

Millimetre-wave and Terahertz Electronics

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Background

Wireless systems find countless applications in general communications and remote sensing applications. Their front-end hardware can perform relatively complex signal processing functions directly at microwave (*ca.* 1 to 30 GHz) and optical (*ca.* 400 to 789 THz) frequencies. When combining ubiquitous wireless applications with advances in enabling technologies, a positive spiral can be created that continually drives down manufacturing costs while still allowing functionality to grow. Good examples of such applications are the evolutions in mobile phone and light projector technologies. With the former, at microwave frequencies, low-cost handsets employ an I-Q vector modulator that operates directly on the carrier signal. With the latter, at optical wavelengths, Digital Light Processing™ employs a Digital Micromirror Device™ chip that operates directly on the illuminating white light. It is interesting to note that the DLP® Pico projector is currently being modified for integration into mobile phones, forming a marriage between these two extreme examples.

There are two basic reasons why millimetre-wave (*ca.* 30 to 300 GHz) and terahertz (*ca.* 0.3 to 3 THz, also known as sub-millimetre-wave) electronics have yet to find ubiquitous applications^{†a}. The first reason is the increase in power loss with frequency within materials used to make passive components and circuits. This is coupled with the increasing inability to generate sufficient spectrally clean carrier power, and also the drop in the power gain for an amplifying stage as frequency increases. As a result, the signal-to-noise ratio for an end-to-end system degrades as frequency increases, requiring ever-more expensive solutions that only high-end users (e.g. commercial, scientific or military) are prepared to pay for. The second reason is that wavelength is inversely proportional to frequency; thus, resonant structures become smaller in size as frequency increases. Therefore, fabrication tolerances become more important, requiring more expensive manufacturing technologies to be used at higher frequencies. For example, to define even a simple microstrip transmission line within a *microwave* integrated circuit, relatively low-cost optical lithography can be used with simple printed circuit board (PCB) or screen-printing technologies. For *millimetre-wave* integrated circuits, a more expensive ultra-violet (UV) lithographic system may be needed with a basic microfabrication facility; while for *terahertz* integrated circuits it may be necessary to use very expensive X-ray lithography with more advanced microfabrication processing techniques.

For the above reasons, in terms of consumer-based electronics intended for the masses, the cost of implementing a wireless system at millimetre-wave frequencies is currently prohibitive. As a result, manufacturers are reluctant to invest in the kinds of research and development that is needed to make breakthroughs for the various enabling technologies that can bring prices down to affordable levels. This impasse is even more acute with operation at terahertz frequencies. The relatively recent emergence of “T-ray” technologies, for applications that include medical imaging, had been predominantly through the use of (quasi-)optical techniques in preference to those found at longer wavelengths.

^{†a} 60 GHz indoor wireless local-area networks and 77 GHz autonomous cruise control systems have a long way to go before they are considered ubiquitous applications.

Overview

The basic thesis for the advancement of millimetre-wave and terahertz electronics is represented in four sections: *Signal Processing*, *Component Design and Realization*, *Modelling and Materials*, and *Paradigm Shift*. The first section is at system and circuit levels and reports on complex signal process functions that have been performed directly on the millimetre-wave carrier signal, intended for realizing low-cost and adaptive communications and radar systems architectures. The second section is at circuit and component levels and reports on techniques for the design and realization of low-loss passives for use at millimetre-wave frequencies. The third section is at component and material levels and reports on modelling techniques for passives for use at both millimetre-wave and terahertz frequencies. Finally, the fourth section introduces a revolutionary new technology that represents a paradigm shift in the way millimetre-wave and terahertz electronics (i.e. components, circuits and systems) can be implemented. As found with the new generation of mobile phone handsets, a fusion of two extreme technologies can take place; here, complex signal processing operations could be performed both directly on the carrier signal and with the use of a spatial light modulator.

Based on a selection of 20 papers (co-)authored by the candidate ^{†b}, and published over a period of 15 years, it will be seen that a coherent theme runs throughout this body of work, for the advancement of knowledge in millimetre-wave and terahertz electronics.

