Institution: University of Leeds

Unit of Assessment: UoA13 – Electrical and Electronic Engineering, Metallurgy and Materials

a. Overview

This submission is based on research carried out in the School of Electronic and Electrical Engineering, which was ranked top in its UoA in RAE 2008 with a GPA of 3.05. The School's research continues to be focused into two Institutes, each comprising a critical mass of staff and infrastructure, targeting discovery- and challenge-led research of international importance.

The Institute of Microwaves and Photonics (IMP) has a history of pre-eminence in high frequency electronics, incorporating fundamental understanding, design, modelling, and fabrication of devices, components, and subsystems from 1 GHz through to terahertz (THz) frequencies. Over the last decade, the scope of the Institute has expanded significantly to include quantum electronic devices and semiconductor nanotechnology, and the emerging field of bio-nanoelectronics.

The Institute of Integrated Information Systems (IIIS) has a long-standing international reputation for communications, signal processing, control systems and instrumentation. The last decade has seen significant expansion into optical communications and networking, engaging with all major telecommunication companies. New activity is developing ultrasonic technologies for healthcare.

Institute research strategies are refreshed annually, and inform recruitment, funding priorities, and development of international, industrial, and academic collaborations. Our 20 staff in this submission (which includes 6 ECRs) had a research income of £16.8M (£168k/cat-A staff/annum) in this period (a 75% improvement on our position at RAE 2008); this includes 2 EPSRC Programme grants, 2 EPSRC Critical Mass grants, and 2 ERC 'Advanced' grants. We have awarded 91 PhD degrees over this period, 53% more per annum than at RAE 2008, and published 350 papers in primary archival international journals, the majority collaborative with authors outside the School.

b. Research strategy

A detailed, and evidenced, discussion on how we met, and in many cases exceeded, our RAE 2008 research objectives is now given, followed by our refreshed strategic vision going forward.

1. Institute of Microwaves and Photonics (IMP)

The IMP's strategy is to strengthen its pre-eminence in high-frequency electronics from microwave/millimeter wave to THz, and in nanostructured electronic, optoelectronic and molecular systems, through the understanding, design, modelling, and fabrication of devices, components, and subsystems, and their implementation in applications of societal relevance.

Research objectives set out at RAE 2008, and achieved in this period are detailed in §1.1–1.4 below. In summary, they include: 'development of nanoscale electronic devices for future high frequency circuits (>500 GHz)' [1.1, 1.2, 1.4]; 'creation of a step-change from the quantum mechanical design of optoelectronic devices to the development of advanced components/sub-systems' [1.1, 1.2]; 'design of near-infrared detectors/modulators for CMOS-compatible silicon photonics' [1.2]; 'incorporation of THz quantum cascade lasers (QCLs) into imaging systems with photonic band gap/plasmonic beam control' [1.1]; 'use of microwave, millimetre-wave and THz sensors to measure remote objects' [1.1, 1.4]; 'development of integrated semiconductor/glass photonic systems' [1.2]; 'tailoring of optoelectronic functionalities through inclusion of nanostructured materials' [1.1, 1.2]; 'introduction of biological functionality into nanostructured electronic devices' [1.3]; and, 'development of arrayed sensor technologies for medical/biological sensing' [1.3, 2.2 (with IIIS)].

§1.1 Terahertz (THz) Electronics and Photonics

In collaboration with universities including Harvard, Paris Sud, Paris 7, École Normale Supérieure, and Texas, we continue to play a leading role internationally in developing THz-QCLs (pioneered in 2002 by EC WANTED, led by AGD/EHL (for staff initials, see REF1), demonstrating, *inter alia*:

- First use of photonic crystal structures [output AGD-1 in REF2], graded photonic heterostructures [AGD-2], and 'spoof' surface plasmons [LL-1] to engineer the beam profile, and improve output power of THz QCLs, all published in Nature Group journals;
- First demonstration of a THz pulse amplifier based on a QCL cavity [EHL-1], and active mode-locking of THz QCLs [AGD-3] – both published in Nature Group journals, leading to the first measurement of sampling coherence in a QCL [DPS-1];
- New active region and waveguide designs, including world-record temperature operation [EHL-2].

