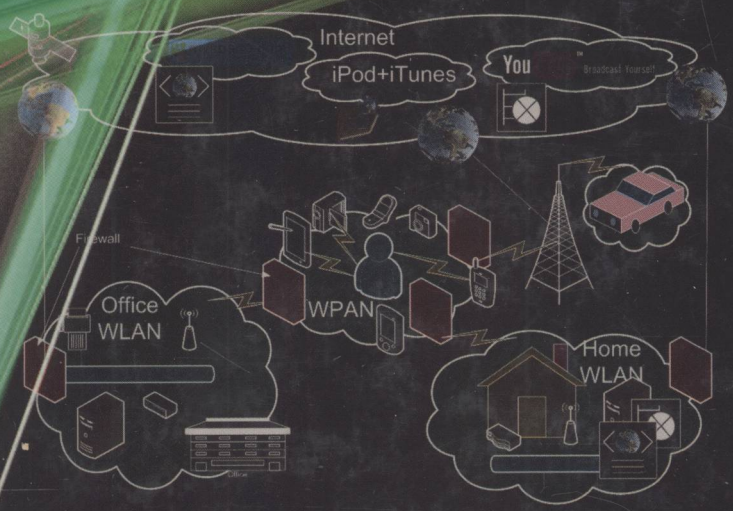
RF and Microwave Handbook

Second Edition

RF AND MICROWAVE APPLICATIONS AND SYSTEMS



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Preface

The first edition of the *RF and Microwave Handbook* was published in 2000. The project got off to an inauspicious start when 24 inches of snow fell in Denver the evening before the advisory board planned to hold their kick-off meeting. Two members of the board were trapped for days in the Denver airport since planes were not arriving or leaving. Because of road closures, one member was stranded only miles away from the meeting in Boulder. And the remainder of the board was stranded in a Denver hotel 10 miles from the airport. Despite this ominous beginning, a plan was formed, expert authors recruited, and the book was developed and published. The planning and development of this second edition have been very smooth and uneventful in comparison to our first efforts. Since publication in 2000, the value of the *RF and Microwave Handbook* has been recognized by thousands of engineers throughout the world. Three derivative handbooks have also been published and embraced by the microwave industry. The advisory board believes that this edition will be found to be of even greater value than the first edition.

Prior to the 1990s, microwave engineering was employed almost exclusively to address military, satellite, and avionics applications. In 1985, there were a few limited applications of RF and microwave systems that laymen might be familiar with such as satellite TV and the use of satellite communications for overseas phone calls. Pagers were also available but not common. In contrast, by 1990 the wireless revolution had begun. Cell phones were becoming common and new applications of wireless technology were emerging every day. Companies involved in wireless markets seemed to have a license to print money. At the time of the introduction of the first edition of the *RF and Microwave Handbook*, wireless electronic products were pervasive, but relatively simple, early generations of the advanced wireless products available today. At present, the number of people using wireless voice and data systems continues to grow. New systems such as 3G phones, 4G phones, and WiMAX represent emerging new wireless markets with significant growth potential. All of these wireless products are dependent on the RF and microwave component and system engineering, which is the subject of this book. During this time the military, satellite, and avionics systems have also become increasingly complex. The research and development that drives these applications continues to serve as the foundation for most of the commercial wireless products available to consumers.

This edition of the handbook covers issues of interest to engineers involved in RF/microwave system and component development. The second edition includes significantly expanded topic coverage as well as updated or new articles for most of the topics included in the first edition. The expansion of material has prompted the division of the handbook into three independent volumes of material. The chapters are aimed at working engineers, managers, and academics who have a need to understand microwave topics outside their area of expertise. Although the book is not written as a textbook, researchers and students will find it useful. Most of the chapters provide extensive references so that they will not only explain fundamentals of each field, but also serve as a starting point for further in-depth research.

