

Background and Impact

1. Science and Engineering

Wireless systems find countless applications in general communications and remote sensing applications. Their front-end hardware can perform relatively complex signal processing functions directly at microwave (*ca.* 1 to 30 GHz) and optical (*ca.* 400 to 789 THz) frequencies. When combining ubiquitous wireless applications with advances in enabling technologies, a positive spiral can be created that continually drives down manufacturing costs while still allowing functionality to grow.

There are two basic reasons why millimetre-wave (*ca.* 30 to 300 GHz) and terahertz (*ca.* 0.3 to 3 THz, also known as sub-millimetre-wave) electronics have yet to find ubiquitous applications. The first reason is the increase in power loss with frequency within materials used to make passive components and circuits. This is coupled with the increasing inability to generate sufficient spectrally-clean carrier power and maintain power gain within an amplifying stage as frequency increases. As a result, the signal-to-noise ratio for an end-to-end system degrades as frequency increases, requiring ever-more expensive solutions that only high-end users (e.g. commercial, scientific or military) can afford. The second reason is that wavelength is inversely proportional to frequency; thus, resonant structures become smaller in size as frequency increases. Therefore, fabrication tolerances become more important, requiring more expensive manufacturing technologies to be used at shorter wavelengths. For example, to define a simple microstrip transmission line within a *microwave* integrated circuit, UV can be used with simple printed circuit board or screen-printing technologies. For *millimetre-wave* integrated circuits, a more expensive deep-UV lithographic system may be needed with a basic microfabrication facility; while for *terahertz* integrated circuits it may be necessary to use very expensive E-beam/X-ray lithography with more advanced microfabrication processing techniques.

For the above reasons, in terms of consumer-based electronics intended for the masses, the cost of implementing a wireless system even at millimetre-wave frequencies is currently prohibitive. As a result, manufacturers are reluctant to invest in the kinds of R&D that is needed to make breakthroughs for the various enabling technologies that can bring prices down to affordable levels. This impasse is even more acute with operation at terahertz frequencies. The relatively recent emergence of “T-Ray” technologies had been predominantly through the use of (quasi-)optical techniques in preference to those found at longer wavelengths.

Historically, apart from purely scientific experiments, there was relatively little activity at terahertz frequencies. The main reasons for the fall-off in activity with reducing wavelength was the lack of demand for commercial exploitation, limited scope for realizing affordable front-end subsystems, high manufacturing costs and the lack of commercial equipment for undertaking accurate measurements. Today, the upper-millimetre-wave and terahertz parts of the frequency spectrum are slowly opening up to commercial exploitation. This is because of continual advances being made in the development of low-cost front-end hardware, reduced manufacturing costs and the expanding market in commercial turnkey measurement systems.

There is no doubt that terahertz technology is rapidly gaining in importance, as reflected by the terahertz activities that have sprung up around the world over the past 6 years. Terahertz technology offers unique solutions for many strategically important applications in 3D imaging and spectroscopy (e.g. security screening and detection, dental/medical imaging, non-destructive testing, material characterisation and pollution monitoring), as well as TBit/s communications for backbone telecommunication networks and ‘instant’ high-definition video-on-demand optical links.

2. Existing World-leading UK Activities

The UK has always led the world in satellite remote sensing at THz frequencies, currently with Astrium Ltd (Portsmouth, Stevenage and Poynton). ThruVision Systems (Abingdon) created the world's first stand-off passive imaging system capable of detecting metals, plastic, liquids, gels, ceramics and narcotics concealed beneath a person's clothing. In addition, TeraView Ltd (Cambridge) is one of the world's leading suppliers of commercial equipment for close-in active imaging and spectroscopy at THz frequencies. Therefore, within the context of international activities in THz R&D, the UK has historically been and currently still is in a strong position.

3. UK THz Community

It is not possible to know exactly how big the terahertz community is within the UK. In 2009, a database of 100 known active researchers within the UK was created from the 2nd *UK/Europe-China Workshop on Millimetre Waves and Terahertz Technology*. From this non-exhaustive list, the following was extracted:

16 UNIVERSITIES were represented by 58 attendees from: Bath, Birmingham, Cambridge, Cardiff, Durham, Imperial College London, Kent, Leeds, Liverpool, Manchester, Oxford, Queen Mary, Queen's University of Belfast, St Andrews, Strathclyde and University College London.

5 NATIONAL LABORATORIES were represented by 21 attendees from: the National Physical Laboratory, Rutherford Appleton Laboratory, Daresbury, Diamond Light Source and Royal Observatory Edinburgh.

13 COMPANIES were represented by 21 attendees from: Agilent Technologies, BAE Systems, Edinburgh Instruments, EADS Astrium, E2V, Flann Microwave, MMIC Solutions, QinetiQ, QMC Instruments, Rohde & Schwarz UK, TeraView, Thomas Keating, ThruVision Systems.