We have developed new THz frequency imaging/spectroscopy components and systems, and explored the interactions of THz radiation with materials of societal relevance, including:

- First demonstration of new THz QCL imaging/spectroscopy methodologies, including use of emitting QCL cavity as a radiation self-detector, providing system miniaturization, with Univ. Queensland [PD-1], and absorption-coefficient-sensitive reflection imaging, with HMGCC [AGD-4];
- First comparison of quantum mechanical and classical simulations of THz spectra, focusing on high explosive PETN [JEC-1], with HMGCC, DSTL, HOSDB/CAST, HMRC, and Univ. Bradford, and also first systematic experimental/theoretical study of molecular size on THz spectra [EHL-3];
- First spectroscopy of functional single crystal proteins under physiological conditions [ADB-1].

We have developed new materials/system concepts for future high-frequency devices, including:

- Demonstration of InGaAs(P) for 1.5 µm photoconductive THz generation/detection, patented with CIP/Huawei, and being considered by TeraView for affordable, compact THz systems [CDW-1];
- First demonstration of THz evanescent field microscopy/spectroscopy using lithographically-defined microstrip filters [JEC-2], and single-mode low-loss THz Bragg fibres [IDR-1];
- Investigation of the high frequency response of 2D electron systems, and its understanding in the theoretical context of universal conductivity scaling in the quantum Hall regime [JEC-3].

§1.2 Quantum Electronics and Integrated Photonics

Based on our track-record in semiconductor device modelling and nanofabrication, we have developed advanced opto-electronic components, and designed integrated photonic systems. We have:

- Modelled [PH-1] and fabricated [DPS-2] integrated semiconductor/active-glass/polymer systems, underpinning e.g. patented media for random lasing. Optimization of such hybrid materials [DPS-3] led to a patented glucose sensor, spun-out as GlucoseSense Diagnostics. Furthermore, development of 11.2–15.3 µm mid-infrared QCLs [PH-2] found application in trace-gas sensing;
- With experimental collaborators, modelled CdSe-based quantum dots (QDs) using atomistic calculations, and accurately determined size-dependent absorption coefficients [MC-1] and conduction/valence band energies [MC-2], providing definitive calibration curves for photovoltaic design;
- Explained the long-standing disparity between experimentally-measured multiple exciton generation rates in InAs nanocrystals [MC-3], and provided a unified interpretation of trapping mechanisms in semiconductor nanocrystals for optimization of optoelectronic devices [MC-4];
- Demonstrated InAs quantum rod structures leading to the first TM-polarized semiconductor laser [LL-2], and InAs QD structures for solid-state implementations of quantum electrodynamics [LL-3]. An *in situ* MBE wafer cleaning technology for monolithic 3D integration [LL-4] has also been patented, with application to QD single-photon sources for quantum key distribution, *inter alia*;
- Analyzed carrier scattering in p-/n-Si(Ge) quantum wells [RWK-1], designed the first strain-symmetrized Ge-based QCL sources on a Si substrate [RWK-2], and demonstrated Ge-SiGe optical modulators for communications systems [RWK-3], through the UK Si Photonics consortium;
- Investigated integrated semiconductor device design, e.g. heat transport modelling in QCLs [PH-3], self-focusing Kerr effect [PH-4], and short-channel self-heating suppression in FETs [RWK-4].

§1.3 Bio-Nanoelectronics

Building on our cross-disciplinary strategy to introduce biological functionality into electronic devices, and to translate this work to medical and biological end-users (see also, §2.2) we have:

- Demonstrated patented, miniaturized label-free electronic diagnostic platforms for multiplexed protein sensing [CPW-1], including incorporation of artificial antibody mimetics [CPW-2], leading to funded collaborations with Avacta, Abbott Diagnostics, and Swiss Precision Diagnostics;
- Demonstrated patented, phospholipid electrochemical sensors, for pollution sensing [DPS-4];
- Developed patented, high-yield (>90%) photo-cleavable self-assembled-monolayers [CPW-3], with applications in liquid crystal devices, *inter alia*;
- Developed protein-based directed self-assembly mechanisms, enabling sophisticated protein encapsulated systems to be incorporated into macroscopic electronic devices [CPW-4];
- Demonstrated patented, surface acoustic wave techniques for contact-free particle manipulation [JEC-4], leading to use in enrichment of bone marrow stem cells with the Leeds Dental School.

