T-rays to the rescue!

Professor Derek Abbott describes the fascinating and largely untapped potential of T-rays, discussing why this exciting electromagnetic radiation has been little exploited and sharing his ambitions for novel future applications

Can you open with a short introduction to terahertz radiation?

Terahertz (or T-ray) radiation is considered to be a part of the spectrum between 0.1 and 10 terahertz (THz). It's sandwiched between the world of microwaves and that of infrared. Traditionally, this part of the spectrum was called the submillimetre wave region and was used for passive detection by astronomers. However, active in-lab experiments did not take off until the mid-1990s, as it was then that efficient techniques for THz generation were developed using femtosecond lasers.

What have been your most significant accomplishments to date?

Together with our collaborators, we have demonstrated a number of sensing applications; for example, label-free avidin-biotin bioaffinity detection; sensitive liquid spectroscopy; non-contact discrimination of RNA polytypes; anthrax detection; detection of racemic mixtures, which is of importance for quality control of pharmaceuticals; discrimination between monomeric and fibrillar structures – of interest for vaccine quality control; and detection of GP2 peptides, which is of significance as a convenient cancer biomarker within human saliva.

In terms of hardware, alongside our collaborators we have demonstrated THz computed tomography, THz functional imaging, porous fibres for THz propagation and a whole host of metamaterial structures for manipulating THz radiation.

Could you explain the ways in which T-rays are being explored for use in disease identification?

In the field, THz radiation is being used to non-invasively detect diseases, from the plant kingdom through to humans. For example, in the timber industry there has been interest in detecting nematode disease in pinewood. In humans, THz has been used to detect the pathology of the human cornea, cirrhosis of the liver, misfolded proteins, moisture content and various carcinomas, among others. In terms of cancer, our group has performed fundamental studies on detection of skin cancer (via direct scanning of the skin) and detection of cancer biomarkers in human saliva.

Does their application extend beyond healthcare?

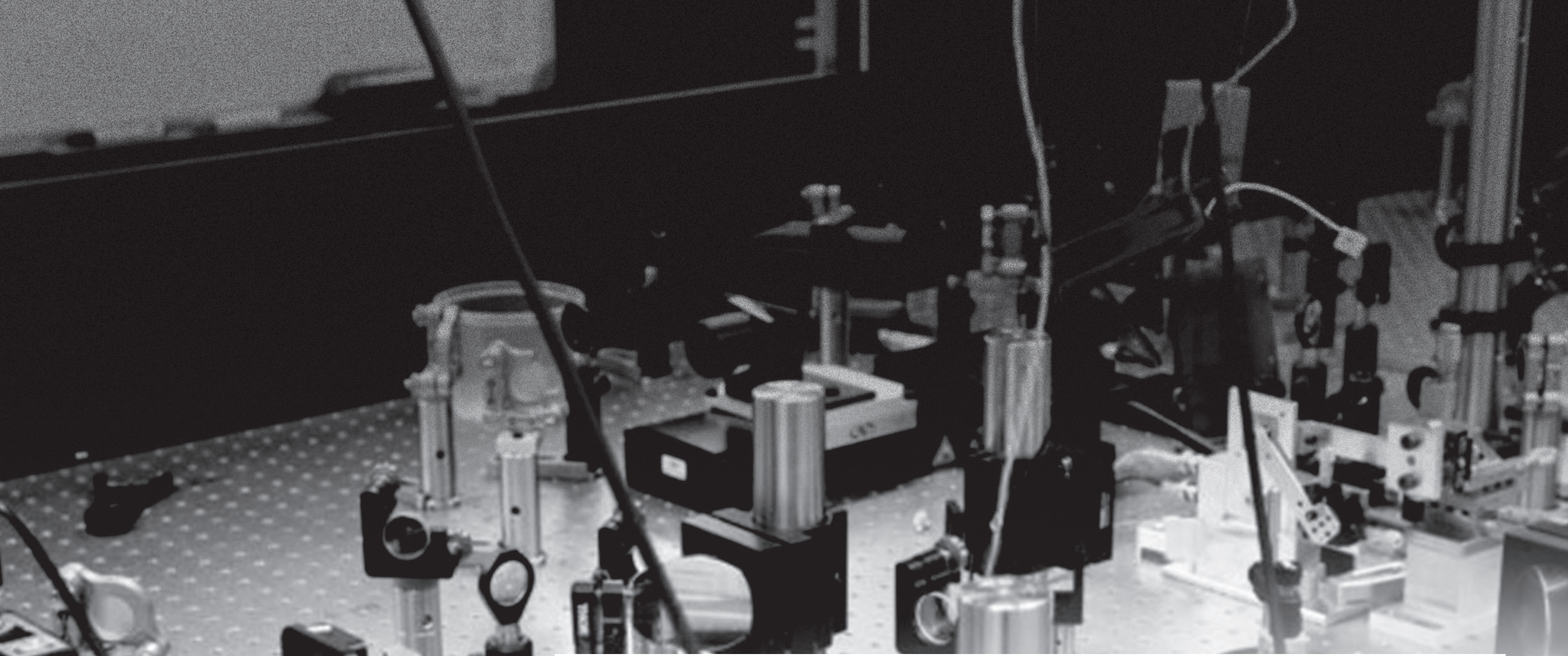
My team has contributed to security applications ranging from checking envelopes for anthrax, through to detecting explosives in plastic moulded suitcases. More broadly, T-rays can be used for sensitive gas detection, which can forewarn a security hazard. The detection of a broad range of biohazardous materials is possible. Screening for weapons such as ceramic knives and plastic 3D-printed guns, for example, is where X-rays fail, but T-rays can save the day.