Signal Processing

With a traditional transceiver used for wireless communications, conventional wisdom dictates that better end-to-end performance is achieved by down-conversion of the radio frequency (RF) signal to one, or more, intermediate frequency (IF) stages and then down to baseband for data extraction using digital signal processing (DSP). While such superheterodyne approaches give optimal signal-to-noise performance, this is at the expense of unnecessary hardware complexity, size, mass and cost. Since DSP software is relatively inexpensive, when compared to high frequency hardware, there has been a continual migration over the years to extend DSP operations from baseband through the IF stages and up into the RF stage. In essence, this is the main feature of what is known as *software radio*. One of the technologically limiting factors to this migration is the cost of implementing the transmitter digital-to-analogue converter (DAC) and the receiver analogue-to-digital converter (ADC). As the operating frequency of the wireless system increases then so does the required bandwidth for the DAC and ADC. Therefore, for the same level of dynamic range, the cost of such interfaces and associated digital hardware also increases with frequency, leading to a state of diminishing returns. While technology continually advances, it is still some way off from being economically viable to perform DSP operations at millimetre-wave frequencies.

There is, however, a strong case for combining DSP with front-end RF electronics, such that adaptive signal processing can be performed directly on the carrier signal. This is because the required bandwidth for the DAC and ADC is now only related to that of the baseband signal, and not the carrier frequency ^{†c}.

^{†b} The 20 cited papers have all been peer reviewed and can be downloaded from the internet. Another 15 publications are included in these footnotes. With all these publications, none have been used by the candidate for the purpose of obtaining any other degree. Generally, the last author for each indicates the project supervisor.

^{†c} S. Lucyszyn and I. D. Robertson, "Vector modulators for adaptive and multi-function microwave communication systems", *Microwaves 94 Conference Proceeding*, London, UK, pp. 103-106, Oct. 1994

This approach also eliminates the need for expensive down-conversion hardware (e.g. filters, mixers and oscillators), as it shifts the complexity to DSP software. To this end, suitable high-performance RF hardware building blocks needed to be investigated, in order to be able to implement fast signal processing directly on a carrier signal.

Monolithic microwave integrated circuit (MMIC) technology ^{†d} is ideally suited for implementing high performance tuneability ^{†e}. Therefore, the first ever broadband MMIC tuneable building blocks were reported in [1]. Here, MMICs were used to realize X-band tuneable control circuits (e.g. phase shifters, delay lines and attenuators) [1]. Hybrid technology was also used to realize an L-band group delay synthesizer ^{†f} [1]. It was found that these control circuits are ideally suited for use as generic building blocks for carrier signal processing applications. For example, a 360° phase shifter can be used to implement digital modulation (i.e. M-ary phase shift keying) and small-shift frequency translation ^{†g,h}. Alternatively, four attenuators can be combined, using appropriate directional couplers, to create a 4-channel I-Q vector modulator for implementing various types of digital modulation, small-shift frequency translation and power amplifier linearization using RF predistortion ^{†i}. In order to assess the general behaviour of a vector modulator for performing multiple functions, a proof-of-concept demonstrator was realized. The hardware was made by cascading X-band monolithic analogue phase shifters and attenuators, to create a single-channel vector modulator [2]. With combined silicon DSP and GaAs MESFET-based MMIC chip-sets, unfiltered multilevel digital modulation (e.g. QPSK, 32-PSK and 16-QAM) was demonstrated at 10 GHz for the first time [2].

While the use of a 360° phase shifter creates a more efficient vector modulator, MMIC implementations can be rather large for wideband applications. A compact 2-channel I-Q vector modulator was, therefore, conceived by Lucyszyn [3], employing two orthogonal balanced bi-phase attenuators operating in a push-pull mode. This unique topology was designed specifically for operation at millimetre-wave frequencies, due to its ability to cancel the unwanted nonlinear tuning effects from the intrinsic parasitic elements within the solid-state devices of the analogue attenuators. The first ever proof-of-concept consisted of a single-chip AlGaAs/InGaAs pHEMT-based MMIC modulator that demonstrated 256-QAM at both 38 and 60 GHz [3]. The same technology was later employed to extend the frequency range to 110 GHz [4]. This proved, for the first time, that upper-millimetre-wave electronics can also incorporate complex signal processing operations. Here, a 110 GHz transmitter demonstrated 64-QAM modulation with 60 Mb/s pseudo-random data.

