Microwaves in Europe

Roberto Sorrentino, *Fellow, IEEE*, Terry Oxley, *Life Fellow, IEEE*, Georges Salmer, André Vander Vorst, *Life Fellow, IEEE*, Leo P. Ligthart, *Senior Member, IEEE*, Peter Russer, *Fellow, IEEE*, Giorgio Gerosa, *Life Associate Member, IEEE*, G. Pelosi, *Fellow, IEEE*, Jørgen Bach Andersen, *Life Fellow, IEEE*, Antii V. Räisänen, *Fellow, IEEE*, Erik Kollberg, *Fellow, IEEE*, Jozef Modelski, *Fellow, IEEE*, Orest G. Vendik, *Member, IEEE*, Irina B. Vendik, *Member, IEEE*, Tibor Berceli, *Fellow, IEEE*, Magdalena Salazar-Palma, *Senior Member, IEEE*, Joao Costa Freire, *Senior Member, IEEE*, Nikolaos Uzunoglu, *Senior Member, IEEE*, and Asher Madjar, *Fellow, IEEE*

Invited Paper

***Abstract*—An overview of microwave activities and infrastructures in Europe is presented. The material is organized in 17 sections, each devoted to a country or group of countries and prepared by an internationally renowned microwave expert. In general, each section contains some history of microwaves in the region, and highlights some microwave activities in association with research centers, laboratories and institutions, industry, education, and national conferences.**

***Index Terms*—Austria, Balkan, Baltic, Belgium, Czech, Denmark, Europe, Finland, France, Germany, Hungary, Ireland, Israel, Italy, microwave industry, microwave professional societies, microwave research, microwave technology, microwaves, Poland, Portugal, Russia, Slovak, Spain, Sweden, Switzerland, The Netherlands, U.K.**

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R. Sorrentino is with the Department of Electronic and Information Engineering, University of Perugia, 06100 Perugia, Italy (e-mail: r.sorrentino@ieee.org).

T. Oxley, retired, was with GEC Research Ltd., Marconi Research Center, GT. Baddow, Chelmsford, Essex CM2 8HN, U.K. He is now at Railside, Station Lane, Farnsfield Neward, Notts. NG22 8LB, U.K. (e-mail: t.oxley@ieee.org).

G. Salmer is with the University of Lille, IEMN, UMR CNRS 8520, Université des Sciences et Technologies de Lille, 59652 Villeneuve d'Aseq Cedex, France.

A. Vander Vorst is with the Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium (e-mail: vandervorst@emic.ucl.ac.be).

L. P. Ligthart is with the International Research Centre for Telecommunications-transmission and Radar, Microwave Laboratory, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: L.P.Ligthart@ITS.TUDelft.NL).

P. Russer is with the Institute of Hochfrequenztechnik, Technische Universitaet München, D-80333 Munich, Germany (e-mail: russer@ei.tum.de).

G. Gerosa is with the Department of Electronic Engineering, Università di Roma "La Sapienza," 00184 Rome, Italy (e-mail: giorgio@die.ing.uniroma1.it).

G. Pelosi is with the Department of Electronics and Telecommunications, University of Florence, I-50134 Florence, Italy (e-mail: pelosi@det.unifi.it).

J. Bach Andersen is with the Center for Personkommunikation, Aalborg University, Aalborg DK-9220, Denmark (e-mail: jba@cpk.auc.dk).

A. V. Räisänen is with the Radio Laboratory, Millilab, and Institute of Digital Communications, Helsinki University of Technology, FIN-02015 HUT, Finland (e-mail: antti.raisanen@hut.fi).

E. Kollberg is with the Department of Microlelectronics, Chalmers University of Technology, SE-412 96, Göteborg, Sweden (e-mail: kollberg@ep.chalmers.se).

J. Modelski is with the Institute of Radioelectronics, Warsaw Institute of Technology, 00-665 Warsaw, Poland (e-mail: J.Modelski@ire.pw.edu.pl).

O. G. Vendik is with the Department of Electronics, St. Petersburg Electrotechnical University, St. Petersburg 197376, Russia (e-mail:OGVendick@eltech.ru).

I. B. Vendik is with the Department of Microelectronics and Radio Engineering, St. Petersburg Electrotechnical University, St. Petersburg 197376, Russia (e-mail: IBVendick@eltech.ru).

T. Berceli is with the Department of Microwave Telecommunications, Technical University of Budapest, Budapest H-1111, Hungary (e-mail: berceli@nov.mht.bme.hu).

M. Salazar-Palma is with the Departamento de Señales, Sistemas y Radiocomunicaciones, Escuela Tecnica Superior de Ingenieros de Telecomunicacion, Universidad Politecnica de Madrid, Ciudad Universitaria, 28040 Madrid, Spain (e-mail: m.salazar-palma@ieee.org).

J. C. Freire is with the Instituto Superior Tecnico, 1096 Lisbon, Portugal (e-mail: jcf@lisboa.lx.it.pt).

N. Uzunoglu is with the Microwave and Fiber Optics Laboratory, National Technical University of Athens, Athens, Greece (e-mail: nuzu@cc.ece.ntua.gr).

A. Madjar is with the Monolithic Microwave Integrated Circuit Design Group, RAFAEL, 8H350 Haifa, Israel (e-mail: madjar@rafael.co.il).

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NOMENCLATURE

AlGaAs	Aluminum GaAs.
BiCMOS	Bipolar CMOS.
BWT	Backward-wave tube.
CMOS	Complimentary metal–oxide semiconductor.
EM	Electromagnetic.
EW	Electronic warfare.
FET	Field-effect transistor.
FM CW	Frequency modulation continuous wave.
GaAs	Gallium arsenide.
Ge	Germanium.
HBT	Heterojunction bipolar transistor.
HEMT	High electron-mobility transistor.
IMPATT	Impact avalanche and transit time.
InP	Indium phosphide.
LDMOS	Lateral diffused metal–oxide semiconductor.
MASER	Microwave amplification by stimulated emission of radiation.
MBE	Molecular beam epitaxy.
MCM	Monte Carlo method.
MEMS	Microelectromechanical structures.
MESFET	Metal–semiconductor FET.
MIC	Microwave integrated circuit.
MMIC	Monolithic microwave integrated circuit.
RF	Radio frequency.
Si	Silicon.
SiC	Silicon carbide.
SIS	Superconductor–insulator–superconductor.
TED	Transferred electron device.

TEGFET Two-dimensional electron gas field-effect transistor.
TWT Traveling-wave tube.

I. EDITORIAL

THIS papers aims at providing an overview of microwave activities and infrastructures in Europe. Europe is meant here in a broad sense, as a cultural rather than geographical entity. Electromagnetic science was born in Europe, and in Europe comprehensive advances in microwaves have been achieved. An exhaustive account of even a small part of microwave activities in Europe is beyond both possibilities and intentions. Europe is not a single country, though its nations share a common cultural background as well as similar traditions. A sign of this common heritage has been the establishment of a series of European microwave symposia, called the European Microwave Conference (EuMC). The first EuMC was held in London, U.K., in 1969. After reaching an international reputation in terms of scientific and technical contents, the EuMC has recently grown considerably; in 1998, the European Microwave Week (EuMW) was created, incorporating the EuMC, as well as two other conferences on related subjects (solid-state RF devices and wireless systems) and a large technical exhibition, with a format similar to the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium.

To place European microwave activities on a firm legal basis, the Management Committee of the EuMC decided in 1997 to create the European Microwave Association (EuMA). The EuMA is an international association under Belgian law, with the aim of developing, on a nonprofit basis and in an interdisciplinary way, education, training, and research activities. The focus being, among others, to promote European microwaves, networking, and unite microwave scientists and engineers in Europe; to provide a single voice for European microwave scientists and engineers; to promote public awareness and appreciation of microwaves; to attain full recognition of microwaves by the European Union; to organize European Microwave Symposia, in particular the EuMC, as well as the EuMW with all the associated events; and to circulate information among European microwave scientists and engineers.

The Association is allowed to perform all actions directly or indirectly related to its objectives. In particular, it may organize any form of cooperation between its members, symposia, seminars, study schemes, and to carry out and publish studies, magazines, or books, etc.

The registered office of the Association is located at Place du Levant 3, B-1348 Louvain-la-Neuve, Belgium, with André Vander Vorst as secretary treasurer. The founding members of the Association are Roberto Sorrentino (Italy), Leo Ligthart, (The Netherlands), Asher Madjar, (Israel), Holger Meinel (Germany), Steve Nightingale (U.K.), and André Vander Vorst (Belgium).

The material in this paper is organized in 17 sections, each corresponding to a country or group of countries; the paper structure somewhat mirrors the constitution of the Management Committee of the EuMC. A number of internationally renowned microwave experts from various parts of Europe have been asked to prepare an account about the microwave infrastructures in their respective countries or groups of countries. Although geographically outside the European continent, many cultural links do exist between Israel and Europe, as testified by the EuMC being held in Jerusalem in 1997, and for this reason, Israel has been included in this overview.

Due to space limitation, only short accounts per author were permitted, thus, each had the difficult task of highlighting just a few salient aspects, putting aside most of the material that could have been presented should more space have been available. Much of each section reflects the personal view of the author. To help uniformity through the paper, however, guidelines were suggested that the various sections should mainly reflect some information on, for example, the history of microwaves in the region; microwave research centers, laboratories and institutions; microwave industry; microwave education; and national conferences and events.

R. Sorrentino

II. U.K. AND REPUBLIC OF IRELAND

A. Background

Microwave activities within the U.K. and Republic of Ireland (UK&RI) may be traced back to radar interests of the 1930s. For example, the General Electric Company (GEC) and Birmingham University, Birmingham, U.K., work on the first magnetrons, and the Marconi Company work on design/installation of the "Chain Home" network of radar equipment. Microwave development during World War II was outstanding. Since then, the microwave infrastructure has grown extensively, encompassing university, industry, and government ministries, in support of comprehensive research, development, and production of microwave practices to meet wide-ranging applications covering all microwave fields from radio to terahertz frequencies. In the early decades, this was motivated by military needs, more recently, however, civil broadcast and communication interests have become increasingly dominant. Over the years, as the result of company mergers, many major industries involved in the microwave business have been restructured with rationalization of their autonomous product companies. Further, much of industry research and development (R&D) has been decentralized to the responsibility of product companies and universities.

It is outside the scope of this section to cover all aspects of the UK&RI microwave involvement. One of the most exciting fields of advancing technology over the last 50 years, however, has been in microwave solid-state devices with associated integrated circuits. Originating from the work in the 1940s by GEC Research Laboratories and British Thomson Houston Research Laboratories (merged with GEC in the 1960s) on receiver point-contact diode technology, there have been many participating establishments, which have contributed to the UK&RI world competitive position in the field, and provided the focus for internationally recognized technical achievements. Only a few of the principal research contributors can be briefly highlighted in Sections II-B–E.