How has the ability to produce T-rays in the laboratory been advanced?

Microwaves are generated by using high-speed oscillating devices, while infrared is generated thermally or by other light sources. Infrared sources become very dim as we approach the THz region and, to this day, high-speed electronic devices struggle to generate waves much above 500 gigahertz. However, recent advances in femtosecond laser technology have facilitated the convenient generation of short bursts of THz radiation, thus opening up a new part of the spectrum for further study.

You are Founder of the National T-ray Facility at the University of Adelaide. Can you elaborate on the history of the Facility?

I had not heard of T-rays until 1995. I was quickly inspired and began to collaborate with the Rensselaer Polytechnic Institute (RPI) in New York, which at the time had the premier THz lab in the world. Then, in 1997, I applied for an Australian Research Council grant in the area, which was summarily rejected – the governing panel had never even heard of T-rays! It probably sounded like fiction back then. However, in 1998, after some judicious rewording, I reapplied and won. That grant commenced in January 1999 and since that time I have continuously won grants in the area. It was in 2005 that I won about AUS $3 million in one year and was able to establish the National T-ray Facility. This was the



Between two worlds

The University of Adelaide is home to the Adelaide T-ray Group; an expert team of researchers responsible for Australia's first T-ray imaging programme. Going from strength to strength in a number of ongoing projects, the team is working towards exciting and impactful future applications in areas as diverse as healthcare and security

IMAGINE BEING ABLE to photocopy a book without even opening it. Sounds like science fiction but the seemingly limitless potential of T-rays could make this vision a future reality. Although terahertz (THz or T-ray) technology is not new and T-rays have been detected for many years, it has taken scientists a long time to be able to generate T-rays in the lab. The elusive nature of T-rays is due to their position on the electromagnetic spectrum, where they bridge microwaves and infrared light, constituting a gap in the science of light and energy; the THz gap. The challenge has been first generating enough light in the T-ray frequency band and, second, creating a detector sensitive enough to react with the T-ray and with high enough resolution for imaging.

The T-ray region became more accessible to scientists in the 20th Century thanks to time-domain spectroscopy with ultrashort-pulse laser sources and detectors based on pulsed laser excitation, which generate and detect free space T-ray radiation. "In the late 1980s Columbia University was the first to generate coherent pulses of THz energy, but the field did not take off until the mid-1990s when AT&T Bell Laboratories successfully demonstrated THz pulsed imaging (TPI), coining the term 'T-rays'," explains founder of Adelaide University's National T-ray Facility and Head of the Adelaide T-ray Group Professor Derek Abbott. "The Adelaide team has contributed to this effort, including a patented approach for producing compact reflective T-ray systems."

NOVEL PROSPECTS

Since 1997, the talented team, based in the University's School of Electrical and Electronic Engineering, has been working to unlock the potential of T-rays in diverse and novel applications. Realising the great promise T-rays hold in a range of areas, Abbott and his collaborators are striving to better understand and exploit them. The Group runs a range of THz research programmes that primarily encompass biosensing, security, short-path communications. "I first read about T-rays in 1995, and was inspired straight away by their potential to perform direct spectroscopy based on resonances of the whole molecule," Abbott enthuses. "It is this ability that gives rise to exciting prospects of biosensing." The Group's investigations follow two paths: the study of metamaterials to manipulate THz radiation in new ways; and experiments to detect biological substances.

KEY CONNECTIONS

Over the course of their work, the Group has been engaged in a number of crucial partnerships. Their first collaboration, in 1995, was with Rensselaer Polytechnic Institute (RPI), and the team's ongoing ties with the organisation have enabled Abbott to send

first fully fledged THz laboratory in the Southern Hemisphere.

Are you able to reveal any exciting projects on the horizon?

The ongoing Holy Grail project is high-throughput label-free scanning of biochips, and achieving this will require a number of new innovations. Aside from this, a new exciting direction is enhanced biosensing at THz frequencies by exploiting surface plasmons on graphene. We also have our sights on extending the work on carbon-based graphene to silicon-based silicene.

