Scanning the Issue: T-Ray Imaging, Sensing, and Retection

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I. INTRODUCTION

The inspiration for this Special Issue grew out of a T-ray workshop held at the University of Adelaide, December 2004, sponsored by the Defence Science and Technology Organisation (DSTO), Australia; U.S. Air Force Office of Scientific Research, Asian Office of Aerospace Research and Development (AFOSR/AOARD), USA; IEEE South Australia Section, IEEE Joint Antennas and Propagation/Microwave Theory and Techniques Chapter; Coherent Scientific; and the US Office of Naval Research Global. Many of the contributions in this issue developed out of this meeting. T-rays are a relatively unexplored part of the electromagnetic spectrum, and lie in the frequency range where molecular resonances dominate. This part of the spectrum has traditionally been called the "terahertz gap" due to the lack of efficient sources that could generate frequencies in this range. Thus the field is rich in scientific open questions but, due to its recent emergence, the technology—although rapidly progressing—is relatively immature. Therefore it is highly appropriate that this issue focuses on emergent applications and technology in order to inspire and motivate further progress in the engineering domain.

T-rays have become an important tool for noninvasive sensing of various materials and structures, with key applications in defense, security, and biosensing.

II. DEFINITIONS

The field is so new that it can still be considered at the ground floor and thus is ripe for cutting-edge new science and engineering. Due to such a recent emergence, the terminology and definitions used in the field have by no means reached a consensus, and those that have may be foreign to a new reader. Therefore, to help readers new to the area, we begin with some recommended definitions. It is our hope these recommendations will also contribute to setting future standards in the field.

A. Naming the Frequency Band

As recently as the mid-1990s, the term "T-rays" was coined by Bell Labs. Initially, the term appeared to be used in the context of T-ray pulsed imaging (TPI) and by the present day it has broadened to generally refer to radiation in a frequency range that spans the "terahertz gap," straddling the far-infrared band and part of the millimeter wave band. In the term "T-rays" the "T," of course, stands for *terahertz*. Currently, many publications simply use the term "terahertz radiation" to mean the same thing. So, today, we have alternative equivalent terms: *T-rays* and *terahertz radiation*. The term "terahertz radiation" has become exceedingly popular, and this has been in some part due to its success with wowing funding agencies. However, in our opinion, "terahertz radiation" is rather an illogical and misleading term for scientific use. "Terahertz" is really the name of the base unit that spans three decades and

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includes frequencies in the visible range. Therefore its usage is as jarring as if we were to call microwaves "gigahertz radiation," for example. Thus our recommendation is that the term "T-rays" distances itself from this incongruence, and its use should be more widely encouraged. For the new reader that encounters the term "terahertz radiation," our recommendation is to read this as shorthand for "radiation centered on the *terahertz gap*" and not to confuse it with the units of terahertz. There are two main arguments against the use of the term "T-rays," which deserve some discussion. The first argument, is that all radiation at a higher frequency than visible light is labeled "rays" (e.g., gamma rays, X-rays) and radiation below visible frequencies is called "waves" (e.g., radio waves, microwaves). This, however, is incorrect. For example, the literature interchangeably refers to "infrared rays" and "infrared waves" together with "visible rays" and "visible waves." The usage depends on whether we are operating in a regime where geometric optics or wave theory dominates. For the most part, we are dealing with line-of-sight scenarios where the term "T-rays" is entirely appropriate. In the case when one has to deal with object feature sizes from hundreds of micrometers downwards, where wave theory applies, then it becomes necessary to use the term "T-waves"—which is gradually starting to appear in the literature. A second, more emotive, argument against the term "T-rays" is that the public has a poor perception of the term "rays" and negatively associates it with dangerous X-rays. Therefore, we must choose our terminology wisely from a marketing point of view. This argument is somewhat specious on a number of levels. First, it confuses the goals of appropriate scientific labeling with presentation to the public—these issues are routinely dealt with separately in the fields of medicine and biology, for example. Second, you can never please the public: the term "radiation" has dangerous connotations, such as in "nuclear radiation," and the term "waves" has a poor perception in the term "microwaves" where the public commonly refer to their use in reheating food as "nuking."