This book, *RF and Microwave Applications and Systems*, includes a wide range of articles that discuss RF and microwave systems used for communications, radar and heating applications. Commercial, avionics, medical, and military applications are addressed. An overview of commercial communications systems is provided in an introductory chapter titled "Terrestrial and Satellite Mobile Radio Systems." Past, current and emerging cellular systems, navigation systems, and satellite-based systems are discussed. Specific voice and data commercial systems are investigated more thoroughly in individual chapters that follow. Detailed discussions of military electronics, avionics, and radar (both military and automotive) are provided in separate chapters. A chapter focusing on RF/microwave energy used for therapeutic medicine is also provided.

Systems considerations including thermal, mechanical, reliability, power management, and safety are discussed in separate chapters. Engineering processes are also explored in chapters about corporate initiatives, cost modeling, and design reviews. A final section of the handbook considers the underlying physics of electromagnetic propagation and interference.

Acknowledgments

Although the topics and authors for this book were identified by the editor-in-chief and the advisory board, they do not represent the bulk of the work for a project like this. A great deal of the work involves tracking down those hundreds of technical experts, gaining their commitment, keeping track of their progress, collecting their manuscripts, getting appropriate reviews/revisions, and finally transferring the documents to be published. While juggling this massive job, author inquiries ranging from, "What is the required page length?", to, "What are the acceptable formats for text and figures?", have to be answered and re-answered. Schedules are very fluid. This is the work of the Managing Editor, Janet Golio. Without her efforts there would be no second edition of this handbook.

The advisory board has facilitated the book's completion in many ways. Board members contributed to the outline of topics, identified expert authors, reviewed manuscripts, and authored several of the chapters for the book.

Hundreds of RF and microwave technology experts have produced the chapters that comprise this second edition. They have all devoted many hours of their time sharing their expertise on a wide range of topics.

I would like to sincerely thank all of those listed above. Also, it has been a great pleasure to work with Jessica Vakili, Helena Redshaw, Nora Konopka, and the publishing professionals at CRC Press.

Editors

Editor-in-Chief

Mike Golio, since receiving his PhD from North Carolina State University in 1983, has held a variety of positions in both the microwave and semiconductor industries, and within academia. As Corporate Director of Engineering at Rockwell Collins, Dr. Golio managed and directed a large research and development organization, coordinated corporate IP policy, and led committees to achieve successful corporate spin-offs.

As an individual contributor at Motorola, he was responsible for pioneering work in the area of large signal microwave device characterization and modeling. This work resulted in over 50 publications including one book and a commercially available software package. The IEEE recognized this work by making Dr. Golio a Fellow of the Institute in 1996.

He is currently RF System Technologist with HVVi Semiconductor, a start-up semiconductor company. He has contributed to all aspects of the company's funding, strategies, and technical execution.

Dr. Golio has served in a variety of professional volunteer roles for the IEEE MTT Society including: Chair of Membership Services Committee, founding Co-editor of *IEEE Microwave Magazine*, and MTT-Society distinguished lecturer. He currently serves as Editor-in-chief of *IEEE Microwave Magazine.* In 2002 he was awarded the N. Walter Cox Award for exemplary service in a spirit of selfless dedication and cooperation.

He is author of hundreds of papers, book chapters, presentations and editor of six technical books. He is inventor or co-inventor on 15 patents. In addition to his technical contributions, Dr. Golio recently published a book on retirement planning for engineers and technology professionals.

Managing Editor

Janet R. Golio is Administrative Editor of *IEEE Microwave Magazine* and webmaster of www.golio.net. Prior to that she did government, GPS, and aviation engineering at Motorola in Arizona, Rockwell Collins in Iowa, and General Dynamics in Arizona. She also helped with the early development of the personal computer at IBM in North Carolina. Golio holds one patent and has written six technical papers. She received a BS in Electrical Engineering Summa Cum Laude from North Carolina State University in 1984.

