Introduction to the IEEE JOURNAL OF MICROWAVES

PETER H. SIEGEL[1,2,3] (Life Fellow, IEEE)

(Special Inaugural Issue Editorial)

[1]THz Global, La Canada, CA 91011 USA
[2]Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125 USA
[3]NASA Jet Propulsion Laboratory, Pasadena, CA 91109 USA (e-mail: phs@caltech.edu).

ABSTRACT The new IEEE JOURNAL OF MICROWAVES strives to be a broad-scoped publication serving the whole of the microwave community, both within and beyond the IEEE. This opening article outlines our philosophy and content, presents our editorial team, and introduces our special Inaugural Issue.

Microwaves Are Everywhere "CMB: Hiding in Plain Sight"

PETER H. SIEGEL[1,2,3] (Life Fellow, IEEE)

(Special Series Paper)

[1] THz Global, La Canada, CA 91011 USA
[2] Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125 USA
[3] NASA Jet Propulsion Laboratory, Pasadena, CA 91109 USA (e-mail: phs@caltech.edu)

ABSTRACT This article is the first in a continuing series of general interest papers on the applications of microwaves in areas of science and technology that might not be evident to the casual observer. What better topic to start the series than an introduction to the most pervasive microwave field in the universe: the cosmic microwave background (CMB). The prediction, discovery, and importance of the CMB from a microwave engineering perspective are reviewed and discussed.

Microwave Pioneers: John C. Mather "A Singular Purpose"

PETER H. SIEGEL[1,2,3] (Life Fellow, IEEE)

(Special Series Paper)

[1] THz Global, La Canada, CA 91011 USA
[2] Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125 USA
[3] NASA Jet Propulsion Laboratory, Pasadena, CA 91109 USA (e-mail: phs@caltech.edu)

ABSTRACT This article is the first in a continuing series of biographical pieces on individuals who have made significant and continuous contributions to microwave science, technology, and applications over the course of their careers. It is intended to bring to the reader, especially those new to the field, a portrait of an individual who serves as a role model for the community and a detailed description of their accomplishments. At the same time, it tries to bridge with commonality, the experiences of the subject with those of the scientists, engineers, and technologists who are following in their footsteps or hope to establish a similar record of success. The articles are composed only after an extensive face-to-face interview with the subject and are helped immensely by additional input and editing by the subjects themselves. The focus of this article is Dr. John C. Mather, recipient of the 2006 Nobel Prize in Physics, for the first complete measurement of the cosmic microwave background (CMB) blackbody spectrum, and the first confirmed findings of CMB anisotropy. For astronomers and cosmologists at least, these were arguably two of the most important and influential experimental discoveries of the 20th century. For microwave engineers, the satellite mission that Dr. Mather conceived and worked on for more than fifteen years is a crowning achievement in a very large suite of successful microwave science instruments that NASA has developed, built, and delivered to space.

Microwaves in Chemistry

DANIEL R. SLOCOMBE AND ADRIAN PORCH

(Invited Paper)

Centre for High Frequency Engineering, School of Engineering, Cardiff University, CF10 3AT Cardiff, U.K.

CORRESPONDING AUTHOR: Daniel R. Slocombe (e-mail: SlocombeD1@cardiff.ac.uk).

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ABSTRACT The unique properties of microwaves make them useful in many diverse applications across a wide range of fields, spanning much of engineering and science. In the chemical sciences, microwaves provide a toolkit of electric and magnetic effects with which, at high power, unconventional heating modes can be used to produce new materials not obtainable by conventional heating. At low power, unique microwave properties can be used to make revealing spectroscopic measurements. In this review, we consider the current outlook for microwaves in chemistry beginning with the theoretical framework for our understanding of microwaves interactions and the causes of results observed. We then survey major application areas including in synthesis and emerging areas in catalysis, energy, and environmental applications. Finally, we review new concepts in dielectric and magnetic spectroscopy at microwave frequencies with a focus upon dielectric property measurement and electron paramagnetic resonance. This nonexhaustive review seeks to highlight important and emerging areas in the chemical sciences and put into context recent developments and advances in our understanding of microwave applications in this diverse area of science and engineering.

Instrumentation for THz Spectroscopy in the Laboratory and in Space

JOHN C. PEARSON, BRIAN J. DROUIN (Member, IEEE), AND SHANSHAN YU

(Invited Paper)

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA

CORRESPONDING AUTHOR: Brian J. Drouin (e-mail: brian.j.drouin@jpl.nasa.gov).

This work was supported by the National Aeronautics and Space Administration (NASA).

ABSTRACT Spectroscopic measurements in the millimeter, submillimeter, or THz range, with resolutions exceeding a MHz, provide for highly specific detections of gas-phase absorption and emission by atoms and molecules. Due to relatively low excitation energies involved in the transitions, multiple features are observable in most physical systems, and thus such observations dominate the scientific discovery of molecules in space and contribute significantly to remote sensing of the Earth and planetary bodies. The methods and techniques of THz spectroscopy continue to evolve as capabilities and technologies expand. In this article, we review the genesis of THz spectroscopy in both the laboratory and in space, and follow its development to date, providing background on the challenges, and context for the current developments that promise to extend both remote and *in-situ* gas composition sensing.

Innovative RFID Sensors for Internet of Things Applications

PAOLO MEZZANOTTE (Member, IEEE), VALENTINA PALAZZI (Member, IEEE), FEDERICO ALIMENTI (Senior Member, IEEE), AND LUCA ROSELLI (Fellow, IEEE)

(Invited Paper)

Department of Engineering, University of Perugia, I-06125 Perugia, Italy

CORRESPONDING AUTHOR: PAOLO MEZZANOTTE (e-mail: paolo.mezzanotte@unipg.it).

This work was supported by the University of Perugia, Fundamental Research 2019 programme, through the project "Wireless sensors on green materials for IoT applications."

ABSTRACT Radio-Frequency IDentification (RFID) devices and sensors are among the main innovations of the last years, with an enormous impact on the Internet of Things (IoT) physical communication layer as well as on logistics and robotics. The aim of the present paper is to review the main technologies available for RFID sensors, and to identify the corresponding state-of-the-art when these technologies are applied to realistic IoT scenarios. Firstly, the concepts of radio bascattering and harmonic bascattering are analyzed, highlighting the pros and cons of each approach. Then, state-of-the-art solutions are reported, and the performance of each of them are discussed, to provide an overview of the potential of RFID-based sensing in different scenarios.

Sensing of Life Activities at the Human-Microwave Frontier

CHANGZHI LI[1] (Senior Member, IEEE), VICTOR M. LUBECKE[2] (Fellow, IEEE), OLGA BORIC-LUBECKE[2] (Fellow, IEEE), AND JENSHAN LIN[3] (Fellow, IEEE)

(Invited Paper)

[1]Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409 USA
[2]Department of Electrical and Computer Engineering, University of Hawaii, Honolulu, HI 96822 USA
[3]Department of Electrical Engineering, University of Florida, Gainesville, FL 32611 USA

CORRESPONDING AUTHOR: Changzhi Li (e-mail: changzhi.li@ttu.edu).

The work of Victor M. Lubecke and Olga Boric-Lubecke was supported by the National Science Foundation (NSF) under Grant IIS-1915738. The work of Changzhi Li was supported by NSF under Grants ECCS-1808613 and CNS-1718483.

