Institution: University of Leeds

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

Title of case study: Techniques for precision high-frequency (RF to THz) characterization of electronic components, materials, and biological samples (Impact Case Study 2)

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

Research at the University of Leeds, in partnership with the US company Agilent Technologies, has directly resulted in the development of high performance vector network analyzer instrumentation used by electronics, aerospace and defence companies globally to measure the high frequency properties of electronic devices and materials. University of Leeds research also directly resulted in the development of two further Agilent Technologies products – a high frequency dielectric probe kit and a capacitance scanning probe microscope. Agilent Technologies confirms that the collective sales of these products are in the region of tens of millions of dollars annually since 2008.

2. Underpinning research (indicative maximum 500 words)

The University of Leeds has a long-standing collaboration with Agilent Technologies (formerly Hewlett Packard) dating back to 1981 when Professor Roger **Pollard**, then lecturer in the School of Electronic and Electrical Engineering, took up a consultancy position with Agilent Technologies, Santa Rosa, California. Pollard subsequently assumed an on-going R&D consultancy role in the company, visiting each summer, until 2010 when he retired from the University and took up a permanent, part-time, position with Agilent.

Pollard's research focussed on the study of solid-state devices and circuits operating at microwave frequencies, and in particular the development of techniques to measure the high frequency properties (from a few megahertz up to the terahertz frequency range) of electronic devices and materials. His research exploited vector network analyzers, which are used to measure these high frequency electronic properties – a high frequency signal is applied to a device or material and the output signal analyzed. Key characteristics, termed S-parameters, are measured, which show what proportion of the input radiation is absorbed and what is reflected by the material or device-under-test, and how this changes as a function of frequency.

A key focus of Leeds research since 1993 has been the development of new algorithms to quantify and extract background noise from S-parameter measurements. This research, led by Pollard, resulted in a theory for error correction and noise figure analysis in 1994. An algorithm was developed using load pull measurements to establish very accurate impedance and noise states, working with Agilent to develop the mathematics to derive a noise figure from these noise state measurements [1]. These algorithms now underpin the operation of all Agilent network analyzers, including the PNA-X platform launched in 2008.

In 1997, Leeds researchers under Pollard reported a new way to measure the high frequency properties of materials without the need for the test material to have integral electrical contacts. Instead, an open-ended coaxial cable is placed on the surface of the test sample [2]. Supported in part by EPSRC award GR/K00783 (£114,320, 1994–1996), Pollard developed the algorithms that allow accurate extraction of the microwave frequency properties of materials by this method without needing to form any fixed waveguide on the material surface. The results of this research form the basis of Agilent's 8507E dielectric probe kit launched in 2009, and the body of work to date led, in part, to a major JIF/EPSRC award in 2001 (GR/M87535, £2,188,383, 2001–2003), which developed a 300 GHz microwave and millimeter-wave instrumentation facility at Leeds.

In 2008, Pollard's group (now including **Hunter** who joined the University from Filtronic in 1998) developed the world's first substrate integrated waveguide sensor for measuring microwave properties of small volumes of liquid solvents [3]. This work (carried out in part while Pollard's PhD student, Saeed, was on a five month GRASS-ROOT internship at Agilent in 2008) formed the basis for the development of Agilent's scanning capacitance probe microscope. This is a modified atomic force microscope, which not only produces topographical and morphological images of a surface – as is standard – but also provides information on the high frequency dielectric properties of the surface under examination, allowing doping maps of semiconductors to be produced, for example. The latter application has seen widespread sales of this equipment across the semiconductor sector, *inter alia*.

For his scientific and engineering contributions internationally, Pollard was elected as an IEEE Fellow in 1997. He served as president of the IEEE Microwave Theory and Techniques Society (MTT-S) in 1998, received the IEEE Third Millennium Medal in 2000, was elected to a Fellowship of the Royal Academy of Engineering in 2005, and received the MTT-S Distinguished Service Award in 2006. He was also a Fellow of the Institution of Engineering and Technology.

Key researchers:
Roger Pollard (Senior Lecturer, 01/10/1985 – 31/07/1998; 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).

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

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

[1] C E **Collins**, R D **Pollard**, R E **Miles** and R Dildine, 'A new method for determination of single sideband noise figure', *IEEE Transactions on Microwave Theory and Techniques* 42, 2435–2439 (1994). DOI: 10.1109/22.339778.

[2] D V Blackham and R D **Pollard**, 'An improved technique for permittivity measurements using a coaxial probe', *IEEE Transactions on Instrumentation and Measurement* 46, 1093–1099 (1997). DOI: 10.1109/19.676718.

[3] K **Saeed**, R D **Pollard** and I C **Hunter**, 'Substrate integrated waveguide cavity resonators for complex permittivity characterization of materials', *IEEE Transactions on Microwave Theory and Techniques* 56, 2340–2347 (2008). DOI: 10.1109/TMTT.2008.2003523.

Leeds researchers in bold.