When not working, Golio actively pursues her interests in archaeology, trick roping, and country western dancing. She is the author of young adult books, *A Present from the Past* and *A Puzzle from the Past.*

Advisory Board

Peter A. Blakey

Peter A. Blakey obtained a BA in applied physics from the University of Oxford in 1972, a PhD in electronic engineering from the University of London in 1976, and an MBA from the University of Michigan in 1989. He has held several different positions in industry and academia and has worked on a wide range of RF, microwave, and Si VLSI applications. Between 1991 and 1995 he was the director of TCAD Engineering at Silvaco International. He joined the Department of Electrical Engineering at Northern Arizona University in 2002 and is presently an emeritus professor at that institution.

Nick Buris

Nick Buris received his Diploma in Electrical Engineering in 1982 from the National Technical University of Athens, Greece, and a PhD in electrical engineering from the North Carolina State University, Raleigh, North Carolina, in 1986. In 1986 he was a visiting professor at NCSU working on space reflector antennas for NASA. In 1987 he joined the faculty of the Department of Electrical and Computer Engineering at the University of Massachusetts at Amherst. His research work there spanned the areas of microwave magnetics, phased arrays printed on ferrite substrates, and broadband antennas. In the summer of 1990 he was a faculty fellow at the NASA Langley Research Center working on calibration techniques for dielectric measurements (space shuttle tiles at very high temperatures) and an ionization (plasma) sensor for an experimental reentry spacecraft.

In 1992 he joined the Applied Technology organization of Motorola's Paging Product Group and in 1995 he moved to Corporate Research to start an advanced modeling effort. While at Motorola he has worked on several projects from product design to measurement systems and the development of proprietary software tools for electromagnetic design. He currently manages the Microwave Technologies Research Lab within Motorola Labs in Schaumburg, Illinois. Recent and current activities of the group include V-band communications systems design, modeling and measurements of complex electromagnetic problems, RF propagation, Smart Antennas/MIMO, RFID systems, communications systems simulation and modeling, spectrum engineering, as well as TIA standards work on RF propagation and RF exposure.

Nick is a senior member of the IEEE, and serves on an MTT Technical Program Committee. He recently served as chair of a TIA committee on RF exposure and is currently a member of its Research Division Committee.

Lawrence P. Dunleavy

Dr. Larry Dunleavy, along with four faculty colleagues established University of South Florida's innovative Center for Wireless and Microwave Information Systems (WAMI Center—http://ee.eng.usf.edu/WAMI).

In 2001, Dr. Dunleavy co-founded Modelithics, Inc., a USF spin-off company, to provide a practical commercial outlet for developed modeling solutions and microwave measurement services (www.modelithics.com), where he is currently serving as its president.

Dr. Dunleavy received his BSEE degree from Michigan Technological University in 1982 and his MSEE and PhD in 1984 and 1988, respectively, from the University of Michigan. He has worked in industry for E-Systems (1982–1983) and Hughes Aircraft Company (1984–1990) and was a Howard Hughes Doctoral Fellow (1984–1988). In 1990 he joined the Electrical Engineering Department at the University of South Florida. He maintains a position as professor in the Department of Electrical Engineering. His research interests are related to microwave and millimeter-wave device, circuit, and system design, characterization, and modeling. In 1997–1998, Dr. Dunleavy spent a sabbatical year in the noise metrology laboratory at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Dr. Dunleavy is a senior member of IEEE and is very active in the IEEE MTT Society and the Automatic RF Techniques Group (ARFTG). He has authored or co-authored over 80 technical articles.

Jack East

Jack East received his BSE, MS, and PhD from the University of Michigan. He is presently with the Solid State Electronics Laboratory at the University of Michigan conducting research in the areas of high-speed microwave device design, fabrication, and experimental characterization of solid-state microwave devices, nonlinear and circuit modeling for communications circuits and low-energy electronics, and THz technology.

Patrick Fay

Patrick Fay is an associate professor in the Department of Electrical Engineering at the University of Notre Dame, Notre Dame, Indiana. He received his PhD in Electrical Engineering from the University of Illinois at Urbana-Champaign in 1996 after receiving a BS in Electrical Engineering from Notre Dame in 1991. Dr. Fay served as a visiting assistant professor in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign in 1996 and 1997, and joined the faculty at the University of Notre Dame in 1997.