ABSTRACT Modern microwave radar technologies and systems are taking important roles in healthcare, security, and human–machine interface by remote sensing of human life activities. This paper first reviews the developments in the past decade on the sensing front-end, transponder tag, and leveraging of other wireless infrastructure such as Wi-Fi. Based on the state-of-the-art engineering technologies, several emerging applications will then be studied, including continuous authentication, behavior recognition, human-aware localization, occupancy sensing, blood pressure monitoring, and sleep medicine. As radio frequency spectrum becomes a scarce resource, the allocation and spectrum sharing of life activity sensing bandwidth with other wireless infrastructures will be discussed. Several future research directions will be laid out to solve challenges for ubiquitous deployment of these sensing technologies at the human–microwave frontier.

On the Shoulders of Giants: Reflections on the Creators and Uses of Radio

TOM LEWIS

(Special Invited Editorial)

Emeritus Professor of English, Skidmore College, Saratoga Springs, NY 12866 USA (e-mail: tlewis@skidmore.edu)

"If I have seen further it is by standing on the shoulders of Giants"
Isaac Newton

ABSTRACT This preface-style article contains a brief account of the creators of radio – Lee de Forest, inventor of the triode; Edwin Howard Armstrong, inventor of regeneration, the superheterodyne, and wide-band FM; and David Sarnoff, head of RCA and champion of electronic television – their influences, and the digital age they helped to bring about.

Implementation Challenges and Opportunities in Beyond-5G and 6G Communication

ULF GUSTAVSSON[1], PÅL FRENGER[1], CHRISTIAN FAGER[2] (Senior Member, IEEE), THOMAS ERIKSSON[2] (Senior Member, IEEE), HERBERT ZIRATH[2] (Fellow, IEEE), FRANZ DIELACHER[3] (Senior Member, IEEE), CHRISTOPH STUDER[4] (Senior Member, IEEE), AARNO PÄRSSINEN[5] (Senior Member, IEEE), RICARDO CORREIA[7,8] (Member, IEEE), JOÃO NUNO MATOS[6] (Member, IEEE), DANIEL BELO[6], AND NUNO BORGES CARVALHO[6] (Fellow, IEEE)

(Invited Paper)

[1]Ericsson Research, 11259 Stockholm, Sweden
[2]Chalmers University of Technology, 412 96 Gothenburg, Sweden
[3]Infineon Technologies, 9500 Villach, Austria
[4]Department of Information Technology and Electrical Engineering, ETH Zurich, 8092 Zurich, Switzerland
[5]Center of Wireless Communications, University of Oulu, 90570 Oulu, Finland
[6]Instituto de Telecomunicacoes, Department de Electronica, Telecomunicacoes e Informatica, Universidade de Aveiro, 3810-193 Aveiro, Portugal
[7]Instituto de Telecomunicacoes, Sinuta SA., 3860-529 Estarreja, Portugal
[8]ESTGV, Instituto Politécnico de Viseu, 3504-510 Viseu, Portugal

CORRESPONDING AUTHOR: Ulf Gustavsson (e-mail: ulf.gustavsson@ericsson.com).

ABSTRACT As 5G New Radio (NR) is being rolled out, research effort is being focused on the evolution of what is to come in the post-5G era. In order to meet the diverse requirements of future wireless communication in terms of increased capacity and reduced latency, technologies such as distributed massive Multiple-Input Multiple-Output (MIMO), sub-millimeter wave and Tera-hertz spectrum become technology components of interest. Furthermore, to meet the demands on connectivity anywhere at anytime, non-terrestrial satellite networks will be needed, which brings about challenges both in terms of implementation as well as deployment. Finally, scaling up massive Internet-of-Things (IoT), energy harvesting and Simultaneous Wireless Information and Power Transfer (SWIPT) is foreseen to become important enablers when deploying a large amount of small, low-power radios. In this paper, we will discuss some of the important opportunities these technologies bring, and the challenges faced by the microwave and wireless communication communities.

The Role of Millimeter-Wave Technologies in 5G/6G Wireless Communications

WEI HONG[1,2] (Fellow, IEEE), ZHI HAO JIANG[1,2] (Member, IEEE), CHAO YU[1,2] (Member, IEEE), DEBIN HOU[1], HAIMING WANG[1,2] (Member, IEEE), CHONG GUO[1] (Graduate Student Member, IEEE), YUN HU[2] (Member, IEEE), LE KUAI[1], YINGRUI YU[1] (Member, IEEE), ZHENGBO JIANG[1] (Member, IEEE), ZHE CHEN[1] (Member, IEEE), JIXIN CHEN[1,2] (Member, IEEE), ZHIQIANG YU[1,2] (Member, IEEE), JIANFENG ZHAI[1,2] (Member, IEEE), NIANZU ZHANG[1], LING TIAN[1,2] (Member, IEEE), FAN WU[1] (Member, IEEE), GUANGQI YANG[1,2], ZHANG-CHENG HAO[1,2] (Senior Member, IEEE), AND JIAN YI ZHOU[1,2] (Member, IEEE)

(Invited Paper)

[1]State Key Laboratory of Millimeter-Waves, School of Information Science and Engineering, Southeast University, Nanjing 210096, China
[2]Purple Mountain Laboratories, Nanjing 211111, China

CORRESPONDING AUTHORS: WEI HONG; ZHI HAO JIANG (e-mail: weihong@seu.edu.cn; zhihao.jiang@seu.edu.cn).

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ABSTRACT Ever since the deployment of the first-generation of mobile telecommunications, wireless communication technology has evolved at a dramatically fast pace over the past four decades. The upcoming fifth-generation (5G) holds a great promise in providing an ultra-fast data rate, a very low latency, and a significantly improved spectral efficiency by exploiting the millimeter-wave spectrum for the first time in mobile communication infrastructures. In the years beyond 2030, newly emerged data-hungry applications and the greatly expanded wireless network will call for the sixth-generation (6G) communication that represents a significant upgrade from the 5G network – covering almost the entire surface of the earth and the near outer space. In both the 5G and future 6G networks, millimeter-wave technologies will play an important role in accomplishing the envisioned network performance and communication tasks. In this paper, the relevant millimeter-wave enabling technologies are reviewed: they include the recent developments on the system architectures of active beamforming arrays, beamforming integrated circuits, antennas for base stations and user terminals, system measurement and calibration, and channel characterization. The requirements of each part for future 6G communications are also briefly discussed.

Packaging and Antenna Integration for Silicon-Based Millimeter-Wave Phased Arrays: 5G and Beyond

XIAOXIONG GU (Senior Member, IEEE), DUIXIAN LIU (Fellow, IEEE), AND BODHISATWA SADHU (Senior Member, IEEE)

(Invited Paper)

IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598 USA

CORRESPONDING AUTHOR: Xiaoxiong Gu (e-mail: xgu@us.ibm.com).

ABSTRACT This article reviews current research and development as well as future opportunities for packaging and antenna integration technologies for silicon-based millimeter-wave phased arrays in emerging communication applications. Implementations of state-of-the-art silicon-based phased arrays below 100 GHz are discussed, with emphasis on array architectures for scaling, antenna integration options, substrate materials and process, antenna design, and IC-package codesign. Opportunities and challenges to support phased array applications beyond 100 GHz are then presented, including emerging packaging architectures, interconnect characterization requirements, thermal management approaches, heterogeneous integration of multifunction chiplets, and novel antenna technologies.

Automotive Radar—From First Efforts to Future Systems

CHRISTIAN WALDSCHMIDT[1] (Senior Member, IEEE), JUERGEN HASCH[2] (Senior Member, IEEE), AND WOLFGANG MENZEL[1] (Life Fellow, IEEE)

(Invited Paper)

[1]University of Ulm, 89081 Ulm, Germany
[2]Robert Bosch GmbH, Corporate Sector Research and Advance Engineering, 70465 Stuttgart, Germany

CORRESPONDING AUTHOR: CHRISTIAN WALDSCHMIDT (e-mail: christian.waldschmidt@uni-ulm.de).

