Institution: University of Leeds

Unit of Assessment: UoA 13 – Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: The design of radio frequency (RF) components for cellular mobile communications (Impact Case Study 1)

1. Summary of the impact (indicative maximum 100 words)

Research at the University of Leeds underpinned the development and manufacture of RF filter technology by *Radio Design Ltd*, including the 3G 'Universal RF Combiner Unit' with sales of >£18M (40,000 units) since 2008, which led to the company's Queen's Award for Enterprise (Innovation) in 2011. This technology was subsequently improved specifically for the 2012 London Olympics for shared use by all five cellular operators, and has now been further developed, again using Leeds research, for 4G systems (with >£4.2M sales in 2013). Leeds research has contributed directly to ~75% of *Radio Design's* products, and its expansion from 11 employees in 2008 to 150 employees today. Leeds-designed RF filters have also been widely utilized by other manufacturers, with estimated annual international sales of tens of millions of pounds since 2008.

In parallel, Leeds research on the physical modelling and design of pHEMT switches has been used since 2008 by *RFMD (UK) Ltd* (previously *Filtronic Compound Semiconductors*), who supply all major mobile phone manufacturers – over 2 billion pHEMT switches are used worldwide, with *RFMD*'s estimated sales exceeding £250M since 2008.

2. Underpinning research (indicative maximum 500 words)

The University of Leeds has a long-standing international reputation dating back to the 1970s for the development and exploitation of RF components. Much of our research in this field over the last 35 years has been in partnership with *Filtronic Components Ltd,* which was founded by **Rhodes** from the University in 1977 and floated as *Filtronic PLC* in 1994, as well as with a number of companies that have arisen directly from *Filtronic*.

Here, we focus on two areas of Leeds research, and their impact post-2008: the development of dielectric filters (**Hunter, Rhodes, Pollard**); and, the accurate physical modelling of semiconductor devices, leading to the design of high breakdown voltage power transistors (**Snowden**).

In 1998, Leeds started a new research activity, led by **Hunter**, on the development of dielectric resonator filters for the rapidly expanding mobile communications market. This work, in collaboration with *Filtronic Comtek Ltd,* led to a new method of realizing cross-couplings using non-resonant nodes, the latter being needed to produce zeros in the filter transfer function. A new class of patented **dual-mode filters** resulted, where each dielectric resonator supports two orthogonal resonant modes [1]; hence an eight pole filter requires only four dielectric resonators, leading to a significant and commercially important 50% reduction in size and mass (Hunter and Rhodes, 'Dual TM Mode Composite Resonator' US Patent 6,414,571 B1, priority 15/10/1997).

As cellular networks became deployed more widely, there was a need for interference rejection filters with bandwidths of <1 MHz at centre frequencies of 1 GHz for base stations. Leeds therefore conducted research into the synthesis of filters with significant dissipation loss and **non-uniform Q filters** were patented (Rhodes and Hunter, 'Reflection mode filter and method with a constant loss offset' US Patent 6,448,872 B2, priority 28/02/2001). This new technique took low-Q structures into account, avoiding any reduction in skirt selectivity and was then extended to transmission-mode filters with elimination of the requirement for a circulator [2].

Based on this research, Leeds received funding from two TSB projects with TWI (Cambridge) to develop filter designs ('Adept-Sip' Ref. 461348, £398,401, 1/05/2006–31/10/2009; and 'PPM2' Ref. 475416, £325,000, 1/06/08–31/11/11), as well as consultancies with the Defence Technology Centre for Electromagnetic Remote Sensing to underpin applications in the defence sector.

More recently, with the development of LTE and 4G systems by cellular radio operators, there has been the need to develop directional channel combining filters. To respond to this, and working with *Radio Design Ltd*, Leeds developed a theoretical synthesis technique for the design of directional filters for **4G power combining** systems ('Apparatus for allowing radio frequency selectivity and method of use thereof', Patent Application No. GB1222019.0, priority 7/12/12). These filters enable very high selectivity to be achieved in a small physical size [3].

The quality of this underpinning research is exemplified by: Hunter's FIEEE in 2007; election by the Board of Directors to General Chair of the 2011 European Microwave week; award of an RAEng Research Chair in 2012 (co-funded by *Radio Design Ltd*) on the 'Theory and design of filters for mobile communication systems'; and, FREng in 2013.

In addition to developing filter technology for cellular base station application, from the early 1990s Leeds research also tackled the increasing need for more efficient, and linear, microwave power amplifiers for handsets and base stations. Led by **Snowden**, Leeds focused on the accurate physical modelling of semiconductor devices, initially designing GaAs/AlGaAs power heterojunction bipolar transistors (HBTs) [4] (with the modelling incorporated into commercial CAD suites, such as Agilent ADS). This led to the design of **high breakdown voltage power transistors**, resulting in a seven-fold increase in breakdown voltage for InGaAs/GaAs pseudopmorphic high electron mobility transistors (pHEMTs) in 2001 [5]. This device technology underpinned the establishment of Filtronic's **volume manufacturing facility** [6] at Newton Aycliffe in 2000 – the world's largest 150 mm GaAs wafer facility at the time.