§1.4 Microwave and Millimetre-Wave Engineering

Based on our expertise in modelling, design and implementation of microwave/millimetre-wave components/systems (and underpinning research with Filtronic/Agilent/Radio Design), we have:

- Designed reconfigurable microwave filters using switched delay lines [ICH-1], adaptive control of filter characteristics [ICH-2], and incorporating dual-band designs [ICH-3]. These are used in 3G/4G base stations (Radio Design Ltd) and airborne radar (Selex) – see Impact Case Study 1;
- Designed substrate integrated sensors for liquid solvent analysis [ICH-4], marketed by Agilent

(see Case Study 2), and trialled microwave low cost, hand-held, dielectric sensors [IDR-2];
- Demonstrated world-record output powers for 50–500 GHz semiconductor sources [EHL-4];
- Demonstrated new low-temperature co-fired ceramic technology leading to a 90 GHz slot antenna and 180 GHz bandpass filter using substrate integrated waveguide technology [IDR-3], and incorporation of microfluidic channels [IDR-4];
- Demonstrated a new realization of microelectromechanical (MEMS) phase shifters with the best insertion/return losses over the W-band and a ten-fold increase in power handling [NS-1].

2. Institute of Integrated Information Systems (IIIS)

The IIIS's strategy is to grow and strengthen its international reputation for optical communication systems and networks, signal processing for communications, and instrumentation.

Research objectives at RAE 2008, and achieved in this period, are detailed in §2.1–2.2. They include: 'the design of next generation communications systems' [2.1]; 'the development of modulation and signal processing for optical wireless systems and networks' [2.1]; 'the design of new optical network architectures/protocols, and cross network layers' [2.1]; and, 'the development of enabling 4G/5G technologies' [2.1, 1.4 (with IMP)]. We subsequently also decided to develop activity in quantum communications [2.1] and expand our ultrasonics research [2.2].

§2.1 Optical Communication Systems and Networks

Building on our extensive collaborations with industry on optical wireless systems, energy-efficient communication networks, and wavelength-division multiplexing (WDM) networks, we have:
- Proposed, for the first time, optimum use of renewable energy in optical networks, and introduced measures which led to world record energy efficiency improvement in core networks [JMHE-1];
- Optimized the iPlayer energy efficiency, working with the BBC, and identified optimum content (e.g. video) replication and data centre locations [JMHE-2];
- Demonstrated world record 10 Gb/s optical wireless communication with full mobility (with potential for >40 Gb/s) [JMHE-3], which has been adopted in the Infrared Data Association standard;
- Introduced new beam clustering and relay-assisted electromagnetic-interference-free optical wireless systems for aircraft in-cabin and for hospital applications [JMHE-4].

Building on our innovation in digital signal processing, we have addressed significant challenges in orthogonal frequency division multiple access (OFDMA) for 4G, and beyond. We have:
- Developed a pilot-aided synchronization technique [LXZ-1] to address different carrier offsets for different users, and a closed form tracking method for the IEEE 802.16e uplink [LXZ-2];
- Developed low complexity interference cancellation and detection algorithms [LXZ-3], and a low complexity high accuracy synchronization technique [LXZ-4];
- Developed simplified/unified receive architectures configurable from the metropolitan scale to the home gateway [SF-1].

We are developing activity in quantum communications through a new appointment. We have:
- Developed new protocols for robust long-distance quantum communications [MR-1], undertaken the first quantitative evaluation of quantum memory requirements for UK-wide quantum cryptography [MR-2], and proposed solutions for home users to access quantum key distribution [MR-3].

§2.2 Instrumentation and ultrasonics

Building on our long-standing expertise in developing ultrasonic instrumentation for the chemical and process sectors, we have expanded our activities, targeting medical applications. We have:
- Developed lab-on-chip technology to verify the acoustic properties of functionalized microbubbles with a payload for drug delivery [JRM-1], patented technology to position/control such microbubbles within flowing arteries [SF-2] and, patented technology underpinning combined contrast imaging and ultrasound-aided drug delivery [SF-3];
- Developed signal processing protocols for ultrasonic measurements through metal walls, leading to funded commercial uptake with BP, Sellafield, Spier Hunter, and National Grid [SF-4].

3. Vision

Over the next REF period, we will continue to define the international agenda, building on our unique expertise and infrastructural investment. In particular, we will:
- Exploit our expertise in THz/microwave technology to enable the control, direction, and accurate measurement of picosecond current pulses, and investigate the picosecond response of quantum-confined electronic structures, underpinning development of nanoscale electronics for future high frequency devices. We will develop photonics-enabled coherent control of THz QCLs, un-

derpinned by world-leading MBE growth, and drive the pull-through of engineered QCL devices to engineered systems, such as integrated local oscillators for astronomical/environmental applications. We will also develop coupled, multiscale simulation approaches for the design of optoelectronic components and sub-systems, with performance tailored using nanostructured materials.

