**TERANET: AN EPSRC NETWORK FOR RESEARCHERS IN TERAHERTZ SCIENCE AND TECHNOLOGY**

**(EPSRC GRANT EP/M00306X/1)**

**A Brief Summary of The Current State of UK Terahertz Research at the Start of the Programme*.***

**Introduction**

The challenges of the terahertz (THz) frequency regime are now well known: THz sources can be complex and difficult to use; they have unfavourable operating requirements, such as low-temperatures; and they usually provide insufficient output power. Moreover, although excellent detection capability is available, especially for radio astronomy and some other specialist applications, the development of room temperature detection systems is still at a modest stage and low cost camera-style detection is in its infancy. Whilst there has been a commendable and extensive effort over the last two decades in component research and development in the UK, and to a considerable extent in the engineering of ultra-fast laser optically-based systems, there remains a marked absence of cheaper, versatile, relatively powerful and compact equipment that might be deployed in a range of applications. The nature and extent of such applications is, of course, determined by the interactions that take place between THz radiation and matter. These applications include, already: biology and medicine; communications; non-destructive testing and analysis of materials, components and structures; surveillance and security; space and astronomy; and quantum information processing. However, it remains of great importance that the technical advances made in recent years are harnessed for further system development and application in these, and also potentially new, areas.

The UK has a remarkably strong record of leadership and innovation in the field of THz science and technology, as demonstrated by: the range and quality of its academic outputs; the size of current public investment; its management of many successful European and International projects; the presence of several small, but successful, SMEs; a variety of novel and creative collaborations; and a broad range of approaches that include electronic and optical traditions. Furthermore, the field has benefitted considerably from the high quality of the semiconductor growth and processing activity in the UK and from the range of background skills and underpinning technologies that are available.

The UK Terahertz Technology Network (TeraNet) was recently set up, via an EPSRC grant to Leeds University. One of the Network’s aims is to bring together the current UK THz community, largely working in academia, small /medium enterprises (SMEs) or in central facilities, to consider how their discoveries and developments can be exploited for general use. An aspiration ‘to make THz electronics more like conventional electronics’ may be a key factor, together with many others, in achieving this aim. One important action by the Network will be to hold discussion meetings with selected non-academic partners, largely drawn from UK industry, the Health Services and government agencies. The purpose of such meetings will be to identify new application areas where current and foreseen advances in THz component and systems technology can bring benefit.

The Network is also charged with the responsibility of assembling a Roadmap for future research and development activity in the UK. In order to undertake this activity, it will first be necessary to assemble a ‘baseline’ listing of current research and development, so that our strengths and weaknesses may be assessed against international benchmarks and coherent plans can be developed. This listing, together with a suggested categorisation scheme, is presented below. Furthermore, in view of the extent of UK work and the growing number of application areas, the present information may also be helpful in informing the community itself of other topics within the general field.

**Listing and Categorisation of UK THz Work**

The recent *Research Excellence Framework* (REF) exercise testifies to the strength, breadth and *impact* of current UK research and development in THz science and technology; see:

* [http://results.ref.ac.uk/Search?uoaId=&orgId=&formId=&searchText=terahertz](https://owa.dur.ac.uk/owa/redir.aspx?C=n0kZArluekSGu4BTRYpLs8GKL-xZHtIIzPcNlzYgBvrCnDfqAvUbnbT6Jz-sWfslPmsIZgKDjEg.&URL=http%3a%2f%2fresults.ref.ac.uk%2fSearch%3fuoaId%3d%26orgId%3d%26formId%3d%26searchText%3dterahertz" \t "_blank)

Below are listed, usually with a little explanation, the research topics as given on the UKRC websites. This is, therefore, only a snapshot of current interests; but several recently completed grant topics have been included for completeness. We remark that all of the Councils, the exception being Social Science, have THz grants listed on their books! It may also be noteworthy that the two highest-value current grants involve the development of (potentially) low-cost photonic systems and the use of ‘big facilities’ for research (value approximately £6M each). The approximate current value of all UK funded THz grants is £35M and the approximate division of grants, by number, is: components 27%; systems 18%; applications in basic science- 37%; and applications in other areas 18%.