The quality of this underpinning research is exemplified by Snowden's award of: the 2004 RAEng Silver Medal; FRS in 2005; knighthood in 2012; and the 2012 European Microwave Association *Outstanding Career Award*. Ref. 4 received the 1999 International IEEE Microwave Prize – only the second UK recipient in 43 years.

Key researchers:

Ian Hunter (Senior Research Fellow, 01/08/1998–31/08/2001; Reader, 01/09/2001–31/05/2003; and Professor, 01/06/2003–present).

Roger Pollard (Lecturer, 01/09/1974–30/09/1985; Senior Lecturer, 01/10/1985–31/07/1998; and Professor, 01/08/1998– 30/09/2010, when he retired). Pollard also served as Head of the School of Electronic and Electrical Engineering (1999–2002), and inaugural Dean of the Faculty of Engineering (2002–2010).

Christopher Snowden (Professor, 01/07/1983–05/04/2005, when he left to become CEO of Filtronic Compound Semiconductor). Snowden also served as Head of the School of Electronic and Electrical Engineering (1995–1998).

David Rhodes (Professor, 01/04/1975–31/12/1993; Industrial Professor, 01/01/1994–09/10/2003, when he retired).

3. References to the research (indicative maximum of six references)

[1] I C **Hunter**, J D **Rhodes** and V Dassonville, 'Dual-mode filters with conductor-loaded dielectric resonators', *IEEE Transactions on Microwave Theory and Techniques* 47, 2304–2311 (1999). DOI: 10.1109/22.808975.

[2] A C **Guyette**, I C **Hunter** and R D **Pollard**, 'The design of microwave bandpass filters using resonators with nonuniform Q', *IEEE Transactions on Microwave Theory and Techniques* 54, 3914–3922 (2006). DOI: 10.1109/TMTT.2006.884627.

[3] I C **Hunter**, E Musonda, R Parry, M Guess, and M Meng, 'Transversal directional filters for channel combining', *Proceedings of the IEEE MTT-S International Microwave Symposium*, Seattle, WA (2013), in press, and distributed electronically at conference (July 2013).

[4] C M **Snowden**, 'Large-signal microwave characterization of AlGaAs/GaAs HBTs based on a Physics-Based Electrothermal Model', *IEEE Transactions on Microwave Theory and Techniques* 45, 58–71 (1997). DOI: 10.1109/22.552033.

[5] W **Batty**, C E Christoffersen, A J **Panks**, S **David** and C M **Snowden**, 'Electrothermal CAD of power devices and circuits with fully physical time-dependent compact thermal modelling of complex nonlinear 3-D systems', *IEEE Transactions on Components and Packaging Technologies* 24, 566–590 (2001). DOI: 10.1109/6144.974944.

[6] M F **O'Keefe**, J S **Atherton**, W Bösch, P **Burgess**, N I Cameron and C M **Snowden**, 'GaAs pHEMT-based technology for microwave applications in a volume MMIC production environment on 150-mm Wafers', *IEEE Transactions on Semiconductor Manufacturing* 16, 376–383 (2003). DOI: 10.1109/TSM.2003.815631.

Leeds researchers in bold.

Outputs 1–2, 4–6 are all published in internationally leading peer-reviewed archival journals, and are recognised internationally in terms of originality, significance and rigour. Outputs 1, 2, and 4

are particularly highlighted to underpin the impact described in this case study.

4. Details of the impact (indicative maximum 750 words)

Much of our research in microwave/millimetre-wave frequency components post-1993, together with its translation and impact post-2008, has been in partnership with *Filtronic* or companies that have arisen from *Filtronic*. In October 2006, *Filtronic* sold the majority of its wireless infrastructure division, *Filtronic Comtek*, to *Powerwave* (USA), with key staff from the filters division forming a new company *Radio Design Ltd* in August 2007. In March 2008, *Filtronic Compound Semiconductor*'s GaAs business was sold to *RF Micro Devices Inc.*, and the facility (*RFMD (UK) Ltd*) became the largest volume manufacturer of GaAs devices in Europe. In August 2008, *Filtronic* sold its defence business to *Teledyne Technologies Inc.*, forming *Teledyne Defence Ltd*.

In this case study, we focus on the creation of impact post-2008 of two areas of Leeds research: the development of RF filters principally through *Radio Design Ltd*, and the design and manufacture of high breakdown voltage power transistors through *RFMD (UK) Ltd*. However, all the companies discussed above derived from *Filtronic PLC* and were all underpinned by Leeds research and researchers post-1993 – *Filtronic Wireless*, *Filtronic Broadband*, *RFMD (UK)*, *Radio Design Ltd* and *Teledyne Defence Ltd* between them had >500 employees and a total turnover of ~£80M in the most recent financial year [A].