ABSTRACT Although the beginning of research on automotive radar sensors goes back to the 1960s, automotive radar has remained one of the main drivers of innovation in millimeter wave technology over the past two decades. Today, millions of sensors are produced each year, which was made possible by inexpensive and mature millimeter wave technology. The technology maturity, in turn, enables research to be carried out on systems that are considerably more complex and powerful than was possible just a few years ago. The focus of research has thus shifted from purely hardware-oriented and device-level topics to sophisticated millimeter wave systems and RF signal processing topics. This opens up new research topics such as digital modulation schemes, radar networks, radar imaging, and machine learning. In this review paper, we sketch the path from the very beginning through the state of the art with sophisticated multiple-input multiple-output (MIMO) antenna arrays and mature assembly and interconnect concepts to today's key research topics of automotive radar.

Coherent Automotive Radar Networks: The Next Generation of Radar-Based Imaging and Mapping

MICHAEL GOTTINGER[1] (Member, IEEE), MARCEL HOFFMANN[1] (Graduate Student Member, IEEE), MARK CHRISTMANN[2], MARTIN SCHÜTZ[2], FABIAN KIRSCH[2], PETER GULDEN[2] (Member, IEEE), AND MARTIN VOSSIEK[1] (Fellow, IEEE)

(Invited Paper)

[1]Institute of Microwaves and Photonics (LHFT), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany
[2]Analog Devices Inc., 85579 Neubiberg/Munich, Germany

CORRESPONDING AUTHOR: MICHAEL GOTTINGER (e-mail: michael.gottinger@fau.de).

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ABSTRACT Imaging radar is a key perception technology for automotive and industrial applications. A lot of progress has been made with high channel count systems, deploying, for example, 12 transmit and 16 receive channels with cascaded monolithic microwave integrated circuit solutions. Nevertheless, fully automated driving requires even higher angular resolution for drive-under/drive-over decisions and exact predictions of object trajectories in dense urban driving scenarios. Both problems can be solved by increasing the antenna size and building larger radars. However, there is a physical limit to what can be placed on the front of a car, and manufacturing very large arrays is quite difficult. Thus, coherent automotive radar networks are a way to achieve high spatial resolution and obtain the complete velocity vector of an object from a single measurement. This solution is commercially attractive, as the sensor can remain relatively small, and complexity can be moved from the physical hardware to algorithms and processing. Two different test setups, each comprised of two multiple-input multiple-output radar units in the 76–77 GHz band, are presented in this article. To obtain azimuth and additional elevation information, the setups use a 1D and a 2D antenna array, respectively. Processing-based coherent evaluation is employed to create an additional radar image with doubled azimuth resolution and improved signal-to-noise ratio and to enable the estimation of vectorial target velocities. These benefits are presented and compared with optical reference images in traffic scenarios.

RF Systems Design for Simultaneous Wireless Information and Power Transfer (SWIPT) in Automation and Transportation

DIEGO MASOTTI[1] (Senior Member, IEEE), MAZEN SHANAWANI[1], GHULAM MURTAZA[1], GIACOMO PAOLINI[1] (Graduate Student Member, IEEE), AND ALESSANDRA COSTANZO[2] (Senior Member, IEEE)

(Invited Paper)

[1]Department of Electrical, Electronic and Information Engineering "G. Marconi," University of Bologna, 40136 Bologna, Italy
[2]Department of Electrical, Electronic and Information Engineering "G. Marconi," University of Bologna, 47521 Cesena, Italy

CORRESPONDING AUTHOR: ALESSANDRA COSTANZO (e-mail: alessandra.costanzo@unibo.it).

ABSTRACT This work presents some recent solutions that exploit the wireless power transfer (WPT) technology for energizing moving vehicles and machinery tools. Such technology is currently experiencing unprecedented interests in non-traditional RF/microwave sectors fields, such the industrial automation and the railway transportation safety. Near-field electromagnetic coupling solutions are presented showing that, in order to obtain efficient performances for broad ranges of operating conditions, the nonlinear electromagnetic co-design of the entire WPT system, from the energy source to the receiver load, needs to be carried out. This technology can be combined with wireless data transfer, thus realizing integrated systems able to simultaneously control the energy transfer and the transmission of data. The adopted operating frequencies are in the MHz range, which is only recently considered for this kind of applications. In particular this work focuses on three different systems: the first one demonstrates the constant powering of "on the move" industrial charts at 6.78 MHz, regardless of the relative position of the transmitter and the receiver sub-systems; the second one presents a novel design of a balise transportation system adopting a high efficiency GaN-based transmitter designed to keep its performance over a wide range of loading conditions; the last one consists of the simultaneous wireless power and data transfer, to a rotating machinery tool, automatically controlled by the powering system based on the coexistence of frequency-diverse inductive and capacitive couplings.

Microwave Photonic Array Radars

SHILONG PAN (Senior Member, IEEE), XINGWEI YE (Student Member, IEEE), YAMEI ZHANG (Member, IEEE), AND FANGZHENG ZHANG (Senior Member, IEEE)

(Invited Paper)

Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

CORRESPONDING AUTHOR: FANGZHENG ZHANG (e-mail: zhangfangzheng@nuaa.edu.cn).

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ABSTRACT Phased array radars have remarkable advantages over radars with single-element antenna in terms of agility, flexibility, robustness, and reconfigurability. Current pure-electronic phased array radars face challenges when operating with a large frequency tunable range and/or with broad instantaneous bandwidth. Microwave photonics, which allows wide bandwidth, flat frequency response, low transmission loss, and immunity to electromagnetic interference, is a promising solution to cope with issues faced by pure electronics. In this paper, we introduce a general architecture of microwave photonic array radar systems and review the recent advancement of optical beamforming networks. The key elements for modelling the response of the true time delay (TTD) and/or phase-shifting unit are presented and discussed. Two typical array antenna structures are introduced, i.e., microwave photonic phase shifter based array and optical true time delay based array, of which the principle and typical implementations are described. High-resolution inverse synthetic aperture radar (ISAR) imaging is also realized based on a microwave photonic array radar. The possibility of on-chip integration of the microwave photonic array radar is discussed.

Micrometer Sensing With Microwaves: Precise Radar Systems for Innovative Measurement Applications

FABIAN MICHLER[1] (Student Member, IEEE), BENEDICT SCHEINER[1] (Student Member, IEEE), TORSTEN REISSLAND[1] (Student Member, IEEE), ROBERT WEIGEL[1] (Fellow, IEEE), AND ALEXANDER KOELPIN[2] (Senior Member, IEEE)

(Invited Paper)

[1]Institute for Electronics Engineering, Friedrich-Alexander University Erlangen-Nuremberg, 91058 Erlangen, Germany
[2]Institute of High-Frequency Technology, Hamburg University of Technology, 21073 Hamburg, Germany

CORRESPONDING AUTHOR: Fabian Michler (e-mail: fabian.michler@fau.de).

ABSTRACT Radar sensors have been widely used to estimate speed and displacement of remote targets. A novel market for contactless radar sensing is emerging in the field of automatization and process analysis, where non destructive testing and evaluation methods are desired. Here, modern radar systems offer various advantages over conventional sensors since they enable the contactless, continuous, and cost-efficient measurement of static or dynamic ranges. These can further be used for vibration and vital sign characterization. Advances in microwave technology, an increasing integration density, and the development of novel algorithms keep boosting the performance of the systems. After introducing the most common operation principles, such as unmodulated and frequency-modulated continuous-wave radar, different design aspects and building blocks of cutting-edge systems are explained in detail. In the second part, selected applications are described in detail. These include the sheet thickness monitoring of metallic foils, and the measurement of the ground speed of vehicles with the latest approaches. Exemplary low-power radar systems are presented to show the limits in terms of power consumption while still offering a high measurement precision. In addition, the topics of mechanical vibration sensing and vital sign sensing are addressed by introducing tailored systems.

