrical properties of nanomaterials. This was certainly the trend seen at the recent International Symposium on Terahertz Nanoscience (TeraNano), held jointly with the Workshop of International Terahertz Research Network on 24–29 November 2011 in Osaka, Japan. Around a quarter of the 147 presentations were related to the study of carbon nanotubes, graphene derivatives and nanostructured devices.

"Although the THz waves are not in the nanometre regime, there are common backgrounds that link THz science and nanoscience," explained Masayoshi Tonouchi from Osaka University, the general chairperson of the conference. He pointed out that THz time-domain spectroscopy operating from 10 fs to 1 ps, which is suitable for measuring lattice scattering and electron scattering, is a good example of this shared background. The excitation energy of nanostructured devices such as superconductors, quantum wells and carbon nanotubes is usually in the range of 1–100 meV, which corresponds to a wavelength regime of 0.244–244 THz. THz waves therefore represent a powerful tool for investigating the optical and electrical properties of nanostructured devices.

According to Jun-Ichiro Kono from Rice University in the USA, the unusual transport properties of graphene and metallic carbon nanotubes should allow population inversion to be achieved in THz frequency region, even at room temperature. "Furthermore, the simultaneous occurrence of intra- and interband transitions in the THz frequency range corresponds to strong broadband absorption. This optical feature opens up new possibilities for developing ultrabroadband, fast and sensitive detectors using these materials," he added. In the case of carbon nanotubes, the most significant issues are the heterogeneity and random orientation of carbon nanotubes, which have metallic and semiconductor phases depending on the chiral angle of the nanobubes, Kono explained.



NORIAKI HORIUCHI

Around 200 participants attended the symposium and workshop, which was held in the Osaka University Nakanoshima Center.

Kono presented his work on the carrier dynamics of metallic and semiconducting carbon nanotubes, in which he successfully separated two types of carbon nanotubes and carried out spectroscopic measurements of the separated samples from the THz to the ultraviolet range. His found that the THz and infrared responses were both dominated by free-carriers for metallic carbon nanotubes, whereas semiconducting carbon nanotubes were not responsive in the THz range. He also presented his work on a THz polarizer based on aligned carbon nanotubes, which he says is one of the first examples of the anisotropic nature of individual carbon nanotubes manifesting itself in the electromagnetic characteristics of a macroscopic sample. Unfortunately, however, the carrier dynamics in carbon nanotubes and graphene are not yet fully understood, as the Drude model becomes no longer applicable in the presence of one- and two-dimensional confinement.

"New dynamical phenomena beyond the realm of the celebrated Landau–Fermi liquid theory are expected," Kono concluded in his talk.

Sergey Ganichev from the University of Regensburg in Germany reported an intriguing phenomenon in nonlinear transport, whereby illuminating a graphene monolayer with circularly polarized THz waves causes a photocurrent due to the circular a.c. Hall effect.

"The study of nonlinear transport in graphene will provide additional access to the interaction between light with charge carriers. It will also impact the study of non-equilibrium processes in semiconductors," said Ganichev.

Ganichev emphasized that his findings are beyond classical theory because the photocurrent was generated when the THz waves were incident normal to the surface. He found that the photocurrent reached its maximum when the laser spot was situated at the edge of graphene monolayer, but rapidly decayed when the spot moved away from the edge. This behaviour is well-described by microscopic theory based on the Boltzmann kinetics equation approach.

"Apart from the circular a.c. Hall effect, the photocurrent can also be caused by the local symmetry breaking at the sample edges due to an asymmetric scattering of carriers driven by the electric field of the THz waves," Ganichev added.

Taiichi Otsuji from Tohoku University in Japan has been using THz photon echo spectroscopy to investigate ultrafast carrier relaxation dynamics in optically pumped graphene. The key to his spectroscopic technique was the sample configuration, in which he sandwiched the graphene sheet between a silicon substrate and a thin CdTe crystal. By changing the thickness of the CdTe crystal, Otsuji was able to control the THz probe timing delay, and observed amplified stimulated THz emission. "The gain could be further increased for graphene installed in a cavity, leading to a new type of THz laser," he said.

Chiko Otani from RIKEN in Japan reported clear evidence of a vibrational mode in poly(3-hydroxybutyrate) (PHB). Investigating the vibrational modes of organic materials is complex and demanding because it requires a combination of skeletal and intermolecular vibration modelling. However, Otani experimentally confirmed the dependence of the sharp absorption peak at 2.9 THz on the relative configuration between the polarization direction of the THz waves and the *c*-axis of PHB, which is the stretch mode of the helix structure. He also found that the absorption peak at 2.5 THz was due to the hydrogen bond between the helix structures.

"This finding is an important clue for the analysis of THz spectroscopy because most organic materials, such as polymers, proteins and pharmaceutical products, have hydrogen bonds. It would provide quite useful information regarding the intermolecular structure formed by hydrogen bonds," Otani stressed.

The use of THz waves in the study of nanomaterials is evidently abundant. The studies discussed at the conference, involving the carrier dynamics of metallic and semiconducting carbon nanotubes, nonlinear transport in graphene, ultrafast carrier relaxation dynamics in optically pumped graphene and the vibrational modes of organic materials, represent only a small range of the potential applications offered by THz technology.

"I hope these findings will provide feedback to help improve THz nanodevices," said Tonouchi. ❐

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Correction

In the Research Highlight 'Integrated isolators' (*Nature Photon.* **5,** 571; 2011), a silicon waveguide system was reported as being able to function as an optical isolator. A technical comment recently published (*Science* **335,** 38b–38c; 2012) has now clarified that the waveguide structure is in fact Lorentz reciprocal and cannot function in this manner as it exhibits a symmetric scattering matrix.

This Research Highlight has now been removed from the *Nature Photonics* website.

In the Technology Focus Industry Perspective 'Harnessing slow light' (*Nature Photon.* **5,** 731–733; 2011), the distances marked in Fig. 2a should have been 400 μm.

This error has been corrected in the HTML and PDF versions.