The new reader should also be aware of a third alternative term: *submillimeter wave radiation*. This term has been used, for many decades, particularly by astronomers who regularly use this frequency region for imaging stars and galaxies. However, the point here is that astronomers use *passive* detection. Another problem is that the submillimeter wave band is strictly above 0.3 THz in frequency. By contrast, the new term "T-rays" is more inclusive and intended highlight the renaissance in the field, now that broadband laboratory based sources have become available.

B. Quantifying the T-Ray Frequency Band

Another source of consternation for the new reader is that there is no consensus on the definition of the T-ray band itself, due to the immaturity of the field. Over 100 groups working in this field around the world have recently emerged and there is sufficient critical mass that discussions for an IEEE standard may soon be appropriate. Three common definitions, in the literature, for the T-ray band are: 0.1–10 THz, 0.3–3 THz, and 0.3–30 THz.

The variance is quite alarming and this motivates the need for formation of a standard. Our recommendation is to reject 0.3–30 THz on the grounds that it encroaches well into the mid-IR band, where efficient detectors and sources already exist. We recommend rejection of 0.3–3 THz on the grounds that at room temperature $kT/h =$ 5.9 THz, and therefore this definition falls short of the physically interesting centre of the "terahertz gap." Note that kT/h represents the boundary between the classical and quantum worlds, at room temperature. It is the frequency at which thermal energies match photon energies. This also highlights a key reason why there is a "terahertz gap" in the first place: because of the consequent thermalization of energy levels it becomes difficult to make broadband direct laser sources in this regime at room temperature. Another consideration is that, particularly for crystalline materials, there is a strong molecular fingerprint region in the 0.1–5 THz portion of the spectrum. Thus T-ray band definitions that begin at 0.3 THz or end at 3 THz, lose a working part of the useful T-ray range and do not fully include the region that captures a characteristic application of T-rays.

For these reasons we might favor the remaining definition, which is 0.1–10 THz, as it nicely straddles $kT/h = 5.9$ THz. The reader may be curious as to why the two previous definitions spanned decades offset by a three, and whether it matters that our preferred definition does not. It should be pointed out that the tradition, of choosing the offset of three, is purely a matter convention as the speed of light in SI units begins with a three. This is a convenience for simplifying conversion to wavelengths and has no physical basis. This has its roots in IEEE standards for communications bands. The T-ray band is not primarily a communications band and its main role is in noninvasive sensing systems. Thus is it better to choose the 0.1–10 THz band as the definition, as it is rooted in a physical basis rather than in some inappropriate communications convention.

A reader new to the area may question that the 0.1–10 THz definition encroaches parts of the millimeter and far-infrared bands. In rebuttal, it should firstly be noted that T-ray techniques offer superior SNRs in this region. Secondly, the precedence for overlapping definitions in the electromagnetic spectrum already exists—for example, the definitions of the X-ray and gamma ray bands do overlap.

C. T-Ray Functional Imaging

For the new reader, the term *functional imaging* may be foreign. Fortunately, it has a standard accepted meaning in the context of T-ray imaging. In conventional imaging, each pixel just contains amplitude information, as photosensors detect instantaneous amplitude only. However, in *functional imaging* each pixel of an image contains spectral information. This is typically achieved by TPI systems that use a pump-probe configuration so that both amplitude and phase information is recorded.

D. T-Ray Retection

A useful property of T-rays is that dry, nonpolar, and nonmetallic substances such as paper, cardboard, and plastics are transparent in these frequency band. As this includes many packaging materials, the implication is that T-rays have potential applications in quality control and security. The content of packages can be noninvasively probed and T-rays can produce a molecular fingerprint to identify the contents. This is useful in the quality control of pharmaceuticals, where tablets can be probed through a plastic blister pack, for example. Envelopes can potentially be scanned for harmful substances. The relatively new engineering usage of the word *retection* is defined as "detection of an object through a concealed layer." The word comes from the Latin *retectionem* meaning to "uncover" or "disclose" (*The Oxford English Dictionary*, 2nd Edition, Eds. J. A. Simpson and E. S. C. Weiner, vol. XIII, Clarendon Press, Oxford, 1989, pp. 774). It is worth taking a few moments to relate a rather amusing anecdote that tells the story of how we adopted the word "retection" for engineering usage. A paper entitled "Powder detection using THz imaging" was accepted for publication in 2002. Due to the error of the publisher, the paper appeared in press with the title "Powder retection using THz imaging" (S. Wang, B. Ferguson, C. Manella, D. Abbott, and X.-C. Zhang, *OSA Trends in Optics and Photonics* (TOPS), *Proceedings of Conference on Lasers and Electro-Optics*, vol. 73, Long Beach, CA, p. 132, 2002). We decided not to complain about this typographical error because, as luck would have it, the word "retection" actually appeared in the Oxford dictionary—albeit a somewhat disused 16th century term. Serendipitously the paper happened to be about detecting powders in envelopes and so the word "retection" actually more accurately described the scenario than the original word "detection." Thus we recommend the continued usage of the word "retection" and encourage its adoption, not just for T-ray sensing, but also for other modalities such as X-ray and penetrating radar techniques.

