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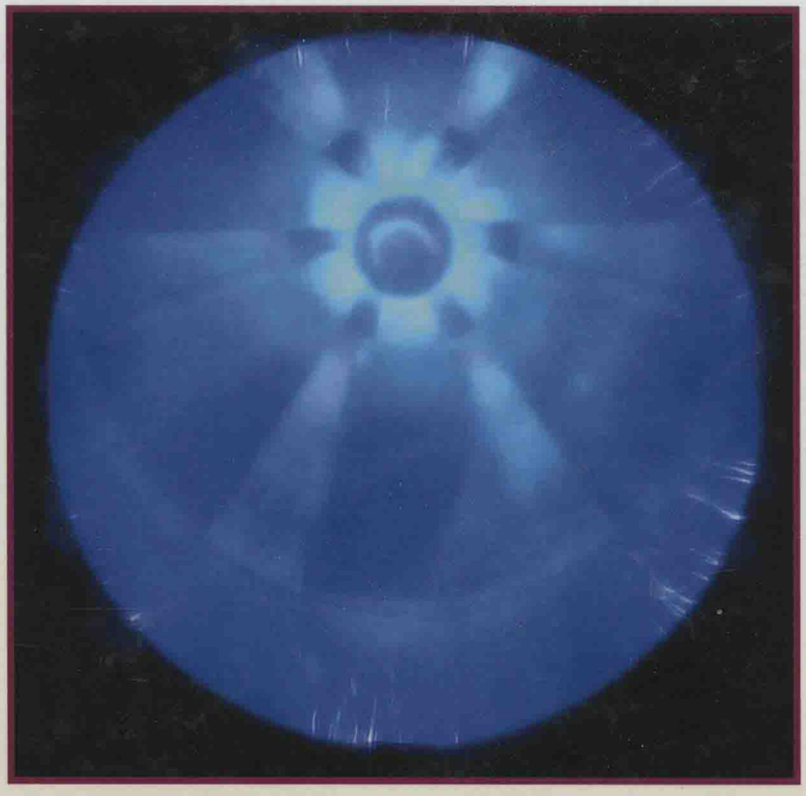
High Power Microwaves

Third Edition



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CRC Press
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Al, Gerry, and Jennifer Swegle
Elmira and Selin Schamiloglu

List of Acronyms

ADS	Active Denial System
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AFWL	Air Force Weapons Laboratory
A-K	Anode-Cathode
ANSI	American National Standards Institute
ARL	Army Research Laboratory
ARM	Antiradiation Missile
ASAT	Antisatellite
BASS	Bulk Avalanche Semiconductor Switches
BINP	Budker Institute of Nuclear Physics
BWG	Beam Waveguide
BWO	Backward Wave Oscillator
CAEP	Chinese Academy of Engineering Physics
CARM	Cyclotron Autoresonance Maser
CERN	European Center for Nuclear Research
CFA	Crossed-Field Amplifier
CHAMP	Counter-electronics High-powered Microwave Advanced Missile Project
CIAS	Carbon-Impregnated Aluminosilicate
CLIC	Compact Linear Collider
CONOPS	Concept of Operation
COTS	Commercial-off-the-Shelf
CSG	Competitive Strategies Group
CSR	Cost Savings Ratio
CVD	Chemical Vapor Deposition
CW	Continuous Wave
DCM	Dielectric Cerenkov Maser
DEW	Directed Energy Weapon
DSRD	Drift Step Recovery Diode
EAST	Experimental Advanced Superconducting Tokamak
ECCD	Electron Cyclotron Current Drive
EC H&D	Electron Cyclotron Heating and Current Drive
ECM	Electron Cyclotron Maser
ECM	Electronic Countermeasure
ECRH	Electron Cyclotron Resonance Heating
EED	Electro-Explosive Device
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EPFL	Ecole Polytechnique Federale de Lausanne
ERP	Effective Radiated Power
ETA	Experimental Test Accelerator
FCC	Federal Communications Commission
FCG	Flux Compression Generator
FEL	Free Electron Laser
FLAPS	Flat Parabolic Surface
FWHM	Full-Width-at-Half-Maximum
FZK	Forschungszentrum Karlsruhe GmbH
GA	General Atomics
GMBK	Gigawatt Multibeam Klystron
GPS	Global Positioning System
GPU	Graphics Processing Unit
HAT	High-Power Amplifier Transmitter
HDL	Harry Diamond Laboratories
HE	High Explosive
HEMTT	Heavy Expanded Mobile Tactical Truck
HPM	High Power Microwaves
HPPA	High Pulsed Power Antenna
HUD	Heads-up Display
IAE	Institute of Applied Electronics
IAP	Institute of Applied Physics
ICHE	Institute of High-Current Electronics
ICRH	Ion Cyclotron Resonance Heating
IED	Improvised Explosive Device
IHCE	Institute of High-Current Electronics
ILC	International Linear Collider
INPE	National Institute for Space Research
IRA	Impulse Radiating Antenna
IREB	Intense Relativistic Electron Beam
IREE	Institute of Radio Engineering and Electronics
ITER	International Thermonuclear Experimental Reactor
JCTD	Joint Concept Technology Demonstration
JDAM	Joint Direct Attack Munition
JIEDDO	Joint Improvised Explosive Device Defeat Organization
JINR	Joint Institute of Nuclear Research
JNLWD	Joint Nonlethal Weapons Directorate
JSOW	Joint Standoff Weapon
KdV	Korteweg de Vries
KE	Kinetic Energy
KEK	High Energy Accelerator Research Organization
KIT	Karlsruhe Institute of Technology
KL-BWO	Klystron-Like Backward Wave Oscillator
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LEO	Low Earth Orbit
LEP	Large Electron-Positron
LHC	Large Hadron Collider
LHH	Lower Hybrid Heating
LIA	Linear Induction Accelerator
LLNL	Lawrence Livermore National Laboratory
LNA	Low Noise Amplifier
LTD	Linear Transformer Driver
MANPADS	Man-Portable Air Defense System
MCG	Magnetocumulative Generator
MDO	Magnetron with Diffraction Output
MIG	Magnetron Injection Gun

