

IST-511415

TeraNova

**Novel Terahertz Sensing & Imaging Systems
For Biotechnology, Healthcare, Security
& Process Monitoring**

Integrated Project

**Information Society Technologies:
Optical, Opto-electronic &
Photonic Functional Components**

**PUBLISHABLE FINAL ACTIVITY
REPORT**

(Deliverable: D2.6)



SUMMARY

TeraNova has been an Integrated Project funded by the European Union under the Sixth Framework Programme. The Project brought together the key workers in the field of terahertz (THz) technology from large and small industry and academia. The overall aim of the Project has been the development of new functional components, sub-systems and systems operating in the hitherto unexploited THz region of the spectrum. This report summarises the activities and achievements of the TeraNova consortium since its start in September 2004.

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Start Date:	September 1 st 2004
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Person-months:	722 person-months plus additional 337 non-EC funded person-months (AC partners)
Project Cost:	6.9M€
Project EU funding:	5M€
Project Status:	Completed

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SHORT SUMMARY OF MAJOR ACHIEVEMENTS

Terahertz (THz) radiation possesses many useful properties, and has actual or potential applications in areas as diverse as: security and surveillance, biotechnology, medical imaging, non-destructive testing and quality control. Generation of this type of electromagnetic radiation has proven difficult until recently. TeraNova has realised new tools and techniques for the generation, manipulation and detection of THz radiation. Major achievements include:

- ❖ TeraNova partner *Femtolasers Produktions GmbH* has developed a near infrared, ultra-short pulse laser to be used in conjunction with a special transducer system to generate broadband THz pulses. As a result of this programme: the footprint of the opto-mechanical components, including the pump laser and diagnostic devices, has been reduced to 0.13 m²; intra-cavity power of 2.5 W, with 30 fs long pulses, can be achieved with a 5 W pump source; integrated diagnostics have been included, which enable the system to be operated by a non-expert; and fibre technologies have been implemented for the transmission of femtosecond near infrared pulses over 1.5 m of single mode fibre. This system is now commercially available and is ideally suited to a variety of THz applications in non-destructive testing, biotechnology and other areas.
- ❖ TeraNova partners: *Alpes Lasers, Leeds University, University of Neuchâtel, Université Paris VII Denis Diderot, SNS Pisa and ETH Zurich* have achieved world-leading status in the development of *Quantum Cascade Lasers (QCLs)*. These devices rely on the subtle electronic properties of advanced semiconductor structures, made in the form of “sandwiches” of differing materials (usually grown from the Gallium Arsenide family of semiconductors) with layer thicknesses corresponding to just a few atoms. They emit THz radiation directly, with continuous wave (CW) or pulsed output, and with output powers of a few milliwatts. As a result of this programme: laser operation at temperatures up to almost 200K, and at frequencies down to 0.8THz, have been achieved; distributed feedback (DFB) resonators with stable and predictable single mode emission have been realised; vertical emission micro-disk and micro-ring lasers with approximately five degrees beam divergence and up to 10 mW output power have been fabricated; and lasers made from the Indium Phosphide family of semiconductors have also been developed for the first time. TeraNova partner *Alpes Lasers* has developed a “plug and play” QCL system that requires no refrigerants, but only connection to a wall-plug socket. Two start-up companies outside *TeraNova* (but in strong collaboration with *TeraNova* partners) have now been formed targeting industrial production of THz QCLs for specific applications in security and biotechnology.
- ❖ As an alternative source technology, TeraNova partners at *Alcatel Thales III-V Lab, Université Paris VII Denis Diderot* and *Thales R&T* have developed CW THz sources using cheap photonic components (used routinely in optical fibre telecommunications) in combination with QCL devices operating at room temperature. This arrangement offers the possibility of low-cost, stable, tuneable CW THz generation. The primary application of these subsystems is

as local oscillator (LO) sources for sensitive heterodyne detector arrays, for use in surveillance and security systems.

- ❖ TeraNova partners University Neuchatel, *Université Paris VII Denis Diderot*, *Technische Universität Wien Photonik Institut* have produced the world's first THz amplifier. Using a combination of broadband THz pulses and QCL technologies, they have realized amplifiers with a ten-fold gain, together with fast modulator devices. These developments by TeraNova open up the way to new opportunities in ultra-wide bandwidth THz communication systems, together with many other applications where a broadband, powerful source of THz radiation is required.

The TeraNova partnership have also focussed attention on a number of areas of basic scientific study that, together with the developments in functional components noted above, have been deployed in the design and realisation of a number of Demonstrator systems. Major achievements have included:

- ❖ Detailed measurements of 'street' drugs-of-abuse samples have demonstrated that THz techniques can distinguish the key drug component in a range of seized drug compounds. Furthermore, this identification is possible for drug samples concealed inside a range of common packaging materials employed in freight transport.
- ❖ The technical developments that have taken place to underpin this work include understanding: (a) the origin of the THz spectra used to "fingerprint" the drugs and explosives; and (b), the nature of the scattering process as THz radiation passes through powders and clothing. TeraNova partners at *Durham* and *Leeds* have used this information to specify the system requirements for a variety of security scanner and detection systems.
- ❖ Building on this work, TeraNova partners at *Durham* and *Leeds* have developed THz systems for tomography which may be used to determine the presence of small items (~ 50µm) embedded within non-metallic structures. This is relevant to a whole range of non-destructive testing applications.
- ❖ TeraNova partner the *Technical University of Denmark* have developed advanced THz equipment that can rapidly distinguish between inflammable and water-based liquids, through plastic and glass bottles, with clear security screening implications.
- ❖ They have also used this type of equipment to measure and understand the THz spectra of minute quantities of biological material (e.g. DNA). This information is relevant to non-contact THz mutation detection studies.
- ❖ Working with TeraNova partner *Technical University of Delft*, the *Technical University of Denmark* has also demonstrated that THz pulses can be satisfactorily transmitted along a new class of polymer-based photonic crystal fibres. This opens up the possibility of THz endoscopes for medical use.

The TeraNova partnership have used both new fundamental knowledge they have acquired, together with the developments that they made in photonic functional components, to construct a number of Demonstrator systems. These systems represent important applications of THz technology and are now being made ready for commercial exploitation by the partners, new spin-out companies that they have formed, or by third parties. Highlights of this part of the TeraNova programme include:

- ❖ TeraNova partners *Rheinisch Westfälische Technische Hochschule Aachen* and *Universität Siegen* have developed a high-throughput biochip genetic diagnostic system with high sensitivity. This is the only system in the world that uses a modular chip-based concept of very low-cost, separable THz components.
- ❖ Later developments have included devices based on frequency selective surfaces and a QCL chip reader.
- ❖ *Universität Siegen* has successfully demonstrated a new flow-through micro-capillary system that can be used for bio-sensing in a fluidic environment. Contrast ratios of up to 10% have been demonstrated between water and air in the microcapillary, probing a volume of just fractions of a nanolitre with the THz beam. The system will be used for online analysis of biomaterials with both QCL and broadband sources.
- ❖ TeraNova partner *Scuola Normale Superiore Pisa* has realized a THz system for single cell imaging based on QCL sources and on the use of apertures to select the area from which the signal is collected. Using this system, the first THz images of a single epithelial tumour cell has been taken.
- ❖ TeraNova partner *Technical University of Delft* has developed a THz microscope system that can provide spectroscopic information in the THz frequency range from experimental samples of around 20µm size. Using this system, the Delft partner has begun to explore the fundamental physics of light transmission through small structures and how it evolves with time. They will be using the microscope in a future range of investigations of biological materials and small-scale semiconductor structures.
- ❖ TeraNova partners *Femtolasers Produktions GmbH*, *TeraView Limited* and *Technische Universität Wien, Photonik Institut* have developed two THz-based systems for use in quality control applications in the semiconductor industry. The first of these, developed by *Femtolasers Produktions GmbH* and *Technische Universität Wien*, uses a THz beam to interrogate a semiconductor wafer during production. The beam scans the wafer and delivers a map of important quality-control information (electrical conductivity, carrier concentration, electrical mobility). In one advanced version, the system can also deliver information about the electrical properties of layers of semiconductor material, such as two-dimensional electron gas structures (as used in High Electron Mobility Transistors). The Demonstrator is now being trialled in an industrial setting.

- ❖ The second semiconductor quality control Demonstrator is a *Time Domain Reflectometer* with a high frequency probe arrangement for use in detecting failure mechanisms in Integrated Circuits through their plastic encapsulation. The current spatial resolution of the system is 10µm. This is also now being trialled by an End User in their production facility.

TeraNova partners have communicated their work to the scientific community through:

- ❖ One hundred and thirty five articles and eight book chapters. The articles appear in peer-reviewed, primary, archived journals such as: *Nature*, *Applied Physics Letters*, *Applied Optics*, *IEEE Transactions*, *Journal of Applied Physics*, *Optics Express*, *Physical Review* and *Physical Review Letters*.
- ❖ One hundred and seventy six invited, plenary or keynote talks, together with ninety eight other conference contributions. TeraNova partners have spoken or presented at events in Asia, Australia, America and Europe, including meetings held under the auspices of: *American Chemical Society*, *American Physical Society*, *CLEO*, *European Materials Research Society*, *European Physical Society*, *IEEE*, *Infra Red and Millimeter Waves Conference (IRMMW)*, *OPTRO EUROPE*, *Photonics West* and *SPIE*.
- ❖ A variety of training events aimed at the technical, industrial, academic and End-User communities. These have taken place at a number of locations, including the *Royal Society* in London. TeraNova has also attended a number of Trade Fairs and Exhibitions throughout the Community, attracting attention from Commission Officials, senior industrialists, government scientists and academics.

Despite the background of an adverse macro-economic climate, the Exploitation outcomes have been excellent for the TeraNova consortium. These have included:

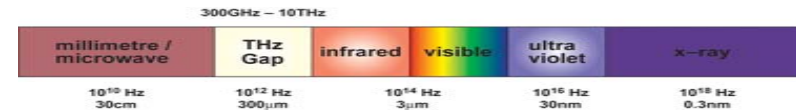
- ❖ Formation of three spin-out companies.
- ❖ New products are now available for purchase.
- ❖ Several products are now nearing commercial release.
- ❖ Five demonstrators are moving towards commercialisation.
- ❖ Eight patents and patent applications have been filed.

For further information, please see later in this *Report*.

INTRODUCTION

TeraNova has been an Integrated Project in Framework VI, co-funded by the European Commission under the IST programme. The consortium consisted of 21 members drawn from large and small European Industry, and from Academia. The consortium has joined its efforts to deliver new types of functional component, sub-system and system operating in the hitherto largely unexploited terahertz (THz) region of the electromagnetic spectrum.

The THz range lies between millimeter waves and infrared ie. 300 GHz – 10 THz in frequency (which corresponds to: wavelength, 1000 µm – 30 µm; energy, 1.25 meV – 37.5 meV; and, temperature, 14K – 480 K). (see below).



Schematic representation of the electromagnetic spectrum identifying the THz region.

Until recently, this region of the spectrum has resisted attempts to harness its potential for application, largely because of the difficulty in providing suitable radiation sources which were usually weak, bulky, expensive, and incoherent. This led to the expression 'Terahertz Gap' being used to describe this THz region between lower frequency, electronics-based sources (such as transistors) and higher frequency, optics-based sources (such as lasers). The useful properties of this radiation are:

- ❖ THz radiation is non-ionising, and intrinsically safe;
- ❖ Many visually opaque materials are transparent to THz;
- ❖ THz radiation provides a means of identification of specific materials, including biomedical materials such as DNA. This is because molecular rotations, vibrations or librations occur in this frequency range;
- ❖ THz radiation also provides, non-destructively, important quality control information on plastics, semiconductors, ceramics, composites and other materials.