III. THE SPECIAL ISSUE

Recent advances in femtosecond laser technology have enabled the emergence T-rays as a safe imaging modality, which can noninvasively identify substances. T-rays have become an important tool for noninvasive sensing of various materials and structures. Key applications that are currently driving the technology are in defense, security, and biosensing. Historically, industry is transformed every time a new part of the electromagnetic spectrum becomes accessible—T-rays are at the next frontier.

This issue contains papers that cover the use of both CW and pulsed T-ray sources. To compliment this, there are also papers on high-power electron beam sources of T-ray radiation. The electron sources in this issue are limited to large systems such as free electron lasers—small electron sources such as backward wave oscillators (BWOs), for a example, are omitted due to space considerations and that these have already recently been touched upon elsewhere (P. H. Siegel, "Terahertz technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 910–928, 2002 and P. H. Siegel, "THz technology: An overview," *International Journal of High Speed Electronics and Systems*, vol. 13, no. 2, pp. 351–394, 2003).

The collection of papers has also been chosen so that key application areas from biochemical sensing through to homeland security are represented. There are also two papers in the collection that bridge the theme between T-rays and mm-wave technology, as they are closely related and complimentary.

This issue spans a wide range of hardware and signal processing issues in the field and thus will stimulate a broad readership. Technical issues revolve around the generation, propagation, detection, and processing of T-ray signals. The T-ray part of the spectrum sits on the border between where we perceive electronics and photonics to exist—this gives the field wide interest as, in practice, the area utilizes both electronic and photonic techniques. The papers in this special issue cover this exciting range of technical topics. We divide up this issue into six major themes described as follows.

A. T-Ray Imaging and Retection

The issue begins with the paper "Terahertz spectroscopy and imaging for defense and security applications" by Liu *et al.*, which shows the promise of T-rays for the standoff detection and identification of explosives. Proof-of-concept examples are demonstrated for retection of features within a shoe and a suitcase. This is followed by "T-ray sensing and imaging" by Withayachumnankul *et al.*, which demonstrates various spectroscopic sensing and retection examples, as well as T-ray 3-D tomography. The paper "Detection of concealed explosives at a distance using terahertz technology," by Baker *et al.*, achieves T-ray standoff detection of explosives at a distance of 1 m in normal atmospheric conditions. The retection of substances within envelopes is addressed in "THz-wave spectroscopy applied to the detection of illicit drugs in mail" by A. Dobriou *et al.* In order to speed up the sorting of envelopes, a two-pass protocol is proposed in this paper. The first pass simply searches for a scattering signature to determine which envelopes contain any type of powder. The second pass then performs a slower scan on the resulting subset of envelopes to search for the signatures of illicit drugs. A range of T-ray imaging applications, exploiting both CW and pulsed sources, are explored in "All-optoelectronic terahertz imaging systems and examples of their application" by Löffler *et al.*

B. T-Ray Bio- and Chemical Sensing

The study of cell ion channels is of great importance for the design of future pharmaceuticals. The molecular structure of a drug must be designed so that it can target these channels to enter through the wall of a cell membrane. Traditionally ion channel measurements have always been carried out invasively using metal electrodes. The paper "Electronic terahertz antennas and probes for spectroscopic detection and diagnostics," by Grade *et al.*, is visionary in that it represents the first step towards noninvasive probing of cell membranes and ion channels using T-rays. The paper "Chemical recognition with broadband THz spectroscopy," by Fischer *et al.*, demonstrates both free-space chemical sensing and biosensing using T-rays. The T-ray probing of an RNA array biochip and also the chemical recognition of various crystalline materials are demonstrated. This type of capability represents the first early steps towards the ultimate vision of *customized medicine* (*IEEE Spectrum*, vol. 41, no. 1, p. 80, 2004), where drugs can be targeted to the individual, based on high-throughput T-ray mediated label-free DNA microarray data, for example. In the paper "Terahertz measurements of protein relaxational dynamics," by Knab *et al.*, the exciting potential for the exploitation of T-rays in probing protein dynamics is explored.