MILO	Magnetically Insulated Line Oscillator
MIT	Massachusetts Institute of Technology
MITL	Magnetically Insulated Transmission Line
MOPA	Master Oscillator/Power Amplifier
MPM	Medium Power Microwaves
MWCG	Multiwave Cerenkov Generator
MWDG	Multiwave Diffraction Generator
MWS	Missile Warning System
NAGIRA	Nanosecond Gigawatt Radar
NINT	Northwest Institute of Nuclear Technology
NKCE	Nonkinetic Counter-Electronics
NLC	Next Linear Collider
NRL	Naval Research Laboratory
NUDT	National University of Defense Technology
OC	Open Circuit
Pasotron	Plasma-Assisted Slow-Wave Oscillator
PCM	Plasma Cerenkov Maser
PCSS	Photoconductive Solid State
PDA	Personal Digital Assistant
PFL	Pulse Forming Line
PFN	Pulse Forming Network
PI	Physics International
PIC	Particle-In-Cell
PPM	Periodic Permanent Magnet
PRF	Pulse Repetition Frequency
PRR	Pulse Repetition Rate
PV	Photovoltaic
RCS	Radar Cross Section
RDG	Relativistic Diffraction Generator
REICO	Relativistic Extended-Interaction-Cavity Oscillator
RF	Radiofrequency
RKA	Relativistic Klystron Amplifier
RKO	Relativistic Klystron Oscillator
RMS	Root Mean Square
RPD	Receiver Protection Device
RPM	Recirculating Planar Magnetron
RR-BWO	Resonant Reflector Backward Wave Oscillator
RWR	Radar Warning Receiver
S&T	Science and Technology
SAM	Surface to Air Missile
SAR	Specific Absorption Rate
SBK	Sheet Beam Klystron
SCO	Split Cavity Oscillator
SDI	Strategic Defense Initiative
SES	Switched Energy Storage
SLAC	Stanford Linear Accelerator Center
SLC	Stanford Linear Collider
SLED	SLAC Energy Development
SLR	Sidelobe Ratio
SNL	Sandia National Laboratories
SOS	Semiconductor Opening Switch
SPS-ALPHA	Solar Power Satellite by means of an Arbitrarily Large Phased Array
SUSCO	Sectioned Un-Severed Cerenkov Oscillator
SWO	Surface Wave Oscillator
SWS	Slow-Wave Structure
TB-NLC	Two-Beam Next Linear Collider
TBA	Two-Beam Accelerator
TE	Transverse Electric
TEM	Transverse Electromagnetic
TFA	Time-Frequency Analysis
TKA	Triaxial Klystron Amplifier
TM	Transverse Magnetic
TPI	Tomsk Polytechnic Institute
TR	Transmitter/Receiver
TTU	Texas Tech University
TWT	Traveling Wave Tube
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Air Vehicle
UESTC	University of Electronic Science and Technology
UM	University of Michigan
UMD	University of Maryland
UNM	University of New Mexico
USAF	United States Air Force
UWB	Ultrawideband
VEPP	Russian Electron-Positron Collider Concept
VMD	Voltage Modulation Depth

Preface

This third edition has the following revisions compared to the second edition published in 2007:

- Every chapter has been significantly updated.
- The chapter previously called Ultrawideband Systems is titled Beamless Systems and includes nonlinear transmission lines.
- Chapter 10 now focuses entirely on vircators due to a resurgence of interest in them.
- Chapter 11 is a new chapter that covers gyrotrons, electron cyclotron masers, and free electron lasers.

As with previous editions, this book is meant to communicate a wide-angle, integrated view of the field of high power microwaves, or HPM. Our treatment of HPM is actually rather brief; by limiting the book's length to a manageable number of pages, we hope to encourage the reader to further explore the field, rather than skip to select sections of narrower interest, which often happens with lengthier tomes. Our presentation is broad and introductory with the flavor of a survey; however, it is not elementary. For the reader seeking greater detail, we have provided an extensive set of references and guidance to the literature with each chapter.