These outputs are all published in internationally leading peer-reviewed archival journals, and are recognised internationally in terms of originality, significance and rigour. All three outputs underpin the impact described in this case study.

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

The underpinning University of Leeds research has had a direct and substantial economic impact during the review period through sales generated by Agilent Technologies. Our research has also had a broader impact through the companies within the electronics sector that have bought the Agilent Technologies instrumentation for the design and testing of new products, which were themselves released onto the market. Further impact has been generated through the use of this instrumentation in, for example, the metrology and standards industry.

The PNA-X platform, which is the microwave industry's highest performing network analyzer in terms of its noise performance and accuracy, together with portable RF analyzers incorporating the same technology (the FieldFox platform), are sold to the wireless, aerospace and defence industries and were all directly brought about by research at Leeds [A]. The results from the research on noise measurement [1] were incorporated into the PNA-X platform as an option from 2008. Customers include (but are not limited to) in aerospace and defence: Northrop Grumman, Astrium, Selex, Raytheon, multiple defence agencies; in telecommunications: NSN, Ericsson, Motorola; in computing: Cisco, Huawei, Intel; and, in microwave electronics: Mini-circuits, Miteq, and Filtronic (itself an earlier spin-out from the School). This work contributed to Agilent becoming a global leader in network analyzers, with a greater market share than all other companies combined. Owing to commercial sensitivity, Agilent is unable to provide precise figures for sales of its products, however, a senior Agilent executive confirms: *"The revenue from the noise figure option to the PNA-X is in the tens of millions of dollars annually*" [A].

The algorithms described in reference [2] were incorporated into the Agilent dielectric probe measurement kit (model number 85070E) in 2009 [A]. The University of Leeds related work with Agilent on the extraction of material parameters from substrate integrated waveguide cavity resonators [3] led directly to the Agilent Technologies scanning probe microscope range, with models 5400 and 5600LS first brought to market in 2009. Specifically, this work led to a new modality being incorporated into this instrumentation (SMM mode), which enables complex impedance (resistance and reactance), calibrated capacitance, and topography measurements within the same instrument [A]. This microscopy modality outperforms traditional AFM-based scanning capacitance microscopy techniques, since it does not require any contact between the probe head and the sample. The instrument is now being sold routinely to the semiconductor industry for calibrated dopant density measurements on silicon wafers, as well as to research organisations worldwide [A]. Again, precise sales figures of the dielectric probe kit and scanning probe microscope range are not available for commercial reasons, but a senior Agilent executive states: "*I can confirm that the key academic work on which these developments were based was published in two papers by Pollard and co-workers (References [2] and [3]) ... The specific revenue from these solutions is in the tens of millions of dollars annually*" [A]. Furthermore, "*collective sales of all these products (network analyzers, open-ended dielectric probes, and scanning probe microscope) have been in the region of hundreds of millions of dollars per year*" [A].

To give one example of the broader impact that University of Leeds research has achieved through the organizations that have bought Agilent Technologies instrumentation, there has been substantial impact in the metrology sector, with the network analyzers being used by, for example, the National Physical Laboratory (NPL) for accurate calibration of high frequency instrumentation [B]. Agilent's network analyzers, incorporating technologies developed at Leeds as discussed above, are now considered to be the industry standard for these measurements – "*we have specifically chosen Agilent Technologies Network Analysers for the high precision that they offer, for their ability to offer state-of-the-art error correction routines, and, for their ability to provide implementations of the very latest measurement and calibration techniques*" [B]. NPL has also confirmed that the availability of this Agilent Technologies instrumentation has enabled them to offer a wide range of measurement capabilities to its customers "*that have led to an income over the period 2008–2013 of approximately £50M*" [B]. The fan-out/impact from the customer calibration services also provides a major source of income for many third-party laboratories involved as links in the measurement assurance/traceability chain – for example, one calibration from NPL can validate tests made on many thousands of devices on many industrial shop floors and production lines [B].

This case study exemplifies how the School of Electronic and Electrical Engineering at Leeds adopts a long-term and sustainable approach towards ensuring the impact of its research. Agilent Technologies (and formerly Hewlett Packard) have sponsored 15 PhD students in the School over this on-going period of collaboration. Furthermore, the School has also trained a number of researchers who have taken up employment with Agilent, providing further impact from the research. Four current staff at the company obtained their doctoral degrees through work performed in collaboration with Leeds, under the supervision of Pollard. The staff are: Mark Pierpoint (PhD completed 1987), who is currently Vice President/General Manager of the Software and Modular Solutions Business section of Agilent; Loren Betts (PhD 2009), an engineer responsible for many of the Agilent's vector network analyzer products; Dave Blackham (PhD 1999) who specializes in measurement uncertainties; and, Joel Dunsmore (PhD 2004), an Agilent Fellow developing measurement applications.

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

[A] Testimonial from a General Manager, Agilent Technologies, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403, 19 September 2012.

[B] Testimonial from the Lead Scientist (RF & Microwave Measurements division), National Physical Laboratory, Teddington, Middlesex, 9 September 2013.