This Report is a summary of what we set out to do, how the work was carried out, and the achievements of the Project. The TeraNova Project has been a large and complex undertaking with outputs in the generation of new knowledge, new devices and components, new technical approaches and tangible demonstrator systems. The Project has directly led to: the creation of spin out companies and jobs; patents, scientific and technical articles of the highest quality; dissemination at national and international technical meetings; and outputs directed at the public understanding of science and technology.

One of the above outputs has been over 135 articles in peer-reviewed journals. The details of these are carried on the TeraNova website (www.teranova.info) which will be maintained for a further two years.

OBJECTIVES

The overall objectives of the project have been to:

- ❖ Deliver an internationally competitive programme on the development of THz frequency functional components;
- ❖ Realise technology demonstrators, using these functional components;
- ❖ Conduct fundamental scientific investigations and feasibility studies to ensure that new application areas are identified and addressed;
- ❖ Stimulate the co-operation of SMEs, academia and larger industry to solve problems of mutual concern in the field of THz technology development;
- ❖ Execute an exploitation and technology awareness strategy to the benefit of the participants themselves and European industry as a whole;
- ❖ Undertake the dissemination of results through high quality channels, thus publicizing European activity in the field;
- ❖ Conduct high quality training and educational programmes in the area aimed at technical staff, academics, research staff and End Users.

These objectives have been translated into a series of specific actions organised according to four *Themes*: (A) Underpinning technologies; (B) Applications Phase #1 - Basic Science, Technology & Proof-of-Principle Demonstrators; (C) Applications Phase #2 - Field Demonstrator Systems; and (D), Scientific Coordination, Review, Exploitation, Dissemination and Training.

AN OVERVIEW OF THE PLANNED WORK

- ❖ **Theme A: Underpinning technologies.** This consists of: development of functional components for subsequent evaluation and use in selected systems applications. Components have included: a compact near infrared laser, which is used to generate broadband THz pulses; new types of semiconductor laser sources, known as Quantum Cascade Lasers (QCLs); sources that generate THz radiation by combining the output of lasers operating at wavelengths commonly used in the telecommunications industry; and THz amplifiers and modulators.
- ❖ **Theme B: Applications Phase #1: Basic Science, Technology & Proof-of-Principle Demonstrators.** This includes: development of an integrated biomolecular sensing array; a THz near-field microscope for bioscience; a THz semiconductor wafer and device scanner; and basic studies of spectroscopy, scattering, the transmission of radiation through inhomogeneous materials, and the identification of secreted objects.
- ❖ **Theme C: Applications Phase #2: Field Demonstrator systems.** This Theme takes forward a limited number of Demonstrators to the stage of use in the field. The choice of system to be so developed has been based on a bidding process that began at Month #18 and was open to all partners.

- ❖ **Theme D: Scientific Coordination, Review, Exploitation, Dissemination and Training.** In this Theme, the routes towards exploitation are explored, training is provided, conferences and other technical meetings are organized and the results of the work disseminated. This Theme provides the basis of scientific coordination for the programme.

Nota Bene:

- ❖ Each *Theme* was further subdivided into *Workpackages*. Workpackages are denoted A1, A2..., and B1, B2... etc.
- ❖ Appendix I provides a full summary of the initial technical objectives of each Workpackage

CONSORTIUM MEMBERS AND ROLES

TeraNova Number	Partner	Type	Contribution
#1	University of Leeds	U	<ul style="list-style-type: none"> Administrative Coordination Spectroscopy of Drugs and Explosives
#2	University of Durham	U	<ul style="list-style-type: none"> Scientific Coordination Dissemination and Exploitation Scattering, Signal Processing and Simulations
#3	Rheinisch Westfälische Technische Hochschule Aachen (Aachen University)	U / RI	<ul style="list-style-type: none"> Development of Bio-analytical Systems
#4	Alpes Lasers	SME	<ul style="list-style-type: none"> Quantum Cascade Laser Systems Integration
#5	BAe Systems (Operations) Ltd	LSI	<ul style="list-style-type: none"> End User of Security and Non-destructive Testing Systems
#6	Technical University of Delft	U	<ul style="list-style-type: none"> Development of THz Microscopy
#7	PerkinElmer Cellular Technologies Germany GmbH (Formerly Evotec Technologies GmbH)	LSI / LC	<ul style="list-style-type: none"> End User of Bio-analytical Systems
#8	Femtolasers Produktions GmbH	SME	<ul style="list-style-type: none"> Development of Compact Femtosecond Near- infrared Laser Systems
#9	Albert-Ludwigs-Universität, Freiburg	U / LC	<ul style="list-style-type: none"> Spectroscopy of Biological Materials
#10	University of Neuchâtel	U / LC	<ul style="list-style-type: none"> Quantum Cascade Lasers
#11	Université Paris 7 Denis Diderot	U	<ul style="list-style-type: none"> Development of THz Sources Based on Laser-mixed Systems
#12	Scuola Normale Superiore (SNS), Pisa	U	<ul style="list-style-type: none"> Quantum Cascade Lasers Bio-analytical systems(MIST)
#13	Renishaw Plc	LSI / LC	<ul style="list-style-type: none"> End Users of Microscope system
#14	TeraView Limited	SME	<ul style="list-style-type: none"> Systems Integrators Semiconductor Scanner Development Security Studies
#15	Thales R&T	LSI	<ul style="list-style-type: none"> Laser-mixed Sources and Receiver Systems
#16	Technische Universität Wien, Photonik Institut	U / RI	<ul style="list-style-type: none"> Semiconductor Scanner THz Amplifiers and Modulators
#17	Alcatel Thales III-V Lab	LSI	<ul style="list-style-type: none"> Laser-mixed Sources and Receiver Systems
#18	Universität Siegen	U	<ul style="list-style-type: none"> Bio-analytical Instrumentation (including MIST)

TeraNova Number	Partner	Type	Contribution
#19	Technical University of Denmark	U	<ul style="list-style-type: none"> Spectroscopy of Biological Materials Foodstuffs and Liquids Instrumentation Development
#20	Istituto Sperimentale Italiano "Lazzaro Spallanzani" (ISILS)	RI	<ul style="list-style-type: none"> Sample Provision and Testing for Bioanalytical Equipment - End User (MIST)
#21	ETH Zurich	U / RI	<ul style="list-style-type: none"> Quantum Cascade Lasers

Key:

- ❖ LSI= Large Scale Industry (>100 employees)
- ❖ LC = Left Consortium before Final Review Date
- ❖ RI= Research Institute (not-for-profit)
- ❖ SME= Small-medium industry (<100 employees)
- ❖ U = University



TeraNova Partner Locations



TeraNova Partners- European Commission, May 2009

Details of the Management Structure are presented in Appendix V.

SCIENTIFIC AND TECHNICAL HIGHLIGHTS

In the next section of this *Publishable Final Activity Report*, we summarise some of the technical highlights of the TeraNova project. It is intended that this Summary can be understood by a general reader.

A full summary of all of the technical highlights is given in Appendix I. The full technical descriptions of the work undertaken are presented, in great detail, in the four *Periodic Activity Reports*.

TERAHERTZ COMPONENTS & SUBSYSTEMS

Sources of Terahertz Radiation

Generating THz radiation presents particular complications: given that this region lies between "radio" and "light", it turns out that conventional sources for either of these varieties of electromagnetic radiation are not at all efficient in the THz region. This is due to a combination of basic physics, technology limits and materials properties. The types of source that were available until quite recently were expensive, bulky and usually inappropriate for practical applications. TeraNova has made great strides in the development of several new types of THz source that overcome, to some extent, these problems. Here, we highlight two new ways to generate THz radiation: the first, which creates broadband radiation (i.e. radiation from around 0.2THz to approximately 5THz); and the second, which is a compact laser source that holds great promise as a source of continuous wave (cw) or pulsed radiation operating at

specific frequencies in the THz band.

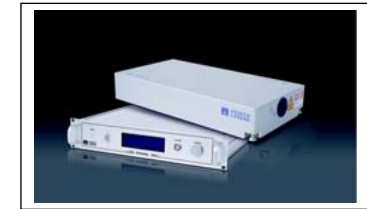


Figure 1: Femtosecond near infra red lasers developed during TeraNova by Femtolasers of Vienna.

The first of these sources, which generates broadband radiation, depends crucially on a highly sophisticated laser that operates in the near infrared part of the spectrum (with an emission wavelength around 800nm). This may seem strange, but engineers and physicists have found that when very, very short pulses of this radiation, lasting a few femtoseconds (abbreviated to *fs*: there are one thousand, million, million femtoseconds in a second!), fall on a transducer device, THz radiation is emitted. The transducer is a specially designed piece of semiconductor material which emits THz pulses with frequencies over a broad range. The key to useful THz generation by this method is to keep the near infra-red pulses as short as possible and to ensure that the laser power levels are sufficiently high (tens of milliwatts, or more) to ensure efficient THz generation. The response of materials to THz radiation is measured by sensitive detection schemes, using an idea borrowed from radar, in which the detector is "woken up" by one of

the near infrared pulses, and information taken over a (short) timescale (or, in the jargon: in "the time domain") is transformed mathematically into information over a frequency range (or, in the jargon, the "frequency domain"). This approach is widely used in research applications, but TeraNova has adopted it to practical applications in semiconductor quality control, biotechnology and security.

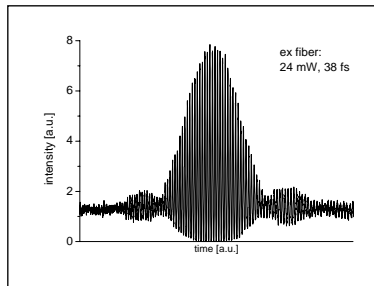


Figure 2: Autocorrelator trace showing pulse with suitable power and length to generate THz pulses at the end of a long optical fibre.

To facilitate these developments, the TeraNova partner *Femtolasers*, an SME company based in Vienna, have created a laser system that is compact, relatively inexpensive and which does not require regular maintenance by laser experts. This is shown in Figure 1. The crucial developments have been: to improve the laser stability, making it fit for THz applications in medicine, security, non-destructive testing and other areas; to reduce the space requirements by combining components (e.g. the "pump" laser); and to develop strategies for transporting femtosecond pulses along fibres. The delivery of very short near infrared pulses along pulses, in

such a way that they retain their "shape", makes them very useful indeed for the generation of THz radiation exactly where it is needed in, for example, a difficult environment such as a vacuum chamber, or on an industrial production line. This last problem is especially challenging: the shorter the pulse duration (in this case a few femtoseconds) the more sensitive are pulses to changes in profile when travelling along a few metres of fibre.

Taken together, the advances made by *Femtolasers* within TeraNova have drastically simplified system integration. The result is that lasers can deliver sufficient power (up to one hundred milliwatts) over a few metres of optical fibre and still have pulses that are short enough to generate THz radiation. This step has needed a considerable technical effort in the use of novel optical fibres and the development of "compressor" technology (which compensates, using optical methods, the natural dispersion, or spreading-out, of pulses as they travel along a fibre). Figure 2 shows a measurement, using a special instrument known as an autocorrelator, of the temporal length of such a pulse- in this case, 38 fs, which is delivered at the end of a fibre several metres long.

The outstanding outcomes of this work undertaken in TeraNova will have far-reaching impact on future applications of ultrashort laser pulses in the health and security segment. Optical pulses with time durations of only 10 to 20 femtoseconds are finding their way out of research laboratories to application-oriented commercial

high-end products. Their use is not solely limited to THz applications, but also includes optical coherence tomography, multi-photon imaging, time-resolved spectroscopy and materials processing. In all of these fields, the advances made by TeraNova will be directly applicable.