Microwave and Millimeter Wave Power Beaming

CHRISTOPHER T. RODENBECK[1] (Senior Member, IEEE), PAUL I. JAFFE[1] (Senior Member, IEEE), BERND H. STRASSNER II[2], PAUL E. HAUSGEN[3], JAMES O. McSPADDEN[4] (Senior Member, IEEE), HOOMAN KAZEMI[5] (Senior Member, IEEE), NAOKI SHINOHARA[6] (Senior Member, IEEE), BRIAN B. TIERNEY[1] (Member, IEEE), CHRISTOPHER B. DePUMA[1], AND AMANDA P. SELF[3]

(Invited Paper)

[1]U.S. Naval Research Laboratory, Washington, DC 20375-5307 USA
[2]Sandia National Laboratories, Albuquerque, NM 87185 USA
[3]Air Force Research Laboratory, Kirtland AFB, NM 87117-5776 USA
[4]Raytheon Technologies Corporation, Dallas, TX 75243 USA
[5]Raytheon Technologies Corporation, Thousand Oaks, CA 91361-4443 USA
[6]Research Institute for Sustainable Humanosphere, Kyoto University, Uji 611-0011, Japan

CORRESPONDING AUTHOR: Christopher T. Rodenbeck (e-mail: chris.rodenbeck@ieee.org).

ABSTRACT Power beaming is the efficient point-to-point transfer of electrical energy across free space by a directive electromagnetic beam. This paper clarifies the basic principles of power beaming in simple terms, and proposes a benchmarking methodology for improving the comparative assessment of power beaming systems and technology. An in-depth historical overview tracing the worldwide progress in microwave and millimeter wave (mmWave) experimental demonstrations over the past 60 years shows clear evidence of a significant increase in activity during the last 5 years. In addition, a review of progress in scalable rectenna arrays for the reception of microwave power beaming shows sufficient maturity for new research to initiate on the ruggedization, productization, and system integration aspects of the technology. A review of regulatory issues including spectrum management and safety indicates the need for additional technical solutions and international coordination. Breaking results reported in this paper include 1) data from the first in-orbit flight test of a solar-to-RF "sandwich module", 2) the construction of multiple US in-orbit demonstrations, planned for 2023 launch, that will demonstrate key technologies for space-based solar power, and 3) a 100-kW mmWave power beaming transmitter demonstrating inherent human life safety.

Microwave Imaging in Security—Two Decades of Innovation

SHERIF S. AHMED

(Invited Paper)

Stanford University, Stanford, CA 94305 USA (e-mail: sherifahmed@ieee.org).

ABSTRACT The microwave spectrum is one of the most valuable natural resource used nowadays in communication, navigation, and remote sensing. With over a century of heritage, imaging with electromagnetics had been puzzling researchers and engineers alike. When science and technology advanced enough, early imaging solutions at the lower end of the microwave spectrum were revealed. Airborne synthetic aperture radars (SAR), and later spaceborne SAR, were first to evolve. With their unprecedented capabilities in earth observation and reconnaissance, researchers became even more eager to extend SAR imaging to higher frequencies and for different applications. The last two decades have remarkably delivered breakthroughs and innovations to re-invent microwave technologies for personnel security screening purposes. Microwave signals can safely penetrate clothing and reveal concealed threats, e.g., explosives and firearms, without imposing any health risks or side effects. This paper presents a historical overview of this evolution and highlights the latest advances in security microwave imaging.

History and Innovation of Wireless Power Transfer via Microwaves

NAOKI SHINOHARA (Senior Member, IEEE)

(Invited Paper)

Research Institute for Sustainable Humanosphere, Kyoto University, Kyoto 6110011, Japan (e-mail: shino@rish.kyoto-u.ac.jp)

ABSTRACT Wireless power transfer (WPT) has a long history of over 100 years since the first experiment conducted by Nicola Tesla. However, the most interesting innovation of WPT was born in the 21st century. In this decade, near-field WPT commercialization was advanced, and we now use many near-field WPT products, such as wireless chargers for mobile phones and electric vehicles. In the next decade, we can expect the development of far-field WPT via microwaves, through which we can drive Internet of Things (IoT) sensors without batteries based on transmitted or ambient microwave power. We can charge mobile phones with microwave power. When we focus microwave power on a target by beam forming technology, we can transmit higher wireless power to fly drones or from space to the earth. In conjunction with the research & development of microwave-based WPT, radio regulations suitable for each country need to be discussed. In this paper, I review the history, innovation, and status of the radio regulations of WPT via microwaves with the classification of wide-beam WPT, including harvesting, and narrow-beam WPT.

Russian Gyrotrons: Achievements and Trends

ALEXANDER G. LITVAK (Member, IEEE), GREGORY G. DENISOV (Member, IEEE), AND MIKHAIL Y. GLYAVIN (Member, IEEE)

(Invited Paper)

Institute of Applied Physics RAS, Nizhny Novgorod 603950, Russia

CORRESPONDING AUTHOR: MIKHAIL Y. GLYAVIN (e-mail: glyavin@appl.sci-nnov.ru).

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ABSTRACT The last decade has contributed to the rapid progress in the gyrotron development. Megawatt-class, continuous wave gyrotrons are employed as high-power millimeter (mm)-wave sources for electron cyclotron heating (ECH) and current drive in the tokamaks and stellarators. The progress in gyrotron development pushes ECH from a minor to a major heating method. Also gyrotron based technological complexes successfully applied in electron cyclotron resonance ion sources, for microwave ceramic sintering and diamond disk production. The paper describes the main features of high frequency gyrotrons. Some data about pulsed and CW tubes, working in the terahertz frequency range, are given. These gyrotrons operate (in some specific combinations) at very low voltage and beam current, demonstrate an extremely narrow frequency spectrum or wide frequency tuning. Although in comparison with the classical microwave tubes the gyrotrons are characterized by greater volume and weight due to the presence of bulky parts (such as superconducting magnets and massive collectors where the energy of the spent electron beam is dissipated) they can easily be embedded in a sophisticated laboratory equipment (e.g., spectrometers, technological systems, etc.). All these advantageous features have opened the road to many novel and prospective applications of gyrotrons.

Carver Mead: "It's All About Thinking," A Personal Account Leading up to the First Microwave Transistor

PETER H. SIEGEL (Life Fellow, IEEE)

(Special Series Paper)

THz Global, La Canada, CA 91011 USA
Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125 USA
NASA Jet Propulsion Laboratory, Pasadena, CA 91109 USA (e-mail: phs@caltech.edu)

ABSTRACT This article is the second in a continuing series of biographical pieces on individuals who have made significant contributions to microwave science, technology and applications over the course of their careers. It is intended to bring to the reader, especially those new to the field, a portrait of an individual who serves as a role model for the community and a detailed description of their accomplishments. At the same time, it tries to bridge with commonality, the experiences of the subject with those of the scientists, engineers and technologists who are following in their footsteps or hope to establish a similar record of success. The articles are composed only after an extensive face-to-face interview with the subject and are helped immensely by additional input and editing by the subjects themselves. The focus of this article is Caltech Professor Carver A. Mead, perhaps best known for his ground breaking work on VLSI design techniques, but also for the first demonstration of the GaAs MESFET and the originator of Moore's Law. However, Professor Mead has contributed so much more, and to so many disciplines other than electrical engineering. From his own description of his interests and focus, he is a chameleon of knowledge, scrambling into, blending with, and then distinguishing himself in a new field every thirteen years or so, over a career spanning seven decades and still going. At age 86, his latest paper, on an intuitive approach to electromagnetically coupled single-electron quantum systems, was just published this summer. Although we cannot do justice to all his contributions, we hope the reader will see something of the polymath in Professor Mead as we focus just on his earliest work, where he single handedly conceived, constructed, and tested the world's first Schottky barrier gate transistor in his modest laboratory at Caltech.