B. Industry

Plessey Research (Caswell) Ltd., established in 1940, became GEC-Marconi Materials Technology Ltd. (merger of GEC and Plessey) in 1990, then part of Marconi Optical Components Ltd, and is currently part of Bookham Technology plc. Work on GaAs in the 1960s, led to the world's first demonstrated GaAs FET in 1966, to the announcement of the world's first commercial GaAs FET for microwave applications in 1970, and to the publication of the world's first FET-based GaAs MMIC in 1976. R&D since that time has grown to encompass a wide range of GaAs-based devices with commercial exploitation of GaAs commencing in the 1980s, with the establishment of a production MMIC foundry. The latest facility is currently upgrading to handle 150-mm wafers for microwave and optical applications. Currently, the Caswell site locates a major commercial MMIC foundry within the UK&RI. ***Hirst Research Centre,*** formerly GEC Research Laboratories (founded in 1924), exploited the earlier work on Si, Ge, and then GaAs devices with associated broad range of two- and three-terminal devices. The Centre was recognized as a principal contributor to microwave receiver technology via point-contact diodes, planar devices, and MICs, over the frequency range of 1–100 GHz. In the 1980s, it established a GaAs MMIC technology capability up to 100 GHz, and a MMIC foundry basis. Following the merger of GEC and Plessey, the GaAs HRC and Caswell activities were consolidated at the Caswell site in 1990. ***Standard Telecommunication Laboratories*** (STL), now Nortel Networks, commenced GaAs technology R&D in the 1960s and made important contributions to GaAs TEDs. In 1971, STL demonstrated GaAs diode-based monolithic integrated circuits applied to millimeter wavelengths. Involved in pioneering work on optical fiber transmission, it moved its semiconductor interests to opto-electronics in the 1980s. ***Philips Research Laboratories*** (PRL), originally Mullard Research Laboratories (in association with Philips Semiconductors), is internationally recognized for its millimeter-wave GaAs device and hybrid MIC technology, and for its work on advancing parametric amplifier techniques. The laboratories developed the first European liquid helium MASER used to receive TV satellite signals across the Atlantic. ***BAE Systems Advance Technology Centre*** Great Baddow, established in 1939 as a Marconi Research Centre, can trace its origins as a Marconi Research Department created in 1913. The Centre traditionally involved in state-of-the-art communications and radar studies embraces wider ranging activities in the microwave/millimeter-wave/optical fields, with extensive on-site support resources. ***ERA Technology Ltd.***, a leading U.K. Research and Technology organization, has carried out much innovative work on antennas and waveguiding systems since the 1970s and now has one of the largest groups in Europe in this field. ***Filtronics Ltd.***, established in 1977, went public in 1994, is a spinoff from The University of Leeds, and currently represents the U.K.'s most successful university spinoff company employing over 3500 staff worldwide, with a turnover of several hundred million U.S. dollars. Originally recognized for producing filters for telecommunications, it has become a leading supplier of wireless infrastructure subsystem products, and is now involved in III–V compound semiconductors with related product R&D, and manufacture. Finally, ***M/A-COM***, formerly Microwave Associates Ltd., has had an independent operation in the U.K. since the early 1960s, with many contributions in the R&D fields of microwave solid-state device, components, and subsystems.

C. University

University College London (UCL) was possibly the founder in 1945 of microwave engineering as a recognized UK&RI academic discipline; it played a leading role in the study of millimetric waveguide as a long-distance communication medium. Since then, many universities established microwave activities and initiated work in solid-state and related circuits and, in recent years, several, some with Engineering and Physical Sciences Research Council (EPSRC) government support, have established centres of excellence. To highlight just a few may include ***Queen Mary & Westfield College*** (QMW) on antennas; ***University of Manchester Institute of Science and Technology*** (UMIST) was awarded, in 1999, a several million-pound EPSRC grant for the establishment of an Electromagnetics Centre for microwave and millimeter-wave design and applications, and in 2001, an industry/government grant was awarded to establish a 6-in wafer III–V materials MBE facility for microwave applications; ***University College Dublin*** (UCD) in nonlinear microwave device modeling and computer-aided design (CAD); ***University College Cork*** work on millimeter-wave devices led to a spinoff in formation of a commercial company, Farran Technologies; ***Queen's University Belfast*** (QUB) in silicon technology for microwave/millimeter-wave applications; ***King's College London*** in heterojunction microwave and optoelectronic devices and circuits;. ***University of York*** in low-noise solid-state oscillators; ***The University of Leeds*** initiated work on microwaves in 1963, formed the Microwave Solid State Group in the mid-1970s and the current Institute of Microwaves and Photonics in 1997. Recently, it has been awarded a several million-pound government (EPSRC) grant to expand its millimeter-wave and terahertz facilities.

To the credit of the UK&RI academic and industrial training qualities, UK&RI may claim to have made a real impact in the microwave world in training microwave engineers; many taking up leading overseas positions.

D. Ministry

The Ministry of Defence (MOD) support in R&D, both technical and funding, has played an important role in advancing UK&RI microwave practices. Of the many MOD establishments initially involved, that at Malvern, originally Telecommunications Research Establishment (TRE), best known as Royal Signals Radar Establishment (RSRE), now Defence Evaluation and Research Agency (DERA) Malvern, and the Agency in London, best known as Directorate of Components Valves and Devices (DCVD), have been key contributors, with many production devices and components being realized via this route. ***DERA Malvern***, with in-house technology facilities, has been involved in wide-ranging microwave activities; pioneering work on GaAs- and InP-transferred electron effects, development of key radars including solid state and, more recently, R&D into optomicrowave integrated circuits.

E. Professional Societies

The technical interests of the UK&RI community have been served well by the national Institute of Electrical Engineers (IEE) and the IEEE. The 1969 first EuMC was held under the auspices of the IEE. The IEEE ED/MTT/AP/LEO joint chapter within the UK&RI Section represents the IEEE MTT-S interests. This chapter was formed in 1987 and has grown in status in all aspects of membership and organization of events. Technical meetings average 20 each year and the chapter has launched major annual events. For example, the IEEE International Symposium on Electron Devices for Microwave and Optoelectronic Applications (EDMO); the IEEE European Millimeter-Wave, Microwave and RF, Integrated Circuit Design and Simulation Workshop (MIDAS) with a selected topic each year; and the IEEE High-Frequency Postgraduate Student Colloquium.

T. Oxley

III. France

A very large quantitative growth, as well as continuous advances in research, industrial development, and education, has characterized the last 50 years of microwave history in France. Such evolution has been spurred by the dramatic growth of applications, particularly of telecommunications systems. At the same time, the main research fields have evolved substantially. For example, from the mathematical solution of Maxwell's equations in conventional waveguides in the 1960s, to the complete analysis of three-dimensional (3-D) circuits including passive and active devices under dynamic conditions; from the optimization of microwave power tubes (1950–1970) to the present studies of new generations of transistors (HBTs, FETs) for power or very high bit-rate applications; and from the design of discrete devices or components to the design of complete active phase-array antennas.

In the 1970s, thanks to the action of several research institutions such as the Centre National de la Recherche Scientifique (CNRS) and the Centre National d'Etudes des Télécommunications (CNET), with the support of several ministries and national organizations (for instance, the Délégation Générale à l'Armement (DGA) of the French army), a national network of microwave research centers and then a scientific community have been constituted, and a strong cooperation among them has been developed. For example, initiated in 1976 by Professors Y. Garault and E. Constant, the biennial National Microwave Conference brings together up to 800 people from industries, universities, and national research centers to present original and state-of-the-art results, and to exchange ideas and suggestions for future cooperative work.

In terms of research organization, all microwave areas are presently covered in France. In order to reach critical masses, the creation of large laboratories grouping from 50 to 100 permanent researchers has been encouraged; Thomson LCR, Philips LEP, Alcatel Space for the industrial part, and IEMN (Lille), IRCOM (Limoges), LAAS (Toulouse) for the academic part. Specific facilities in terms of microwave measurements are available in all the above laboratories, while LCR, LEP, IEMN, and LAAS also possess device-processing facilities. In addition, local microwave groups in various parts of France (Paris, Brittany, South-West, etc.) have been initiated. Several cooperative research works on microwave telecommunication systems have been developed in Brittany with the support of the CNET. Since 1997, the network Ile de France has organized an annual specialized workshop devoted to specific microwave topics.

Industrial research centers (LEP Philips, Thomson LCR, Alcatel Space) have focused their activities mainly on microwave devices, MMICs, and millimeter-wave components. A large cooperation with academic laboratories often specialized on specific topics (for instance, IEMN on devices simulation, characterization, and technology; IRCOM on CAD of microwave components and systems in active devices; LAAS on noise) has enabled the French research community to achieve state-of-the-art results. For example: LEP in the 1970s on high-efficiency IMPATT diodes; LEP and Thomson LCR in the 1980s on GaAs monolithic digital circuits; and, more recently, Alcatel Space in the field of 3-D MCM. It is worth mentioning that L. T. Nuyen fabricated the first AlGaAs/GaAs TEGFET in 1980 at Thomson LCR, at the same time as Fujitsu.

A great deal of academic studies is focused on topics close to industrial development activities. For example, microwave antennas in Rennes and Nice; filters and resonators in Limoges; packages and Si RF devices in Grenoble; millimeter-wave circuits and packaging in Lille; microwave materials in Paris; and measurement methods in Orsay (IEF), etc. Successful studies have also been performed by academic research groups on microwave radiometry and imagery in Orsay (LSS) and Lille (IEMN), in support of industrial and biomedical applications; and on radar polarimetry (Nantes), with the support of the DGA. The French microwave community has played a very significant role in the field of submillimeter-wave devices and components for application to spaceborne radiometers (for instance, EADS-ASTRIUM in Toulouse), and to radio astronomy research (DEMIRN, Observatoire de Paris).

In the past, the main part of research on microwave telecommunication systems was undertaken by CNET (in Lannion and Paris); since 1996, the CNET has become France Telecom R&D. In the 1980s, they have proposed and studied a number of very promising millimeter-wave systems. More recently, the network of telecommunication engineering schools (ENST) has brought a large contribution to this domain. Finally, much research work has been undertaken over more than ten years in the field of microwave/optical devices, for applications such as local loops in telecommunication systems and phased-array antennas for radars. Such studies have been performed in cooperation between academic (Lille, Grenoble, etc.) and industrial groups (Alcatel, Thomson and Dassault Electronique). Very innovative solutions have been proposed both in terms of specific devices for detection (for instance, HBTs) and in terms of millimeter-wave systems at 38 and 60 GHz.