> The fact that many materials are transparent to terahertz radiation means it has use in a number of quality control and biosecurity applications, where a substance can be detected through its packaging

INTELLIGENCE

BIOSENSING WITH TERAHERTZ RADIATION

OBJECTIVES

- To manipulate terahertz radiation in new ways to explore the fundamentals of the technology
- To perform experiments with terahertz radiation to detect biological substances

KEY COLLABORATORS

Professor Xi-Cheng Zhang, University of Rochester, USA • **Professor Lynn Gladden**, University of Cambridge, UK • **Dr Bernd M Fischer**, French-German Research Institute of Saint-Louis, France • **Professor Willie J Padilla**, Duke University, USA • **Professor Emma Pickwell- MacPherson**, Chinese University of Hong Kong, Hong Kong, China • **Professor Masayoshi Tonouchi**, University of Osaka, Japan • **Professor Anton P J Middelberg**, University of Queensland, Australia • **Dr Martin Nagel**, Institut für Halbleitertechnik, RWTH Aachen University, Germany • **Professor Peter Uhd Jepsen**, Technical University of Denmark, Denmark

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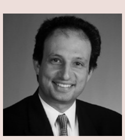

DEREK ABBOTT received a BSc (Hons) in Physics from Loughborough University, UK, and a PhD in Electrical and Electronic Engineering under K Eshraghian and B R Davis from the University of Adelaide, Australia, in 1982 and 1995, respectively. He was with the GEC Hirst Research Centre, London, UK, from 1978-86, and Austek Microsystems, South Australia, from 1986-87. Since 1987, he has been with the University of Adelaide, where he is currently a professor with the School of Electrical and Electronic Engineering. He was awarded an ARC Future Fellowship in 2012.

THE UNIVERSITY of ADELAIDE

a number of PhD students there, including two Fulbright Scholars. Another important collaboration is with Cambridge University, with whom the Group successfully demonstrated T-ray computed tomography using a quantum cascade laser. The researchers have also been working with the City University of Hong Kong (CUHK) on several fundamental studies on THz interaction with the peptide GR2, which is derived from a protein marker for cancer. "In addition, we have collaborated with the University of Freiburg, RWTH Aachen University, Technical University of Denmark, University of Leeds and Osaka University, to name a few," Abbott explains. "Key domestic collaborations have been with the University of Queensland, where we have studied the interaction between THz and monomeric versus fibrillar protein structures with a view to quality control of artificial vaccines. With RMIT University we collaborated on numerous metamaterial structures in the THz range."

The team was awarded a large Australian Research Council (ARC) grant in 1999, which enabled them to develop Australia's first T-ray imaging programme. Later, in 2005, the researchers won a major infrastructural ARC grant to develop the world's first laser-based T-ray user facility – a facility that has been in high demand. "A recent realisation is that the feature sizes of THz metamaterials are in the submillimetre region and thus can be readily manufactured using standard lithographic techniques or even high-end 3D printers," Abbott reveals. "This has led to a whole host of metamaterial-based resonators and components for manipulating THz waves in clever ways, to enhance their sensitivity for biosensing."

MAKING THE INVISIBLE VISIBLE

The vast potential of T-rays comes from their combined properties. Owing to their short wavelength they are able to pass through dry, non-polar objects that are opaque at visible wavelengths. The fact that many materials are transparent to THz radiation means it has use in a number of quality control and biosecurity applications, where a substance can be detected through its packaging. Importantly, T-rays can distinguish between different chemical compositions inside a material, and information about the properties of the material can be gleaned by measuring how an object absorbs the THz radiation. For example, the radiation can discriminate anthrax from salt in an envelope, as anthrax molecules have different vibrational frequencies. "It turns out that the frequency range of THz is in the region where resonances of many biomolecules lie. Thus, it is an ideal modality for spectroscopic identification of biomolecules," details Abbott. The frequency range of T-rays, 0.1-10 THz, has been shown to be useful for, among other things, probing biological substances and detecting them for medical applications.

HEALTH APPLICATIONS

In addition to sensing parts of the body that X-rays cannot, penetrating thin layers of skin and producing high-resolution images, T-ray photons are non-ionising and therefore, unlike X-rays, do not damage cells. As an example, THz technology could be useful in skin cancers, eliminating the need for tissue biopsies. "The photon energy of X-rays is too high for shallow surface layers on the human body and also for laboratory biochips, and this results in no contrast," Abbott elaborates. "T-rays on the other hand cannot penetrate the depths achieved by X-rays, but provide good contrast in thin layers. Thus T-rays and X-rays are complementary rather than competing modalities."

It will be some time before skin cancers can be scanned *in situ* using T-rays due to the complexity and variability of the problem. However, Abbott and his team see great and almost tangible potential for them to be used in scanning dental caries or imaging the human cornea, for example, as there is greater homogeneity in these areas.

FIRST PLACE

The Adelaide T-ray Group has encountered challenges associated with the large wavelength of T-rays that makes it impossible to resolve the spot size on a near conventional DNA biochip. "My team has been working on exploiting metamaterials and near-field effects where the physics fundamentally changes and the conventional wavelength resolution limit is broken," explains Abbott. Looking ahead, he and his team see important future applications for T-rays, notably in customised medicine in the area of label-free screening of biochips, which the researchers predict will be possible in the mid-term future. The goal will be to use THz to rapidly scan for thousands of genetic diseases at once, which will be a huge step forward for customised medicine.