- Design energy efficient optical networks, content distribution networks and data centre architectures for high-performance routing and switching, and protocols for quantum communication. We will develop modulation, coding and signal processing for optical wireless systems, opening new areas in high capacity, short reach, optical data communications. We will integrate the IIIS's communications networks and signal processing research with the IMP's microwave and millimetre-wave subsystem expertise to develop energy-efficient network architectures for Gb/s hybrid fibre-wireless systems for the Internet of Things and mobile cloud computing applications.
- Introduce biological functionality into nanostructured electronic devices to provide new methodologies both for memory/switching operation and medical/biological sensing, and to develop new functional materials and devices. We will establish techniques to convert chemical/biological signals into electronic information, and to use electronic signals to control (bio)molecular activity and cell organization/selection dynamically and reversibly. We will exploit functionalized microbubbles for targeted therapeutic delivery, and utilize surface acoustic wave and GHz–THz frequency lab-on-a-chip systems to investigate and control (bio)molecular conformation and dynamics.

c. People, including:

i. Staffing strategy and staff development

Proven formal mechanisms are used to support and develop staff. Each Institute comprises a critical mass of staff and shared research infrastructure, pursuing complementary research activities. This structure: engenders researcher collaboration; provides focus and critical mass for sustainability, infrastructural development and large grant applications; and, creates communities with well-defined leadership to support, in particular, ECRs, postdoctoral research associates (PDRAs) and PhD students. By directing recruitment into the Institutes, and especially when targeting new and adventurous research, we ensure that recruited staff at all levels are supported from the start.

We not only headhunt internationally leading researchers, and ECRs with clear international potential, but also successfully develop our own staff through the academic pipeline. A rigorous (two-day) interview process is employed for tenured appointments to ensure best fit to our research, leadership and teaching requirements. This includes open events to which all School staff are invited to contribute – this ensures transparency, and equality and diversity, in the process.

During this period we have made a number of strategic new appointments, as set out in our RAE 2008 vision and refreshed annually through the University's *Integrated Planning Exercise*. Following departure of Obayya (to a Chair) and Strangeways, we strengthened our communications activity with the targeted recruitment of a new lecturer (MR), and two further appointments will reinforce this group over the next REF period. Following retirement of Pollard, we supported our microwave research through recruitment of a new lecturer (NS), who will focus on cross-Institute, energy-efficient network architectures for hybrid fibre-wireless systems. We strengthened our MBE growth activity through a new appointment (LL), and following retirement of Miles, we have expanded our THz research through one university-funded (CDW), and two externally-funded (PD, ADB), research fellows. We refocused our ultrasonics/instrumentation research following departure of Mei (to a Chair) and Hoyle (part-time), in part through appointment of an externally-funded research fellow (JRM). This appointment, together with that of ADB and CDW, also aligns with our on-going vision (§b) to address new technologies for medical/biological sensing.

We reward excellence through discretionary awards, and promotion. Promotions since 2008: LXZ (to Senior Lecturer); JEC and CPW (to Reader); JEC, MG, RWK and CPW (to Chair) – JEC, MG, CPW were promoted to Reader/Chair directly from external research Fellowships.

The University was awarded the EC *Human Resources Excellence in Research* Award in 2010, in recognition of our commitment to good working conditions and career development for researchers. Established staff benefit from the annual Staff Review and Development Scheme (SRDS) with their Institute Director/HoS; a two-way discussion to identify needs, goals, support and methods to achieve ambitions. PDRAs (and new tenured staff) take part in the University's probation scheme, which sets clear research targets over, typically, the first two years. Our staff benefit from the University's *Next Generation Researcher* programme, developed in line with the *UK Concordat to Support the Career Development of Researchers* and the *Researcher Development Framework*.

This provides guidance on activities commensurate with each stage of a research career, identified through the SRDS. A 10-month *Tomorrow's Leaders* programme to develop senior staff, nominated by the Faculty Dean, into leadership roles (and to support the University's succession management) was attended in this period by JEC, RWK, JMHE, and CPW. Courses are organized by the Staff and Departmental Development Unit (SDDU; www.sddu.leeds.ac.uk), supplemented by specialist local training in, e.g., laboratory facilities, health and safety, and research ethics.