We anticipate that our readers will include researchers in this field wishing to widen their understanding of HPM; present or potential users of microwaves who are interested in taking advantage of the dramatically higher power levels that are being made available; newcomers entering the field to pursue research; and decision makers in directed energy weapons acquisitions and related fields, such as radar, communications, and high-energy physics, who must educate themselves in order to determine how developments in HPM will affect them.

This book has its origins in many short courses we have taught in the United States and western Europe. Over time, as we have continued to update and widen the scope of our classes, our outlook in the field of HPM has expanded considerably. Although we approached the field by initial investigations with particular HPM sources, we found ourselves asking questions with increasingly more global implications, which this book addresses:

- How does HPM relate historically and technically to the conventional microwave field?
- What applications are possible for HPM, and what key criteria will HPM devices have to meet in order to be applied?
- How do high power sources work? Are there really as many different sources as the nomenclature seems to indicate? What are their capabilities, and what limits their performance?
- Across the wide variety of source types, what are the broad fundamental issues to be addressed in the future?

We believe that addressing these questions has profited us—and ultimately the reader—and that our perspectives are largely complementary: our primary research interests lie with different source types. While James Benford works largely as an experimentalist, John Swegle is a theorist. The new coauthor since the Second Edition, Edl Schamiloglu, describes himself as an applied theorist.

The reader is encouraged to read Chapter 1, the introductory chapter, where we outline the historical trends that have led to the development of HPM and compare the capabilities of HPM with those of other domains, such as conventional microwaves and THz sources. A premise of this book is that the field can be divided into two sectors, which sometimes overlap: one applications-driven and the other technology-driven. Chapter 2 is entirely new and deals with both perspectives. Chapter 3 directly treats the applications of HPM. The other chapters are focused on technologies. Chapter 4 on microwave fundamentals is a guide to the major concepts used in later chapters. Chapter 5 on enabling technologies describes the equipment and facilities surrounding the sources in which microwaves are generated. These are the elements that make the system work by supplying electrical power and electron beams to the source, radiating microwave power into space, and measuring microwave properties. Chapter 6 deals with the ultrawideband or beamless technologies. Chapters 7 through 11 deal in detail with the major source groups. The Appendix contains the High Power Microwave Formulary. Finally, in the frontal matter we have included a List of Acronyms to assist the reader.

We thank our colleagues for helping in the preparation of this book: Gregory Benford, Steven Gold, John Luginsland, Dominic Benford, Bill Prather, David Price, Edward Goldman, Keith Kato, David Giri, Carl Baum, William Radasky, Jerry Levine, Douglas Clunie, David Price, John Mankins, Kevin Parkin, Richard Dickinson, Bob Forward, Bob Gardner, George Caryotakis, Daryl Sprehn, Mike Haworth, Sid Putnam, Yuval Carmel, Joe Butler, Sonya Looney, Michael Petelin, Ron Gilgenbach, Larry Altgilbers, Mike Cuneo, James McSpadden, and Mats Jansson.

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Finally, we thank Francesca McGowan of Taylor & Francis Group for shepherding us through this third edition.

Very special thanks go to our wives for their patience.

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James Benford is the president of Microwave Sciences, Inc., in Lafayette, California. He does contracting and consulting in high power microwaves. His interests include high power microwave systems from conceptual designs to hardware, microwave source physics, electromagnetic power beaming for space propulsion, experimental intense particle beams, and plasma physics. He earned his PhD in physics from the University of California San Diego. He is an IEEE fellow and an EMP fellow. He has taught 26 courses in high power microwaves in 10 countries. In 2013, he coedited *Starship Century*, dealing with the prospect of star travel. Visit jamesbenford.com for papers on these topics.

John A. Swegle is currently employed at the Savannah River National Laboratory in Aiken, South Carolina, and also works as an independent consultant on high power microwaves. He began his career at Sandia National Laboratories in Albuquerque, New Mexico, where he was a member of the plasma theory group, and then moved to the Lawrence Livermore National Laboratory. He has obtained his PhD and MS degrees in plasma physics from Cornell University and BSEE and MSEE degrees from the University of Washington, Seattle. He has served two terms as an associate editor of *The Physics of Plasmas*, and as an editor of a special issue of the IEEE *Transactions on Plasma Science*, devoted to high power microwaves. He has conducted short courses or extended workshops on the subject of high power microwaves in the United States, Europe, and China.

Edl Schamiloglu is a distinguished professor of electrical and computer engineering at the University of New Mexico. He earned his BS and MS degrees from Columbia University, New York, and his PhD from Cornell University in 1988. He is an IEEE fellow and an EMP fellow. His research interests are HPM source development and their effects on networked infrastructure. He is a recipient of numerous awards, most recently the 2013 IEEE NPSS Richard F. Shea Award and the 2015 IEEE NPSS Pulsed Power Science and Technologies' Peter Haas Award. He conducts numerous short courses and lectures all over the world.

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