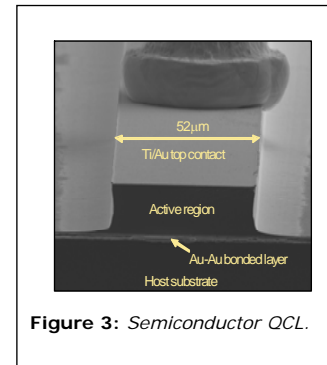


Figure 3: Semiconductor QCL.

The second type of source, a semiconductor laser, provides THz radiation at essentially just one frequency. The laser that has been developed by TeraNova is called a Quantum Cascade Laser (QCL) and, just like the laser that is used to control a TV set, is small and made of an advanced semiconductor material. However, the similarities stop at this point! The QCL devices that TeraNova has developed rely, uniquely, on the ideas of Quantum Mechanics and are made with sophisticated semiconductor growth equipment that can deposit very thin layers (perhaps just a few tens of atoms thick) with amazing regularity and precision (see Figure 3). To understand how the QCL works, and how it differs from the TV remote control laser, it is first necessary to do a very rapid review of semiconductor physics.

Physicists describe the way that electricity is carried through a semiconductor in terms of the motion of electrons and, surprisingly, absences of electrons that are given the name of *holes*. Together, electrons and holes are termed "carriers". In a normal semiconductor material, such as Gallium Arsenide (GaAs), the carriers are pictured as having a range (or *band*) of permitted energies. It turns out that electrons occupy one such band (termed the *conduction band*) and holes another (the so-called *valence band*). In the familiar TV controller device, a laser is constructed which relies on movement of electrons from a conduction band to a valence band. The difference in energies of these two states is, essentially, the energy of the emitted light (or, in the jargon, the *photon energy*) from the laser. This is fine for a TV controller device, but unfortunately the characteristic light energy is way too big (about four or five hundred times too small, in fact) to make them useful for THz generation. Instead, a device that utilises the principles of Quantum Mechanics has been conceived and, in the TeraNova programme, has been developed to the highest level yet. In this device, the photon energy size is determined principally by the width of very thin layers of semiconductor material, grown by one or two remarkable methods, to a thickness of a few tens of atoms. One way to picture this structure is as a sandwich, with bread and cheese corresponding to different semiconductor materials. In this type of arrangement, electrons only (i.e. no holes are involved) move between energy states (or *levels*)

with a separation that corresponds to a few milli-electron volts. Lasers are then designed and built using such semiconductor sandwiches. The same principles that engineers apply to other laser systems also are used here: the electrons have to be *injected* into a high level energy state, from which they relax to a lower energy state and emit radiation of the desired energy or frequency. It is also essential that the electrons in the lower energy state are removed efficiently. By building sections of semiconductor layers that do a different job, and by combining these suitably, a strong laser process can build up (this idea gives rise to the *cascade* in QCL). Last but not least, it is also vital that the THz radiation generated in the device can be extracted efficiently and that the active medium (as the semiconductor structure is called) is placed within some type of *cavity* (typically consisting of a parallel mirror arrangement) to ensure that the laser radiation building up with suitable strength, and with the correct spatial pattern required.

The technical and scientific achievements of the TeraNova partners in four years have been spectacular and have substantially contributed to securing the European leadership in the field of THz QCLs. Research has proceeded along three main development lines, each targeting an aspect of specific relevance for the successful implementation of the quantum cascade technology in THz applications. These three lines have been to realize lasers that operated: at as low a frequency in the THz range as possible; at as high a temperature as possible; and with output at only one specified frequency with the least spread in output energies (*single mode* operation.)

The results of this activity have had a profound impact non only on the scientific and technological community (with many publications on leading scientific journals like *Nature*, *Nature Photonics*, *Physical Review Letters*, etc.) but have raised the technological level to the point

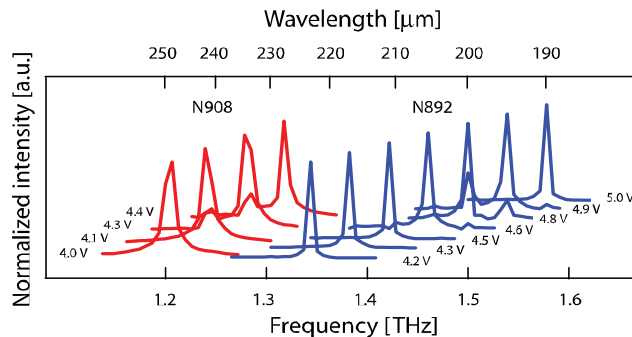


Figure 4: Quantum Cascade Lasers operating down to low frequencies.

that now THz quantum cascade lasers can in many respects be considered ready for commercial developments. A company (Alpes Lasers) was involved in the developments from the beginning, and two start-up companies outside TeraNova (but in strong collaboration with TeraNova partners) have now been formed targeting industrial production of THz QC lasers for specific systems.



Figure 5: Closed-cycle cooling system for QCL operation.

At the beginning of the project the consortium had just demonstrated a QC laser operating around 2.5 THz, with the MIT group having instead shown laser emission at 2.1 THz. TeraNova's target was to tackle the frequency range below 2 THz, which is the most interesting one for security use given the atmospheric transparency and that of fabrics and packaging materials (see Figure 4). The operating frequency of the devices has then been constantly extended from the initial record low 2.5 THz towards longer and longer emission wavelengths, breaking the 1 THz barrier and demonstrating the versatility of the QC concept as a spanning over two decades of frequencies.

The key to success in this work has been to improve the injector sections of the semiconductor structures and to ensure rapid extraction of electrons, as indicated earlier. To achieve this, very sophisticated adjustments have been made in the nature, thickness and arrangement of the semiconductor layers. To extract the radiation efficiently, special metal layers (waveguides) have been deposited on the semiconductor structure; this feature is extremely important if it is intended that the device operates at lower frequencies. The TeraNova partners also found that even striking results could be obtained if a magnetic field was applied appropriately to the semiconductor structure; in the best case, a useful operation frequency as low as 0.8THz (800GHz) could be obtained by this method.

At the beginning of the project activity, TeraNova partners had already demonstrated THz QC lasers operating above the temperature (approximately -200 Celsius; or 77K)) at which liquid nitrogen boils. Once again, by careful optimisation of the way in which the layers were grown, and by developing a sophisticated wafer-bonding procedure, it has been possible to record high operating temperatures of 178 K. This value is still a bit less than the 200 K originally targeted by the programme, but may nevertheless be just enough for allowing operation on with a simple cooling system (a Peltier cooler). It is also worth mentioning that partner Alpes Lasers have developed a version of this arrangement (see Figure 5) with the QCL cooled by a closed

cycle cooler arrangement. This occupies a reasonably small volume, requires only to be plugged in to a power outlet, and will be used in another EU project (MUTIVIS: Multispectral Imaging and Spectroscopy).

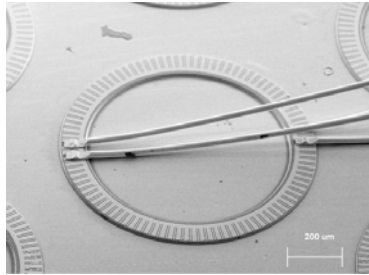


Figure 6: Highly collimated single-mode vertical emission is achieved with metallic gratings.

TeraNova partners working on QCL development have also realised the world's first THz laser made from the Indium Phosphide (InP) family of semiconductors, rather than from the Gallium Arsenide family. This opens up the possibility of more efficient lasers, including those that might operate at even higher temperatures. Work in this area is continuing.

Finally, the TeraNova partners have had great success in developing lasers that operate in *single mode* (see earlier). Several strategies were deployed to achieve this result, involving the use of grid-like structures placed on the semiconductor active layers to encourage operation at one frequency. Hand in hand with this activity, TeraNova partner SNS Pisa has developed a *microdisk* laser that can emit radiation in a vertical direction, making them ideal for many practical applications where a highly collimated emitted beam and powers of around 10mW are required. This is shown in Figure 6.

In conclusion TeraNova has pioneered QCLs over the past four year period and is currently the recognized world leader in the field.

Amplifiers and Modulators for Terahertz Radiation

The Quantum Cascade Lasers (QCLs) described above have another potentially very important application as amplifiers.

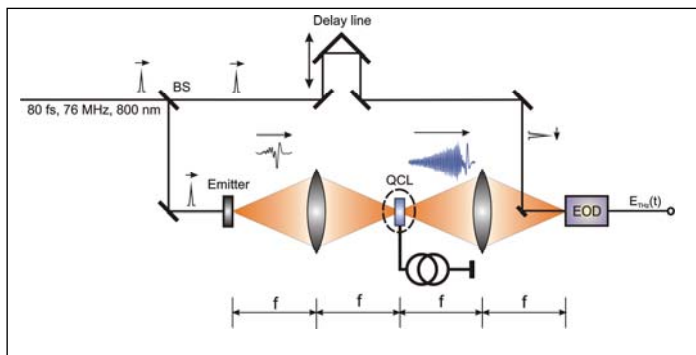


Figure 7: Equipment used by TUW to directly study the evolution of THz

These components are an essential ingredient for use in THz systems for ultra-broadband communications, remote-sensing, security and medicine. Before the project started, there were no compact THz amplifiers based on solid-state sources. A related need is to develop modulator devices which can be used to vary the THz signal size, and hence convey information on the THz wave as the "carrier" (adopting principles that go back to the beginning of radio technology at the start of the 20th century). TeraNova partner TU Wien (TUW) has developed components of this type for the first time.

The successful application of QCLs as THz amplifiers and modulators demands new insights into the fundamental mechanisms that

responsible for amplification or oscillation; in this case, it is the semiconductor structure in the QCL itself. For a laser system, a curious process known as "population inversion" gives rise to this gain. Crudely speaking, this takes place when electrons are in a (quantum mechanical) state of a higher energy than they should naturally have. To understand this process properly (and hence to enable design engineers to develop semiconductor structures that exhibit really useful gain) it is vital that to probe both the size (and amplitude) and timing (or phase) of the electric field of the wave. In the nature of things, the build up of useful gain (for example, for an amplifier) is often limited by processes such as scattering at (relatively) rough internal surfaces and other subtle

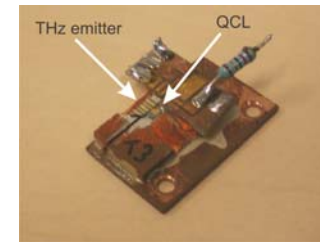
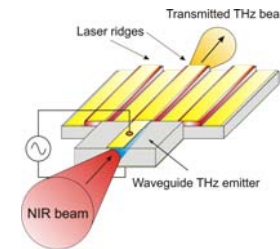


Figure 8: Compact THz amplifier/generator of synchronized coherent pulses: schematic drawing (left panel) and photograph of the experimental unit assembly (right panel).

give rise to laser action in the Quantum Cascade (QC) structures. In particular, it is vital to understand the actual evolution of the THz wave (in time) as it emerges from the QCL. The term used by physicists to describe a key property of an amplifier or oscillator that determines if it will be useful is the so-called "gain" of the "active medium" that is

effects. Physicists refer to the study of "gain dynamics" to describe the way in which this gain develops.

To study the way in which the gain dynamics is affected by differences in QCL design, the group at TUW have developed powerful new methods to probe the QCL laser structure with broadband THz

pulses that are generated using the type of equipment produced by *Femtolasers* (as discussed above.) This allows, for the first time, the direct observation of electric field emission and the optical response of a THz QCL in the time domain. In contrast to frequency domain measurements, the internal dynamics and the evolution of the oscillating light wave can be surveyed. Figure 7 is a schematic diagram of this equipment.