A workload model balances research, teaching and administration, with significant research commitments reflected by reduced teaching/administration. We support/retain researchers by providing: generous laboratory provision; excellent research facilities; funding for small items of equipment/consumables; funding for attendance at international conferences and visiting academic/industrial partners; and, direction in prosecuting, patenting and reporting research. We give priority to new academics in DTG studentship allocation, and provide access charges to university facilities. We develop individual career paths for each PDRA through regular meetings, establishing them as independent researchers. Our Institutes' seminar series, delivered by national and international speakers, cover a wide-range of contemporary topics and help staff develop contacts.

We vigorously support outstanding younger researchers for externally funded fellowships, with a structured School/Faculty programme to identify suitable candidates and mentor them through their application. Since 2008, two PDRAs received EPSRC Fellowships (ADB – Postdoctoral (EP/I026657); PD – Career Acceleration (EP/J002356)), JRM received a Leverhulme Early Career Fellowship (ECF-2013-247), and two further PDRAs (CDW and Johnson, now at York) were awarded university-funded five-year Fellowships following international open competition. PD and CDW have subsequently been appointed as permanent members of staff on our '*University Research Fellowship*' scheme, with a formal mechanism for promotion to Reader/Associate Professor (or above) subject to achieving mutually-agreed research/teaching targets at years 3 and 5. MC's Royal Society URF was successfully renewed in this period, EHL was awarded an EPSRC '*Dream Fellowship*' (EP/J005282), and ICH received a Royal Academy of Engineering Research Chair with Radio Design (Ref: 10143/74). We also develop and support our staff into senior university positions; in this period PH became University Dean of Postgraduate Research Studies, and AGD became Pro-Dean for Research & Innovation in the Faculty of Engineering.

Faculty support includes: IT, HR, H&S, Finance, Marketing, Careers, and Graduate Support Offices; Mechanical/Electronic workshops; and secretarial provision. The University's Research and Innovation Service supports establishment of research contracts (UK and EC), knowledge-transfer, patents, and licensing issues, together with the University's Venture Capital partner, IP Group.

The School is proud to be multi-cultural. Opportunities are open to all by transparent processes for recruitment, promotion, appointment to School positions, and in allocation of duties. We are sensitive to staff with childcare responsibilities through considerate lecture/meeting timetabling. We have staff (DPS) and student representatives on the Faculty's Equality & Diversity Committee, which promotes best practice. The University and Faculty are both recognized in their support of women in the traditionally male-dominated fields of science/engineering by Athena SWAN awards.

ii. Research students

In this period, PhD students have been funded by the EPSRC DTG, the EPSRC *Life Sciences Interface* CDT, the EPSRC *Molecular-scale Engineering* CDT (EP/J500124) (funding students in both the IMP and IIIS), Research Council grants, ERC Advanced Grants, University funding, ORSAS, international government scholarships, industry (including Agilent, Filtronic, Pace, Abbott) and government agencies (including HMGCC, DSTL), and CASE partnerships (including Hitachi, Abbott, NPL). We awarded 91 PhD degrees over this period, 53% greater per annum than at RAE 2008. Our completion rate for those qualifying by the end of the 2012–2013 academic year is >90%. 81% of our journal publications in this REF period have a PhD student co-author.

Recruitment is organized through the Faculty Graduate and Marketing Offices, providing professional and prompt service. A number of students are taken on from our undergraduate/MSc base, encouraged by our policy to embed project work in research laboratories and to provide competitive 8-week (or longer) summer laboratory placements (School funded, or via e.g. the Nuffield Research Placement/EPSRC vacation bursary). We host open days and recruitment events, and advertise on e.g. www.findaphd.com. Prospective external students are invited to see facilities and discuss aspirations; if a visit is not practical, all take part in a Skype interview.

Our on-line Postgraduate Development Record allows students to log supervision meetings, and stores meeting notes, progress reports and training plans. All students have a minimum of two supervisors (who are required to undertake formal training by SDDU), and have fortnightly minuted supervision meetings to review progress, determine goals, and identify/rectify problems. The Postgraduate Tutor meets each student annually, and the Institute Directors offer an open-door policy. Students are embedded in areas of research strength via the Institutes, creating supportive cohorts with well-defined leadership, and are provided with transferrable and specialist training skills by SDDU e.g. research management, presentation skills, research/thesis writing, career/interview skills. The School's research-led undergraduate/post-graduate courses, together with the seminar series, further allows students to build on their existing knowledge base. All students enjoy recently refurbished offices, and receive a new computer/software on arrival. Social/team-building exercises are organised throughout the year. Internal awards reward excellence, and many of our students have received external recognition (e.g. Ms F Bateman received the national SET Award for the Best Materials Student in 2012).