^{†d} I. D. Robertson and **S. Lucyszyn** (Editors), “RFIC and MMIC Design and Technology”, *Published by The Institution of Electrical Engineers*, Nov. 2001; Chinese Translation: *Published by the Publishing House of Electronics Industry*, Feb. 2007

^{†e} **S. Lucyszyn** and I. D. Robertson, “Monolithic narrow-band filter using ultrahigh-Q tunable active inductors”, *IEEE Transactions on Microwave Theory and Techniques*, vol. 42, no. 12, pp. 2617-2622, Dec. 1994

^{†f} **S. Lucyszyn**, I. D. Robertson and A. H. Aghvami, “Negative group delay synthesiser”, *IEE Electronics Letters*, vol. 29, no. 9, pp. 798-800, Apr. 1993

^{†g} **S. Lucyszyn**, I. D. Robertson and A. H. Aghvami, “24 GHz serrodyne frequency translator using a 360° analog CPW MMIC phase shifter”, *IEEE Microwave and Guided Wave Letters*, vol. 4, no. 3, pp. 71-73, Mar. 1994

^{†h} **S. Lucyszyn**, Y. Pilchen, I. D. Robertson and A. H. Aghvami, “Ku-band serrodyne frequency translator using wideband MMIC analogue phase shifters”, *23rd European Microwave Conference Proceedings*, Madrid, Spain, pp. 819-822, Sep. 1993

^{†i} D. S. McPherson, M. G. Stubbs, J. S. Wight and **S. Lucyszyn**, “A 28 GHz HBT vector modulator and its application to an LMCS feedforward power amplifier”, *28th European Microwave Conference Proceedings*, Amsterdam, The Netherlands, pp. 523-528, Oct. 1998

In 2001, this work represented the highest reported frequency of operation for direct multilevel carrier modulation using monolithic technology [4]. As frequency increases, scaling of dimensions with the use of traditional directional couplers becomes a limiting factor, but the basic concept and topology do not have inherent frequency limitations, making this a possible contender for terahertz electronics in the not too distant future.

At the same time, a rigorous analysis was undertaken to investigate the suitability of the new millimetre-wave I-Q vector modulator for performing simultaneous signal processing functions, without the need for any additional front-end hardware [5]; for example: *arbitrary waveform generation, digital modulation, small-shift frequency translation (SSFT), spectral filtering and power amplifier linearization using RF predistortion*. While software radio has attracted a great deal of attention in recent years, the concept of software radar was, at that time, still relatively new. One of the challenges was to generate wideband FMCW radar signals at 77 GHz [5]. Indeed, while this was easily demonstrated, it was found that the only limitation was the bandwidth of the available measurement system. In addition, 64-QAM modulation and SSFT were demonstrated at 77 GHz [5]. Simultaneous signal processing functions of digital modulation, SSFT, spectral filtering and predistortion had already been demonstrated at 60 GHz ^{†j}.

To summarise the contributions to knowledge from this section, papers [1-5] were the first to implement broadband signal processing on a carrier signal using monolithic technology; with each paper pushing the boundaries of signal processing complexity and/or carrier frequency of operation.

Component Design and Realization

As technology advances so do the expectations of consumers, with next generation products needing to have better performance, greater functionality and, of course, being smaller, lighter and cheaper. Within circuits and systems, guided-wave structures play a vital role. With its large internal surface areas, which minimizes conduction current density, the metal-pipe rectangular waveguide (MPRWG) exhibits the lowest power loss and highest quality (Q)-factor of any distributed element component. For this reason, solid-state devices (e.g. used as signal sources, in-line amplifiers and signal detectors) are found inside MPRWG structures. However, conventional MPRWG circuits are not small, light or cheap. Instead, the MMIC is the obvious choice for implementing a small and lightweight circuit. However, when one tries to miniaturize passives, power losses increase. For example, with a microstrip transmission line within a conventional millimetre-wave integrated circuit, the levels of loss are too high to realize high-order filters; confining them to impedance matching networks and interconnects.

The answer was to turn technology inside out by integrating MPRWGs into MMICs. The substrate integrated waveguide (SIW) is now a *hot* topic in microwave conferences and journals. The first ever dielectric-filled MPRWG was demonstrated on GaAs back in 1995, having a designed centre frequency of 100 GHz [6]. While the measured performance of this experimental proof-of-concept was predictably poor [6], with careful design and a better fabrication process, a follow-on investigation predicted that an exceptionally high performance is theoretically possible for practical applications at 150 GHz [7]. Shortly after this work, conclusions from another detailed investigation were published that compared and contrasted the attributes of dielectric-filled over hollow MPRWGs [8].