His educational initiatives include the development of an advanced undergraduate laboratory course in microwave circuit design and characterization, and graduate courses in optoelectronic devices and electronic device characterization. He was awarded the Department of Electrical Engineering's IEEE Outstanding Teacher Award in 1998–1999. His research interests include the design, fabrication, and characterization of microwave and millimeter-wave electronic devices and circuits, as well as high-speed optoelectronic devices and optoelectronic integrated circuits for fiber optic telecommunications. His research also includes the development and use of micromachining techniques for the fabrication of microwave components and packaging. Professor Fay is a senior member of the IEEE, and has published 7 book chapters and more than 60 articles in refereed scientific journals.

David Halchin

David Halchin has worked in RF/microwaves and GaAs for over 20 years. During this period, he has worn many hats including engineering and engineering management, and he has worked in both academia and private industry. Along the way, he received his PhD in Electrical Engineering from North Carolina State University. Dave currently works for RFMD, as he has done since 1998. After a stint as a PA designer, he was moved into his current position managing a modeling organization within RFMD's Corporate Research and Development organization. His group's responsibilities include providing compact models for circuit simulation for both GaAs active devices and passives on GaAs. The group also provides compact models for a handful of Si devices, behavioral models for power amplifier assemblies, and physics-based simulation for GaAs device development. Before joining RFMD, Dave spent time at Motorola and Rockwell working

in the GaAs device development and modeling areas. He is a member of the IEEE-MTT and EDS. Dave is currently a member of the executive committee for the Compound IC Symposium.

Alfy Riddle

Alfy Riddle is vice president of Engineering at Finesse. Before Finesse, Dr. Riddle was the principal at Macallan Consulting, a company he founded in 1989. He has contributed to the design and development of a wide range of products using high-speed, low-noise, and RF techniques. Dr. Riddle developed and marketed the Nodal circuit design software package that featured symbolic analysis and object-oriented techniques. He has co-authored two books and contributed chapters to several more. He is a member of the IEEE MTT Society, the Audio Engineering Society, and the Acoustical Society of America. Dr. Riddle received his PhD in Electrical Engineering in 1986 from North Carolina State University. When he is not working, he can be found on the tennis courts, hiking in the Sierras, taking pictures with an old Leica M3, or making and playing Irish flutes.

Robert J. Trew

Robert J. Trew received his PhD from the University of Michigan in 1975. He is currently the Alton and Mildred Lancaster Distinguished Professor of Electrical and Computer Engineering and Head of the ECE Department at North Carolina State University, Raleigh. He previously served as the Worcester Professor of Electrical and Computer Engineering and Head of the ECE Department of Virginia Tech, Blacksburg, Virginia, and the Dively Distinguished Professor of Engineering and Chair of the Department of Electrical Engineering and Applied Physics at Case Western Reserve University, Cleveland, Ohio. From 1997 to 2001 Dr. Trew was director of research for the U.S. Department of Defense with management responsibility for the $1.3 billion annual basic research program of the DOD. Dr. Trew was vice-chair of the U.S. government interagency group that planned and implemented the U.S. National Nanotechnology Initiative. Dr. Trew is a fellow of the IEEE, and was the 2004 president of the Microwave Theory and Techniques Society. He was editor-in-chief of the *IEEE Transactions on Microwave Theory and Techniques* from 1995 to 1997, and from 1999 to 2002 was founding co-editor-in-chief of the *IEEE Microwave Magazine.* He is currently the editor-in-chief of the *IEEE Proceedings.* Dr. Trew has twice been named an IEEE MTT Society Distinguished Microwave Lecturer. He has earned numerous honors, including a 2003 Engineering Alumni Society Merit Award in Electrical Engineering from the University of Michigan, the 2001 IEEE-USA Harry Diamond Memorial Award, the 1998 IEEE MTT Society Distinguished Educator Award, a 1992 Distinguished Scholarly Achievement Award from NCSU, and an IEEE Third Millennium Medal. Dr. Trew has authored or co-authored over 160 publications, 19 book chapters, 9 patents, and has given over 360 presentations

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