4. Major THz Activities Worldwide

Worldwide, the number of published articles in terahertz technology appears to be experiencing an exponential growth over the past decade. A very recent announcement was the future launch of the *IEEE Transactions on Terahertz Science and Technology*, in the fourth quarter of 2011.

To the best of our knowledge, there are currently 5 THz networks and two societies worldwide; these are listed below:

UK: NPL Measurements Network (<http://www.npl.co.uk/measurement-network/>) – organised by the National Physical Laboratory, established in 2006. This *ad-hoc* network holds its *Millimetre-wave Users Group* meeting twice a year, focusing mainly on the millimetre-wave side of measurement systems.

CHINA: THz Research and Development Network (<http://www.thznetwork.org.cn/english/>) – very active network, with a great deal of activity and collaborations worldwide.

JAPAN: Terahertz Technology Forum (http://www.terahertzjapan.com/lang_english/index.html) – established in 2009, and covers the frequency spectrum from 0.1 to 100 THz.

USA: THz Science and Technology Network (<http://thznetwork.net/>) – established in 2004, this network consists of 9 core university partners and 2 national laboratories; they have even established their own twitter and Facebook sites: <http://twitter.com/THzNetwork> & http://networkedblogs.com/followblog.php?name=thz_science_technology_network.

EUROPE: TeraNova (<http://www.teranova-ist.org/>) – European Union Framework VI Network of Excellence (NoE), began in Sep. 2004 and finished in Feb. 2009, included the Universities of Durham and Leeds and also BAE Systems (Operations) Ltd. Note that, as a matter of policy, a NoE from FP6 cannot be extended into FP7.

EUROPE: EOS Focus Group on Terahertz Radiation

(http://www.myeos.org/members/focus_group/terahertz) – The European Optical Society has had a

bi-annual topical meeting since 2008. This focus group covers the spectral range of 0.1 to 10 THz and has five council members: Delft University of Technology (Chair), University of Braunschweig, University of Savoie, Scuola Normale Superiore and Thales.

INTERNATIONAL: GDR-I Network on Semiconductor Sources and Detectors of Terahertz Frequencies (<http://www.terapole.univ-montp2.fr/GRI/>) – established in 2006, led by the French CNRS and the French Universities of Montpellier, Paris and Lille with institutes in Russia(x2), Poland and Lithuania. Since 2010, the network has expanded to include collaboration from institutes in Spain and Japan(x2).

INTERNATIONAL: International Society of Infrared, Millimeter, and Terahertz Waves (<http://www.irmmw-thz.org/index.html>). Officially incorporated in 2009, they hold an annual conference IRMMW-THz (evolving from an annual conference series going back to 1974), hosted in various countries around the world, and has the *Journal of Infrared, Millimeter, and Terahertz Waves (JIMT)*.

Other relevant international meetings, not mentioned in this section, include the following:

1. *International Workshop on Optical Terahertz Science and Technology (OTST 2009)*
2. *International Symposium on Terahertz Science and Technology between Japan and Sweden, 2009*
3. *2nd UK/Europe-China Workshop on Millimetre Waves and Terahertz* (hosted by RAL in 2009)
4. *International Symposium on Space Terahertz Technology* (jointly hosted by Oxford and RAL in 2010)
5. *International Workshop on THz Radiation: Basic Research and Applications (TERA'2010)*
6. *Workshop on Terahertz Technology (TeraTech'10)*
7. *1st Workshop of German-Russian THz Center "Terahertz Radiation Induced Photocurrents", 2010*
8. *International Symposium on Terahertz Radiation: Generation and Application, 2010*
9. *2008-2011 terahertz conferences under the UK's Knowledge Transfer Networks*

5. Academic Impact

UK interest in the terahertz spectrum has arisen from several quite separate communities. The ability to observe thermal emission lines within dark interstellar dust clouds is a key scientific interest, and the UK is already playing a leading role in pioneering technologies for its high altitude telescope facilities. The cryogenic SCUBA bolometer cameras, in conjunction with the James Clerk Maxwell Telescope (JCMT), are a case in point. More recently, the STFC Rutherford Appleton Laboratory has been nominated as the sole European front-end integration centre for the international ALMA radio telescope. The UK also has an outstanding heritage (both scientific and technical) in Earth Observation and meteorology, and passive terahertz sounding of the atmosphere at millimetre and sub-millimetre wavelengths from space will continue to be an essential tool for both weather forecasting and climate monitoring beyond 2020; A third strand involves the development of new classes of electronics/photonics. Pulsed laser systems for generating terahertz radiation (including Quantum Cascade Lasers) have led to pioneering work in, for example, spectroscopic imaging, with applications in the pharmaceutical industry and medicine. In addition, UK universities are playing a leading role in developing new manufacturing techniques for terahertz circuits through reduced cost overheads.