All students write an outline report/literature review at six months, reviewed by their supervisors, followed by a formal report at the end of their first year, assessed by *viva voce* examination with an independent examiner, before progression. A *viva voce* examination with independent examiner, including review of thesis plan and exemplar publication, takes place at the end of the second year.

PhD students/post-doctoral researchers who have left during this period and have taken up high profile positions in industry/academia, include e.g. Dr R Joyce (2013) – Director of Radio Access Technologies, OooRedoo, Qatar; Dr M Guess (2012) – Design Engineer at Radio Design Ltd; Dr S Johnson (2012) – lectureship at York University; Dr S Khanna (2011) – Northwestern, then CSIR-National Physical Laboratory (Delhi); Dr K Saeed (2011) – Tunstall Telecoms; Dr D Evans (2010) – Senior Scientist, SESMOS, Edinburgh; Dr T Puangmali (2010) – Khon Kaen University, Thailand; Dr H Alshaer (2009) – Eitisalat BT Innovation Centre, UAE; Dr B Bathula (2009) – AT&T; Dr L Betts (2009) – Agilent, US; Dr P Upadhya (2008) – Assistant Professor at IISER (Kolkata).

d. Income, infrastructure and facilities

The School's international research leadership is underpinned by provision of, and on-going investment in, our state-of-the-art research infrastructure/facilities. Not only does this allow us to continue to perform research and innovation at the cutting edge of what is possible, but also provides us with a competitive advantage in the recruitment and retention of the highest calibre staff and students (see §c). We aim for all facilities to have long-term sustainability – on-going planned financial investment from research grants, external users, and a ring-fenced School budget, allows us both to replace older equipment, and expand capability/capacity. Our major facilities include:

- A III-V MBE facility, supporting IMP research on sophisticated opto-electronic devices, including THz-frequency QCLs, superlattice electronic devices, broadband photoconductive THz sources, THz detectors, and high-mobility low-dimensional electronic systems. These materials/devices underpin a wide-range of international collaborations with Europe, the US and Far-East (see §e).
- A THz Photonics Laboratory – the largest, best-equipped university THz research facility in Europe/Asia, and recognized explicitly in the EPSRC ICT capability theme. It comprises nine optical benches. In 2008, this 160 m^2 £2.3M facility included: five pumped Ti:Sapphire/THz time-domain spectroscopy systems; a Bruker 66V-FTIR; and, four cryostats. In this period, a replacement 10 fs femtosecond laser system and a cryogen-free 1.2 K cryostat (with 8 T magnet) have been provided by the University (£300k), and the facility augmented by a new cryogen-free dilution refrigerator (with 12 T magnet) and an additional femtosecond laser (through EP/F002084).
- A Nanotechnology Cleanroom, which supports cross-disciplinary activities of ~30 University researchers, and training for ~50 MSc/undergraduates per annum. Investment of >£1.5M since 2008 has provided: an electron-beam evaporator; atomic layer deposition system; sputtering system; wafer saw; scriber; lapper; wafer bonder; and, a mask aligner. A second technician (trained in the Faculty) has also been appointed to support the existing full-time EO and Technician.
- A bioelectronics facility comprising state-of-the-art molecular biochemistry facilities / characterization equipment, including AFM, confocal, TIRF and multiphoton microscopy, and dual polarization interferometry. It is a focus for inter-disciplinary work in the University, and wider, with academics and industry (see REF3a), and supports the CDT in Molecular-Scale Engineering (EP/J500124).
- An electron-beam lithography facility (commissioned April 2012), funded by an EPSRC critical mass grant (EP/I000933, £2.7M), University investment (£1.1M), and JEOL (£350k), in collaboration with the Universities of Sheffield/York, staffed by full time EOs at Leeds and York. This fulfills

our RAE 2008 goal to upgrade our aged Raith system (now used for research-led teaching).

- Europe's first 1.1 THz network analyzer, commissioned in October 2012, and funded by strategic investment from the University/Agilent, building on our long-term partnership with Agilent (see Impact Case Study 2). This underpins our strategy to bridge the 'THz gap' from both electronic and optical sides of the spectrum, allowing complementary THz/microwave studies of, e.g., high mobility transistors/waveguides. It also complements our existing microwave laboratories, including a 300 GHz network analyzer, a Protolaser-200 circuit prototyping system, and LTCC fabrication technology, allowing development of integrated microwave circuits.
- A new £300k optical communication networks laboratory supported by programme grant EP/H040536 including optical switches, NetFPGA transponders, routers, electronic switches and servers, forming a versatile reconfigurable optical networks testbed.
- Dedicated new laboratories, including Class 2 biological incubators, to support the diversification of our ultrasonic engineering research, supported by School, end-user (BP, Speir Hunter), and healthcare research grant investment; this further complements the IMP bio-electronics facility.