While the production of base-stations for GSM and UMTS constitutes a very important market in the field of microwave telecommunication systems, the most advanced part of the development activities concerns the millimeter-wave range (for instance, at Thomson TCC). In the domain of spatial activities, Alcatel Espace and Astrium working in cooperation with ESA and CNES have reached high international recognition, both in the CAD area and in the technology for spatial components, specific packages, and 3-D assemblies. Several departments of Thomson such as TCM, RCM, and Dassault-Electronique, which recently joined together to constitute THALES, have developed large systems for civil and military applications; radar, airborne, and countermeasure systems, etc. They have reached a high international level, not only in terms of technology for passive and active circuits, for instance, a multilayer approach and low-cost millimeter-wave packages (MUSE concept), but also concerning TR modules and phased-array antennas (passive or active). In this domain, very innovative solutions have been proposed by these groups both for the conventional C- and X-bands (RADANT, COBRA, APAR) and for frequencies up to the 94-GHz range (BALMI prototype developed in 1994). Civil applications have also been considered with the development of front-end modules at 77 GHz for collision-avoidance radars.

In strong cooperation with the academic people who are in charge of the National Microwave Conference, Prof. V. Fouad Hanna launched an IEEE MTT-S chapter in 1988. Counting about 250 active members, the chapter organizes every year a specialized two-day workshop on topics such as nomadic technologies or materials for microwaves, as well as several technical meetings, and gives support to the organization of national microwave conferences and EuMCs.

The considerable growth of microwave research in academia has strongly been associated with a large development of education capabilities in this country. At the same locations as the main research centers (Limoges, Lille, Paris, and its surroundings, Nantes, Rennes, Toulouse, Brest, Grenoble, Bordeaux), numerous schools of engineers and universities have initiated specific curricula in order to provide the microwave industry with highly qualified engineers. Over 200 Ph.D.'s in microwaves are recognized each year in France to meet the large demand of qualified microwave positions from both French and international industries.

G. Salmer

IV. Belgium

Fifty years ago, in his 1945 Ph.D. dissertation at the Université Catholique de Louvain (UCL), V. Belevitch developed the concept of scattering matrix for microwave circuits (*Journal of Applied Physics*, 1948), exploring problems of physical realizability, with his theory suggested by the earliest use of scattering parameters (1920); the interest for microwave circuit theory is still present at UCL. Later, at the Universiteit Gent (RUG), J. Van Bladel solved a number of problems, mainly in radiation and coupling, covering electromagnetic- and acoustic-wave theory; the group at RUG is still interested in solving electromagnetic problems. Currently, Belgian microwave theory and techniques research develops essentially in four universities, i.e., the Katholieke Universiteit Leuven (KUL), Universiteit Gent (RUG), Université Catholique de Louvain (UCL), and Vrije Universiteit Brussel (VUB) [1]; extensive cooperation exists between the universities, for instance, on national projects, and duplication is avoided. Activities are developed through European, national, regional, and industrial grants and contracts.

The KUL group is well known for analyzing and designing planar antennas and arrays with multiple dielectric and patch layers. They developed several models, as well as near-field measurement techniques. They also investigate MMICs with HEMTs, focusing on modeling and design. They are involved in microwave propagation; in particular, indoor applications.

At RUG, the main activity is in high-speed and high-frequency analog devices, covering the modeling of waveguides ranging from metallic to fully optical ones, embedded in multilayered structures. They developed a planar simulator with via-holes. They also specialize in complex measurement problems for boards, connectors, and packages. Hypothermia has been a successful topic, with investigations on noninvasive measurement of temperature.

UCL has a large microwave laboratory, with research in space and terrestrial propagation, electronics from materials to systems, bioelectromagnetics, and humanitarian de-mining, experimentally up to 110 GHz and by simulation near the terahertz region. They participated in the OTS and Olympus ESA experiments. They develop and use variational principles, and extended the scattering matrix concept to optomicrowaves. Technologically, they focus on silicon-on-insulator structures, and are investigating nanostructures and MEMS. They have been successful in bio microwaves.

The VUB team has developed new measurement techniques using signal-processing methods and tools, through measuring, modeling, and identification. They distinguish three layers: basic measurement techniques, identification tools, and interpretation with a knowledge-based system, assisting microwave engineering by a large amount of computer-aided simulation and design systems.

The company most active in microwave theory and techniques developments has been Bell Telephone, now Alcatel Bell, covering the whole range of microwave equipment for space and terrestrial communications. Alcatel-ETCA developed earth stations for OTS, while Newtec has developed a variety of earth stations, including for Olympus. SAIT has a reputation for maritime communications. The Hewlett-Packard Company has been active in promoting joint activities on simulation software. A number of companies are, of course, active in the field of mobile communications.

A. Vander Vorst

V. The Netherlands

The major Netherlands organizations active in microwave theory and techniques areas may be summarized as the Delft University of Technology (DUT) and Eindhoven University of Technology (EUT), ESA-ESTEC, Noordwijk, Applied Physics Research Organization, TNO, Thales-Nederland, Hengelo, and Philips, KPN (Netherlands PTT), and The Netherlands branches of Lucent Technologies, Ericsson, Siemens, and Nokia.

Here, some latest Netherlands microwave and millimeter-wave activities are selected, based on the authors' opinion to describe some expected Netherlands breakthroughs of microwave theory and techniques applications in the near future.

The International Research Centre for Telecommunications-transmission and Radar (IRCTR) of DUT focuses its microwave theory and techniques research on the development of advanced RF front-ends (including antennas) for integration into novel microwave and millimeter-wave radar and radio systems and networks. Specific technologies are developed for ultra-wide-band (UWB) radar technologies (50-MHz–6-GHz frequency band) to be applied in various ground penetrating radar (GPR) systems. Advanced modeling (in cooperation with the Electro-Magnetics Laboratory) and technologies are underway in order to create improved detection rate and reduced false-alarm rate when using GPR for landmine detection.

Atmospheric Doppler-polarimetric radar research, as part of international research on global climatic change, necessitates new developments in hybrid multibeam antenna systems and transmit/receive technologies.

The Delft Institute of Micro-Electronics and Submicron Technologies (DIMES) has a specific microwave program with high novelty rating on silicon-based 17-GHz radio system parts with realization of on-chip devices, and integration of MEMS circuitries using bipolar, CMOS, and BiCMOS technologies.

EUT (major groups radio communications and electromagnetics) is involved in state-of-the-art research on 20/30/50-GHz technologies for radiometry, also on 60-GHz radio technologies for indoor communications and on optical technologies.

ESA-ESTEC is active in all areas of microwave circuits, devices, and systems related to space applications. In recent years, the Electro-magnetic Division started intensive cooperation with IRCTR on antenna and device diagnostics using UWB frequency- and time-domain measurement techniques.

TNO has extensive programs on MMIC design in various frequency bands for radar and telecommunications.

Finally, it is certainly worth mentioning that at Thales-Nederland (formerly Hollandse Signaal Apparaten) highly integrated transmit/receive modules have been developed as part of an active full 3-D advanced phased-array radar (APAR).

L. P. Ligthart

VI. Germany, Austria, and Switzerland

A. Industry

Major applications of microwaves in Germany are public communication, broadcasting, sensing, traffic control, and medical treatment. The applications include commercial, consumer, and military. Numerous companies are involved in the production of microwave components, antennas, a variety of microwave systems, and measurement equipments. Some of the leading companies engaged in the field of microwaves are Bosch, DaimlerChrysler, EADS, EPCOS, Infineon, Rohde & Schwarz, Siemens, and Spinner. In the last decade, mobile communications and broad-band optical communications gave a strong impact to industrial activities whereas the military sector decreased considerably.

Siemens covers large areas in microwaves; with business units in automation and drives, components, energy, information and communication, medical technology, traffic technology, and transportation system. Siemens is also engaged in terahertz bandwidth fiber optical systems; an example of outstanding research is a fiber-optic link with 40 Gbit/s per channel in the baseband. The main focus of R&D objectives has changed from hardware-oriented to system and software-oriented topics.

Siemens Semiconductors became Infineon Technologies in early 1999. It has entered into development partnerships and production joint ventures with IBM, Motorola, Nokia, and Sun Microsystems. This wireless products business unit produces semiconductor devices and complete system solutions for a range of wireless applications, including cellular and cordless telephone systems, and devices used in connection with GPS. Products include standardized baseband ICs (logic and analog), and standardized and customized RF ICs.

EPCOS emerged from the Siemens Matsushita Components joint venture and ranks as one of the world's largest manufacturers of passive electronic components. It has pioneered the field of miniaturized and innovative passive components and is playing a key role as a manufacturer of surface acoustic-wave devices.

Many companies are now engaged in traffic sensing and vehicular technology, with applications of microwaves to automotive technologies being focused by the demand for intelligent and reliable safety systems in today's vehicles. Through its Automotive Electronics (TEMIC) business unit, DaimlerChrysler is a leading supplier of electronic systems for propulsion, safety, and driving comfort in cars, e.g., a 24-GHz near-range sensor system is under development. Beside other companies within the DaimlerChrysler group, TEMIC lists virtually all well-known car manufacturers among its customers.

The European Aeronautic Defense and Space Company (EADS) is Europe's premier (rated third worldwide) aerospace and defense company, with headquarters in Ottobrunn (near Munich) and Paris. It comprises the activities of the founding partners Aerospatiale Matra S.A. (France), Construcciones Aeronáuticas S.A. (Spain), and DaimlerChrysler Aerospace AG (Germany).

Rohde & Schwarz is a major manufacturer of test and measurement equipment and supplier of radio communications, radio location, and broadcast equipment.

The Spinner company is a leading manufacturer of passive microwave components, including waveguide components, coaxial connectors, cable assemblies, coaxial, waveguide switches, and optical waveguide components, and is also involved in the manufacture of broad-band optical transmission systems.

B. Universities

At German universities, the area of microwaves is mainly covered under high-frequency engineering (i.e., hochfrequenztechnik) within electrical engineering departments. German universities, with minor exceptions, are state universities. The main financial basis of state universities is the budget supplied from the state, supplemented by federal and state funding of research projects and by revenues from industrial research cooperation and industrial sponsorship. Tuition fees are not required at German universities. Full professors usually have held senior positions in industrial R&D before moving to the university.

The Fakultätentag für Elektrotechnik und Informationstechnik (FTEI), i.e., the Electrical Engineering and Information Technology Faculties assembly, is a confederation of electrical engineering departments of German universities with the professors of the corresponding faculties as the members. FTEI has the objective to achieve and maintain cooperation in fundamental topics of education, research, and academic self-administration. In Germany, 29 universities include electrical engineering departments with High-Frequency Engineering or Microwave Engineering Departments represented in FTEI. For example, Aachen (Rheinisch-Westfälische Technische Hochschule Aachen); Berlin (Technische Universität Berlin); Bochum; Braunschweig; Bremen; Chemnitz; Clausthal; Darmstadt; Dortmund, Dresden, Duisburg, Erlangen-Nürnberg, Hagen, Hamburg–Harburg, Hannover, Ilmenau, Kaiserslautern, Karlsruhe, Kiel, Magdeburg; Munich (Technische Universität München); Paderborn; Rostock; Saarbrücken; Stuttgart; Ulm; Wuppertal; and the German Military Universities (Universität der Bundeswehr); Hamburg and Munich. Representatives of the Electrical Engineering Departments of the Austrian universities Graz, Leoben, Linz, Vienna (Technische Universität Wien), and the Swiss Federal Institute of Technology Zürich are invited to the annual general meetings of the FTEI. In education, the situation in Austria and Switzerland is comparable to that in Germany.