^{†j} M. Chongcheawchamnan, K. S. Ang, D. Kpogla, S. Nam, S. Lucyszyn and I. D. Robertson, "Low-cost millimeter-wave transmitter architecture using software radio techniques", *IEEE International Microwave Symposium Digest*, pp. 1949-1952, Jun. 2000.

The main findings were that the dielectric-filled MPRWG could be miniaturized, at the expense of some degradation due to increased ohmic losses, to realize more compact interconnects, resonators and radiating elements on a chip [8].

Within the microwave industry, multi-chip modules (MCMs) have demonstrated their worth; they can exhibit a higher level of performance when compared to an equivalent hybrid integrated circuit, while being a small fraction of the cost for a single-chip solution. As frequency increases towards millimetre wavelengths, traditional bond-wire and ribbon interconnects between the MMIC and carrier substrate exhibit unacceptable levels of series inductive reactance and shunt capacitive susceptance; the interconnect is equivalent to a 3rd-order low-pass filter. As a result, flip-chip technology is used to increase the cut-off frequency of the interconnect filtering, by minimizing the associated parasitics. Unfortunately, even this solution runs out of steam as frequency reaches *ca.* 100 GHz. For this reason, a completely new concept was proposed for implementing MCMs that can operate between *ca.* 75 and 300 GHz with high performance interconnects [9]. Here, dielectric-filled MPRWG interconnects are created, with MMICs slotted vertically into the E-plane of the waveguide. From this work, the concept of being able to realize a high-power transmitter and high-performance receiver, both having integrated phased array antennas, was explored for 140 GHz operation [9]. This technology could find applications in portable full-body scanners that employ radiometric imaging for the detection of concealed weapons in public areas.

Radio frequency microelectromechanical systems (RF MEMS) technology has also demonstrated its worth by its ability to improve the RF performance of a passive component^{†k,l,m} by a few orders of magnitude. An award-winning review of RF MEMS was undertaken, from the perspective of its enabling technologies. This work resulted in a unique roadmap of the subject, which highlighted the complexities and interdependences of the various enabling technologies [10]. It was shown that by improving one key component, the architecture of a wireless transceiver can be dramatically simplified and/or its functionality increased without significant penalty [10].

Even with the use of state-of-the-art microfabrication facilities, the performance of tuneable integrated millimetre-wave filters on a silicon substrate is expected to be poor. By combining bulk-micromachining with silicon wafer bonding techniques, the lowest recorded insertion loss for any micromachined millimetre-wave band-pass filter was demonstrated [11]. This 3rd-order RF-coupled transmission line filter has the additional feature in that the suspended inverted-microstrip lines act as micromechanical cantilevers. By employing electrostatic-actuation, a 60 GHz half-wavelength resonator was tested and the measured results demonstrated high values of unloaded Q-factor and significant frequency tuning [11]. This is the first example of a true RF MEMS coupled-line millimetre-wave tuneable resonator to be reported.

^{†k} J.-Y. Choi, J. Ruan, F. Coccetti and **S. Lucyszyn**, “Three-dimensional RF MEMS switch for power applications”, *IEEE Transactions on Industrial Electronics*, vol. 56, no. 4, pp. 1031-1039, Apr. 2009

^{†l} S. Pranonsatit, A. S. Holmes, I. D. Robertson and **S. Lucyszyn**, “Single-pole eight-throw RF MEMS rotary switch”, *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 15, no. 6, pp. 1735-1744, Dec. 2006

^{†m} M. P. Larsson and **S. Lucyszyn**, “A micromachined separable RF connector fabricated using low-resistivity silicon”, *IoP Journal of Micromechanics and Microengineering*, vol. 16, pp. 2021-2033, Aug. 2006

As previously mentioned, a millimetre-wave integrated circuit generally relies on expensive UV lithography to define the spatial features of its components. In many situations, post-fabrication tuning is not possible. Therefore, a *right first time* philosophy usually needs to adopt expensive microfabrication and characterization processes. One approach for designing and realizing millimetre-wave filters with low-cost manufacturing techniques was to develop a new family of filter transfer functions. The chained-function filter creates a family of transfer functions that have characteristics in between the Butterworth and Chebyshev functions [12]. By knowing, *a priori*, details of the method of manufacturing, this work now makes it possible to select a suitable transfer function that is insensitive to poor fabrication tolerances.