We also make extensive use of other University resources, including the new N8 HPC parallel computing cluster, hosted at Leeds, for simulation of nanoparticles and THz vibrational spectra.

The average annual running cost of our research infrastructure exceeds £750k. To ensure long-term sustainability of our high-value facilities, the nanotechnology cleanroom and MBE facilities are funded as TRAC-based *Major Research Facilities*, whilst the THz, bio-electronics, and electron-beam lithography laboratories are funded as *Small Research Facilities*, with annual costs recovered through access charges from grants, visitors, industrial contracts, and School investment.

We welcome use of our facilities by external research collaborators, both from academia and industry, and seek formal support e.g. through the Royal Society International Exchange. A database (www.n8equipment.org.uk), developed by EHL on behalf of the University for the N8 universities, classifies all equipment (value >£25k) according to a three-level taxonomy, with photographs, technical descriptions, and contact details. It allows us to attract external research collaborators, and maximize facility use, and is acknowledged to be sector leading by RCUK, HEFCE, and BIS.

Our research income over this REF period averages £168K/cat-A staff/annum (£16.8M total), a 75% improvement on our RAE 2008 submission, and with an increased number of ECRs (from three to six), and with a similar split between theoretical and experimental activity. Noteworthy grants with a School PI/Co-I, which demonstrate sustainability and diversity of funding, include:

- EPSRC: Programme Grants (AGD/EHL, EP/J017671, consortium total £6.6M; JMHE, EP/H040536, £5.9M); Critical Mass Grants (JEC/AGD/EHL/ICH, EP/F002084, £1.8M; AGD/EHL/JEC, EP/I000933, £2.7M); Centre for Doctoral Training (AGD/CPW, EP/J500124, £2M), building on two previous Basic Technology grants (EP/C006755, GR/R87086), and a Translation Grant (EHL/AGD, EP/E048811, £1M); and, an IKC (AGD/EHL/CPW, EP/G032483, £4.9M). 'Ideas Factory' grants include EP/E007198 and EP/H003398 (JMHE, £947k total).
- TSB/EPSRC: JMHE, EP/E001696/2 (*HIPNET*), £2.1M; SF, TS/K004476, £1.2M.
- Charity: Welcome Trust/EPSRC Centre of Excellence in Medical Engineering (AGD, WT 088908/Z/09/Z (£11M)); The Leverhulme Trust (JEC/AGD/EHL, F/00122/AM, £213k).
- EC: ERC Advanced Grants (AGD, *NOTES*, €1.5M; EHL, *TOSCA*, €2.5M); European Co-ordinated Research Programme CHIST-ERA (JMHE, *STAR*, €1.4M (EP/K016873)); European Space Agency (AGD/EHL, ESA/IPC(2011)11, item no. 11.1EE.22, €250k); and, Marie Curie International Reintegration Grant (MR, Ref: 277110, €100k).
- Government: HOSDB Grant on Explosives and Weapons Detection (AGD/EHL (£428k)).
- Industrial/innovation funding, including direct investment from industry, and follow-on, proof-of-concept, and regional development funding, *inter alia* – see REF2 '100 words' and REF3a.

We will continue to grow our research income and research impact over the next period, in line with our vision in §b3 and REF3a, and supported through our annual *Integrated Planning Exercise*. We will continue to refresh our existing equipment and infrastructure, and strategically invest in new equipment/laboratories. Planned investment includes: a new molecular beam growth system; a new communications laboratory for quantum/classical networking (complementing our extensive theoretical activity); and, a dedicated UK microbubble chamber aligned to clinical applications.

In this period a £20M investment was made across the Faculty in building maintenance and refurbishment, with a particular goal of improving energy efficiency.

e. Collaboration or contribution to the discipline or research base

Since 2008, we have contributed extensively to our discipline and the national/international research base. We have published 350 papers in primary archival international journals; 38% of our outputs have international co-authors, and 53% have co-authors from outside the School.