Using this complex equipment, the TUW group have obtained insights into the processes that affect gain dynamics in QC structures. Using this information, the group have focused their efforts on building a THz amplifier which can handle signals over a range of 0.5THz. A THz QC structure providing such a bandwidth was designed and fabricated in close collaboration with TeraNova project partners from the *University of Paris VII* (France) and *Leeds University* (UK).

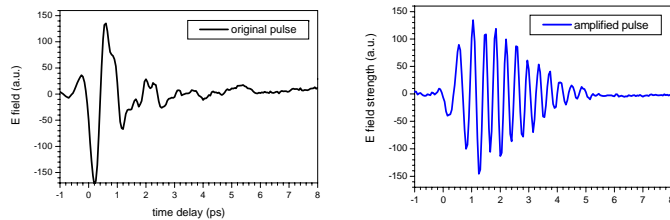


Figure 9: THz pulse without (left panel) and with (right panel) THz amplifying unit in place.

The principle of the THz amplifier unit is sketched in Figure 8. Femtosecond, near infrared pulses drive a transducer device and low intensity pulses of THz radiation are generated. The transducer, or THz emitter, has a special form to optimize the way in which THz

radiation couples in to the section of the device that provides amplification. The weak THz pulses emerging from the amplifier section are reshaped and emerge fully synchronized with the pulse train of the used near infra red laser. This feature opens the possibility of producing powerful, broadband pulses with a range of very interesting applications in, for example, remote sensing, security or medicine.

Finally, Figure 9 shows typical time-domain traces of the THz electric field with and without the amplifying unit. Analysis of this information shows that the amplifier unit is shifting the operational frequency of the QCL and that there is some evidence of amplification. This compact unit could become a basic building block for future THz systems with many applications.

In summary, the TeraNova group at TUW have developed a revolutionary new tool to study

the critical design factors in semiconductor structures that affect gain dynamics and have shown, for the first time that a THz amplifier can be realised.

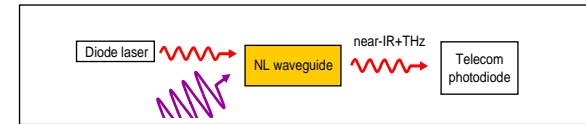


Figure 10: Schematic of the NL up-conversion setup to detect the radiation from a THz QCL.

This breakthrough will have a profound effect on a whole range of applications of very high frequency radiation in the fields of high-bandwidth communications, and of imaging and sensing.

Terahertz Radiation can Piggyback on Near Infrared Light

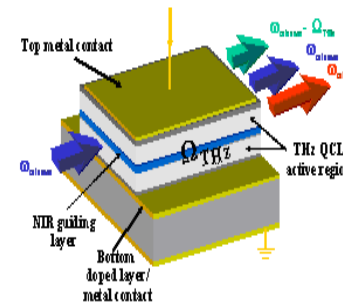


Figure 11: Upconversion arrangement: for explanation see text.

French TeraNova partners at the *University of Paris-Diderot* and the *III-Laboratory* (a joint venture between *Thales* and *Alcatel*) have been investigating how to lower costs of THz sources, and other components, for routine applications where the price-tag is an issue. The partners decided that one possibility would be to use the sort of components found in telecommunications systems (e.g. optical fibre networks), and adapt them for THz use.

As part of this work, they discovered that THz signals could be made to *piggyback* on the near infrared (NIR) signals that are generated by diode lasers used everyday throughout the telecommunications industry. This is a very important finding as it opens up a wide number of possibilities for THz communications and for remote sensing applications, especially when the THz information is obtained from a hostile environment, such as the inside of an industrial process. This approach, of “hybridising” frequencies has been used in other ranges of the spectrum but never before in the THz frequency range. Figure 10 shows the general idea. The diode laser generates radiation at a normal wavelength used for optical communications (1.55 micrometres) and this is directed to a “waveguide” structure. This is a specially designed piece of the semiconductor material Gallium Arsenide, surrounded by a layer of another member of the Gallium Arsenide family, Aluminium Gallium Arsenide. The whole structure is placed between two layers of a metal such as gold. A THz signal (in fact from a QCL) also falls on the waveguide and a “mixing” of the two signals occurs, encouraged by the electrical properties of the semiconductor and the metal layers which build up the electric fields within the device. The THz signal emerges

but is piggybacked on NIR beam. In technical terms, the THz signal has been *upconverted* to the higher frequency of the 1.55 micrometre wavelength beam. This combined signal can then be transported easily along a conventional optical fibre for great distances and then measured with standard telecommunications detectors. Furthermore, the original information provided by the THz signal can also be stripped off from the carrier (as the NIR beam is called) and investigated.

Important though this breakthrough is the French team have taken it one step further. They realised that the waveguide structure could be replaced by another, active, device based on a QCL which acts as its own source of THz radiation. In this arrangement, shown schematically in Figure 11, the NIR beam enters from the left hand side (shown in blue) and interacts with the THz radiation (at frequency Ω_{THz}). Once again, the structure acts to mix the separate frequencies and, with this arrangement there is an added bonus- the weak THz signal is actually also strengthened. On the right hand side, the original NIR frequency beam (shown in blue) emerges and is accompanied by two piggyback signals – with frequencies that differ from the THz frequency Ω_{THz} .

This discovery might be thought of as a merging of THz and conventional telecommunications technologies. One important consequence of these experiments is that the process depicted in Figure 11 can be reversed, leading to THz generation solely from

telecommunications frequency components.

THZ SCIENCE AND SYSTEMS FOR BIOTECHNOLOGY, HEALTHCARE AND FOOD QUALITY CONTROL

How THz Radiation Interacts with Important Biological Materials

The THz frequency range coincides with the frequency range that molecules in almost all biological or organic substances, including living materials, will twist, rotate, vibrate and rock. This implies that, with careful design of the equipment and with a good understanding of the theoretical subtleties, it should be possible to identify such materials from the way in which they can absorb energy from a beam of THz radiation in which there is a wide spread of frequencies present. In many ways, this type of spectroscopic investigation is akin to fingerprinting, as the THz beam reveals the particular absorption frequencies that correspond to molecular motions which really characterise a substance. This “chemical sensing” is accomplished without contact with the material, and can even enable the presence of anomalies and mutations to be detected.

TeraNova partners at the *Danish Technical University (DTU)*, *Siegen University*, the *Scuola Normale Superiore (SNS)* and at *Durham University* have collaborated in this area using equipment that has been developed by partners *Femtolasers* and *Alpes Lasers*. The partners have developed new methods for chemical sensing with THz radiation, and have built new theoretical foundations that enable

the observed effects to be interpreted in terms of molecular motions. On the way, a great number of challenges have had to be overcome; in particular, how to make measurements on very small quantities of materials, or on materials (e.g. biological materials) where water is present and reduces signal sizes to very low levels, thus making the task of identifying the substance very hard.

The applications of this work have been across a number of areas: identification and imaging of Ribonucleic acid (RNA); characterising the strength of alcoholic beverages; sensing the molecules within living cells; and developing sensors that can detect genetic mutations.

As an example of this idea, let us first consider how THz radiation can be used to identify different types of the important biological molecules adenosine and cytosine. These molecules can be attached into long chains of artificial RNA, which provide an ideal “test bed”

DTU have used THz spectroscopy in combination with a simple imaging system to demonstrate that the difference between different artificial RNA strands, specifically poly-A and poly-C, can be detected. This is shown in Figure 12 (left). The difference between the spots of poly-A and poly-C that is evident in the image in Figure 12 originates from differences in the absorption properties of the materials, as confirmed by spectroscopic analysis (right, in figure). This provides a simple example of a THz biochip, and idea which TeraNova partner *Siegen* has taken one step further.

Using THz Probes in Biotechnology: Biochips, Microcapillary Systems and Single Cell Sensors

Since electromagnetic radiation in the THz frequency range has the potential to sense chemical and biochemical compound, the TeraNova consortium has begun to investigate how it might be used to detect molecules within

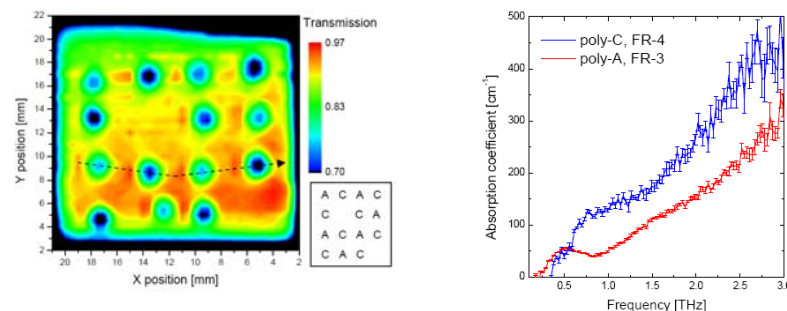


Figure 12: (left) THz transmission image of a polymer substrate with an alternating array of poly-A and poly-C RNA. (right) Absorption spectra of poly-A and poly-C.

for the development of spectroscopic methods for sensing of biomolecules. TeraNova partner

individual living cells and directly sense the important *genomic* molecules (DNA, RNA etc) in

normal and abnormal (mutated) forms. One very important point to stress is that this approach, using THz radiation, does not involve another chemical material except the one that it is desired to study. This is in marked contrast to the conventional approach which uses a *marker* or *chromophore* attached to a bio-molecule. The marker could (and frequently does) "poison" the object which it is intended to sense and results of tests (assays) can, in

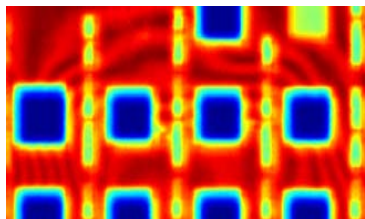


Figure 13: A specially designed surface for THz bio-sensing. The biomolecular samples are placed in the blue areas.

consequence, be hard to quantify. The THz approach, although still very much in its infancy, can overcome this disadvantage.

TeraNova partners at *Siegen University* and at *RWTH Aachen* together with colleagues at *SNS Pisa* and the German Biotechnology Company *Evotec*, with assistance from the Pathology Group at *Regensburg University*, have developed this technology to the point where it is almost ready to be transferred to the clinic. The key to success has been to develop a very sensitive method of measuring the way that THz radiation is absorbed by a small quantity of biological material. The objective of this has been to ensure that the new technology, based on THz probing, is just as sensitive as the chromophore

techniques currently in widespread use. (In technical terms, a sensitivity of <1 femtomol was targeted.) As is so often the case in physics, the way to achieving high sensitivity has been to harness the concept of *resonance*-in this case, a simple structure (a small metal ring or a specially designed surface) provides an environment which encourages build-up of THz electromagnetic fields just at the right frequency needed to probe the biomolecules of interest. A picture of a typical device is shown in Figure 13. TeraNova partners have used both the QCL (single frequency) and broadband (wide frequency range) sources of THz radiation discussed earlier. Finally, the TeraNova

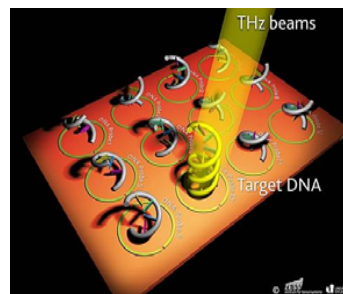


Figure 14: Artist's impression of a functionalised surface THz sensor/reader

partner at *Siegen* are investigating how such a surface can be *functionalized* by coating with specific biomolecules that might sense the presence of other, possibly hazardous, biomolecules in very small amounts. The presence of the species that it is desired to detect would then be "read" by interrogation with a THz beam supplied by a QCL. This is shown conceptually in Figure 14

One of the big problems of trying to use THz radiation for biological sensing or testing is that, unfortunately, biomolecules require water to survive and THz radiation is heavily absorbed by water! TeraNova partners active in this area have approached this problem from a number of directions, but one very simple solution is to use *micro-capillary* delivery (very fine tubes- around 100 micrometres or less in size) to deliver bio-chemicals (such as proteins or blood) between a very sensitive THz source and detector arrangement. This is shown in

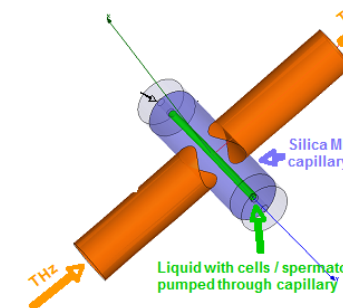


Figure 15: Concept of the micro-capillary delivery arrangement for THz sensing.