C. Novel T-Ray Technology

Traditional ultrafast laser sources that are used in the generation of T-rays, typically result in low power. This is because these sources are in the optical regime and conversion to T-rays is usually either carried out using photoconductive antennas or electrooptical rectification, where conversion efficiencies are typically low. The "holy grail" is to therefore to produce a direct T-ray laser source to avoid the low-efficiency conversion step. The most promising approach to direct laser sources of T-rays is the quantum cascade laser (QCL)—progress in this area is reviewed in "At the dawn of a new era in terahertz technology," by Hosako *et al.* Most of the papers in this issue thus far have focused on free space techniques; however, the area of T-ray guided wave phenomena is becoming of increasing interest especially where subwavelength effects can be exploited—this is catered for in "Finite element method simulations of guided wave phenomena at terahertz frequencies" by Deibel *et al.*

D. T-Rays for Material, Semiconductor, and IC Diagnostics

The potential of T-rays for probing energy levels for semiconductor diagnostics is reviewed in "Physical phenomena in electronic materials in the terahertz region" by Lewis. Noninvasive diagnostics of both semiconductors and intergrated circuits is demonstrated using a T-ray microscope with a convenient fiber coupled probe in the paper "Laser terahertz emission microscope" by Murakami *et al.* The characterization of amorphous materials including polymers and glasses is demonstrated in "Terahertz time-domain spectroscopy for material characterization," by Naftaly and Miles.

E. High Power Electron-Based T-Ray Sources

Traditional laser sources used in T-ray generation have low average powers typically in the micro- to milliwatt regime. Large high-power sources that exploit the principle of Lamour's formula by accelerating electrons at relativistic speeds within a magnetic field have been demonstrated to generate T-ray average powers in the order of Watts. Progress in this area is reviewed in "Compact, high power electron beam based terahertz sources" by Biedron *et al.*; and also in "The free electron laser at Jefferson Lab: The technology and the science," by Thomas and Williams.

F. Bridging the T-Rays to Millimeter Wave Region

T-ray techniques share some commonality and overlap with the neighboring millimeter wave frequency band. Therefore it is instructive review some of the techniques across this border in order to motivate cross-fertilization of these fields. The paper "Millimeter wave and submillimeter wave imaging for security and surveillance" by Appleby and Anderton, focuses on passive imaging based on polarization techniques. A review of standoff spectroscopy in this regime is given in "Standoff detection using millimeter and submillimeter wave spectroscopy" by Hansen.

Finally, we would like to warmly thank all the invited authors for their valuable contributions, as well as our reviewers for the time and effort they have put into providing timely feedback to the authors. We would also like to express our sincere gratitude to Jim Calder, the Managing Editor, for the opportunity to put together this special issue. We also wish to thank Jo Sun for her administrative assistance. ■

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He has led a number of research programs in the imaging arena, ranging from the optical to infrared to millimeter wave to T-ray (terahertz gap) regimes. From 1978 to 1986, he worked at the GEC Hirst Research Centre, London, in the area of visible and infrared image sensors. His expertise also spans VLSI design, optoelectronics, device physics, and noise; where he has worked with nMOS, CMOS, SOS, CCD, GaAs, and vacuum microelectronic technologies. On migration to Australia, he worked for Austek Microsystems, Technology Park, South Australia, in 1986. Since 1987, he has been with the University of Adelaide, where he is currently a Full Professor in the School of Electrical and Electronic Engineering and the Director of the Centre for Biomedical Engineering (CBME). He has appeared on national and international television and radio and has also received scientific reportage in *New Scientist*, *The Sciences*, *Scientific American*, *Nature*, *The New York Times*, and *Sciences et Avenir*. He holds over 300 publications/patents and has been an invited speaker at over 80 institutions, including Princeton, NJ; MIT, MA; Santa Fe Institute, NM; Los Alamos National Laboratories, NM; Cambridge, U.K.; and EPFL, Lausanne, Switzerland. He is a coauthor of the book *Stochastic Resonance*, published by Cambridge University Press, and coeditor of the book *Quantum Aspects of Life*, published by Imperial College Press.

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