As an exemplar from the IMP, 84% of our experimental outputs on THz QCLs alone (§1.1) have an international co-author, including development of high-performance QCLs with Harvard, Paris Sud, and Texas [LL-1, EHL-2, AGD-1,2], locked QCL systems with Paris 7 and École Normale Supérieure [AGD-3, EHL-1, DPS-1], and imaging systems with Queensland [PD-1]. Our Programme Grant EP/J017671 with UCL/Cambridge/LCN exemplifies a national collaboration building on this expertise. Further examples from §1.1–1.2 alone include collaboration with Georgia State (uperera@phy-astr.gsu.edu) and Vilnius (valusis@pfi.lt)) on THz detectors, and with Eindhoven [LL-3] on InAs quantum dot structures. Our work with Melbourne [MC-1] and CSIRO [MC-2] has established definitive size-dependent calibration curves for CdSe quantum dot structures, whilst our theoretical work on Si/SiGe devices underpins the UK Silicon Photonics activities [RWK-1–3].

Our research in the IIIS on optical communication systems and networks (§2.1) exemplifies how we both inform and respond to national/international priorities, such as the current requirement for energy efficient networks, highlighted by our leadership in the GreenTouch consortium [JMHE-1,2], and interference free optical wireless systems for both aircraft and hospital applications [JMHE-4]. Examples of strategic end-user collaborations include Bell Labs (thierry.klein@alcatel-lucent.com), Telefónica (felipej@tid.es), Huawei (yeyabin@huawei.com), BBC (chris.chambers@rd.bbc.co.uk), and BT (louise.krug@bt.com). This objective has also led to development of national collaborations, including researchers from Cranfield, Loughborough, Cambridge, Essex, UCL, and Imperial, enabled though EPSRC awards such as our Programme Grant EP/H040536 with Cambridge.

We collaborate extensively across traditional disciplinary interfaces. We not only work with physical/material scientists, but also have both long-standing and growing activity in each Institute with researchers, and end-users, in medicine/biology (§1.3, §2.2). For example, in the IMP, we have developed electronic diagnostic platforms for disease biomarkers [CPW-1,2], with the School of Molecular & Cellular Biology and the Institute of Molecular Medicine, and end-users including Abbott Diagnostics (sophie.laurenson@abbott.com) and Avacta (ed.quinn@avacta.com). New opportunities include use of surface acoustic waves [JEC-4] for stem cells enrichment with the Leeds Dental School (j.kirkham@leeds.ac.uk). In the IIIS, our research on functionalized microbubbles for medical imaging and targeted drug delivery [JRM-1, SF-2,3] is collaborative with veterinary and clinical end-users in the Institute of Biomedical & Clinical Sciences, and with UCL/Warwick (EP/K029835). Our CDT (EP/J500124) supports these activities across both Institutes.

We regularly host international researchers (e.g. Dr S Dhillon, from École Normale Supérieure, funded by the Royal Society), and have extended visits to leading academic and industrial laboratories internationally. Further evidenced exemplars of our national/international academic and industrial collaborations, our inter-disciplinary research, and how these have informed our, and our collaborators', strategies are given in §b, REF2 '100 words', REF3a, and the impact case studies.

Our academic leadership is exemplified by staff being elected Fellows of learned societies, including: IDR FIEEE (2012) and ICH FREng (2013). AGD received the Royal Society Wolfson Research Merit Award (2011). We have received prestigious external research fellowships (ICH, MC, EHL, PD, ADB, JRM), see §c. JMHE was appointed IEEE Comsoc Distinguished Lecturer, 2013–2014, and received the IEEE Communications Society outstanding service award in 2009.

All staff are members/fellows of learned societies. We review for *Nature*, *IEEE, AIP, IET* and *IOP* journals, *inter alia,* and for funding bodies that include the EPSRC, EC, Royal Society, and RAEng, as well as participation on funding body interview panels, and membership of funding body strategic committees e.g. EPSRC's Cross-Disciplinary Interfaces Strategic Advisory Team (EHL).

We support the academic research base through editing international journals, organizing international conferences, and serving on technical programme committees. For example, ICH (General Chairman), JEC (Treasurer), and IDR (Technical Programme Chair) led European Microwave Week 2011, with >3,000 delegates. JMHE is IEEE ICC'12/ICC'14 Symposium Chair, and Chair of the IEEE Green ICT committee, 2012–2015. SF, IDR, and ICH are/were Editors-in-Chief of *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, the *International Journal of Electronics*, and the *IET Microwaves, Antennas and Propagation*, respectively. AGD/EHL edited the Special Edition of *Electronics Letters* on THz Technology (2010).