Figure 15. One obvious development of this approach has been to attempt to use THz methods in a flow cytometry system to replace current systems that sort cells using fluorescence (i.e. harmful marker chemicals). A possible application highlighted at an early stage was to sort X and Y sperm cells for sex pre-selection in artificial insemination (AI) for animal breeding. With present methods, many spermatozoa are damaged by the chromophore material and a large proportion

(typically 70%) remains unsorted. A difference between X and Y sperm cells in the THz signal might be generated both quantitatively, from the different DNA content existing in the spermatozoa of X and Y type, or from the specific membrane protein contents which could also lead to a variation of the THz absorption pattern.

TeraNova partners at *SNS-Pisa*, *Spallanzani Institute (Milan)* and *Siegen University* have been pioneering this approach to analysis of bio-materials and the first results are very promising. With trial samples, good sensitivity has been achieved and final tests are expected soon. In particular, the system will be designed to have a fast throughput so that it can be used satisfactorily in AI centres in due course.

Finally, TeraNova partner *SNS-Pisa* has been working on a scanning imaging system that will be able to monitor molecules within cells. So far, the instrument they have built can resolve structures of around 7 micrometres in size. Building on this success, *SNS-Pisa* has recently secured funding from Italian national sources and will be developing this instrument further over the next few months. The prospect of looking at the natural world in the energy range that can sense the natural *dance* of biomolecules is now very real.

How Strong is Your Drink? A Contact- free Analysis Tool for the Drinks Industry

Water and other similar liquids have a distinct behaviour in the THz frequency range, determined by the forces between the molecules that make up the liquid. In the presence of THz radiation,

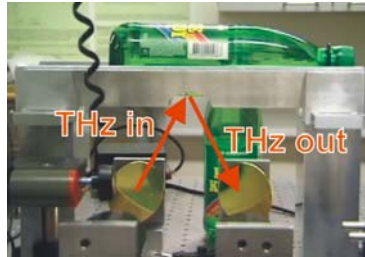


Figure 16: Apparatus for checking contents of bottles for explosive content.

the molecules try to align themselves with the rapidly changing electric field that forms part of the radiation. The subsequent relaxation of the molecules to their original position in the liquid gives a characteristic response that can be measured with THz spectroscopy. In certain cases, this information can be used to identify the liquid. At the same time, many materials used for bottling of liquids (glass, plastic) are transparent for THz light. In consequence, it should be possible to inspect liquids inside their bottles!

TeraNova partner DTU has demonstrated that such a characterisation is indeed possible. Figure 16 shows an experiment where a standard bottle (made of a plastic known as "PET") is inspected from below by a THz probing beam. The reflected signal

contains information about the contents of the bottle, e.g.: whether the liquid is flammable; or what is the ratio of alcohol and water?

Much of this work has involved industrial collaborators and has enjoyed publicity on Danish TV and Radio. More details are given later in this Report.

THZ SCIENCE AND SYSTEMS FOR NON-DESTRUCTIVE TESTING, SECURITY AND SEMICONDUCTOR QUALITY CONTROL

Semiconductor Wafer and Device Scanner

The quality of semiconductor materials is a fundamental requirement for a successful European semiconductor device industry. It has been known for many years that THz radiation can provide extremely important information about semiconductor materials and even packaged devices. TeraNova partner TUV have harnessed this capability and produced a new scanner system that can map out key electrical properties of semiconductor wafers in a non-destructive fashion. At present, semiconductor wafers are randomly removed from the production process, broken into small samples and their electrical characteristics are then measured. This is a highly inefficient process: the new equipment developed by TeraNova provides the opportunity to assess wafers in a much more systematic way and without destroying them. TeraNova believes that this equipment, which relies on a "contact-less" technique, will help ensure that European device manufacturers can achieve

operational economies and remain highly competitive in the global market place.

A further development of this equipment has also been carried out by TeraNova partner Teraview and this has resulted in a measurement system that can identify locations of faults within semiconductor packages of digital systems in a very simple way. Taken together, these two new applications of THz technology will deliver great benefits to the semiconductor industry world-wide.

As has been explained earlier, Physicists describe the way that electricity is carried through a semiconductor in terms of the motion of electrons and, surprisingly, absences of electrons that are given the name of "holes". Together, electrons and holes are termed "carriers". The important things to know for semiconductor material quality control are the electrical conductivity (a measure of the ability of a semiconductor of

from an electric field); and the carrier concentration (a measure of how many electrons and holes there are in a given amount of material). It is also vital for the manufacturer to know how these three quantities vary across a semiconductor wafer as a result of intentional or unintentional variations in the growth process. Another important point is that semiconductor wafers are now often grown with many layers of slightly different semiconductor materials, i.e. materials that actually differ from each other (e.g. Gallium Arsenide and Gallium Aluminium Arsenide) or layers of the same material, but with different electrical properties. Up to now, the only way to obtain this information without breaking the semiconductor was to use microwave radiation in combination with a magnetic field. This type of equipment is manufactured outside Europe and is fraught with difficulties: it cannot produce a fine-detailed map of the semiconductor properties and also cannot investigate the different layers



Figure 17: Photograph of the assembled scanner system: (a) complete system consisting of scanner box and instrument rack; (b) close-up view of the optical arrangement: the paths of laser beams are shown as red lines.

specific size and shape to pass an electric current); the carrier mobility (a measure of the ease with which carriers gain energy

that are often grown on a semiconductor wafer. There are also practical issues relating to the use of a magnetic field.

The wafer semiconductor scanner developed by TeraNova offers an attractive alternative to the existing methods for the accurate assessment of semiconductor electrical parameters. The scanner utilises the interaction of electromagnetic waves at THz frequency with the carriers in the semiconductor. Physicists describe the interaction as involving a “plasma” or large numbers of carriers acting together. Another remarkable feature of the TeraNova equipment is that this information can be obtained with good lateral and depth resolution, so that the individual semiconductor layers can be probed and assessed.

This unique system is shown in Figure 17. THz waves are generated using the type of very fast infrared laser, discussed earlier, and which was developed by TeraNova partner *Femtolasers* in Vienna. The remainder of the equipment was designed, built and tested by the TeraNova partner TUW. THz waves fall onto the surface of the semiconductor wafer and by measuring the reflected electric field at each point on the wafer, the important electrical characteristics of the wafer can be directly measured. The underlying science behind this idea was also developed within the TeraNova group. The scanner is very fast and allows four measurements to be made and processed within one minute. The system has been used successfully with a number of well-known semiconductor materials, such as Gallium Arsenide, Indium Phosphide, Silicon and Indium Gallium Arsenide. The TeraNova consortium are now discussing with European business

partners how this remarkable new application of THz science can be exploited by industrial users as an essential item for any semiconductor growth facility. The primary market for the semiconductor scanner will be in the quality assurance of the semiconductors Gallium Arsenide and Indium Phosphide. Other potentially very lucrative markets for this equipment will be in the assessment of semiconductor wafers grown from the new semiconductor material Gallium Nitride, which will be used to make high brightness light emitting diodes and high power transistors.

Everyone knows that, in radar, pulses of microwave radiation are “shot” from a source and reflected from the target. It is possible to determine the location of the target by measuring the time taken for the pulses to travel to the target and be received back at base. Exactly the same principle applies to a great new application of THz radiation that has also been developed, as part of TeraNova, by the partner Teraview. Because THz pulses can travel through materials such as plastic, they can be harnessed to locate potential faults in integrated circuit devices. *TeraView* have developed a unique system that can trace potential causes of breakdown in integrated circuits with an incredible precision of ten micrometres.

In the *Teraview* system, very short THz pulses are generated using the “broadband” technology described earlier: bursts of near infrared radiation travel along specially designed optical fibres to a probe head situated above the device that is being tested. Transducers turn the near infrared

pulses into THz pulses, which then travel through the plastic packaging and sense the presence of discontinuities, breakages or other effects that can be disastrous for the performance of an integrated circuit. The pulses are then reflected back from these features. The measured “time out and time back” are compared with the times that are anticipated for a circuit operating faultlessly and locations where device failure might occur are located. Figure 18 shows reflections (in various colours) of pulses from an object: these measurements show that a precision of around ten micrometres is possible to locate potential causes of faults. Throughout the semiconductor industry there is a need for a rapid, non invasive technique with better resolution and with capabilities that are applicable to more complex device packages. To make matters worse, package dimensions are decreasing to less than 100 micrometres, driven by

the need to incorporate more devices and functionality into smaller ‘real estate’ within consumer devices. This equipment, now being trialled by an End User, offers great promise as a tool to increase productivity in the competitive area of advanced electronics manufacture

THz Security Systems

The TeraNova programme began in late 2004, at a time when the citizens of Europe and beyond were becoming increasingly aware of the appalling consequences of terrorist actions at embassies, airports, railway stations and other public locations. The events of September 2001 in the USA and of July 2005 in the UK challenged scientists, engineers and those charged with civil guardianship to think carefully about new ways of identifying explosives and other contraband substances in as an efficient, safe and discrete way as possible. The security “industry standard” for personnel and baggage screening is of course based on X-ray scanners, which

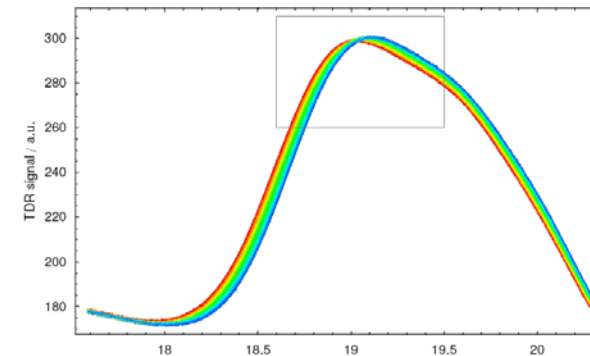


Figure 18: Reflected THz signals from an object as a function of the distance of the object from the THz transceiver. The TeraNova system can locate embedded objects 10 micrometres in size.

have been in use for many years but – despite their efficiency – they do have certain drawbacks. For example, X-ray scanners cannot specifically detect the presence of drugs, plastic explosives or a new range of weapons made from ceramic materials. Furthermore, they are potentially hazardous to security personnel as they involve a dose (albeit low) of high energy radiation over a long period of time.

THz technology has much to offer as a complement and alternative to X-ray scanning for points-of-entry or for sensitive locations. THz radiation passes through many common materials, such as packaging and paper, certain building materials, plastics and

used to gauge the depth of contraband items that are secreted inside, for example, a bar of soap or in the heel of a shoe. The characteristic way in which THz radiation is scattered also can be harnessed to deliver images that distinguish between, say, a plastic explosive and a piece of innocent material.