SiGe HBTs and BiCMOS Technology for Present and Future Millimeter-Wave Systems

THOMAS ZIMMER [1] (Senior Member, IEEE), JOSEF BÖCK[2], FRED BUCHALI[3], PASCAL CHEVALIER [4] (Member, IEEE), MICHAEL COLLISI[5], BJÖRN DEBAILLIE[6], MARINA DENG[1] (Member, IEEE), PHILIPPE FERRARI [7], SEBASTIEN FREGONESE[1], CHRISTOPHE GAQUIERE [8], HAITHAM GHANEM [8], HORST HETTRICH [9], ALPER KARAKUZULU[10], TIM MAIWALD[11], MARC MARGALEF-ROVIRA [7,8], CAROLINE MAYE[8], MICHAEL MÖLLER[5], ANINDYA MUKHERJEE[12], HOLGER RÜCKER[10], PAULIUS SAKALAS[12,13,14,15], ROLF SCHMID[9], KARINA SCHNEIDER[16], KARSTEN SCHUH[3], WOLFGANG TEMPL [3], AKSHAY VISWESWARAN [6], AND THOMAS ZWICK [16]

(Invited Paper)

[1]IMS Laboratory, CNRS, University of Bordeaux, 33400 Talence Cedex, France
[2]Infineon Technologies AG, 85579 Neubiberg, Germany
[3]Nokia Bell Labs, 70435 Stuttgart, Germany
[4]STMicroelectronics, 38920 Crolles, France
[5]Saarland University, 66123 Saarbrücken, Germany
[6]IMEC, 3001 Leuven, Belgium
[7]University of Grenoble Alpes, 38400 Saint-Martin-d'Hères, France
[8]IEMN Laboratory, University of Lille, 59 652 Villeneuve d'Ascq Cedex, France
[9]Micram Microelectronic GmbH, 44801 Bochum, Germany
[10] IHP - Leibniz-Institut für innovative Mikroelektronik, 15236 Frankfurt (Oder), Germany
[11]FAU, Friedrich-Alexander University Erlangen-Nürnberg, 91054 Erlangen, Germany
[12]Technical University of Dresden, 01069 Dresden, Germany
[13]MDPI Corporation, Germany
[14]National Center of Fundamental Sciences and Technology, Vilnius, Lithuania
[15]Baltic Institute of Advanced Technology, 01124 Vilnius, Lithuania
[16]Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

CORRESPONDING AUTHOR: Thomas Zimmer (e-mail: thomas.zimmer@u-bordeaux.fr).

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ABSTRACT This paper gives an overall picture from BiCMOS technologies up to THz systems integration, which were developed in the European Research project TARANTO. The European high performance BiCMOS technology platforms are presented, which have special advantages for addressing applications in the submillimeter-wave and THz range. The status of the technology process is reviewed and the integration challenges are examined. A detailed discussion on millimeter-wave characterization and modeling is given with emphasis on harmonic distortion analysis, power and noise figure measurements up to 190 GHz and 325 GHz respectively and S-parameter measurements up to 500 GHz. The results of electrical compact models of active (HBTs) and passive components are presented together with benchmark circuit blocks for model verification. BiCMOS-enabled systems and applications with focus on future wireless communication systems and high-speed optical transmission systems up to resulting net data rates of 1.55 Tbit/s are presented.

Substrate Integrated Transmission Lines: Review and Applications

KE WU [1] (Fellow, IEEE), MAURIZIO BOZZI [2] (Fellow, IEEE), AND NELSON J. G. FONSECA [3] (Senior Member, IEEE)

(Invited Paper)

[1]Poly-Grames Research Center, Department of Electrical Engineering, Polytechnique Montréal (University of Montreal), Montréal, QC H3T 1J4, Canada
[2]Department of Electrical, Computer and Biomedical Engineering, University of Pavia, 27100 Pavia, Italy
[3]Antenna and Sub-Millimetre Waves Section, European Space Agency, 2200 Noordwijk, Netherlands

CORRESPONDING AUTHOR: Ke Wu (e-mail: ke.wu@polymtl.ca).

ABSTRACT This paper presents a general overview of substrate integrated transmission lines, from the perspective of historical background and progress of guided-wave structures and their impacts on the development of microwave circuits and integration solutions. This is highlighted through a technology roadmap involving the categorized five generations of microwave circuits. In particular, the substrate integration technologies are reviewed and discussed with focus on technical features, design highlights, component developments, structures evolution, and systems integration. A number of examples are presented to showcase some of the selected milestone research and development activities and accomplishments in connection with substrate integrated transmission line technologies, with particular focus on substrate integrated waveguide (SIW) techniques. Practical applications and industrial interests are also presented with key references and technical results, which show more and more product developments in the end-user sectors. It can be found that the popularity of SIW techniques is closely related to the achieved seamless integration of planar and non-planar structures into a unified design space, thereby allowing the possibility of combining major advantages of all the structures while alleviating their potential drawbacks. The future perspectives of the substrate integration technology are discussed through five major research directions, which suggest potential impacts in the development of future generations of circuits and systems such as system-on-substrate (SoS).

CNTFET Technology for RF Applications: Review and Future Perspective

MARTIN HARTMANN [1,2], SASCHA HERMANN[1,2,3], PHIL F. MARSH[4], CHRISTOPHER RUTHERGLEN[4], DAWEI WANG[5], LI DING [6], LIAN-MAO PENG [6], MARTIN CLAUS [7], AND MICHAEL SCHRÖTER[7] (Senior Member, IEEE)

(Invited Paper)

[1]Center for Microtechnology, Chemnitz University of Technology, 09111 Chemnitz, Germany
[2]Center for Advancing Electronics Dresden, 09111 Chemnitz, Chemnitz
[3]Fraunhofer Institute for Electronic Nanosystems, 09126 Chemnitz, Germany
[4]Carbonics Inc., Culver City, CA 90230 USA
[5]Carbon Technology Inc., Irvine, CA 92619 USA
[6]Key Laboratory for the Physics and Chemistry of Nanodevices and Center for Carbon-based Electronics, Department of Electronics, Peking University, Beijing 100871, China
[7]Chair for Electron Devices and Integrated Circuits, Technical University Dresden, 01069 Dresden, Germany

CORRESPONDING AUTHOR: Martin Hartmann (e-mail: martin.hartmann@zfm.tu-chemnitz.de).

(All authors have contributed equally to this work.)

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ABSTRACT RF CNTFETs are one of the most promising devices for surpassing incumbent RF-CMOS technology in the near future. Experimental proof of concept that outperformed Si CMOS at the 130 nm technology has already been achieved with a vast potential for improvements. This review compiles and compares the different CNT integration technologies, the achieved RF results as well as demonstrated RF circuits. Moreover, it suggests approaches to enhance the RF performance of CNTFETs further to allow more profound CNTFET based systems e.g., on flexible substrates, highly dense 3D stacks, heterogeneously combined with incumbent technologies or an all-CNT system on a chip.

Millimeter-Wave Power Amplifier Integrated Circuits for High Dynamic Range Signals

HUA WANG [1] (Senior Member, IEEE), PETER M. ASBECK [2] (Fellow, IEEE), AND CHRISTIAN FAGER [3] (Senior Member, IEEE)

(Invited Paper)

[1]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA
[2]Department of Electrical and Computer Engineering, University of California San Diego, La Jolla, CA 92093 USA
[3]Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296 Göteborg, Sweden

CORRESPONDING AUTHORS: Hua Wang; Peter M. Asbeck; Christian Fager (hua.wang@ece.gatech.edu; asbeck@ece.ucsd.edu; christian.fager@chalmers.se).