At German universities, the course of studies for the Diplom-Ingenieur degree takes five years, including four semesters foundation course up to the Diploma pre-examination, then a further four semesters main course up to the Diploma main examination; one semester internship, and one semester Diploma thesis. The foundation course provides a solid ground in higher mathematics, physics, electromagnetics, circuit theory, and informatics. The professional deepening is achieved in the main course in the third and fourth years. In the main course, the curriculum leading to the Diploma degree in communications generally includes compulsory courses on electrodynamics and/or high-frequency engineering. The possibility for specializing in microwave engineering is given. Some universities in Germany have recognized the necessity to introduce a first degree before the Diploma degree in order to improve the national and international mobility of students. The Munich Model introduces for all students a Bachelor degree after six course semesters and a Bachelor thesis. After this, students may continue either with a Diploma course or a Master course. The Munich Model promotes international student exchange and maintains established principles of German university education.

In the first half of the 1990s, there was a dramatic decline in the number of freshmen in electrical engineering and information technology. The total number of freshmen at all electrical engineering departments of German universities went down from 7684 in 1990 to 3262 in 1995 and now has recovered to 6426 in 2001. Although the graduates specializing in microwaves have excellent professional prospects, only a small fraction, i.e., less then 5% of electrical engineering and information technology students, actually specialize in microwaves.

In order to attract more students from foreign countries, a number of German universities started to offer complete English language master course programs. Starting in October 2000, the Department of Electrical Engineering and Information Technology, Munich University of Technology, introduced a Master of Science in Microwave Engineering (MSMWE) course; the program is established in close cooperation with industry through sponsorship, joint thesis work, and paid internships.

In Germany, beside the University, there is the education system of the Fachhochschule (FH) (University of Applied Technology). The FH is mainly application-oriented and offers courses with a total duration of eight semesters. The FH does not usually include research.

German universities are strongly involved in research activities, generally supported by the Deutsche Forschungsgemeinschaft (DFG), which may be translated as the German Research Council; the Federal Ministry of Education, Science, Research, and Technology; the German state ministries; or by European research funding. The DFG is the central organization to support research projects in German universities and public research institutes. Joint research projects between university institutes and industry and the cooperation with other research institutes play an important role. Many universities have established technology transfer initiatives and support spinoff initiatives of scientists.

C. Government

In Germany the Bundesministerium für Bildung und Forschung (BMBF), i.e., the Federal Ministry for Education and Research, funds research projects at industry, research institutes, and universities. Under a priority scheme, the present programs dealing with microwave topics include mobile communication systems, innovative optical communication networks, and new areas of technology. The DFG, i.e., German Research Council, is the central organization to support research projects in German universities and public research institutes.

The German Aerospace Center (DLR) as national space flight agency, manages German space programs; these are commissioned and defined by the relevant federal ministries. The DLR Institute of Communications and Navigation conducts scientific research for applications in aeronautics, space flight, and traffic. The Institute pursues the business areas of satellite communications, aeronautic communications, terrestrial radio systems, satellite navigation, and traffic guidance systems.

A number of research institutes include research activities in the area of microwaves. Major contributions in microwaves come from the Fraunhofer Institute for Applied Solid-State Physics (IAF), Freiburg, the Ferdinand Braun Institute (FBH), Berlin, and the Heinrich Hertz Institute, Berlin, and the Institute for Mobile Communications and Satellite Technology (IMST), Kamp-Lintfort.

D. Professional Organizations

The Verband Deutscher Electrotechniker (VDE), i.e., Association of German Electrical Engineers, is the professional association for electrical, electronic and information technologies. The Informationstechnische Gesellschaft (ITG) i.e., the Information Technology Society, is a society within the VDE, concerned with all aspects of information technology in industry, administration, teaching, research, and science. The ITG specialist High-Frequency Technology Division is concerned with RF and microwave engineering. The German IEEE Section closely cooperates with the VDE/ITG. In Germany, the members of the IEEE MTT-S are represented in the IEEE MTT/ED joint chapter. In Switzerland, the Schweizer Elektrotechnischer Verein (SEV), i.e., the Swiss Electrotechnical Association, and in Austria, the ÖVE, are the professional organizations of electrical engineers. Austria has an IEEE MTT/COM joint chapter and Switzerland has an IEEE MTT/AP/EMC joint chapter.

P. Russer

VII. Italy

A. Background

Microwave activities in Italy started with Marconi's investigations in 1919–1931. He was the first to address research interests toward microwave frequencies. His first radio transmission experiments at microwave frequencies $(\lambda = 50 \text{ cm})$ were performed in 1931 through a sea link in the Tigullio Gulf on the Riviera Ligure, in the same period as those by A. G. Clavier (at 17.5 cm) across the English Channel. Marconi realized the first ground link in 1932 between Villa Mondragone (near Rome) and the Vatican.

In the same period, the first theoretical studies on microwave propagation and the first experiments on the devices for microwave generation and detection took place. The term "microwaves," in its current meaning, was firstly introduced in an international scientific journal by the Italian physicist N. Carrara [2], while he was working at the Royal Electronic and Communication Institute (RIEC) of the Italian Navy at Longhorn. The Institute had been founded in 1916 at the initiative of G. Vallauri and hosted the first Italian research group in electronics. The Institute maintained a prominent position in this field in Italy for many years, and was the place where Italian microwave and radar techniques took their first steps. An important role was played by U. Tiberio, who has been credited to be one of the inventors of radar [3].

B. Industry

For many decades, microwave industrial activities in Italy, like the rest of the world, had been driven mainly by military needs, with applications to radars and electronic warfare. Companies such as Selenia and Elettronica in Rome developed specific expertise in such areas. With the decline of the military market, microwave industrial activity has been redirected toward civil applications, such as communication services and space.

Alenia Marconi Systems (AMS) (founded in the early 1950s as Microlambda, later evolving into Selenia, and then Alenia) is mainly focused on the production of radars for both military and civil systems. Products range from microwave antennas to solid-state devices, tube transmitters, microwave components, and packaging from 1 to 100 GHz.

Alenia Spazio (originated from Selenia, now an independent company), is one of the leading space communication companies, having RF and microwave technologies as one of its major assets. Specializing in telecommunications, remote sensing, scientific satellites, and space infrastructures, the company pioneered the Ka-band communication with on-board processing, and from the early 1970s, became a leader in microwave technologies for space applications.

STMicroelectronics fabricates RF integrated circuits based on Si and SiGe using both BiCMOS and CMOS technologies. LDMOS transistors are implemented in power circuits used for personal communications, as well as for base-stations.

GaAs microwave technology in Italy started at CISE, Milan, in the late 1970s, where a MESFET process was first established. In 1980, the same group manufactured the first X-band coplanar monolithic GaAs balanced amplifier. The activity on GaAs continued at TELETTRA, where the first air-bridge gate FET technology for GaAs MMICs was developed in 1985. TELETTRA was later acquired by Alcatel, an established French-owned company in commercial microwave applications, having one of its major strengths in the point-to-point microwave market.

In addition to Alcatel, the explosion of the wireless market is also reflected in the activities of some industries owned by foreign companies, such as Ericsson and Siemens. Ericsson Laboratory Italy develops apparatuses and systems for fixed and mobile networks. A MMIC capability center for microwave and millimeter-wave wireless applications has been located in Milan. Siemens ICN Microwave Networks, with headquarters in Milan, develops, produces, and distributes digital radios for microwave communication systems.

C. Research

Until the early 1970s, four major research centers operated in Italy, namely, at the University of Rome "La Sapienza" (at that time, the only university in Rome), at the University of Naples, at the Polytechnic Institute of Turin, and at the Research Institute on Electromagnetic Waves (IROE), formerly Centro Microonde, in Florence. Afterwards, the number of university laboratories involved in microwave research activities has increased significantly, now being over 20.

Italian researchers in the area of electromagnetics, mostly from the academia, but also from industries and public research centers, have formed a National Group on Electromagnetics (GEm). The group, currently consisting of approximately 200 people in 30 research units scattered throughout Italy, was originally formed in the frame of the National Research Council, but has eventually become an independent, although still informal, organization. In addition to coordinating the research activities among the various units through regular annual meetings, the GEm has been organizing, since 1976, the biannual national conference Riunione Nazionale di Elettromagnetismo (RiNEm), where the most recent results of research activities in the various areas of applied electromagnetics are presented and discussed.

Specific attention is devoted to the following research topics: microwave antennas (the largest research groups are located in Naples and Turin, but this topic is pursued in virtually all universities); field theory and EM scattering (Rome "La Sapienza," Rome III, Siena, Turin, Naples); numerical methods and microwave passive circuits (Ancona, Florence, Perugia, Rome, Milan); nonlinear microwave circuits (Bologna, Turin, Rome Tor Vergata); optics and microwave-optical interaction (Padova, Bologna, Ferrara, Turin, IROE); propagation and remote sensing (Milan, Rome La Sapienza, Rome Tor Vergata, Naples); and bio-electromagnetics and electromagnetic compatibility (Ancona, Genoa, Rome La Sapienza). Inter-university research consortia have been formed to coordinate research activities in specific domains, such as: MECSA (Microwave space activities), CIRMA (microwave and antennas), and ICEMB (electromagnetic–biological interactions).

Many microwave activities have been sponsored by the Italian Space Agency (ASI), in the framework of national, European, and International programs. These activities may be grouped into: telecommunications (SIRIO 1977–1985), which collected in Italy and abroad, a unique set of data at 11.6 and 18 GHz, still considered fundamental for the design of later satellite systems (ITALSAT 1991–2000, DAVID satellites); remote sensing (SIR-C/X-SAR shuttle missions); and astrophysics (SOHO, PLANK satellites, etc.).

D. Education

University education in Italy is undergoing a substantial reform starting in the 2001–2002 academic year. The conventional Laurea degree for engineers, corresponding to a curriculum of nominally five years, but, in practice, 7–8 years for the majority of students, is being replaced by two successive degrees of three and two years, respectively, roughly corresponding to the Bachelor and Master degrees. The objective of such a reform is to strongly reduce the number of dropouts, as well as to lower the age of graduated engineers that topped the average value of 26–27 years. Thus, the number of engineers graduated from Italian universities after a three-year program is expected to increase in the coming years.

Although not so popular, microwaves, antennas, and, in general, electromagnetic fields are taught in most Italian universities. The number of engineers with a microwave background is still relatively high in Italy, compared to other countries.

G. Gerosa, G. Pelosi, and R. Sorrentino

VIII. DENMARK

Microwave activities began in Denmark in the 1950s at the Electromagnetics Institute of the Technical University of Denmark (DTU). Originally, this was in Copenhagen, but later moved to a new campus in Lyngby, north of Copenhagen. Both in the academic and the industrial worlds, the activities have increased considerably since that time.