It can be seen that the "THz Gap" offers a wide and extremely diverse range of applications, both within and across disciplines, many still to be discovered; for example, in areas covering the sciences (e.g. chemistry, biochemistry, biological, medical, physics, materials), engineering (e.g. metrology, modelling, passive components, active devices, circuits) and end-user systems applications (e.g. manufacturing, dentistry/medicine, security, communications). For example, from the combination of terahertz technology with conventional imaging methodologies, such as MRI, fresh insights in medical diagnostics can be expected. Numerous individuals within Imperial already have their own

momentum in THz-related activities (from blue-skies research to real applications). As a result, the CTT will provide a unique forum in which to bring together scientists, engineers, technologists, medical clinicians to share knowledge and access resources that will benefit both the core and wider membership. In other words, the outcome will be greater than the sum of the parts, benefiting individuals, Imperial and potentially UK PLC.

The CTT will encourage knowledge exchange, inherently enhancing the UK's knowledge economy, and stimulate new collaborative research grant proposal applications to address issues of global importance. For example, new and innovative techniques will be developed and applied to real problems in the sciences, medicine, engineering and the marketplace. It is believed that the CTT will generate more research activities in diverse areas, from biological systems (e.g. DNA) to cosmology, and thus inspire more undergraduates to work in terahertz-related areas, and that these activities will diffuse back down into the millimetre-wave and microwave parts of the frequency spectrum.

6. Economic and Societal Impact

Thintri Inc. recently published a report, entitled "*Terahertz Systems 2010: Technology and Emerging Markets*". Just a few of the commercial applications envisioned (in some cases having a profound societal impact) include the following:

- Airport screening of passengers for weapons, explosives, drugs or other contraband
- Secure wireless communications
- Cancer detection, wound inspection and other dental/medical imaging
- Biochip analysis of DNA, proteins and other biological materials
- Detection of land mines and buried explosive devices and also chemical and biological warfare agents
- Monitoring manufacturing processes (e.g. within the US pharmaceutical industry, the FDA are proposing to use THz imaging for standard testing of tablet structures and coating integrity)
- Measuring the water content of food to detect spoilage
- Inspecting finished products through packaging
- Determining the thickness of a layer of paint while it is still wet
- Quality control of insulated wires during manufacture
- Inspecting semiconductor wafers for defects
- Inspecting (and reading) unopened mail

In their study entitled "*Terahertz Technologies, R&D, Commercial Implication & Market Forecast*", Fuji-Keizai suggests that the global market will be US\$400M by 2017. Also, in their study, entitled "*Terahertz Radiation Systems: Technologies & Global Markets*", BCC Research predict the global market will be US\$521M by 2018. According to the Thintri Inc. market study for 2010, the current annual sales for THz equipment amounts to only US\$25M worldwide, with a growth of 10-15% in 2010, but a predicted growth of 50-80% by 2015. Within the security sector, the THz market is likely to exceed US\$300M worldwide by 2020. Within the manufacturing/process control sector, material inspection remains the most promising market opportunity for THz technology, with a predicted forecast of US\$500M worldwide by 2020. The study summarises by stating that "***There will be solid markets for terahertz systems within the forecast period (2010 -2020)***".

With increasingly reported cases of knife crimes (that may include the use of non-metal ceramic knives) and controlled substance abuse, sophisticated detection systems are being considered for use in public areas (e.g. bus, tube and train stations), schools/colleges and even at social/sports venues. Terahertz technologies are already being demonstrated, within relatively compact systems, to undertake the necessary imaging and spectroscopy that can deter would-be criminal activities. This is a clear example of how THz technology can contribute towards evidence-based policy-making and

influencing public policies and legislation at local, regional, national and international levels. Once ubiquitous, these systems will ultimately improve social welfare, social cohesion and national security.

3D THz imaging in dentistry avoids the use of more harmful X-rays, which increase the chances of patients with frequent exposures developing cancers in the mouth. Moreover, in medicine, THz technology can be used to quickly diagnose basal cell carcinomas; a prevalent skin cancer that is on the increase. Process control will ultimately lead to cheaper and higher quality goods; this can only benefit both industrial and domestic consumers. Finally, TBit/s communications for backbone telecommunication networks and 'instant' high-definition video-on-demand optical links will transform the digital economy. All these examples will enhance healthcare, improve business efficiency and lead to cultural enrichment.

As well as fostering obvious economic benefits, terahertz systems are likely to prove crucial to the wider UK society in more tangible ways. For example, atmospheric sounding will help lead to a better understanding of climate change issues and offers the promise of a new capability in air quality monitoring – crucial knowledge required by government, if informed and cost-effective policy decisions are to be made.

From the UK's own Government Office for Science, the Foresight programme highlighted the THz frequency range as of strategic importance to UK industry. The CTT has a unique opportunity to play a world-leading role in exploiting the "THz Gap", to the benefit of UK academia, economy and wider society.