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ABSTRACT The next-generation 5G and beyond-5G wireless systems have stimulated a substantial growth in research, development, and deployment of mm-Wave electronic systems and antenna arrays at various scales. It is also envisioned that large dynamic range modulation signals with high spectral efficiency will be ubiquitously employed in future communication and sensing systems. As the interface between the antennas and transceiver electronics, power amplifiers (PAs) typically govern the output power, energy efficiency, and reliability of the entire wireless systems. However, the wide use of high dynamic range signals at mm-Wave carrier frequencies substantially complicates the design of PAs and demands an ultimate balance of energy efficiency and linearity as well as other PA performances. In this review paper, we will first introduce the system-level requirements and design challenges on mm-Waves PAs due to high dynamic range signals. We will review advanced active load modulation architectures for mm-Wave PAs and power devices. We will then introduce recent advances in mm-Wave PA technologies and innovations with several design examples. Special design considerations on mm-Wave PAs for phased array MIMOs and high mm-Wave frequencies will be outlined. We will also share our vision on future technology trends and innovation opportunities.

Emerging Trends in Techniques and Technology as Applied to Filter Design

RICHARD V. SNYDER [1] (Life Fellow, IEEE), GIUSEPPE MACCHIARELLA [2] (Fellow, IEEE), SIMONE BASTIOLI [1] (Senior Member, IEEE), AND CRISTIANO TOMASSONI [3] (Senior Member, IEEE)

(Invited Paper)

[1] RS Microwave, Butler, NJ 07405 USA
[2] Politecnico di Milano, 20133 Milano, Italy
[3] University of Perugia, 06123 Perugia, Italy

CORRESPONDING AUTHOR: Richard V. Snyder (email: r.snyder@ieee.org).

ABSTRACT In the last decade, the filter community has innovated both design techniques and the technology used for practical implementation. In design, the philosophy has become "if you can't avoid it, use it", a very practical engineering approach. Modes previously deemed spurious are intentionally used to create in-line networks incorporating real or imaginary transmission zeros and also reduce the number of components and thus further miniaturize; spurious responses are re-routed to increase the passband width or stopband width, frequency variation in couplings is used to create complex transfer functions, with all of these developments using what was previously avoided. Clever implementations of baluns into passive and active networks is resulting in a new generation of noise-immune filters for 5G and beyond. Finally, the use of a diakoptic approach to synthesis has appeared an evolving approach in which small blocks ("singlets", "doublets", etc.) are cascaded to implement larger networks, (reducing the need for very complex synthesis), with this new approach promising a large impact on the implementation of practical structures. Filter technology has migrated towards "observe it and then adapt it", pragmatically repurposing tools not specifically originally intended for the applications. Combinations of surface wave and bulk wave resonators with L-C networks are improving the loss characteristics of filters in the region below 2 GHz. Lightweight alloys and other materials designed for spacecraft are being used in filters intended for space, to provide temperature stability without the use of heavy alloys such as Invar. Fully-enclosed waveguide is being replaced in some cases by planar and quasiplanar structures propagating quasi-waveguide modes. This is generically referred to as SIW (Substrate Integrated Waveguide). Active filters trade noise figure for insertion loss but perhaps will offer advantage in terms of size and chip-level implementation. Finally, the era of reconfiguration might be approaching, as the basic networks are evolving, perhaps lacking only the appearance of lower-loss, higher-IP solid-state tuning elements.

Connecting Chips With More Than 100 GHz Bandwidth

WOLFGANG HEINRICH [1] (Fellow, IEEE), MARUF HOSSAIN [1], SIDDHARTHA SINHA [2], FRANZ-JOSEF SCHMÜCKLE[1], RALF DOERNER [1] (Member, IEEE), VIKTOR KROZER[1,3] (Senior Member, IEEE), AND NILS WEIMANN [1,4] (Member, IEEE)

(Invited Paper)

[1]Ferdinand-Braun-Institut (FBH), Leibniz-Institut für Höchstfrequenztechnik, 12489 Berlin, Germany
[2]IMEC, 3001 Leuven, Belgium
[3]Physikalisches Institut, Johann Wolfgang Goethe-Universität, 60323 Frankfurt, Germany
[4]Department High Frequency Electronic Components (BHE), University of Duisburg-Essen, 47057 Duisburg, Germany

CORRESPONDING AUTHOR: WOLFGANG HEINRICH (e-mail: wolfgang.heinrich@fbh-berlin.de).

This work was supported by the German BMBF within the "Forschungsfabrik Mikroelektronik Deutschland (FMD)" framework under Ref. 16FMD02.

ABSTRACT Connecting chips within a module is a basic requirement in transforming MMIC performance to system functionality. More and more applications demand for operation at high mm-wave frequencies or with ultra-large bandwidth. While semiconductor devices have seen tremendous progress in terms of their frequency limits, the chip interconnects lag behind and often form the bottleneck in realizing such systems. This paper reviews the broadband potential of the most common interconnect types in use and their performance demonstrated so far, covering wirebonding, approaches with chips embedded in a substrate, and flip-chip. Additionally, as an intermediate solution between system-on-chip and system-in-a-package, semiconductor hetero-integration on the chip-level is included. As is discussed, bond wire interconnects are most limited in bandwidth among the four types and reach the 100 GHz band only at the expense of narrowband characteristics. Dedicated embedded-chip packaging techniques show significantly better performance, bandwidths in the order of 100 GHz have been shown in the literature. Flip-chip has clearly the highest potential, interconnects covering the range from DC to 500 GHz have been demonstrated and are presented in the paper. Hetero-integration on the chip proves to allow for very broadband interconnects between elements and circuits on the compound chip as well: For an InP-on-BiCMOS process 325 GHz bandwidth were achieved and even higher values seem to be feasible.

Microwave Superconductivity

STEVEN M. ANLAGE (Member, IEEE)

(Invited Paper)

Quantum Materials Center, Department of Physics, University of Maryland, College Park, MD 20742-4111 USA
Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742-3285 USA
Department of Materials Science and Engineering, University of Maryland, College Park, MD 20742-2115, USA (e-mail: anlage@umd.edu)

This work was supported by the U.S. Department of Energy under Grant DESC0018788 (support of SMA) and the U.S. National Science Foundation under Grant DMR2004386.

ABSTRACT We give a broad overview of the history of microwave superconductivity and explore the technological developments that have followed from the unique electrodynamic properties of superconductors. Their low loss properties enable resonators with high quality factors that can nevertheless handle extremely high current densities. This in turn enables superconducting particle accelerators, high-performance filters and analog electronics, including metamaterials, with extreme performance. The macroscopic quantum properties have enabled new generations of ultra-high-speed digital computing and extraordinarily sensitive detectors. The microscopic quantum properties have enabled large-scale quantum computers, which at their heart are essentially microwave-fueled quantum engines. We celebrate the rich history of microwave superconductivity and look to the promising future of this exciting branch of microwave technology.