Radio Design Ltd designs and manufactures single-band and multi-band RF filters and combiners for cellular radio systems, focusing on: inter-operator and technology sharing; tower mounted amplifiers; interference reduction; and, the provision of test equipment. It has grown from 11 staff in 2008, to 70 staff and sales of £8.7M in 2010, to 150 staff and sales of £14.7M in 2012, with '*75% of the company's products derived directly from underpinning research at the University of Leeds*' [B]. Its original (2007) 30,000 sq ft, manufacturing facilities in Shipley, Yorkshire have expanded to include 10,000 sq ft facilities in India (December 2008), and 20,000 sq ft in China (March 2012). Markets include the UK, Ireland, Scandinavia, Eastern and Western Europe, China, India, and recently the USA [B].

As examples of the uptake and exploitation of Leeds research by *Radio Design Ltd*, our development of **non-uniform Q filters** led to the company's 3G Universal Combiner Unit, with sales of >40,000 dual-channel units (total value £18M) from 2008 and creation of >50 jobs; this resulted in the company's Queen's Award for Enterprise (Innovation) in 2011 [B]. Based on the success of this product, *Radio Design Ltd* were contracted to design and build 35 power combiners (each costing ~£35k) to enable all five cellular operators to share a common antenna system at the 2012 London Olympics, removing the need for multiple cellular base stations. Leeds' subsequent development in 2012 of **4G power combining** technology in conjunction with *Radio Design Ltd* has already led to sales in 2013 of 6,000 units (average cost: £700/unit) to cellular radio operators for use in LTE and 4G systems (with anticipated sales going forward of 18,000 units in 2014 and 35,000 units in 2015, leading directly to the creation of a further 50 jobs) [B].

Leeds' development of miniaturized filters has, however, not only led to the growth and success of *Radio Design Ltd*, but also the "*tens of thousands of dielectric resonator filters ... manufactured by Filtronic and subsequently Powerwave ... for use in US cellular radio infrastructure, which has been widely utilised in the period 2008–2013*" [B]. Furthermore, the technology "*is now used by many manufacturers of filters, and I would estimate that there have been sales since 2008 of tens of millions of pounds*" [B]. Bespoke filters were also designed by Leeds for *Selex Galileo*, who have integrated these filters into new designs for wideband defensive airborne radar [C]. (Owing to defence implications a definitive statement on how many £30M fighter aircraft have adopted this technology is not available. Indicative sales are of 500 units (two filters per unit) [C]).

In parallel with the above, between 2008–2013 *RFMD (UK) Ltd* at Newton Aycliffe produced pHEMT switches for all major mobile phone manufacturers, based on the initial Leeds research on the **design of high breakdown voltage power transistors,** which was first commercialized from 2005 through *Filtronic Compound Semiconductors* (CEO: Snowden) [D] – "*I therefore anticipate that during the period 2008–2013 over 2 billion pHEMT switches have been produced and used, all originating from the Newton Aycliffe site and all deriving from Professor Snowden's initial research on the modelling of semiconductor devices. This corresponds to sales in excess of £250M*" [D]. [text removed for publication].

In 2013, RFMD (UK) Ltd sold the volume manufacturing facility established at Newton Aycliffe to Compound Photonics, with the planned creation of an additional 200 jobs [F].

[figure removed for publication]

Figure 1 [text removed for publication]

Our close relationship with *Filtronic* led to Hunter's appointment at Leeds in 1998 as a part-time Senior Research Fellow (full-time from 2001) from his position as Fellow Engineer at *Filtronic*, with the objective of building research collaborations through PhD studentships (12 based at Leeds, 3 in *Filtronic*), and research grants. *Filtronic* also funded an undergraduate degree programme and a Masters degree programme at Leeds, with total sponsorship of over £1M. The impact of this support, and the strength of our underpinning research, is evidenced by the number of former PhD students who held/have taken up senior positions in the UK and overseas over the period 2008–2013, including: Christoph Ernst (PhD awarded 2000), currently head of R&D for passive microwave components European Space Agency, Noordwijk, Netherlands; Vanessa Walker (2003), senior research engineer, Filtronic; Ben Senior (2003) and Michael Guess (2012) filter designers, Radio Design Ltd, Shipley, UK; Andrew Guyette (2006), Research Engineer at Naval Research Labs, Washington DC, USA; Alaa Abunjaileh (2007), antenna designer, EADS/Astrium, Stevenage, UK; Emika Sandhiya (2007), MMIC designer, SELEX Galileo, UK.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] 'Company Financials for *Filtronic Wireless*, *Filtronic Broadband*, *RFMD(UK)*, *Radio Design Ltd* and *Teledyne Defence Ltd*', www.duedil.com, accessed 28 October 2013.

[B] Testimonial from the Managing Director, Radio Design Ltd (formerly Engineering Director, Filtronic), Shipley, West Yorkshire, 20 September 2013.

[C] Testimonial from the Principal Microwave Engineer, SELEX Galileo Ltd, Luton, Bedfordshire, 13 July 2012.

[D] Testimonial from the Chairman, Isotek Oil and Gas, Leeds, West Yorkshire, 27 September 2013 (former Chairman of Filtronic).

[E] [text removed for publication].

[F] 'Compound Photonics buys Newton Aycliffe RFMD factory', 25 July 2013, http://www.bbc.co.uk/news/uk-england-tees-23442184, accessed 24 October 2013.