TeraNova has advanced the whole field of security applications through the following major activities: first, by gaining a far better understanding of the physics of contraband detection (including spectroscopy of materials, propagation and scattering phenomenology); and, second, through improvement of THz technology for better, cheaper sources and detectors.

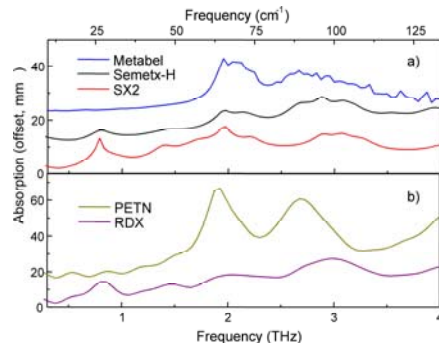


Figure 19: THz Spectra of well known explosives

clothing. Furthermore, the “dance” of molecules at THz frequencies, which has been described earlier, enables specific chemical substances to be identified from the characteristic way in which they absorb or reflect THz radiation i.e. by spectroscopic analysis. As an addition to this capability, the “radar” like properties of THz pulses can be

Figure 19 shows the capability of THz radiation to recognize some well known explosives; these and similar results for drugs-of-abuse have been obtained by TeraNova partner Leeds. By using intelligent software techniques, it is possible to automatically identify the material from knowledge of the frequencies (see Figure) at which maximum absorption occurs.

Furthermore, it is also possible to routinely obtain this information through standard packaging such as FedEx^R envelopes. TeraNova partner Durham have developed a theoretical understanding of the way in which THz radiation can pass through clothing and other “irregular” materials, such as granulated or fibrous structures of the type found in building materials. Durham, together with partners Teraview and Leeds, have used this knowledge to show that suspicious materials can be detected behind clothing or packaging from the characteristic way in which THz radiation is scattered. This is shown in Figure 20.

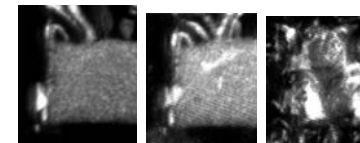


Figure 20 (a): Diffuse image of loose powder in a polythene bag. Figure 20 (b): Diffuse image of loose polyethylene powder in a concealed polythene bag behind a FedEx[®] padded HDPE envelope. Figure 20 (c): Diffuse image of loose polyethylene powder in a concealed polythene bag behind a FedEx[®] padded envelope.

These figures were obtained using a Quantum Cascade Laser (QCL), operating at a specific THz frequency, as the source of radiation. Sources of this type could be used, perhaps in conjunction with broadband (wide frequency) THz sources and even

in combination with millimetre-wave radiation sources, to provide a suite of probes for detecting contraband inside packaging or behind clothing.

Using this combination of component development, experimental study and basic theoretical development, the TeraNova group have concluded that the prospects for commercialisation of THz security systems are very promising. The conclusions are as follows, organised according to the range or distance that they are required to be effective:

- ❖ **Short range (≤ 30 cm):** These systems are now totally feasible for imaging and spectroscopic identification of hidden contraband. As part of the TeraNova programme, this has already been accomplished, with added value provided by a full understanding of scattering effects within targets and the development of new computational strategies to improve the data so that hidden objects as small as 50µm in size can be identified.
- ❖ **Medium range (~1 m):** Medium range systems, for example in Portal Detection, now appear to be essentially feasible for operation at THz frequencies. If such systems were based on broadband (wide frequency) sources, then considerable further development in broad-band pulse amplifiers is necessary. However, for systems based on QCLs, the chief challenge practical devices that operate at as near room temperature as possible Design calculations

suggest that video-rate images could be obtained at this distance.

❖ **Long Range (~10 m):**

Recent developments within TeraNova mean that it is possible to envisage a QCL providing output power of ~10mW at a frequency of around 1.3THz. Although calculations show that, with the current generation of detectors, full imaging would be rather slow, it is still possible to use this type of source to provide spectroscopic identification. This would be particularly valuable in systems that combine THz identification with a millimetre wave scanner (e.g. that operating at 270GHz, made by Thruvision in the UK.)

❖ **Very Long Range (≥30 m):**

The most optimistic systems calculations indicate that this is not achievable without the development of new, high power devices. These are unlikely to be realised using the QCL approach taken in TeraNova, but might be based on vacuum tube devices, perhaps using carbon nanotube sources and micro-machined components. The major application that has been envisaged for very long range work is early detection of toxic gas/ bio-chemical hazards on a battlefield or across a riot scene.

In summary, the outlook for THz-based security systems is now very good indeed. It should also be stressed that the same type of instrumentation is also ideally suited to a number of industrial non-destructive testing applications, such as investigating

structural weaknesses inside plastic assemblies.

A Microscope for the THz Region: Opening up a Whole New Window on Nature

We are all familiar with the idea of the microscope. When van Leeuwenhoek used his amazing invention for the first time, our ideas about the natural world changed in a revolutionary way. In the normal optical microscope, we obtain information about the object under investigation from a small range of the electromagnetic spectrum (typically, wavelengths between 450 and 650 nm). The THz region of the spectrum, which corresponds to much longer wavelengths (typically around a few tenths of a millimetre), can also convey considerable information about the way that the molecules of a material twist, rotate and wobble. It can also provide very important information about semiconductors, and some of this has been discussed in the previous part of this report. However, to date, no-one has really made a satisfactory "microscope" that operates at THz frequencies. Such a device, were it to be successful, might also open up huge vistas and provide profoundly important new information that could benefit many areas such as biotechnology research, pharmaceuticals development, semiconductor quality control and material science. TeraNova partner *TU Delft*, working with partner *Renishaw*, have made great inroads into the development of a THz microscope.

So, what is the problem, and why have no successful THz microscopes been constructed so

far? There is a quite basic rule of physics, known as the Abbé rule, which states that the smallest feature that a normal microscope can see is roughly one half of the wavelength of the radiation that is used to illuminate the sample. For visible light, this is fine, and a resolution of (approximately) one quarter of a micrometre is quite acceptable for many purposes. However, THz radiation has an approximate wavelength of one tenth of a millimetre (or 100 micrometres), which implies that the best resolution possible is of the order of 50 micrometres. Whilst this is fine for certain applications, it is unlikely to be of value for biology (cell sizes are around a few micrometres) or for many applications in the electronics industry. To overcome this problem, physicists need to interrogate the radiation that is scattered from a sample in a region very close to the sample itself. This is termed the "near-field region" and extends about one tenth of a wavelength from the sample.

improving the basic understanding of how it worked. The TeraNova THz microscope combined two very important features: a sharp metal tip (with an end no bigger than ten micrometres) and a very sensitive detection technique known as electro-optic sampling. The combination of these two features enabled very sensitive measurements to be made. What happens is that broadband THz radiation, provided from the type of short-pulse near infrared laser arrangement previously discussed, is scattered from the very small end of the metallic tip. Almost two hundred years ago, the French scientist *Babinet* argued that light scattered from a small object (such as the end of a sharp metal tip) had equivalent properties to light passing through a very small hole of the same size. This is exactly what takes place in the THz microscope. The sensitive detector uses another important idea drawn from classical physics as the operating principle; namely the *Pockels* effect. This effect enables the size (or amplitude) of



Figure 21: Visible light photograph (left) and THz image (right) of a CsI crystal

During the course of the TeraNova project, partner *TU Delft* have set out to determine the viability of building and using a THz near-field microscope for the inspection of objects (e.g. cells and powder grains) with a spatial resolution down to a few micrometres. The work consisted of two parts: building the instrument and

the THz electric field to be measured indirectly, but very sensitively, through the influence of that field, via the use of a special (electro-optic) crystal on certain properties of the near infrared beam. (For the technically minded: the property concerned is the polarization of the near infrared beam.)

To understand the precise workings of the microscope, TeraNova partners at Delft came up with a mathematical model to describe the way the tip and sample interact. The model described the metal tip as an antenna which has a very distinct frequency dependent response. This model was capable of explaining essentially all the experimental results.

The first step in constructing this new instrument was to build a laboratory version in collaboration with *Renishaw*. This THz microscope was combined with a visible microscope arrangement for alignment purposes and for comparative studies. In the end, a spatial resolution of a few micrometres was obtained, which is very close to the original objectives. Figure 21 shows test experiments on a sample of an inorganic solid, Caesium Iodide (CsI), which has a large absorption peak around a frequency of 1.8 THz. This experiment shows the ability of the instrument to measure and identify a small crystal of sub-wavelength dimensions. Work is continuing, but it is clear that much more has to be done to deliver a working instrument that is suitable for industry, laboratory or clinic, and which can handle difficult wet biological materials.

A rather unexpected finding of this work, which shows that science rarely moves in a predictable manner, is the ability to use the equipment that has been developed, but without the metal tip, to measure the time-dependent electric field in the near-field of metal structures that are less than a wavelength in size.

The measurements show, for the first time, how light behaves on a very small scale. An example of a measurement of the full THz electric field in a plane behind a small square aperture is shown in the Figure 22.

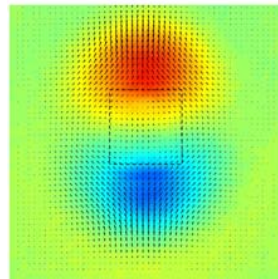
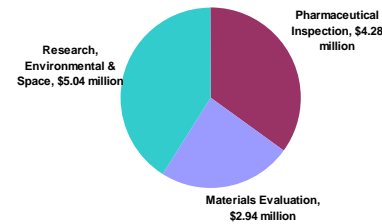


Figure 22: Measurement of the in-plane THz electric field directly behind a square aperture in a 200 nm thick gold film. The colours indicate the presence of negative and positive-going electric fields.

Terahertz Systems Markets, 2007



EXPLOITATION

The advances made during the period of the TeraNova programme have brought THz technology much closer to the market place. From the outset, the TeraNova partners have kept a watching brief on commercial opportunities in their field and have taken all reasonable opportunities to identify such opportunities and, where possible, pursue them through to patents, products and spin-out ventures. Although nominally in the hands of *Durham University*, UK, work in the Exploitation Management area has been undertaken by Dr Debra Barnes, of *Merops Consulting*,

York, UK (<http://www.merops.biz/>). During the course of the TeraNova programme, significant markets have emerged, companies have been formed and trading in THz technological innovations has taken place. A number of market surveys, undertaken by such well-known names as *Frost and Sullivan* (which gives prominence to the work of TeraNova), have informed investors of the shape of the patent field and the size of actual and potential markets. The Terahertz Systems Market was evaluated in 2007 by the US consultancy company *Thintri, Inc.* and their findings are shown in the pie-chart. Since then, changes have taken place and a possibly more conservative evaluation has been given by *Fuji Keizai Inc* of the USA. Their estimates are given in the table below.

The estimate for 2007 is significantly higher in the *Fuji Keizai* report however and large part of this discrepancy is due to the different positions taken on security and surveillance, but TeraNova's own analyses indicate that the upper figure is more likely to be correct.

(\$US millions)	2007	2017
Biomedical	negligible	20
Security and surveillance	13	161
Communications	negligible	50
Agriculture and food	negligible	8
Manufacturing, quality control and NDT	15	136
Environment	negligible	10
Astronomy	4	8
Other	negligible	5
All 'negligible' combined	1.5	n/a
TOTAL	33.5	398

Taken together, these figures indicate a very promising market indeed for products and services derived from a THz technology base. It is noteworthy that the company activity is now significant world-wide and although the US Defence agencies continue to dominate, there are growing signs of investment from companies with portfolios in electronics, pharmaceuticals, surveillance and inspection technologies, food processing and car parts manufacture.

Against this developing market background, how have the TeraNova partners organised their Exploitation management and what have been the outcomes which are likely to lead to direct economic benefit to Europe and her citizens?