MID-Radio Telescope, Single Pixel Feed Packages for the Square Kilometer Array: An Overview

ALICE PELLEGRINI [1] (Member, IEEE), JONAS FLYGARE [2] (Student Member, IEEE), ISAK P. THERON [3] (Member, IEEE), ROBERT LEHMENSIEK[3] (Senior Member, IEEE), ADRIAAN PEENS-HOUGH[4], JAMIE LEECH[5], MICHAEL E. JONES[5], ANGELA C. TAYLOR [5], ROBERT E. J. WATKINS[5], LEI LIU[5], ANDRE HECTOR[5], BIAO DU[6], AND YANG WU[6]

(Invited Paper)

[1] SKA Organization, SK11 9FT Cheshire, U.K.
[2] Onsala Space Observatory, Department of Space, Earth and Environment, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
[3] EMSS Antennas, Technopark, Stellenbosch 7600, South Africa
[4] South African Radio Astronomy Observatory (SARAO), Systems Engineering Department, Cape Town 7925, South Africa
[5] Department of Physics (Astrophysics), University of Oxford, OX1 4BH Oxford, U.K.
[6] Joint Laboratory for Radio Astronomy Technology/The 54th Research Institute of CETC, Shijiazhuang 050081, China

CORRESPONDING AUTHOR: Alice Pellegrini (e-mail: a.pellegrini@skatelescope.org).

ABSTRACT The Square Kilometre Array (SKA) project is an international effort to build the world's largest radio telescope, enabling science with unprecedented detail and survey speed.The project spans over a decade and is now at a mature stage, ready to enter the construction and integration phase. In the fully deployed state, the MID-Telescope consists of a 150-km diameter array of offset Gregorian antennas installed in the radio quiet zone of the Karoo desert (South Africa). Each antenna is equipped with three feed packages, that are precision positioned in the sub-reflector focus by a feed indexer platform. The total observational bandwidth (0.35-15.4GHz) is segmented into seven bands. Band 1 (0.35 – 1.05 GHz) and Band 2 (0.95 – 1.76 GHz) are implemented as individual feed packages. The remaining five bands (Bands 3, 4, 5a, 5b, and 6) are combined in a single feed package. Initially only Band 5a (4.6 – 8.5 GHz) and Band 5b (8.3 – 15.4 GHz) will be installed. This paper provides an overview of recent progress on design, test and integration of each feed package as well as project and science goals, timeline and path to construction.

Microwave Huygens' Metasurfaces: Fundamentals and Applications

VASILEIOS G. ATALOGLOU, MICHAEL CHEN, MINSEOK KIM, AND GEORGE V. ELEFTHERIADES (Fellow, IEEE)

(Invited Paper)

The Edward S. Rogers Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4, Canada
CORRESPONDING AUTHOR: George V. Eleftheriades (e-mail: gelefth@waves.utoronto.ca).

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ABSTRACT In this article, we review the topic of Huygens' metasurfaces with an emphasis on existing and emerging applications at microwave frequencies. Huygens' metasurfaces have demonstrated unprecedented capabilities of controlling electromagnetic wavefronts by means of electric and magnetic dipole moments arranged in a thin sheet. We present the fundamental principles of Huygens' metasurfaces based on the boundary conditions governing their operation. Then, we discuss the aspect of practical realization of Huygens' metasurfaces and the different types of constituent subwavelength scatterers (unit cells). Moreover, we summarize recent developments in several areas related to metasurfaces, such as perfect anomalous refraction, polarization control, antenna beamforming and reconfigurable metasurfaces. Lastly, we provide a brief outlook on emerging metasurface-based microwave technologies that are expected to further grow in the future.

Microwaves in Quantum Computing

JOSEPH C. BARDIN [1,2] (Senior Member, IEEE), DANIEL H. SLICHTER[3] (Senior Member, IEEE), AND DAVID J. REILLY[4,5] (Member, IEEE)

(Invited Paper)

[1]Department of Electrical and Computer Engineering, University of Massachusetts Amherst, Amherst, MA 01003 USA
[2]Google LLC, Goleta, CA 93117 USA
[3]Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305 USA
[4]Microsoft Inc., Microsoft Quantum Sydney, The University of Sydney, Sydney, NSW 2050, Australia
[5]ARC Centre of Excellence for Engineered Quantum Systems (EQuS), School of Physics, The University of Sydney, Sydney, NSW 2050, Australia

CORRESPONDING AUTHOR: Joseph C. Bardin (e-mail: jbardin@engin.umass.edu).

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ABSTRACT Quantum information processing systems rely on a broad range of microwave technologies and have spurred development of microwave devices and methods in new operating regimes. Here we review the use of microwave signals and systems in quantum computing, with specific reference to three leading quantum computing platforms: trapped atomic ion qubits, spin qubits in semiconductors, and superconducting qubits. We highlight some key results and progress in quantum computing achieved through the use of microwave systems, and discuss how quantum computing applications have pushed the frontiers of microwave technology in some areas. We also describe open microwave engineering challenges for the construction of large-scale, fault-tolerant quantum computers.

Microwave Magnetics and Considerations for Systems Design

MICHAEL GEILER, SCOTT GILLETTE, MAHIMA SHUKLA, PIOTR KULIK (Member, IEEE), AND ANTON L. GEILER (Senior Member, IEEE)

(Invited Paper)

Metamagnetics Inc., Westborough, MA 01581 USA
CORRESPONDING AUTHOR: Anton L. Geiler (e-mail: ageiler@mtmgx.com).

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ABSTRACT The adoption of non-linear magnetic devices in Radio Frequency (RF) systems has been relatively slow due to their unique characteristics that do not lend themselves well to traditional design tools and methodologies. Herein we present the practical considerations in employing such devices in modern RF system design with an emphasis on realizable improvements in performance and adaptability in addition to the common design methodology that has been adopted to account for their unique behavior. Specifically, this article begins by presenting how a standalone nonlinear device such as a Frequency Selective Limiter (FSL) can enable a higher-level subsystem such as the Frequency Selective Canceller (FSC). This discussion sheds light on the importance of characterizing the behavior of an FSL and how this behavior is different from other, more traditional RF components such as a Pin Diode Limiter, as explained in the second part of the article. Lastly, a Magnetostatic Wave (MSW) delay line that leverages the recent advancements in non-linear magnetic device design is introduced in order to provide an attractive alternative to traditional delay lines. A more complete understanding of system-level performance benefits and device-level functionality will undoubtedly facilitate the widescale deployment of nonlinear magnetic devices to help mitigate spectrum congestion challenges faced by modern and future RF systems.

Non-Magnetic Non-Reciprocal Microwave Components—State of the Art and Future Directions

ARAVIND NAGULU (Student Member, IEEE), AND HARISH KRISHNASWAMY (Member, IEEE)

(Invited Paper)

Columbia University, New York, NY 10027 USA

CORRESPONDING AUTHOR: HARISH KRISHNASWAMY (e-mail: harish@ee.columbia.edu).

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ABSTRACT Non-reciprocal components such as circulators, isolators and gyrators find utility in numerous microwave wireless applications, including high-power transmitters, simultaneous transmit-and-receive communication and radar systems, and emerging cryogenic quantum computing implementations. Today, such components are implemented using ferrite materials, which lose their reciprocity under the application of an external magnetic field. However, ferrite materials are incompatible with semiconductor integrated-circuit fabrication processes, and therefore ferrite non-reciprocal components are difficult to miniaturize to chip scales, rendering them bulky and expensive. This has motivated significant research into non-magnetic non-reciprocal components over the past 50 years. In recent years, this research has been invigorated by breakthroughs in time-modulated non-reciprocal components, and their integration into silicon integrated circuits. This paper reviews the history of non-reciprocal electronics, surveys recent research results in the area, and describes outstanding directions for future research.