The microwave antenna field has always been active in Denmark, leading to a major commercial activity in the area of satellite antenna design, as well as the development of advanced test facilities at DTU involving a large anechoic chamber, i.e., the DTU-ESA Spherical Near-Field Antenna Test Facility. The modern communication developments in the mobile domain have also led to Danish antenna activities, where the Center for Personkommunikation (CPK), Aalborg University, Jutland, has contributed to the knowledge of design and testing of handset antennas. Propagation of microwaves in the urban environment, as well as indoors, has been studied extensively, especially with regard to the use of multiple antennas for improvement of the mobile channel and for the generation of high-capacity links with high spectral efficiency.

Microwave electronics plays a major role in two domains. One is for front-end circuits in mobile phones, where CPK is involved in system and circuit design to enable use of low-cost silicon technologies to be used in high-performance wireless communication systems, such as IMT-2000. Key research topics also include RF circuit theory, microwave modeling of integrated silicon components, and accurate on-wafer measurement techniques. The other major domain is multiple gigabits-per-second integrated circuits for optical communications at the COM center at DTU, an area where major industrial activities also take place.

Remote sensing has always been high on the Danish microwave agenda, starting with measurements of the thickness of the Greenland icecap. Today, these activities at DTU embrace wide-band synthetic aperture radar (SAR) systems for polarimetric interferometric applications on satellites or aircraft, as well as radiometer systems for remote sensing.

The microwave activities at DTU are now under the umbrella of the Ørsted-DTU Institute; an appropriate name since Ørsted was the main Danish contributor to electromagnetics and, thus, also indirectly to microwaves.

J. Bach Andersen

IX. FINLAND

In Finland, academic education in radio engineering has been provided since 1924, when the first professor of radio engineering began at the Helsinki University of Technology (HUT) and the Radio Laboratory was established. Microwaves in applications to radar and radio links were first dealt with in research and teaching in the 1940s; increasing in the 1950s. The first thesis on a mobile radio appeared in 1949. Beginning with the 1960s, microwave techniques were often studied in connection with radio astronomy and, in the 1970s, millimeter waves were applied. Also, microwave sensors for industrial processes and microwave remote sensing have been studied extensively since 1970. The last 20 years have been the golden era for radio communications; the Nordic countries took the first mobile cellular system, NMT450, into use in 1981, then NMT900 in 1986, and GSM900 in 1992. Today, electronics and communications industry produces over 30% of the Finnish exports. This has certainly reflected strongly in the education of microwave techniques, antennas, and propagation.

In Finland, and especially at HUT, we have been lucky to keep the electrical-engineering curriculum positively based on physics and not changed it toward bits, as has happened in many other universities around the world. At HUT, all students in the Electrical and Communications Engineering Department have followed extensive courses in physics, with obligatory courses in electromagnetics and circuit theory. This has guaranteed good students for microwave engineering, which is most important for Finland's development toward being one of the leading countries in mobile radio communications.

Today at HUT, microwave techniques and related topics such as antennas and propagation are studied and taught by four professors in radio engineering and, in addition, by several professors in electromagnetics, including RF circuit design, circuit theory, microwave remote sensing, and radio communications. Furthermore, the University of Oulu and the Tampere University of Technology have research and teaching activities in these fields. The HUT and VTT (governmental research center) have also established a joint research institute for millimeter-wave techniques, i.e., the Millimeter Wave Laboratory of Finland—MilliLab, which has the status of an European Space Agency (ESA) External Laboratory.

The most outstanding Finnish contributions in the microwave science and technology are, e.g., leadership in mobile communications, both in terminals and in networks; applications of microwave sensors for industrial processes; advancements in electromagnetic theory and microwave remote sensing techniques; and development of millimeter-wave techniques, e.g., for radio astronomy in the front-end.

The current microwave research activities aim, for example, is toward smart/adaptive radios and antennas, direct conversion receivers for WCDMA, improved models of RF components and circuits (e.g., APLAC), radio channel modeling for future mobile radio systems, millimeter-wave beam forming with holograms, and synthetic aperture radiometry.

The biggest employers of microwave engineers in Finland are Nokia (mobile communications), telecom operators, military forces, VTT, and universities. However, there are also many small- and medium-size specialized enterprises for microwave sensors, radars, antennas, RF and microwave components, etc. The Finnish microwave engineers are associated to the Finnish Society of Electronics Engineers (established in 1929 as the Association of Radio Engineers). In 1987, an IEEE chapter on antennas and propagation and microwave theory and techniques was established in Finland. Every second Finnish IEEE Fellow is a member of the IEEE MTT-S.

A. V. Räisänen

X. SWEDEN

During the early 1940s, modern microwave technology teaching and research started at the Royal Institute of Technology, Stockholm, and at the Chalmers University of Technology, Göteborg. Defence-oriented research in propagation, microwave technology, and radar/EW systems became important during the war and, since 1945, has been continued at FOA, today the Swedish defence research agency FOI. Concerning microwave education, the Royal Institute of Technology, Stockholm, has basic courses in microwave engineering, while further microwave aspects are interleaved in wireless and photonics teaching. Chalmers has a full microwave curriculum including antennas and systems engineering, MMIC, and other modern active and passive components. There are also some microwave courses available at the universities of Linköping, Lund, and Uppsala.

FOI, Linköping, is active in the fields of phased-array antenna technology (e.g., antennas, T/R modules, broad-band microwave circuits, and components), high-power microwave protection and electromagnetic compatibility (EMC), radar cross-sectional analysis, and the design of radar and EW systems. The well-known CARABAS synthetic aperture radar developed at FOI points the way ahead for future radar systems. In the 1960s and 1970s, the Microwave Institute Foundation (now ACREO), Stockholm, built up competence in semiconductor microwave components. It is interesting to note that the microwave semiconductor device research in the 1960s became the foundation for the recent success story in optical devices.

Quite early, the Swedish company SRA focused on mobile systems for telephony; a driving person was Åke Lundqvist. Without these initial achievements, Sweden would not have played the role it does today in wireless communications. The cellular systems NMT 450 and NMT 900, developed in Sweden, marked a definite change toward nonmilitary applications of microwaves. The dominating company in the microwave field is Ericsson, with its focus on communications. Ericsson also has a special company focusing on microwave technology, Ericsson Microwave Systems AB, with microwave products for both civilian and military applications, in particular, transmission, certain base-stations and sensor (radar) systems. Saab Bofors Dynamics, Ericsson Saab Avionics, and SaabTech Electronics are mainly in the defence sector, while smaller companies like Saab-Ericsson Space, Sivers IMA, and Allgon are focusing on civilian products for different applications. SaabElectronics AB has a special reputation for radars based on FM CW techniques such as automotive radar applications.

Radio astronomy has for many years been strong in Sweden. In 1949, Chalmers Prof. O. Rydbeck founded the Onsala Space Observatory for radio astronomy. Today, the observatory is responsible for telescopes not only at Onsala, but also in Chile. Due to the inspiration from radio astronomy research, low noise has for many years been an important focus at Chalmers. Recently (i.e., February 2001), the Odin satellite radio astronomy observatory was launched with advanced quasi-optical 500-GHz receiver and amplifiers (IF and 119 GHz) designed and built at Chalmers. Chalmers is also involved in the FIRST (now called Herschel) satellite, to develop, build, and test world-record low-noise temperature heterodyne receivers for terahertz frequencies. A cooled IF amplifier with 2.5-K noise temperature amplifier for 4–8 GHz has been realized with "homemade" HEMT transistors. Other activities concern silicon–carbide (SiC) high-power FETs, MMICs, and array-type SIS receivers.

In Sweden, microwave technology is a concern for members of SNRV (URSI) and the IEEE MTT and AP chapters.

E. Kollberg

XI. Poland, Czech Republic, Slovakia, and Baltic Countries

A. Background

Located in the very center of Europe, for centuries, Poland, just like Czechoslovakia, has been a focus of international exchange, and has also strived to act as an origin of new knowledge and human resources. However, central location has proven to be as much of an asset as of a disadvantage in this regard, making the country susceptible to economical and political turbulences. Those general factors apply to microwave activities considered herein. Poland and Czechoslovakia have numerous achievements of their indigenous microwave research and industrial centers to pride themselves on. However, we will also show that the picture remains incomplete if we do not include contributions of the people, graduates of the Polish and Czech universities, who now live and work abroad.

B. Poland

Poland has over 50 years of successful microwave engineering activities. They date back to the late 1940s with the advent of the first Polish microwave tube; a pulse magnetron model M2 (600 MHz, 300 kW/imp), developed by the Telecommunications Research Institute (PIT) in collaboration with the Warsaw University of Technology (WUT). The manufacture of microwave tubes spread into OBREP and LAMINA, from where new types of magnetrons, klystrons, and TWTs soon emerged. At the same time, a radar technology unit was established at PIT, which developed its first NYSA radar.

The golden decades for Polish microwaves were the 1960s and 1970s. PIT launched its civil radars of AVIA series, which became the country's visit cards alongside microwave tubes. WILMER became known for its moisture meters. Several enterprises undertook the research on microwave materials and, subsequently, their production. Among them, the Institute of Electronic Materials (ITME) concentrated on semiconductors, while POLFER concentrated on magnetic materials. The Institute of Electronic Technology (CEMI) was among the largest developers of semiconductor diodes in Eastern Europe.

It is worth emphasizing that from the very beginning until today, microwave developments in Poland have been based on national research. The aforementioned institutes have been supported by the academia, mainly by microwave departments within four universities, i.e., Warsaw University of Technology, Technical University of Gdansk, Wroclaw University of Technology, and Military University of Technology. They have elaborated a vast original scientific knowledge on a variety of topics, from electromagnetic field theory and circuit theory, through analytical and numerical methods of circuit and field analysis, up to the linear and nonlinear circuit design and measurements. The universities have educated future microwave engineers and entrepreneurs, many of whom have later become internationally known.

The extent of microwave activities in Poland stimulated the emergence of microwave-oriented events and professional societies at an early stage. In 1969, the national microwave conference MIKON was established under the auspices of the Polish Academy of Sciences. In 1994, it was transformed into an international conference recognized by IEEE and, today, it is a leading biannual regional event in Central and Eastern Europe. The IEEE MTT-S chapter in Poland originated in 1990.

After such an encouraging takeoff, the status of microwave research and industry in Poland today certainly benefits from the devoted efforts of microwave scientists, engineers, and managers since the 1940s. Unfortunately, it has also been heavily influenced by transformations in the economy of the European region. During the 1980s and 1990s, many industrial establishments had to close down. Needless to say, governmental financing of research and education was also reduced, and has since been effectively reduced year by year.