This document does not include specific information on current THz grants, with UK participants, that are provided by the European Commission. However, it may be noted that the overall EU funding for such grants amounts to approximately €16M. This has been a particularly useful source of funding in previous Research Frameworks, when specific opportunities for THz work were highlighted. It may also be noted that there are, currently, no EU THz programmes led and managed by UK workers. It should also be pointed out that, in the UK, much excellent THz work has been supported by the European Space Agency and also by the UK Astronomy Technology Centre. It should also be noted that this document does not contain any Market Survey information. However, one fairly recent survey (by consultants BCC, Wellesly, Mass.) indicates that the market for THz radiation devices will grow to $127 million in 2016. The report also states that ‘the diversification of the THz market is expected to accelerate after 2016, and the total market should reach $570 million’ by 2018.

A suggested diagrammatic representation of the current UK activity is shown below. This diagram does not represent the only possible categorisation, and others may indeed be better. Moreover, there are several important points that this diagram does not convey:

* It omits any obvious reference to the essential process of gaining scientific understanding of what is being measured or studied; but focusses rather on showing technology/ science flows. For example, activity in topic B1 on the diagram (which may require a knowledge of material properties at THz frequencies) is informed by several topics within C1 and C2; the arrows therefore only main direction of knowledge flow. Also omitted here (A4) are some important software tools, such as COMSOL or CASTEP, which inform component design or the modelling of spectroscopic data, and which are usually ‘bought in’.
* The ‘blocks’ on the diagram, and the corresponding items in the listing, should not be seen as implying watertight divisions between topics; indeed, one of the hallmarks of THz science and technology is that it embraces optical and electronic ‘traditions’. An example of such a breakdown of divisions is the current work on locking Quantum Cascade Lasers to (electronic) multiplier signals.
* The decision to place B1 and B2 together does not imply that there are no other THz ‘system’ activities: for example, the refinement of receiver systems based on mixer technology and listed in C5 could equally well have been placed in block B.
* Central Facilities now provide ideal opportunities for much THz science in the UK. Their position is shown separately from small/medium scale systems (e.g. TDS). Their development relies not only on accelerator and Free Electron Laser science, but also on developments in detection and other software and component technologies that are also relevant elsewhere.
* A significant omission from the diagram is ‘Training’, which (alongside the process of gaining scientific understanding noted above) is an essential part of current and future programmes. The development of UK based THz training programmes, within CDTs or elsewhere, must be embodied in all future Roadmaps.

Nevertheless, we present the diagram below.

**DIAGRAM OF CURRENT UK THZ ACTIVITY**

**Arrows indicate main direction of science & technology flow.**

A4: Software & Other Underpinning Technology.

A3: Passive Components

A2: Detectors

A1: Sources

B2: Other spectroscopic systems.

B1: Time Domain System Development.

**C: APPLICATIONS**

**B: SPECTROSCOPIC SYSTEMS DEVELOPMENT**

C5: Space Science, Astronomy & Remote Sensing.

C4: Security & Surveillance.

C7: Other Applications.

C6: Communications.

C3: Clinical & Biological.

C1: Condensed Matter Science, Quantum Info Processing.

Central Facility Systems: ALICE, FELIX/FLARE, Miriam B22

C2: Non-destructive Testing & Pharmaceuticals

**A: CORE TECHNOLOGIES**

**LISTING OF CURRENT UK THZ ACTIVITY**

**A. Core technology – Components, Devices, Underpinning Technology and Software for THz systems:**

**A. 1.  *Sources (excluding Central Facility Sources)***

* *Quantum Cascade Lasers (QCLs)* (Cambridge, Leeds):
* Current efforts directed in III-V materials towards: lower THz frequency operation; higher output power; higher temperature operation; improvement of output beam quality (metamaterials); fibre-coupled QCLs; phase-locked, electronically-tuneable QCLs; development of QCL amplifiers for TDS; self-mixing in QCLs; phase measurement & manipulation; and combination with Time Domain Spectroscopy sources for amplification.
* Recent UK activity in Si/SiGe devices with potential for room temperature emission.
* *Electronic Sources*: (Glasgow, Queen Mary, RAL, Teratech)
  + Resonant tunnel diodes (RTDs): multiple RTDs in single oscillators, using MMIC technology for single pixel imaging 0.1 -1THz;
  + Gunn diodes: planar devices operating above 300 GHz; improvements in power management.
  + Multiplier engineering: systems embodying low capacity Schottky diodes; multiple antenna (multenna) Schottky sources.
* *Pulsed Sources, Photomixer (CW) sources, Parametric Amplifiers*. (St. Andrews, Bath, Cambridge, Exeter, Leeds, Nottingham, Oxford, Southampton, TeraView, UCL)
  + Improvements in generator materials for TDS and CW systems: aimed at operation with telecoms wavelength laser sources e.g use of Fe: InGaAs emitters.
  + Diffusion and Schottky based TDS emitters
  + Refinement of UTC photomixer sources and related subsystems.
  + Lateral photo-dember emitter system, multiple and single emitter
  + Generation in gas-filled waveguide for higher power output.
  + Carbon nanotube generators.
  + Parametric oscillator systems: tuneable, microwatt averaged power pulsed THz sources.
  + Vertical cavity coherent THz source based on a polariton laser (theory only).
  + THz phonon sources (SASERS), 0.1-1.0 THz.
* *Vacuum Tube Sources – small scale* (Lancaster, RAL, Strathclyde)
  + Backward wave oscillators
  + Travelling wave tube amplifiers
  + Micromachined klystrons