The robustness of this synthesis technique was demonstrated experimentally by implementing a 37 GHz tuningless 6th-order band-pass filter. This was realized with an optical shadow mask made simply using an office laser printer; the filter was fabricated using standard PCB technology ^{†n}. The measured performance for this millimetre-wave filter was excellent, even under such extremely poor manufacturing conditions.

To summarise the contributions to knowledge from this section, the work on dielectric-filled MPRWGs has demonstrated a unique way to miniaturize low loss passive structures for both monolithic and multi-chip module applications. Each of the papers [6-9] represents some of the first steps in what is now generally known as SIW technology. The work on RF MEMS, covered by papers [10, 11], has advanced our understanding and boundaries for what is possible when microelectromechanics meets RF electronics. Lastly, a unique methodology has been created that represents a significant advancement in the synthesis of manufacturable tuningless millimetre-wave filters.

Modelling and Materials

A number of research groups worldwide have reported discrepancies between loss measurements and classical model predictions for simple millimetre-wave and terahertz structures. For the first time, a comprehensive survey of published experimental data for the room temperature surface resistance of normal metals, from dc up to 12 THz, was undertaken [13]. It was found, from optical-based measurements performed within the far-infrared region (*ca.* 300 GHz to 30 THz), that there does not appear to be any anomalous intrinsic frequency dispersion phenomena at room temperature [13]. This is in direct contradiction to the findings of other research groups. Indeed, the anomalous results can all be attributed to various inherent flaws in measurement strategy ^{†o,p}.

Based on just two data points, from fundamentally flawed millimetre-wave measurements at 35 and 70 GHz, NASA-supported research came up with an elaborate theoretical model to explain *anomalies* in the solid-state physics of carrier transport in normal metals at room temperature, from dc to 6.7 THz. Since this was gaining increased notoriety, it was important to investigate this model in depth.

^{†n} C. E. Chrisostomidis, M. Guglielmi, P. R. Young and **S. Lucyszyn**, “Application of chained functions to low-cost microwave band-pass filters using standard PCB etching techniques”, *30th European Microwave Conference Proceedings*, Paris, France, vol. 3, pp. 40-43, Oct. 2000

^{†o} **S. Lucyszyn**, “Microwave Measurements”, R. Collier and D. Skinner (Editors), 3rd Edition, *Published by the Institution of Engineering and Technology*, Chapter 11, pp. 217-262, Oct. 2007

^{†p} **S. Lucyszyn**, “Lies, damn lies and measurements”, *16th Asia-Pacific Microwave Conference Proceedings*, New Delhi, India, pp. 1-4, Dec. 2004 (**Invited Paper**)

Based entirely on first principles, it was possible to systematically deconstruct the erroneous model [14]. The conclusions from this work reinforce the view that there is neither experimental [13] nor theoretical [14] evidence to support the existence of any anomalous behaviour in normal metals at room temperature.

Commercial electromagnetic modelling software generally employs, by default, overly-simplified models to describe the intrinsic frequency dispersion within normal metals at terahertz frequencies. For the first time, a theoretical review of the various modelling strategies was made [15]. This review covered classical-, semi-classical- and quantum mechanical-based physical models for normal metals and discusses their limitations with frequency at room temperature [15].

Also for the first time, a quantitative analysis for the application of different models used to describe the intrinsic frequency dispersive nature of bulk conductivity at room temperature was undertaken for hollow MPRWGs and associated cavity resonators between 0.9 and 12 THz [16]. One important aspect of this work is that, while approximate mathematical models for the unloaded Q-factor of such resonators have been reported since *ca.* 1946, this is the first time an exact solution has been derived. Moreover, this work highlighted a significant source of errors with terahertz structures operating at room temperatures, which can be rectified by adopting the classical relaxation-effect model to describe the intrinsic frequency dispersive behaviour of normal metals [16].