Some groups of Polish microwave researchers, facing a choice between change of profession or change of country, moved mainly to Sweden, U.S., Canada, and Australia, where they joined earlier smaller scale political emigration of the 1960s and 1970s. Hence, many graduates of the Polish universities now live and work abroad. Their success confirms the quality of education provided by the Polish universities. Many have become widely known for scientific innovations; others have assumed leadership positions at the world's largest research and industrial centers.

Finally, let us come back to indigenous microwave activities in Poland today. PIT assembles the largest group of microwave and radar engineers in the country. It specializes in radar technology, and has gained international esteem for its radiolocation systems (e.g., modern 3-D radars with curtain antennas TRD 1211 type). RADWAR continues the development and manufacturing of civil radars. OBREP and LAMINA produce amplitrons, reflex klystrons, gas-filled TR-tubes, and TWTs. LAMINA has also been working on new pulse tubes and BWTs. Of microwave material enterprises, ITME remains active and visible on the international arena, it exports silicon, GaAs and InP wafers, and epitaxial structures; it is also involved with optoelectronic and microwave devices and sensors. New private companies are being established, and some have already introduced their products onto the international market. The Vector Company is worth mentioning for its cable television devices, and also QWED, a spinoff from WUT, for its electromagnetic simulations software.

C. Czech Republic and Slovakia

The Czech Republic, Slovakia, and Poland are neighbors who share a similar political and social–economic milieu. Therefore, not surprisingly, their microwave activities have all followed similar historical paths, but possibly with the one difference that less people have moved to work abroad.

Until the 1980s, microwave technology in former Czechoslovakia was on a relatively high level. A key manufacturer of microwave equipment was TESLA, a brand name for radars operating from 10 cm to less than 3 cm, which also produced point-to-point radio links and nearly all necessary components, e.g., microwave tubes, waveguides, coaxial cables, directional couplers, oscillators, mixers, parametric amplifiers, antennas, etc. The Czech Republic has been quite successful in developing passive radar technology (RAMONA, TAMARA).

Microwave systems were also produced in southern Moravia (Let Kunovice). The Research Institute for Telecommunications developed and produced semiconductor diodes and transistors, with involvement in MICs and ferrites, including nonreciprocal elements such as isolators and circulators; its technology was very reliable and, thus, popular for military applications.

The three Technical Universities of Prague, Brno, and Bratislava, the Military Academy, and the Institute of Radioelectronics of the Academy of Science provided background scientific support. The Universities graduated about 50 microwave engineers every year.

After 1989 in the Czech Republic, the structure of producers, research institutions, and part education centers has deteriorated. Activity in the field of microwave technology has been substantially reduced, and the market has been reduced by one-half. Big enterprises have been privatized and divided into many small companies competing with one another. TESLA, once the largest producer of radiolocation technology in the world, has only kept the production of radio links. Production of semiconductor devices and ferrites has been terminated. Only the production of ceramics for microwave applications remains. Prague, Pardubice, and Kunovice, where the former big companies have prospered prior to 1990, have served as a nest where several new small and medium companies are now growing to the size of 50–200 employees, and these proceed with programs on radar technology, microwave heating, and hybrid MIC planar technology. For example, ERA makes passive surveillance systems, VERA and RAMET C.H.M. make police radars (velocimeters), RAMER and ALCOMA produce communication systems, and RETIA makes special radar subsystems and C3I.

In Slovakia, the situation after its secession is worse, and it seems that microwave production has nearly disappeared there.

The three technical universities continue to operate, but research institutes have practically disappeared from the scene.

The IEEE MTT/AP/ED joint chapter of the Czechoslovakia section keeps a web page with information on microwaves in the region, and organizes national microwave conferences COMITE each two years.

D. Baltic Republics

The last decade proved turbulent for the former Baltic Republics of the USSR, which have gained independence and undergone vast economical changes.

In the USSR, some of the major RF and microwave enterprises were concentrated in Lithuania. Vilnius Research Institute of Radio-Measuring Devices was a leading research institute in the microwave field in the USSR, with a large plant producing measurement equipment. A similar research institute existed in Kaunas, though with considerably less volume of microwave oriented activities. After the collapse of the USSR, both research institutes were liquidated, and a number of private companies were established on their basis. They are engaged in applied research: Elmika on passive devices and microwave measuring instruments; Geozondas on microwave measuring equipment for antennas and radars; Hybridas on thick-film substrates and hybrid circuits; and Keturpolis on panoramic S-parameters measurement systems. Recently, new companies have emerged through international investments. For example, Giga (Denmark), branch establishment of Intel Corporation, founded its subdivision GigaBaltic, specializing on fast communication devices.

Microwave research and education within the Baltic countries is offered by the Vilnius University in Lithuania and the Riga Technical University in Latvia. Training courses on microwave techniques are also available at the Vilnius Technical University and Kaunas University of Technology. The latter hosts the Annual Conference on Electronics, where some topics usually concern microwave techniques.

Basic research is carried out at the National Academy institutes of the Baltic States, often within the framework of international programs. It comprises investigation on new materials and high-frequency systems and phenomena in the frequency range up to 1 THz.

J. Modelski

XII. RUSSIA

The beginning of microwave activities in Russia may be referred to the investigation of the millimeter-wave mass-oscillator ($\lambda = 50$ mm $- 82$ μm) at Moscow University by A. A. Glagoleva-Arkadieva, in 1922.

R&D in the microwave area was performed in the Academy of Sciences and many universities. In the middle of the 1930s, the industry was involved in the production of microwave equipment in connection with radar techniques, FM broadcasting, and television.

Fundamentals of microwave antennas were developed by A. A. Pistol'kors in the early 1930s. At the same time, extensive research was carried out in the field of high-power microwave oscillators. N. F. Alekseev and D. E. Malyarov suggested a cylindrical multicavity anode magnetron in 1936–1937. The idea of using the electron beam reversed by a negative electrode in a single-resonator oscillator (reflex klystron) was offered by N. D. Devyatkov in 1940.

An intensive research in radar techniques started in the late 1930s. The pulse radar system was developed in the Physico-Technical Institute (now named after A. F. Ioffe) in Leningrad (now St.-Petersburg), by Y. B. Kobzarev in 1937. The production of radar equipment was motivated by military needs during World War II. Many R&D institutes and industrial enterprises have been created and involved in the production of microwave warfare techniques.

A significant development of microwave techniques was provided by fundamental electrodynamics elaborated by G. V. Kisun'ko in the 1940s, and further by L. A. Vainshtein and V. V. Nikol'ski.

The first maser was suggested and investigated at the Institute of Physics of Academy of Sciences in Moscow, by A. M. Prokhorov and N. G. Basov in 1953 (Nobel Prize).

The requirement of radar techniques stimulated the microwave applications of ferrites, which were actively developed in the 1950s. The Nobel Prize winner L. D. Landau developed the theory of tensor permeability of a saturated magnetic material in 1935. The industrial production of ferrite microwave components was initiated by A. L. Mikaelyan.

The first phased-array antenna was designed at the Electrical Engineering Institute in Leningrad in 1955, under supervision of Y. Y. Yurov. The four-element antenna used ferrite phase shifters. The development of phased-array techniques demanded an extensive growth of the microwave infrastructure. Many organizations have been involved in R&D and production of microwave solid-state devices and components. Today in Russia, many radio astronomy, space communication, and military systems employ high-level phased-array antennas. For example, well known is the Russian antiaircraft and antimissiles system "S-300," based on a large phased-array antenna.

A high scientific and technological level of the microwave activity was provided and supported in the Soviet Union by carrying out annual conferences on microwave techniques under the supervision of N. D. Devyatkov, and on antenna theory and technology under the supervision of A. A. Pistol'kors.

In 1950, the Nobel Prize winner P. L. Kapitsa suggested using high-power microwave generators in energetics and developed the theory of the subject. In 1960, A. V. Gaponov-Grekhov (Institute of Applied Physics of Academy of Sciences, Gorki, now N. Novgorod) developed the idea of using the induced cyclotron emission for high-power radiation of millimeter and sub-millimeter waves. Such an oscillator is known as the gyratron.

The first attempts to use ferroelectrics for practical applications at microwaves were undertaken by Y. M. Poplavko in Kiev and by O. G. Vendik in Leningrad during 1960. This branch is now being successfully developed.

Just after discovering the high-temperature superconductivity (HTS) in 1986, the Government Program of investigations in this area, including the microwave applications of HTSs, was developed. The Prime Minister of the Soviet Union, A. N. Ryzhkov, headed the program. The program significantly supported the initial development of HTS physics and practical applications in Russia.

The microwave techniques owes its achievements to a very good organization of higher education in Russia, which provides, as a consequence, a high intellectual and technological potential of scientists and practical experts in this field.

The change of the economical system in Russia after disintegration of the Soviet Union led to great problems for large industrial enterprises, which were not experienced in the market management. However, some of them are now restoring a high level of microwave production. Additionally, many new small private companies supply the market with modern microwave components and subsystems.

O. G. Vendik and I. B. Vendik

XIII. Hungary and Balkan Countries

A. Background

In the 1930s, the telecommunications industry was weak and dependent on the knowhow of multinational companies, such as Standard, Siemens, Philips, and Ericsson, which had subsidiaries in these countries. At the end of the 1940s, these companies were nationalized and the links to the multinational companies were broken. Therefore, the establishment of the national R&D became important.

Centralized R&D institutes were established in these countries in two main areas: microwave links were developed and manufactured in Hungary and Yugoslavia; and radar equipments were worked out and produced in Bulgaria. More details are given for the specific countries in Sections XIII-B–XIII-D.

An international conference series called Microcoll (Colloquium on Microwave Communications) was started in the late 1950s, and then held with a periodicity of four years, in Hungary. Many scientific results were originally presented at Microcoll. Later, a biannual international ferrite conference series was also launched jointly in these countries. However, each country had a national conference on microwave techniques as well. Several contributions were also presented at the EuMC each year.

Microwave university education began in these countries at the end of the 1940s. The main centers of microwave education were Budapest and Györ, Hungary; Ljubljana, Zagreb, Belgrade and Nis, Yugoslavia; Bucharest, Cluj-Napoca and Timisoara, Romania; and Sofia and Varna, Bulgaria.

B. Hungary

In Hungary, the milestone of microwave research was the "Moon experiment." Almost at the same time, independently from the U.S. experiment, the Moon was tested by a radar signal with success. The experiment was based on the L-band radar development at Tungsram Laboratories, conducted by Z. Bay and K. Simonyi.

The TKI, Research Institute for Telecommunications was founded in 1949 with the mission to be the central R&D institute in microwave techniques. The first microwave link utilizing pulse amplitude modulation (PAM) in the band of 2 GHz was put into operation in 1951. It was followed by a high-capacity (TV or 600 phone channels) system operating with six parallel microwave channels in the 4-GHz band in 1958. Then second- and third-generation systems were developed in the 2-, 4-, 6-, 8-, 12-, 15-, and 26-GHz bands, meeting very severe climatic requirements. All these systems were put into production at Fine Mechanics Works (FMV) and ORION factories. Small capacity microwave links were also developed and manufactured at the ORION factory.