***A.2 Detectors***

* *Room temperature detectors*  (Glasgow, Durham, Imperial, Leeds, Liverpool, Oxford, Manchester, NPL, Royal Holloway)
  + Devices with sensor fusion capability.
  + Graphene based sensors; CMOS compatible fabrication.
  + MIS detectors
  + Monolithic detector arrays using uncooled micro-bolometers, video rate operation. Compatibility with CMOS processing.
  + Polarization-sensitive detectors for TDS.
  + Semiconductor nanodiode rectennas
* *Cooled detectors* (Bath, Cambridge, Cardiff, Leeds, Oxford , RAL, QMC Instruments)
  + Developments in closed-cycle cooling of detectors and detector arrays
  + Sensitive detectors and cameras for astronomy: SIS mixers, Transition Edge sensors, Kinetic Inductance Detectors, Schottky Diode mixers, Silicon Nitride bolometers.
  + Self-mixing detectors using QCLs

***A.3 Passive components /software***

* *Frequency selective surfaces and waveplates* (Cardiff, Loughborough, Manchester, QUB, Thomas Keating and RAL)
* *Filters and polarizer development* (Cardiff, QMC Instruments)
* *Metamaterial components* (Durham, Glasgow, Queen Mary, Southampton) for:
  + Control and manipulation of THz light
  + Filters
  + Sensor stacking.
  + Waveguide filters using meta-molecules

***A.4 Software and other Underpinning Technology***

* *Metrology* (NPL, QMC Instruments/ Thomas Keating)
  + Power and wavelength measurements
  + Materials properties (absorption, emissivity, refractive index, scattering)
  + Safety advice.
* *Micro-machining*  (Birmingham, Cambridge, Durham, Leeds, RAL, UCL)
* *Quasi optics:* (Reading, QMC Instruments)
  + Component engineering
  + Measurements of system characteristics
* *Software development* (Brunel, Reading, Southampton)
  + For THz camera operation
  + For time domain spectroscopy (‘chemical analysis at depth’)
  + For time domain spectroscopy, material parameter extraction for converging beams

***B.* Spectroscopic Systems Development**

***B.1 THz-Time domain systems***

* *Low cost spectrometer systems* (Leeds, a non-UK company, UCL)
  + Fibre-coupled, based on Fe: InGaAs mixer and 1.55 μm lasers.
  + Fibre-coupled, based on UTC sources
* *All semiconductor THz spectrometer using semiconductor pulsed lasers, VECSELs* (Southampton)
* *THz systems for spectroscopy of birefringent and optically active materials and proteins (Oxford)*
* *Lateral photo-Dember time domain system* (Southampton Cambridge,)
* *Cryostat spectrometers* (Cambridge, Leeds, Oxford, UCL)
* *Combined with QCL TDS systems for quantum cascade THz amplifier* (Leeds, UCL, Southampton)

***B. 2 Other Spectroscopic Applications***

* Dynamic Nuclear Polarization systems (St Andrews, Thomas Keating)
* *QCL-TDS* (Leeds)
  + Development of QCL amplifiers for TDS;
  + Self-mixing in QCLs; phase measurement & manipulation.
* *Tomography systems* (Leeds)
* *Endoscopy systems* (Teraview)
* *Near-field techniques (Leeds,(Liverpool, UCL)*
  + Instruments with apertures down to <3μm; Investigations of SPS, waveguide modes, SAW in graphite.
  + Instruments based on SNOMs for bio-THz studies.
* *Vibrational circular dichroism* (Oxford)

**C. Applications**

***C.1. Condensed Matter Science, Quantum Information Processing***

* *THz spectroscopy of structure and dynamics in organic materials (Cambridge)*
* *Plasmonics: THz spoof plasmons, sensing and manipulation applications* (Bath, Durham, Exeter, Leeds)
* *Probing nanostructure physics* (Oxford, Leeds, UCL)
  + Nanowires : characterization using THz TDS
  + Single electron devices at cryogenic temperatures probed with co-located QCLs.
* *Spectroscopy for Quantum Information Processing* (UCL, Surrey)
* *Solotronics* (LCN, Surrey/FELIX)
  + Single defects in silicon, analogues of atom-trap placed with atomic-scale precision, investigated by THz for quantum entanglement and information processing

* *Spintronics* (Warwick)
  + Dynamics of mult-ferroic materials investigated by TDS
* *Water ‘Nanopools’*(Strathclyde)
  + Investigating the structure and dynamics of water in liquid and glassy state using THz TDS.