On the Benefits of Glide Symmetries for Microwave Devices

OSCAR QUEVEDO-TERUEL [1] (Senior Member, IEEE), QIAO CHEN [1] (Member, IEEE), FRANCISCO MESA [2] (Fellow, IEEE), NELSON J. G. FONSECA [3] (Senior Member, IEEE), AND GUIDO VALERIO [4,5] (Senior Member, IEEE)

(Invited Paper)

[1] Division for Electromagnetic Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden
[2] Department of Applied Physics 1, ETS de Ingenieria Informatica, Universidad de Sevilla, 41012 Sevilla, Spain
[3] Antenna and Sub-Millimeter Waves Section, European Space Agency, 2200 AG Noordwijk, The Netherlands
[4] Sorbonne Université, CNRS, Laboratoire de Génie Electrique et Electronique de Paris, 75252 Paris, France
[5] Université Paris-Saclay, CentraleSupélec, CNRS, Laboratoire de Génie Electrique et Electronique de Paris, 91192 Gif-sur-Yvette, France

CORRESPONDING AUTHOR: OSCAR QUEVEDO-TERUEL (e-mail: oscarqt@kth.se).

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ABSTRACT The presence of glide symmetries in periodic structures can introduce beneficial modifications in their electromagnetic properties. The difference between glide and non-glide periodic structures is due to the distinctive coupling between their constituent sub-unit cells. In this paper, we describe the recent discoveries on the remarkable properties of glide-symmetric periodic structures, which include widened stopbands, reduced dispersion, as well as enhanced anisotropy and magnetic response. These properties are explained through canonical structures simulated with two methods: mode matching and multimode transfer-matrix analysis. We also review the recent use of these distinctive properties for solving technological problems in practical devices such as filters, gap waveguide components, low-leakage flanges, compressed lenses, low-reflected material transitions and leaky-wave antennas with applications in 5G terrestrial communication systems, millimetre-wave satellite systems and automated contactless measurement techniques.

Sommerfeld Integrals and Their Relation to the Development of Planar Microwave Devices

JUAN R. MOSIG [1] (Life Fellow, IEEE), AND KRZYSZTOF A. MICHALSKI [2] (Life Fellow, IEEE)

(Invited Paper)

[1] École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland
[2] Electrical and Computer Engineering Department, Texas A&M University, College Station, TX 77843-3128 USA

CORRESPONDING AUTHOR: Juan R. Mosig (e-mail: juan.mosig@epfl.ch).

ABSTRACT This paper deals with the mathematical expressions called Sommerfeld integrals. Introduced by A. Sommerfeld in 1909, they are mathematically equivalent to inverse Hankel transforms. The original historical goal of these integrals was to provide an accurate mathematical description of the electromagnetic phenomena involved in long-distance wireless radio and telegraphy. However, their scope was quickly enlarged thanks to the so-called spectral-domain stratified theory, and now they are ubiquitous in the mathematical models associated to many electromagnetic technologies, ranging from EMC lightning modelization and ground penetrating radar to optical and plasmonic integrated devices and going through the familiar microwave and millimeter-wave planar structures using printed circuit technology. In all these areas, Sommerfeld integrals can provide direct evaluations of the involved electromagnetic fields or they can be used as Green's functions in the frame of integral equation formulations. Other disciplines involving stratified media, like seismology and geological prospection, also benefit from these integrals. After discussing the most canonical Sommerfeld integral, appearing in the so-called Sommerfeld identity, this paper reviews three classical structures, namely, the original Sommerfeld problem involving two semi-infinite media, and the microstrip and stripline geometries. It is shown that Sommerfeld integrals provide a unifying treatment of these three problems and that their mathematical features have a direct translation in terms of the physical properties exhibited by the electromagnetic fields that can exist in them.

Advanced RF and Microwave Design Optimization: A Journey and a Vision of Future Trends

JOSÉ E. RAYAS-SÁNCHEZ [1], SLAWOMIR KOZIEL [2], AND JOHN W. BANDLER [3] (Life Fellow, IEEE)

(Invited Paper)

[1] Department of Electronics, Systems and Informatics, ITESO – the Jesuit University of Guadalajara, Tlaquepaque 45604, Mexico
[2] Engineering Optimization & Modeling Center, Department of Engineering, Reykjavik University, 101 Reykjavik, Iceland
[3] Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON L8S 4K1, Canada

CORRESPONDING AUTHOR: JOSÉ E. RAYAS-SÁNCHEZ (e-mail: erayas@iteso.mx).

ABSTRACT In this paper, we outline the historical evolution of RF and microwave design optimization and envisage imminent and future challenges that will be addressed by the next generation of optimization developments. Our journey starts in the 1960s, with the emergence of formal numerical optimization algorithms for circuit design. In our fast historical analysis, we emphasize the last two decades of documented microwave design optimization problems and solutions. From that retrospective, we identify a number of prominent scientific and engineering challenges: 1) the reliable and computationally efficient optimization of highly accurate system-level complex models subject to statistical uncertainty and varying operating or environmental conditions; 2) the computationally-efficient EM-driven multi-objective design optimization in high-dimensional design spaces including categorical, conditional, or combinatorial variables; and 3) the manufacturability assessment, statistical design, and yield optimization of high-frequency structures based on high-fidelity multi-physical representations. To address these major challenges, we venture into the development of sophisticated optimization approaches, exploiting confined and dimensionally reduced surrogate vehicles, automated feature-engineering-based optimization, and formal cognition-driven space mapping approaches, assisted by Bayesian and machine learning techniques.

Simulation and Automated Modeling of Microwave Circuits: State-of-the-Art and Emerging Trends

QI-JUN ZHANG [1] (Fellow, IEEE), EMAD GAD [2] (Senior Member, IEEE), BEHZAD NOURI [1] (Member, IEEE), WEICONG NA [3] (Member, IEEE), AND MICHEL NAKHLA [1] (Life Fellow, IEEE)

(Invited Paper)

[1] Department of Electronics, Carleton University, Ottawa, ON K1S 5B6, Canada
[2] School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada
[3] Faculty of Information Technology, Beijing University of Technology, Beijing 100124, China

CORRESPONDING AUTHOR: Qi-Jun Zhang (e-mail: qjz@ doe.carleton.ca).

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ABSTRACT Microwave modeling and simulation are essential to designing microwave circuits and systems. Although fundamental concepts and approaches for modeling and simulation are mature, the drive to higher frequencies, tighter design margins, and more functionality/complexity of circuits continue to defy the capabilities of existing modeling and simulation methods. Newer algorithms are being developed to address the speed, accuracy and robustness of design algorithms. Coupled with the advent of more powerful computers and algorithms, microwave design automations are solving much more complex problems in much shorter time than previously imaginable. This paper describes the advances and state-of-the-art in automated modeling and simulation. Automated data-driven modeling approaches covering data sampling/generation, model structure adaptation, and model training/validation are described. Simulation of nonlinear microwave circuits is described covering formulations of simulation equations and advanced solution algorithms addressing problem size, convergence speed and solution accuracy. The descriptions highlight fundamental concepts, advanced methodologies, and future trends of development.

Supply Modulation Behavior of a Doherty Power Amplifier

DAN FISHLER (Member, IEEE), ZOYA POPOVIĆ (Fellow, IEEE), AND TAYLOR BARTON (Senior Member, IEEE)

(Contributed Paper)

University of Colorado Boulder, Boulder, CO 80309 USA

CORRESPONDING AUTHOR: Taylor Barton (e-mail: taylor.w.barton@colorado.edu).

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ABSTRACT This paper presents a study of supply modulation in a Doherty power amplifier (DPA). To validate a simplified theoretical model, a 3.5 GHz conventional symmetrical DPA using a 6-W packaged GaN pHEMT is designed for supply modulation of the main and/or auxiliary amplifiers. The DPA is characterized in CW operation over a range of supply voltages, and shows up to 15 percentage point efficiency improvement at 12 dB output back-off when both main and auxiliary amplifiers are varied simultaneously. A comparison of three cases of supply variation is shown and potential benefits for improving back-off efficiency are discussed.