From the outset, TeraNova has:

- ❖ Monitored progress in individual scientific and technical programmes to capture the capabilities of the technology under development.
- ❖ Kept a watch on external technical developments, as revealed by Patents and other means, and on general changes in the market place as companies invest in this area.
- ❖ Assessed the value of TeraNova developments against competitor technologies.
- ❖ Engaged with possible End Users to determine if their problems might be addressed by TeraNova.
- ❖ Operated a local review process, assisted by external scientific and commercial evaluators, to advise the Project manager at the Commission on how best to invest internally in

Demonstrator systems proposed by the Consortium.

- ❖ Assisted TeraNova members with plans to take their work forwards through patenting, spin-outs and other mechanisms.

Despite the background of an adverse macro-economic climate, the outcomes of this process have been excellent for the TeraNova consortium:

- ❖ **Three companies** have come out of TeraNova:
 - UK: *Durham Photonics*
 - Germany: *TeraTec Systems* (Germany)
 - Italy: two companies: a spin-off company from *Siena Nanotech* (yet to be named); and one associated company *New tera technology (Ntt)*

❖ **New products available for purchase:**

- A suite of improved ultra-short pulse lasers for terahertz generation (*Femtolasers*)
- A dispersion management module (MOSAIC) to facilitate THz pulse generation remotely in difficult or hostile environments (*Femtolasers*)
- Terahertz Quantum Cascade Lasers (CW or pulsed from 1.2THz up to 6THz) (*Alpes Lasers*)

❖ **Products nearing commercial release:**

- A Time Domain Reflectometry (TDR) semiconductor fault probe for use in, for example, determining faults in semiconductor integrated circuit packages.
- closed cycle QCL system (i.e. not requiring liquid nitrogen or liquid helium)
- dual wavelength system for GHz production

❖ **Demonstrators moving towards commercialisation:**

- A semiconductor wafer scanner for quality control in growth of complex semiconductor layers
- A versatile liquid analysis tool for security and food industry use.
- Fibre delivery for ultrafast laser pulses using advanced dispersion management
- Software to remove THz image artefacts and improve signals.
- A miniature thermopile to detect THz radiation cheaply and sensitively.

❖ **Eight patents & patent applications.**

These commercial outcomes are, of course, in addition to the Dissemination activities that are described in this Report and summarised in the Appendices.

It must also be stressed that new applications arise almost daily: the TeraNova partners hosted a meeting in February 2009 at the prestigious *Royal Society* in London. There were more than 120 delegates for the event which was intended to educate and inform industrialists of the opportunities presented by THz technology in general and the work of the TeraNova partners in particular. Attending this meeting were representatives from sectors and companies such as: Security, Electronics, Military and Defence, RF and Microwave, Medical Imaging, landmine detection, pharmaceuticals and food processing. During the day, it became apparent that there were a wide variety of possible new opportunities for THz technology and these are now being pursued by the partners.

Although there are considerable difficulties at present for launching any new technological development, the TeraNova partners are confident that their efforts will soon bear fruit and these THz components and systems will become commonplace throughout Europe and the world during the next few years.

INFORMING, EDUCATING & TRAINING

MEETINGS AND COURSES, DISSEMINATION AND PUBLIC AWARENESS ACTIVITIES IN TERANOVA

Since the beginning of the project, the TeraNova community has taken every opportunity to publicise the technological achievements and the new capabilities that were under development within academia, amongst potential users in industry, as well as the wider European and International public. This activity has been closely allied to *Exploitation*, attracting out of field interest from application areas or groups previously unaware of the benefits of this technology.

Given the complex and interdisciplinary nature of the *TeraNova* programme, it is hardly surprising that a wide variety of *knowledge outputs* have been generated. Wherever it has been consistent with commercial

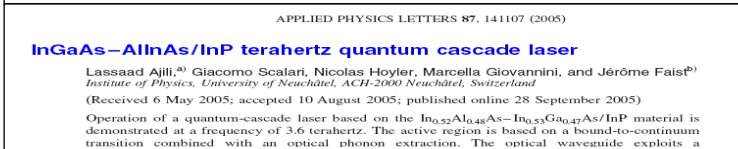
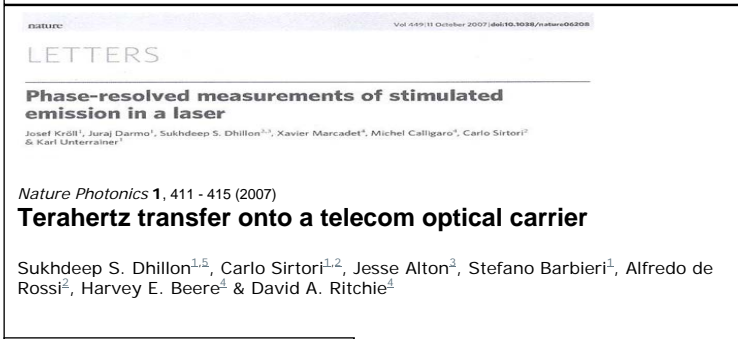
sensitivity, all Partners have been encouraged to deliver high quality information to dissemination channels such as:

- ❖ The WWW (see website image, below);
- ❖ Refereed journals in appropriate fields;
- ❖ Conferences and workshops including trade fairs;
- ❖ Talks to high schools, community and economic interest groups;
- ❖ Broadcasts (Television and Radio);
- ❖ Press articles.



ARTICLES IN THE SCIENTIFIC & TECHNICAL PRESS

TeraNova members have, together, written one hundred and thirty five articles and eight book chapters. The articles appear in primary, archived journals on technical topics that are directly related to the work of the programme. These have appeared in such prestigious international journals as: *Nature*, *Applied Physics Letters*, *Applied Optics*, *IEEE Transactions*, *Journal of Applied Physics*, *Optics Express*, *Physical Review*, *Physical Review Letters* and *SPIE Proceedings*. These articles have been well-received by the scientific and technical community, have received significant numbers of citations and have provided a clear indication of the strength of the TeraNova activity on the world stage. Full details are given in *Appendix II*.



TALKS AND CONFERENCE PRESENTATIONS

TeraNova members have been active in presenting their work at *fora* across the world. One hundred and seventy six invited, plenary or keynote talks have been given by consortium members, together with ninety eight other conference contributions. TeraNova partners have spoken or presented at events in Asia, Australia, America and Europe, including meetings held under the auspices of:

- ❖ American Chemical Society
- ❖ American Physical Society
- ❖ CLEO (Europe, Pacific rim)
- ❖ European Materials Research Society
- ❖ European Physical Society
- ❖ IEEE, Infra Red and Millimeter Waves Conference (IRMMW)
- ❖ OPTRO EUROPE
- ❖ Photonics West
- ❖ SPIE.

Full details are given in *Appendix III*.



TeraNova Posters at a Dissemination Event.

TRAINING AND DISSEMINATION EVENTS ORGANISED BY TERANOVA

In addition to attending established events and to holding internal training and dissemination seminars, TeraNova has organised ten external meetings. The objective of these workshops, training events and small conferences has been to publicise TeraNova activities and interests amongst wider academic, industrial and government audiences. These have included:

- ❖ *Advanced Research Workshop on Identification of Materials: Terahertz Frequency Detection and Identification of Materials and Objects*, Spiez, Switzerland, July 2006
- ❖ *European Optical Society focus group on Terahertz Radiation*, Paris, France, September 2008
- ❖ *International School of Solid State Physics: Physics and Technology of THz Photonics*, Erice, Italy, July 2005.
- ❖ *Intersubband Transitions in Quantum Wells*, Ambleside, UK, September 2007.
- ❖ *Japanese European Seminar on Terahertz Technology*, British Embassy, Tokyo, Japan, 21st November 2005.
- ❖ *Physics of Intersubband Semiconductor "Emitter" (POISE) Summer School*, Palazzone di Cortona, Italy, June 2006
- ❖ *Terahertz Systems and Industrial Applications*, Royal Society, London, UK, February 2009.
- ❖ *Terahertz Photonics 2007*, Weetwood Hall, Leeds, UK, October, 2007.

Full details are given in *Appendix IV*.



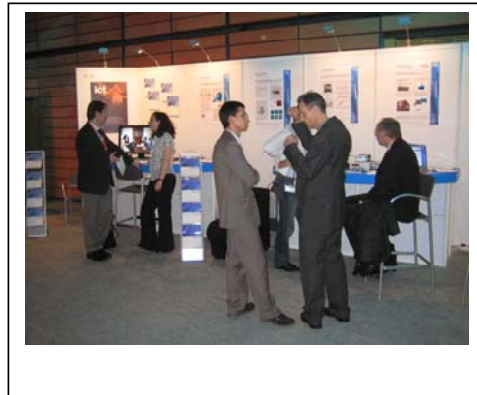
A speaker addressing delegates at the TeraNova Workshop on Terahertz Systems and Industrial Applications, held at the Royal Society in London, February 2009.



Lubos Hvozدارa, from Alpes Lasers, demonstrates a Quantum Cascade Laser Imager to EU Officials.

EXHIBITIONS AND TRADE FAIRS

TeraNova partners have presented the activities of the consortium at twelve Exhibitions and Trade Fairs across the world. These have included the well known *Laser* exhibitions (Laser 2005, 2006 and 2007), together with trade exhibitions attached to a variety of international dissemination events and conferences in places as far apart as Britain, Korea, Japan, China and the US (Arizona, California and Washington DC). In addition, TeraNova has been invited to attend and exhibit at events directly connected with the European Commission, such as the opening of *Iberian Nanotechnology Institute* in Braga, Portugal (November, 2007) and the *ICT Exhibition*, held in Lyon, France (November 2008). Full details are also given in *Appendix IV*.



TeraNova partners speaking to visitors at the ICT Exhibition in Lyon, France, November 2008.



TeraNova Partner Femtolasers with the joint booth: Laser 2005, Muenchen Germany.



TeraNova Partner Peter Haring Bolivar meets Viviane Reding, EU Commissioner for Information Society and Media, at the opening of the Iberian Nanotechnology Institute, Braga, Portugal, November 2007.

PUBLIC AWARENESS OF SCIENCE AND TECHNOLOGY ACTIVITIES

The TeraNova consortium has, since the beginning of the programme, taken the opportunity to publicise their work and inform their fellow citizens of their activities through a variety of channels. It is particularly appropriate to do this, as the partners' work has crossed the boundaries of physics, mathematics, electronic engineering, materials physics, materials science, biology, chemistry and medicine. Furthermore, some of the work undertaken has had, or will have, a direct impact on aspects of life for many of Europe's taxpayers.

However this is not an easy task: explaining the background, the work in progress and the implications of TeraNova's discoveries for lay-persons can be challenging. Considerable efforts have been expended across the consortium to bring the work of the group to the notice of the public, through radio and TV broadcasts, Press Articles, popular lectures and demonstrations. Younger audiences, in particular, have been targeted. A total of eleven press articles, seven TV /radio/internet broadcasts and four popular lectures have been given. Details are provided in Appendix IV.



TeraNova partner DTU (Peter Uhd Jepsen) features on Danish Television evening news.

TERANOVA AND RELATED ACTIVITIES IN THE REST OF THE WORLD

The TeraNova programme in Europe began in a climate of growing European and other international activity in THz technology and applied science. This growth was initially fuelled by increasing technical capabilities, especially coming from the semiconductor and laser industries, and by the claims that THz technology might offer solutions to significant problems in society, such as the detection of explosives and drugs or the monitoring of cancers at an early stage of development. At the end of the TeraNova programme it is noteworthy that the THz field is still continuing to develop, with technology being commercialised by an industry that is growing in confidence in both the products being offered, and also in their ultimate usefulness. This, it should be emphasised, is taking place against in difficult financial times.