Using such products, about 100 000 channel/kilometer links were installed in several countries of Eastern Europe, Asia, Africa, and South America. Most of the production was exported to the Soviet Union. However, the microwave products of the Hungarian industry were also used to establish a nationwide telecommunication network containing high-, medium-, and small-capacity links for the transmission of television programs and multiplexed telephone channels.

The R&D was concentrated on microwave telecommunication links. In the framework of this activity, significant research results were achieved in the field of microwave circuits and systems. For example, in such areas as microwave waveguide and microstrip filters; injection-locked oscillators; AM compression and AM–PM conversion meter; dielectric surface waveguides; supergain antennas; nonlinear microwave circuits; like oscillators; up- and down-converters; and frequency multipliers; etc.

The microwave education began at the Technical University of Budapest in 1949. Since that time, a number of textbooks were published. R&D were also carried out there and significant results were obtained on microstrip antennas, parametric circuits, remote sensing, and modulation theory, etc.

C. Balkan Countries

In Yugoslavia, microwave industry was represented mainly by the Iskra Company in Ljubljana. Small capacity systems were developed and produced there. Research was performed at IMTEL in Belgrade on antennas, semiconductor microwave circuits, etc., for radar equipment.

In Romania, R&D was concentrated on semiconductor devices. Some manufacturing was also performed mainly for such devices.

In Bulgaria, research, development, and manufacture of radar equipment took place in Varna. Research on microwave circuits and ferrite devices was conducted in Sofia at academic institutes.

D. Current Situation

The situation has completely changed in all the above countries at the beginning of the 1990s. The nationalized companies were privatized and purchased by multinational companies such as Nokia, Ericsson, Siemens, Philips, Motorola, IBM, etc., and mainly component production is carried out at their subsidiaries. Their R&D activity mostly consists of software work.

Currently, higher education is also in a transition state. Most of the hardware-oriented courses have been reduced or eliminated and replaced by software-oriented courses. That tendency is also reflected in research topics at the universities. However, some hardware-oriented R&D is also conducted such as in the fields of microwave photonics, microstrip antennas, MMICs, ferrite devices, small-capacity microwaves, and optical links, etc.

Additional information can be found in [4]–[7].

T. Berceli

XIV. SPAIN

According to OECD, the investment in R&D, averaged with respect to the Spain gross domestic product, has grown from 0.72% in 1988, to 0.89% in 1999. This growth is mainly due to public investment (0.31% in 1988, 0.42% in 1999) compared with industry investment (0.41% in 1988, 0.47% in 1999). These figures reflect well the situation in Spain, where a large R&D effort has been carried out during the last decade, although both public and industry investments are still lower than those corresponding to other European countries comparable to Spain in terms of population and natural resources. Currently, the strongest activities in microwaves are in antennas, device modeling, design and implementation, transceivers, wireless and mobile communications, microwave heating, and electromagnetic compatibility. End applications such as telecommunications, defense, and manufacturing are more emphasized than technology.

Microwave theory and techniques and related topics are taught in schools for telecommunication engineering and faculties of physics of a large number of universities. The central (Ministry of Sciences and Technology, its Center for Technological Development of Industries, and the Ministries of Defense and Education) and regional governments fund education and research, both directly and through grant schemes. The European Union (EU) supports a wide variety of programs, from medium-size projects to macro-projects (e.g., EUROFIGHTER 2000), as well as networks of excellence and researchers and students mobility. ESA and other European institutions have also funded projects. Most university groups have contracts with national industries and service companies.

Microwave activities began over 30 years ago at the Universidad Politécnica de Madrid (UPM). During these years, UPM activities included modeling, design, implementation, and measurements of active and passive devices (MICs, MMICs, waveguide technologies), numerical techniques and electromagnetic simulators, antennas, antenna measurements, radar cross-sectional measurements, radar systems, smart antennas, wireless and mobile communications, broad-band radio systems (e.g., LMDS), photonics, biological effects, material characterization, radio astronomy, radiation, and propagation. The creation of U. P. Cataluña (UPC), was also instrumental for the success of microwave R&D. UPC groups have contributed to previously mentioned areas plus inverse imaging and fractal antennas. Currently, strong groups are also working in U. P. Valencia (with special focus on industrial applications), U. Cantabria, U. Vigo, U. Sevilla, U. País Vasco, U. Pública de Navarra, U. Las Palmas de Gran Canaria, U. Valladolid, U. Málaga, U. Carlos III de Madrid, U. Alcalá, U. Zaragoza, U. Valencia, U. Complutense de Madrid, U. Ramón Llul, U. Barcelona, U. La Coruña, U. Murcia, U. Salamanca, U. Jaén, U. Vic, U. Santiago de Compostela, U. La Laguna, U. P. Cartagena, U. Granada, U. Oviedo, U. Burgos, U. Islas Baleares, U. Castilla La Mancha, U. Extremadura, U. Rey Juan Carlos, U. Alfonso X el Sabio, U. Europea, U. Alicante, U. Navarra, U. P. Cartagena, and P. Mataró.

The main public research institutes with microwave activities are ascribed to the Centro Superior de Investigaciones Científicas (Scientific Research High Center) and the Instituto Nacional de Técnica Aerospacial (National Institute for Aero Spatial Techniques). Other research centers and companies are grouped in several Parques Científicos y Tecnológicos (Science and Technological Parks).

Companies with microwave activities are ACORDE, ALCAD, AMPER, ARTEIXO TELECOM, BTESA, CASA, CDC, CETECOM, CYS, EGATEL, Ibérica de Componentes, FAGOR Electrónica, FRACTUS, Grupo STC, INDRA, INTELSIS, IKUSI, JCM Technologies, LINK Comunicaciones, MIER Comunicaciones, OMB Sistemas Electrónicos, OMNITEL, Page Ibérica, RYMSA, Shelcom Sistemas, TELEVES, TTT, VIMESA, and ZIGOR. A number of telecommunication operators and service providers are active on microwaves (e.g., ABRARED, AIRTEL, EUSKALTEL, HISPASAT, INFOGLOBAL, RETEVISIÓN, Sky Point, Telefónica, UNI2), as well as multinational companies located in Spain, e.g., ALCATEL group, Ericsson, Kenwood, Lucent Technologies, Marconi, Matra-Nortel group, Motorola, Nokia, Philips, Siemens, and Thomson. Detailed information may be found through the National Association of Electronic and Telecommunication Industries (ANIEL).

During the last decade, the number of papers published by Spanish researchers in international journals and symposiums has substantially increased, as well as collaborations with foreign research groups. In 1993, the UPM organized the 20th EuMC in Madrid, achieving a great success. A number of symposiums are held annually at the national level with some foreign contributions. A highlight could be the URSI National Symposium cosponsored by the IEEE Spain section with around 300 papers in the microwave area.

M. Salazar-Palma

XV. Portugal

Portuguese R&D in the microwave area was always related to the Academia. Initially (1960s), the teaching of microwaves included only passive structures and wave propagation. Since the 1970s, local industry developed VHF and UHF equipments mainly for military applications and, during the 1980s, also microwave heating equipment. Microwave electronics were introduced in some university curricula by the mid-1980s, and research activities were launched with ETSIT UPM support. During the 1990s, after Portugal entry in the EU, higher investments in the infrastructure have lead to an increase in R&D activities.

Currently, the strongest activities are in antennas, microwave electronics, propagation studies for satellite and mobile planning, and microwave systems integration. R&D activities are mainly located at the Institute of Telecommunications, a private nonprofit research center owned by the Instituto Superior Técnico (Technical University of Lisbon), Aveiro University, University of Coimbra, and Portugal Telecom (Telecom operator). Funds come mainly from the Ministry of Education (manpower) and the Ministry of Science and Technology (MST) (infrastructure and research projects grants). Since 1990, the EU has funded research programs from theoretical studies to development of hardware, systems integration, and test. Since Portugal has been integrated recently into ESA, a further increase on microwave activities should be expected. Contracts with local industries and service companies have increased during the last decade.

Currently, MST supports two-thirds of R&D (one-third basic investment, one-third projects), while the rest comes from EU, local industries, and service companies.

J. Costa Freire

XVI. Greece

The fundamental theory of guiding of electromagnetic waves in a dielectric waveguide, known today as fiber-optic line, was analyzed rigorously in 1909 by D. Hondros [8], who at that time, was an Assistant at the School of Physics, National Kapodistrian Athens University (NKUA), obtaining his Ph.D. degree in Munich, Germany, under the supervision of P. Debye. In the era before World War II, wireless high-frequency transceivers were build at the National Technical University of Athens (NTUA) for the needs of the Hellenic Navy. During the same time, a prototype CW microwave (3 GHz) radar was developed by the Chair of Physics at NTUA to provide an early warning of approaching enemy airplanes. This pioneering effort was stopped because of the war situation the country entered in 1940.

In the decades of the 1960–1970s, the curricula at the School of Electrical Engineering, NTUA and School of Physics, NKUA were enriched with courses on high-frequency and microwave topics. New courses on related topics were also introduced in the newly established Schools of Electrical Engineering and Physics, at the Aristotelian University of Thessaloniki (AUTH), University of Patras (UNPA), and Demokritian University of Thrace (DUTH). Following the entrance of Greece to the European Community in 1980, research in various topics of microwave theory and techniques grew steadily. This increased the number of young researchers working toward their Ph.D. degrees at the above-mentioned academic institutions. An experimental GaAs foundry was established in 1987 in Herakleion, Crete. Microwave-related research activities carried out by the teams in Greek Universities are focused on telecommunications (terrestrial, mobile, and satellite), radar engineering, antennas and propagation, bioelectromagnetism, computational electromagnetism, and sensor systems. Currently, a microtron linear accelerator facility is being constructed with the cooperation of the NTUA and NKUA. The number of research scientists involved with RF and microwaves is approximately 150.

In industry, there are currently several companies active in the field of microwave technology such as INTRACOM S.A., ANCO S.A. (telecommunications), C2T- ACT (EMC and military systems), HAI (avionics), and HELIC (design and development of microwave circuits). Recently, the decision to launch the first geostatic satellite has been taken and, along this line, a private company called HELLAS-SAT was established.

N. Uzunoglu

XVII. Israel

Microwave activities in Israel began during the 1960s at RAFAEL, a government-owned research institute. A motivated and dedicated team of scientists and engineers worked hard to lay the foundation of microwave engineering in Israel, beginning from scratch. A few years later, two more microwave groups were founded, one in Elta, a subsidiary of the Israel Aircraft Industry (IAI) and one in ELISRA (then named AEL-Israel). These three centers led the microwave activity for about a decade. In 1977, the first commercial microwave company was established as a cooperation between RAFAEL and the U.S.-based MA/COM. The new company was named Mikrokim, and still exists. During the 1980s, more companies entered the microwave field, such as Optomic, Eyal, and General Microwave (Israel). During the 1990s, many communications start-up companies were established and quite a few more microwave centers were started, e.g., CyOptics, Foxcom, Gilat, Helicomm, MTI, RAVON (mini-circuits), Motorola, Tadiran, Witcom, etc.