***C.2 Non-destructive Testing and Pharmaceuticals***

* *Art and artefacts* (Reading, Teraview)
  + Imaging plastered or painted-over artworks /archaeology

* *Automotive paint thickness measurement using TDS with intelligent feedback (*Cambridge)
* *Determination of processing parameters for functional pill coatings with intelligent feedback* (Cambridge, Liverpool)
* *On-chip studies of polymorphism in pharmaceuticals using THz TDS* (Leeds)
* *Electrical characterization /testing* (Oxford, Teraview)
  + Fault analysis in integrated circuits by THz time domain reflectometry
  + Inspection of solar cell materials for cracks
* *Food/drink analysis* (De Montfort, Teraview)

***C.3 Clinical and Biological:***

* *Amyloid fibrils and precursors; probing chemical composition and changes in crystalline structure* (Leeds)
* *Cancer diagnosis using TDS* (KCL, Teraview, UCL) and ALICE (Liverpool)
  + Tissue types: esophagus; bowel; breast; cervix; liver; oral; prostate and skin.
* *Circulating tumour cell detection at sub-THz using various resonators and microfluidic systems.* (Imperial)
* *DNA spectroscopy* (Reading)
* *Fast tunnelling processes in enzymes investigated by THz EPR* (Manchester)
* *Subtle biological effects of THz* radiation (Durham, Liverpool)

***C.4 Security & Surveillance***

* *Gas phase spectroscopy for airborne threat detection* (Teraview)
* *Hazard screening with electronics-based systems:* (Digital Barriers/ Thruvision, Manchester Metropolitan, TeraTech )
  + On-body concealed weapon detection using a phased antenna array
  + Passive stand-off people screening units (<200GHz)
  + Development of multi-frequency active and passive imaging (<360GHz)
* *Hazard screening with optics-based systems* (Leeds, Teraview)
  + Active screening for drugs, explosives including mail screening using TDS
  + Spectroscopy of explosives and drugs-of-abuse using TDS and QCLs

***C.5 Space Science, Astronomy & Remote Sensing***

* *Terrestrially-based astronomy*  (Cambridge, Cardiff, Open University, Oxford, Thomas Keating, RAL, UK Astronomy Technology Centre)
  + ALMA telescope (30-1000GHz): calibration standards, receiver front-end development
  + ALMA Greenland Telescope: development of 100GHz on-chip systems; 90 GHz focal plane array development.
  + Ice desorption studies of the interstellar medium (laboratory based)
  + IRAM telescope: lumped element kinetic inductance detector systems
  + James Clerk Maxwell: development of the SCUBA -2 camera system using superconducting transition-edge detectors.
* *Space-borne astronomy* (RAL, UK Astronomy Technology Centre)
  + SOFIA instrumentation: Hot Electron Bolometer development (Reading
  + Herschel Satellite instrumentation development
* *Other space-borne applications* (Leeds, RAL, Surrey Satellites Ltd)
  + Satellite remote sensing using heterodyne mixing in a QCL

***C.6 Communications***

* *Wireless link operating at 40 Gb/s based on UTC technology (<200GHz)* (UCL)
* *Component development for a 300 GHz link (Birmingham, RAL)*

***C.7 Other Applications***

* *0.3 -1.0 THz imaging and sensing for road-vehicle applications* (Birmingham)

**C. INDUSTRIAL COLLABORATIONS**

The following UK companies o*r organisations appear, from the current list of EPSRC grants, to be collaborating with UK academic institutions on THz projects:*

Agilent; Airbus UK; Bae Systems; Bionanocentre Ltd; e2v, Elite Antennas; HOSDB; Jaguar Land Rover; L-3 TRC Technology; MESL; PfizerQMC Instruments/Thomas Keating; Robert Bosch; Roke Manor Research; Selex-Galileo; Smiths Detection; ST Microlectronics; Teratech; Teraview; Thales; TRL Technology

FINAL VERSION

*JMC, February 22nd 2015*