Against this background, how has the TeraNova offering performed?

It may be first helpful to review the general economic drivers and to summarise the major actors elsewhere, together with their own areas of expertise. TeraNova's considerable achievements may then be seen in context.

First, consider the economic drivers. During the last four years, very significant funding has been diverted into THz science and technology, and there is no doubt that much of this has arisen from the need to realise new systems for forensic detection and security. In the US, the events of

September 11th 2001 inevitably led to investment in all types of technology advance and basic scientific investigation that might lead to safer environments secured through less invasive methods. In Japan several billion Yen were set aside for national programmes in this area, with especial reference to the stand-off detection of poisonous air-borne biological agents and the screening of postal packages for both biological and explosive hazards. Healthcare, in its broadest sense, has also been a strong potential market for THz devices and systems during the period 2004-9; this need has driven government agencies and private companies to provide funding for new pharmaceuticals testing equipment, biochips and clinical instrumentation. Finally, and as noted elsewhere in this report, funding sources across the world have indicated significant interest in THz methods for non-destructive testing of: foodstuffs; semiconductor materials and device packages; and layers of paint and plastics.

Second, who are the other major actors elsewhere and how have they contributed to the world-wide development for this last unexploited part of the spectrum over the last four years? As the reader will have already noted, advances in the field involve both academic and industrial participants. TeraNova contains almost all of the distinguished academic scientists in the THz field, within Europe, who build their technology on an optical, rather than an electronic, platform. Within the US, the equivalent community contains such optical leaders as the groups

at Renssalaer Polytechnic (X-C Zhang), Rice (D. Mittelman) and Harvard (Q Hu). In Japan, first-class research and development has been undertaken at RIKEN and the Universities of Osaka. Companies that are active in the US and Japan include: Goodrich, Picometrix, Northrup-Grumman, Phiar, Spire Corporation, Nikon, IMRA and Hamamatsu.

TeraNova has, during the four years of its activity, delivered components, such as Quantum Cascade Lasers (QCLs) with operating temperature exceeding that realised by Harvard. It has demonstrated the first use of this type of component in imaging and tomography. TeraNova's short pulse near infrared lasers deliver shorter pulses, occupy less space and are more readily adaptable for THz applications than any other. TeraNova has developed completely new subsystems, such as amplifiers, and demonstrated to competitors across the world how systems such as semiconductor wafer scanners and biochip sensors can be realised.

Hand-in-hand with these advances in technology development, TeraNova has undertaken much basic work in the underlying science that will not only allow the present generation of systems to be commercialised satisfactorily, but will also lead to new developments in the future. For example, TeraNova scientists now can produce complete descriptions of the spectra of almost all common drugs and explosives and can understand how THz radiation is transmitted through packaging, clothing and powders. Using this information, it should be possible

to design better security systems in the future.

It should also be emphasised that TeraNova has strengthened the European Research Area and has led to the creation of new jobs, through spin-out companies, and the preservation of employment in advanced technical manufacturing and development. TeraNova has delivered a wealth of fundamental science and technology, which has been disseminated by many routes. The co-operation between its members, from all backgrounds, has been enviously noted by colleagues in the USA and elsewhere, and steps are now being taken through their own programmes to establish similar mechanisms for technology advance.

FINANCE

Up to 21 partners (although there were originally 16) have received contributions in undertaking activities of the *TeraNova* project.

The majority of the expenditure has concerned personnel. The expenditure for Partner #1: Leeds, as coordinator has included: management expenses and salary for the administrative coordinator/project manager; audit certificate costs on behalf of consortium members; and a subcontractor, Cambridge, to produce semiconductor wafers on behalf of Consortium members. The expenditure for Partner #2: Durham has included costs for an Exploitation Management (sub-contractor, Merops Consulting Ltd).

Preliminary figures show that management costs were 5.4% (i.e. €0.27M) of the total EC contribution for *TeraNova*.

Draft accounts of *TeraNova* show that the Commission's contribution of €5M, corresponding to a total

project budget of €6.9M has been used as a contribution to the €5.08M of eligible costs incurred by the *TeraNova* Consortium partners. Approximately €5.7M has been spent on RTD costs, €0.7M on the semiconductor scanner demonstrator and €0.5M on the MIST demonstrator (see pie-charts, Figure 23).

722 person-months have been spent on the project with an additional 337 non-EC funded person-months being spent on the project by AC partners. Additional person-months funded from non-EU sources - examples include: microscope development at TU Delft (FOM funded); work at Danish National Clean Room Facility (DANCHIP) in WP#B4; Durham-funding of graduate student by HMGCC and Experimental Officer by Regional Development Agency in WP#B4; and, Leeds-funding EPSRC 'Technologies for Crime Prevention' Programme, studentship and post-doc in WP#B4, HMGCC, DSTL.

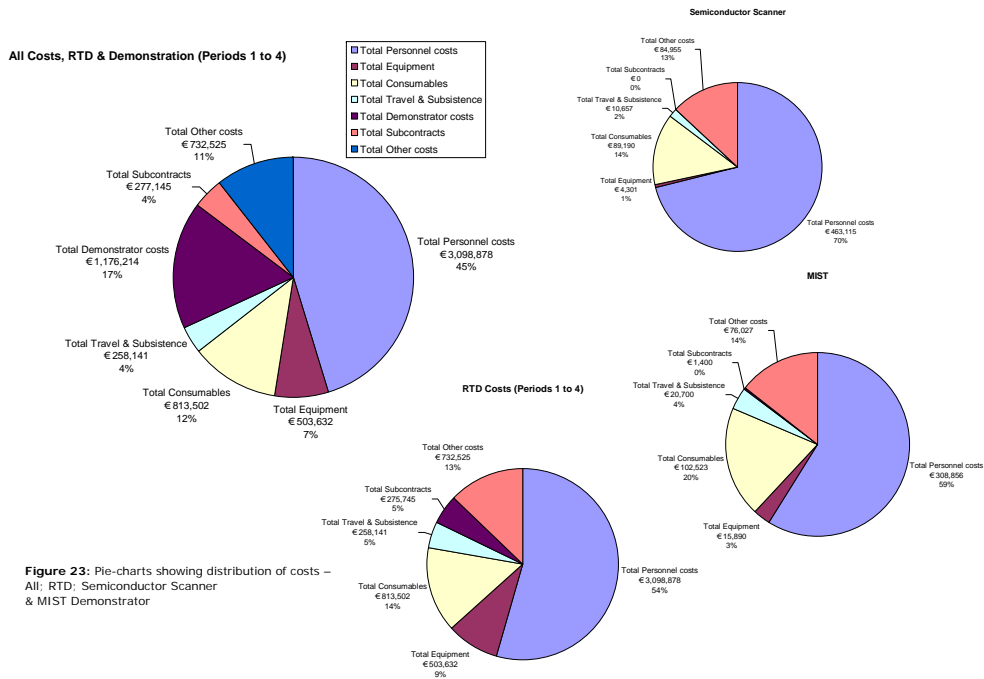


Figure 23: Pie-charts showing distribution of costs – All: RTD: Semiconductor Scanner & MIST Demonstrator

ENVOI : INTO THE FUTURE

As a result of the TeraNova project, the capabilities of THz technology have advanced enormously. Components have been developed that will be key to the design of new systems for a range of applications. For example, as a result of TeraNova, QCL laser sources can now be operated at frequencies down to 1THz and with output powers that are entirely suitable for security, medicine and analytical systems. A THz frequency amplifier has been developed, for the first time, and will form an essential component in sensing, communication and imaging applications. Systems and subsystems have been devised for deployment in the laboratory, production facility, clinic, or at a port-of-entry, for example:

- ❖ THz biochip probes will open up the way to genetic diagnosis via a contactless assay;
- ❖ A wide-frequency THz scanner will reliably, accurately and non-invasively characterise multi-layer semiconductor wafers and failure modes of integrated circuits;
- ❖ The water, alcohol or explosive content in food and drink can be reliably assessed through packaging;
- ❖ Single cells and flowing liquids can be probed at THz frequency.
- ❖ Realistic security solutions can now be developed, building on TeraNova's fundamental studies of propagation through packaging, powders and textiles and spectroscopy of contraband substances.

The TeraNova programme has thus provided a great stimulus for future research, development and manufacturing, building on excellent foundations created over the past four years of activity. Within the EU, R & D programmes that specifically take forward TeraNova work include: MUTIVIS (<http://www.mutivis-ict.eu/>), which will develop monolithic, multispectral terahertz, infrared, and visible focal plane array imaging systems; and OPTHER (<http://www.opther.eu/>), which will innovatively combine (QCL) and photo mixing systems with miniaturised vacuum systems. TeraNova has already stimulated the national research programmes of individual member countries. Examples include: Austria-Advanced Material Identification in Security and Quality Control (<http://www.amatid.com/>), where THz techniques are combined with other modalities to identify materials for security screening or in industrial non-destructive testing; and from the UK- Artificial Materials for Terahertz Frequency Applications (£350,000; EPSRC: EP/C534263/1) and Terahertz Detection of Drugs and Explosives (£428,000; Home Office Scientific Development Branch)

The TeraNova partnership have informed the technical community throughout the world of their achievements through published articles in peer-reviewed journals and via invited talks and other contributions to conferences. They have also informed the wider community of Europe's citizens of their research and how their findings might reap benefits in a wide variety of applications. TeraNova have organised conferences and training sessions, in order to train and educate in an

interdisciplinary area. They have engaged in exploitation activity and the TeraNova programme has led to job creation, through the formation of spin-out companies, and the preservation of jobs through increased commercial activity.

So what of the future? What will be the next steps in the development of THz technology within Europe, and how will it benefit the wider community?

Almost certainly, imaging and sensing applications will begin to rely more and more on QCL technology. The prospect of a room-temperature (or close to room temperature) source is now a real possibility, perhaps based on devices made from the Indium phosphide family of semiconductors. Whilst large-footprint, high resolution broadband sources will continue to be used in niche research applications; there will be an increasing pressure to drive costs downwards. Already, the TeraNova group have shown the feasibility of building THz sources using the type of component routinely used in Telecommunications systems and this trend will continue (it is noteworthy that in the UK a national programme has identified a similar goal and development route). Detection systems will achieve higher degrees of sophistication and, although heterodyne detection will remain essential for the most demanding applications, the emergence of large-area bolometric detectors based on thin film approaches seems probable. Hand in hand with these advances in active devices, the emergence of artificial materials (or metamaterials) will

enable new types of modulators, filter devices and imaging tools to be produced. Photonic Crystal Fibres and other approaches will also ensure that the current difficulties with remote delivery of THz pulses are overcome. Wider use of signal processing, learning from standard techniques from radar and pulse-shaping procedures will also become more widespread and will lead to greater sensitivity and the ability to monitor dynamics of processes more closely.

Over the next five years, and building on the work done in TeraNova, applications in semiconductor quality control and failure analysis will increase. Bio-technology will become a more obvious focus for THz technologies, but significant challenges remain in the development of near field microscopes that will be genuinely useful to biological and clinical needs. There is also likely to be a revival of interest in medical imaging and sensing, driven by QCL developments, possibly combined with ultrasound systems. Security systems, especially those utilising two-frequency (e.g. millimetre wave and THz) operations, will become widely seen at ports-of-entry and will also take advantage of QCL and, possibly, hybrid vacuum tube (Backward Wave Oscillator) capabilities. Food quality inspection systems that rely on the THz technology developments described in this Report will also begin to appear commercially and at a lower cost.

The TeraNova partnership remains optimistic about the future of their technology, and sincerely thanks the Commission of the European Communities for their support of this programme.