The microwave activity at universities is quite limited. Most of the related research is in electromagnetics. Good electromagnetic centers exist in the Technion, Haifa, Tel Aviv University, and Ben-Gurion University, Beer-Sheva. Due to this fact, most of the scientific and engineering advancements in microwave components, systems, and technology were performed in RAFAEL. Later on, contributions were also made by Elta and Elisra. One of the major scientific contributions performed in RAFAEL in the early 1970s was the development of software for microwave analysis and design; this pioneering work was led by the late H. Rabin, and performed several years before the development of the first commercial CAD tool, e.g., Touchstone, by Compact Software in the U.S.

The IEEE AP/MTT chapter in Israel was established in 1973 by A. Madjar with help from L. Young, who was then on sabbatical in the Technion. Since its creation, the chapter has served as an important tool to organize technical meetings, including 16 full-day symposia. L. Young was very instrumental during his sabbatical in establishing a sound basis for microwave engineering in Israel. Recognition of the high standard of microwave activity in Israel led to the decision of the EuMC management committee to hold the conference in Israel. The conference was indeed successfully when it was held in Jerusalem in September 1997 and it represented a turning point in the conference series: the year after, the series of EuMWs began and the EuMA was founded.

Pioneering MIC activity started in RAFAEL during the early 1970s, which later migrated to other companies (Elisra, Elta, Optomic, etc.). GaAs MMIC activity started in Israel during the 1980s and increased substantially by the creation of a GaAs consortium in the 1990s. Today, there are established MMIC design groups, as well as a GaAs foundry.

The beginning of the microwave activity was purely military, and it made outstanding contributions to the defense of the country. During the years, the activity has drifted slowly toward commercial applications and, today, there exist many start-up companies in this area, as well as companies that purchase microwave hardware. The activity covers systems and components up to 100 GHz.

A. Madjar

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Roberto Sorrentino *(Editor)* (M'77–SM'84–F'90) is currently a Professor at the University of Perugia, Perugia, Italy. His research activities have mainly concerned numerical methods and with the analysis and design of microwave and millimeter-wave circuits. He has authored or co-authored approximately 100 technical papers in international journals and 120 refereed conference papers. He has also edited a book for the IEEE Press and has recently co-authored a book on advanced modal analysis.

Dr. Sorrentino is a member of the High Technical Council of the Italian Ministry of Communications. He was the editor-in-chief of the IEEE MICROWAVE AND GUIDED WAVE LETTERS (1995–1998). Since 1998, he has served on the Administrative Committee (AdCom) of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He also served on the International Union of Radio Science as vice chair (1993–1996) and then chair (1996–1999) of the Commission D (electronics and photonics). Since 1996, he has been the chairman of the Management Committee of the European Microwave Conference and the chairman of the European Microwave Association since its constitution in 1998. He was one of the recipients of the IEEE Third Millennium Medal. and was the recipient of the 1993 IEEE MTT-S Meritorious Service Award.

Terry Oxley (M'73–SM'78–F'92–LF'99) joined the GEC Hirst Research Centre, Webmley, Middlesex, U.K., in 1946 following wartime service in the Royal Navy. His professional career in microwave electronics proceeded with GEC-Marconi until his retirement in 1988. Upon retirement, he became a consultant on an independent basis.

Georges Salmer received the Doctorat-ès-Sciences Physiques degree from the University of Lille, Lille, France in 1966.

He is currently a Professor at the University of Lille and Head of the Institut d'Electronique et de Microélectronique du Nord (400 people). He is involved with microwave solid-state devices (IMPATT, BARITT, MESFET, HEMT, HIGFET), mainly on device modeling and characterization.

André Vander Vorst (M'74–SM'68–F'86–LF'01) was born in Belgium, in 1935.

With the Université Catholique de Louvain, Louvain-la-Neuve, Belgium, he has held the titles of Professor, Head Microwave Laboratory, Head Electrical Engineering Department, Dean of Engineering, Vice-President of the Academic Council, President of the Open School in Economic and Social Politics. He has authored or co-authored textbooks, book chapters, and a variety of papers.

Dr. Vander Vorst has been the recipient of numerous awards.

Leo P. Ligthart (M'94–SM'95) received the Doctor of Technology degree from the Delft University of Technology, Delft, The Netherlands, in 1985, the Doctorate degree (*honoris causa*) from the Moscow State Technical University of Civil Aviation, Moscow, Russia, in 1999, and the Doctorate degree (*honoris causa*) from the Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia, in 2001.

Since 1994, he has been the Director of the International Research Center for Telecommunications-Transmission and Radar, Delft University of Technology. His principal areas of specialization include antennas and propagation, radar, and remote sensing, in addition to satellite, mobile, and radio communications.

Peter Russer (SM'81–F'94) received the Ph.D. degree from the Vienna University of Technology, Vienna, Austria.

In 1971, he joined the Research Institute of AEG-Telefunken. Since 1981, he has been a Professor and Head of the Institute of Hochfrequenztechnik, Technische Universität München, Munich, Germany. He has authored over 300 scientific papers in the areas of electromagnetic fields, MMICs, statistical noise analysis, and CAD of microwave circuits.

Giorgio Gerosa (A'58–LA'96) received the Electrical Engineering degree (*cum laude*) from the Università di Roma "La Sapienza," Rome, Italy, in 1956.

Since 1956, he has been with the Università di Roma "La Sapienza," where he is engaged in electromagnetic research and teaching activities and where, since 1967, he has been a Full Professor of electromagnetic fields. He has authored or co-authored 140 scientific papers.

G. Pelosi (F'00) is currently a Full Professor of electromagnetic fields at the University of Florence, Florence, Italy. He has authored three books. His current research activity is mainly devoted to the development of numerical procedures in the context of the FEM, with particular emphasis on microwave and millimeter-wave engineering.

Jørgen Bach Andersen (LF'00) received the M.Sc. and Dr.Techn. degrees from the Technical University of Denmark, Copenhagen, Denmark, in 1961 and 1971, respectively.

He was with the Electromagnetics Institute, Technical University of Denmark, until 1973, after which he joined Aalborg University, Aalborg, Denmark, where he is currently a Professor of radio-communications and Head of the Center for Personkommunikations (CPK).

Antti V. Räisänen (S'76–M'81–SM'85–F'94) is currently a Professor (Chair) of radio engineering at the Helsinki University of Technology (HUT), Helsinki, Finland. He has been a Visiting Scientist at the University of Massachusetts, Chalmers University of Technology, University of California at Berkeley, Jet Propulsion Laboratory, and the California Institute of Technology. He will be with the Paris Observatory, Paris, France, for one year (2001–2002). At HUT Radio Laboratory, he supervising research in millimeter-wave techniques. He has authored and co-authored over 300 scientific or technical papers and five books.

Erik Kollberg (M'83–SM'83–F'91) is a Professor at the Chalmers University of Technology, Göteborg, Sweden. He has authored or co–authored over 250 papers concerning microwave devices.

Prof. Kollberg was the recipient of the 1986 Microwave Prize presented at the 12th European Microwave Conference, and the 1986 Gustaf Dahlén Gold Medal. He was also the recipient of a 2000 Honorary Ph.D. degree presented by the Technical University of Helsinki, Helsinki, Finland.

Jozef Modelski (SM'91–F'01) was born in Kawnice, Poland, in 1949.

He is currently a Professor at the Warsaw University of Technology, Warsaw, Poland, and Director of the Institute of Radioelectronics, Warsaw University of Technology. He has authored over 120 technical papers and four books in the areas of microwave phase modulators and shifters, dielectric resonators, integrating waveguide technology, and antennas.

Orest G. Vendik (M'92) received the Degree of Engineer in radio engineering, the Ph.D. degree, and D.Sc. degree from the Leningrad Electrical Engineering Institute (now the St. Petersburg Electrotechnical University), St. Petersburg, Russia, in 1954, 1957, and 1966 respectively.

He is currently a Professor with the St. Petersburg Electrotechnical University, St. Petersburg, Russia. His research has concerned the foundation of solid-state electronics (ferrites, ferroelectrics, superconductors) and microwave physics and techniques.

Irina B. Vendik (M'96) received the Electronics Engineer diploma and the Ph.D. degree from the Leningrad Electrical Engineering Institute (now the St. Petersburg Electrotechnical University), St. Petersburg, Russia, in 1959 and 1964 respectively, and the D.Sc. (Physics) degree from the A. F. Ioffe Physicotechnical Institute, St. Petersburg, Russia, in 1990.

She is currently a Professor with the St. Petersburg Electrotechnical University, St. Petersburg, Russia. Her research has concerned solid-state physics and microwave electronics.

Tibor Berceli (SM'77–F'94) is a Professor of electrical engineering at the Technical University of Budapest, Budapest, Hungary. His main interest is combined optical-microwave techniques and active nonlinear microwave circuits. He has authored 116 papers and six books.

Magdalena Salazar-Palma (M'89–SM'01) received the Ingeniero de Telecomunicación and Ph.D. degrees from the Universidad Politécnica de Madrid, Madrid, Spain.

She is currently a Profesor Titular at the Universidad Politécnica de Madrid. She has authored or co–authored over 200 papers. Her research interests concern numerical methods for microwave structures, design, and measurement of MICs, MMICs, and waveguide passive devices.

Joao Costa Freire (S'82–A'84–SM'89), received the Ph.D. degree from the Instituto Superior Técnico, Lisbon, Portugal.

He is currently an Associate Professor at the Instituto Superior Técnico and Head of the Microwave Electronics Research Group, Instituto de Telecomunicações, Lisbon, Portugal. He has authored or co-authored over 50 papers in conference proceedings and journals. His main interests are in the modeling of passive and active devices for CAD and the design, integration, and testing of nonlinear MMICs.

Nikolaos Uzunoglu (M'82–SM'87) is currently a Professor at the National Technical University of Athens, Athens, Greece. He has authored or co–authored 150 papers in refereed international journal and five books. His research interests include telecommunication and radar systems and applied electromagnetic theory and technology in biomedical engineering.

Prof. Uzunoglu is an elected member of the Armenian Academy of Science (1999) and Honorary Professor of the State Engineering University of Armenia (1994). He received an honorary Ph.D degree by four Universities of Romania.

Asher Madjar (S'77–M'79–SM'83–F'97) received the B.Sc. and M.Sc. degrees from the Technion, Israel Institute of Technology, Haifa, Israel, in 1967 and 1969, respectively, and the D. Sc. degree from Washington University, St. Louis, MO, in 1979.

Since 1969, he has been with RAFAEL, Haifa, Israel, and with the Technion. He has authored or co-authored over 100 papers in the areas of microwave components and devices, MICs, MMICs, linear and nonlinear microwave circuits, microwave device modeling (including optical effects), and optical links at microwave frequencies.