While low loss metals (e.g. silver and gold) have been employed in millimetre-wave applications for many decades, other metals are also used. For example, in recent years, electroplated nickel has been adopted as a structural support material in RF MEMS components. However, very little is known about the RF characterization of nickel [17]. A unique investigation into some of the issues associated with both measurement and modelling of nickel has been undertaken. It was concluded that RF engineers are currently faced with the problem that there is insufficient data available to undertake simulation designs with a high level of confidence at either microwave or millimetre-wave frequencies [17].

New materials are continually being sought for improving the performance of a device and, in turn, their adopted circuits and systems. For example, at millimetre-wave frequencies, RF signal detectors based on Schottky junctions suffer from poor impedance matching over very wide video bandwidths, are insensitive to very weak signals and exhibit high levels of thermal and shot noise. For this reason, a new concept was proposed which suggested that C₆₀ nanowhiskers could offer the possibility for realising robust, sensitive millimetre-wave sensors with significantly reduced shunt capacitance and improved noise performance [18]. This work is still in its infancy, but recent advances in the growth of C₆₀ nanowhiskers have been demonstrated and their nonlinear I-V characteristics have been investigated^{†q}. From the initial results, this technology looks promising for the not too distant future.

To summarise the contributions to knowledge from this section, papers [13-16] have, in one way or another, defended the classical relaxation-effect model for normal metals at room temperature. Each paper has uniquely addressed a different aspect and, together, this work has opened-up a new field of research. The papers on nickel [17] and C₆₀ nanowhiskers [18] have, for the first time, brought out important issues of characterization for these new materials, which may well prove beneficial if they are to be adopted in future applications at millimetre-wave frequencies.

^{†q} M. P. Larsson, J. Kjelstrup-Hansen and **S. Lucyszyn**, "DC characterisation of C₆₀ whiskers and nanowhiskers", *The Electrochemical Society Transactions*, vol. 2, no. 12, pp. 27-38, 2007

Paradigm Shift

Traditional methods for implementing millimetre-wave and terahertz systems rely on conventional techniques, whereby permanent physical components are used to create permanent physical circuits. This tried and trusted philosophy can be prohibitively expensive if tuneable circuits are to be implemented and/or architectures need to be made electronically reconfigurable. Moreover, such requirements are not compatible with a compact solution. The answer may require a paradigm shift in the way engineers realize their components, circuits and systems.

The interaction between photon energy and a semiconductor is nothing new. Indeed, the influence of light from a halogen bulb, used in conjunction with a microscope during the testing of an MMIC, has been studied in detail [19]. For the first time, a qualitative assessment was made of the effects of photonic absorption within both GaAs MESFET-based and AlGaAs/InGaAs pHEMT-based MMIC tuneable control circuits. The principal mechanism that accounts for performance degradation was found to be due to the excess of free carriers from photo-induced electron-hole plasmas [19].

While photo-induced plasmas have an adverse effect on conventional MMICs, it has been found that this phenomenon could be exploited to create *virtual* metal walls that can be defined by patterns of incident light. Indeed, taken to its logical conclusion, an entirely new way of implementing *virtual* MPRWGs has been demonstrated through simulations from 100 to 350 GHz [20]. Instead of having traditional hollow structures with fixed solid metal sidewalls, waveguides have photo-induced *virtual* sidewalls within high resistivity silicon. This compact SIW technology allows components and circuits to be tuneable and system architectures to be reconfigurable, simply by changing light source patterns [20].

To summarise the contributions to knowledge from this section, the findings from paper [19] give a detailed insight into the adverse effects of optically-induced carriers within a semiconductor. It was from this basic idea that the Reconfigurable Terahertz Integrated Architecture (RETINA) idea was born and reported in [20]. It is believed that, while still in its infancy, this technology could have a profound impact on future millimetre-wave and terahertz electronics.

Summary of Personal Contributions

Prior to starting my PhD, I was employed for a short time as a digital systems research engineer and later as a communications systems engineer, within the French and UK space industries, respectively. This experience helped me to see the *big picture* of satellite communications; how complete system architectures are built-up from individual subsystem circuits, within which a single passive component or active device technology can play a critical role in the overall end-to-end performance.

By the end of my 3-year PhD, in 1992, I had already published 12 papers in four areas: directional couplers; Schottky junction varactor diodes; analogue phase shifters (which combined the couplers and diodes); and measurement techniques. This wide-ranging experience at microwave frequencies laid the foundations for knowledge that allowed profound contributions to be made in the fields of millimetre-wave and later terahertz electronics.

By the early 1990s there was already a great deal of commercial activity within the lower part of the millimetre-wave spectrum, in the area of up/down-conversion without any form of signal processing on the carrier signal. Beyond *ca.* 110 GHz, there were some research and development activities taking place within the upper part of the millimetre-wave spectrum.

However, apart from purely scientific experiments, there was relatively little activity at terahertz frequencies. The main reasons why the level of activity decreased with wavelength during this time was the lack of demand for commercial exploitation, the limited knowledge for realizing front-end subsystems, high manufacturing costs and the lack of commercial equipment for undertaking measurements.

Against this backdrop, it soon became evident that the millimetre-wave part of the frequency spectrum was fertile ground for the introduction of signal processing. Moreover, lagging behind millimetre-wave technologies, the terahertz part of the frequency spectrum was still in need of more accurate techniques for designing passive structures. Over the past 18 years, I have personally made great strides in both these areas; undertaking rigorous experimental and theoretical investigations, respectively.

From my industrial experience, I was able to understand the need for creating a low-cost method of implementing adaptive signal processing directly on the millimetre-wave carrier signal. To this end, as a post-doctoral research fellow, I demonstrated programmable M-ary digital modulation and serrodyne frequency translation functions, using monolithic phase shifters that I had previously designed during my PhD. Later, I added tuneable monolithic bi-phase attenuators, to create a single-channel vector modulator, and subsequently demonstrated higher levels of digital modulation. Using a novel topology and biasing approach, I invented an I-Q vector modulator that, in principle, could operate at any frequency; this was later demonstrated by one of my PhD students (D. S. McPherson) at 77 and 110 GHz. In conclusion, by 2001, I had pioneered a technology for performing complex signal processing functions directly on millimetre-wave carrier signals.

During the mid-1990s, I thought it would be *cool* to turn technology inside-out by integrating a metal-pipe rectangular waveguide into a monolithic microwave integrated circuit, instead of the other way around. At that time there was no practical application for this technology. However, the resulting demonstrator appears to be one of the first examples of what is now known as a substrate integrated waveguide, now being used for realising low-loss millimetre-wave interconnects.

Over the past decade I have been proactive, through the work of my PhD students (J.-Y. Choi and S. Pranonsatit), in the design and measurement of novel high performance microelectromechanical systems components, including high power switches, rotary switches and filters. In addition, through the work of my PhD student (C. Chrisostomidis), I helped to develop a new family of transfer functions that can be used specifically to design low-cost millimetre-wave filters. All these activities have made significant contributions to knowledge for the design of components and their manufacture for millimetre-wave applications.

Since the mid-1970s, a number of papers have been published that claim anomalous intrinsic frequency dispersion in normal metals at room temperature. Over the past few years I have systematically deconstructed these claims, with the use of mathematical proofs based on nothing more than first principles. While this may seem to be a trivial exercise, it soon became apparent that there were two approaches to the subject. The first is with little or no knowledge, and this can result in severe design errors at terahertz frequencies. The second is with a great deal of theoretical knowledge in condensed matter physics, but this is of little use to an engineer. My unique activities in this area have resulted in the creation of a third approach, based on developing an engineering insight into accurate modelling of intrinsic frequency dispersion in normal metals at room temperature.

In more recent times, with the help of my PhD student (Y. Zhou), I have been pioneering a technology that has resulted in a paradigm shift in the way millimetre-wave and terahertz components, circuits and systems can be implemented. The basic idea originally came from

the experimental work that I was involved with, back in 1998, to study the effects of photo-induced plasmas within MMICs. To date, this RETINA technology has only been investigated through detailed optoelectronic and electromagnetic simulations. Even so, it appears to have the potential to revolutionize upper-millimetre-wave and terahertz electronics.

Today, the upper-millimetre-wave and terahertz parts of the frequency spectrum are slowly opening up to commercial exploitation. This is because of increased knowledge for designing front-end hardware, reduced manufacturing costs and the availability of commercial measurement equipment. It is believed that, with the substantial contributions to knowledge outlined here, ubiquitous wireless applications at these frequencies will begin to appear in the not too distant future.

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