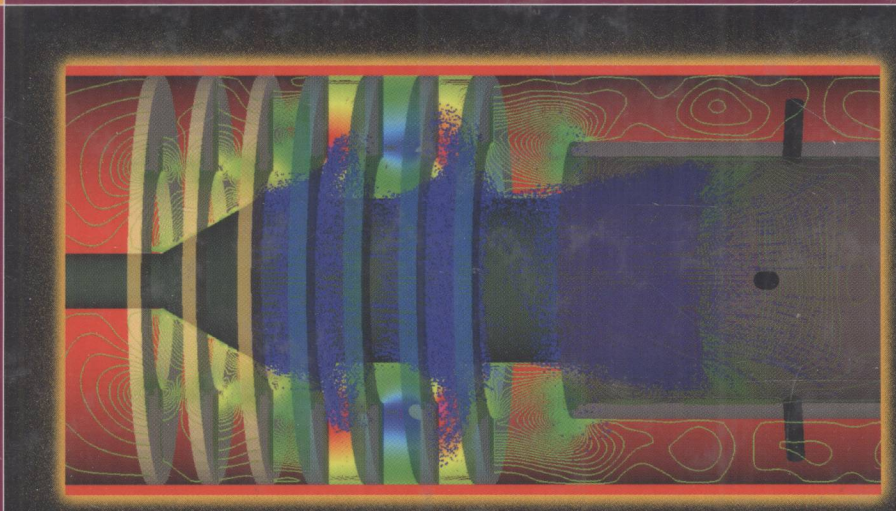
SERIES IN PLASMA PHYSICS



HIGH POWER MICROWAVES

SECOND EDITION

JAMES BENFORD
JOHN A. SWEGLE
EDL SCHAMILOGLU

Taylor & Francis
Taylor & Francis Group

Series in Plasma Physics

High Power Microwaves
Second Edition

James Benford
Microwave Systems Inc.
Lafayette, California, USA

John A. Swegle
J-Two
Walnut Creek, California, USA

Edl Schamiloglu
University of New Mexico
Albuquerque, New Mexico, USA

Taylor & Francis
Taylor & Francis Group
New York London

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-7503-0706-4 (Hardcover)
International Standard Book Number-13: 978-0-7503-0706-2 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Benford, James.
High power microwaves / James Benford, John A. Swegle, and Edl Schamiloglu. -- 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-7503-0706-2 (alk. paper)
ISBN-10: 0-7503-0706-4 (alk. paper)
1. Microwave devices. 2. Microwaves. I. Swegle, John Allan, 1952- II. Schamiloglu, Edl. III. Title.

TK7876.B44 2007
621.381'3--dc22 2006026489

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

High Power Microwaves
Second Edition

Series in Plasma Physics

Series Editor:

Steve Cowley, Imperial College, UK and UCLA, USA

Other books in the series:

Controlled Fusion and Plasma Physics
K Miyamoto

Plasma Electronics: Applications in Microelectronic Device Fabrication
T Makabe and Z Petrović

An Introduction to Inertial Confinement Fusion
S Pfalzner

Aspects of Anomalous Transport in Plasmas
R Balescu

Non-Equilibrium Air Plasmas at Atmospheric Pressure
K H Becker, R J Barker and K H Schoenbach (Eds)

Magnetohydrodynamic Waves in Geospace: The Theory of ULF Waves and their Interaction with Energetic Particles in the Solar-Terrestrial Environment
A D M Walker

Plasma Physics via Computer Simulation (paperback edition)
C K Birdsall and A B Langdon

Plasma Waves, Second Edition
D G Swanson

Microscopic Dynamics of Plasmas and Chaos
Y Elskens and D Escande

Plasma and Fluid Turbulence: Theory and Modelling
A Yoshizawa, S-I Itoh and K Itoh

The Interaction of High-Power Lasers with Plasmas
S Eliezer

Introduction to Dusty Plasma Physics
P K Shukla and A A Mamun

The Theory of Photon Acceleration
J T Mendonça

Laser Aided Diagnostics of Plasmas and Gases
K Muraoka and M Maeda

Reaction-Diffusion Problems in the Physics of Hot Plasmas
H Wilhelmsson and E Lazzaro

Dedication

For

Hilary and Eloise Benford

Al, Gerry, and Jennifer Swegle

Elmira Schamiloglu

Preface

This second edition is changed from the 1992 first edition in significant ways:

- It is a textbook, intended for classroom use or self-study, with problem sets. Teachers can obtain solutions from the authors.
- Chapter 2, on HPM Systems, is a new chapter on this complex activity, with a detailed example that we call SuperSystem.
- "Ultrawideband Systems" (Chapter 6) is another new chapter, a survey of a class of high power radiators, with very different technologies and applications, that has fully emerged since the first edition.
- Our new HPM formulary contains a handy compilation of frequently used rules of thumb and formulas.
- Every chapter is rewritten, not merely updated.
- Despite the new material, we have kept the length of this new edition about the same as the first. See the Microwave Sciences Web site for new problems, updates, and errata: http://home.earthlink.net/~jbenford/index.html.

This book is meant to communicate a wide-angle, integrated view of the field of high power microwaves (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 explore the field, rather than skipping to select sections of narrower interest, as 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 being made available; newcomers entering the field to pursue research; and decision makers in 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 origin in many short courses we have taught in the U.S. 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 brought to the field by our initial investigations with particular HPM sources, we have found ourselves asking questions with increasingly more global implications, which this book is intended to address:

- 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 (No!)? What are their capabilities, and what limits their performance?
- Across the wide variety of source types, what are the broad fundamental issues?

In addressing these questions, we feel it has profited us, and ultimately the reader, that our perspectives are largely complementary: our primary research interests lie with different source types. One of us (James Benford) works largely as an experimentalist, while the other (John Swegle) is a theorist. Edl Schamiloglu does both.

Every reader is encouraged to read the introduction (Chapter 1), where we outline the historical trends that have led to the development of HPM and compare the capabilities of HPM to those of conventional microwaves. A thrust of this book is that the field can be divided into two sectors, sometimes overlapping: applications-driven and 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 to be 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 technologies. Chapters 7 to 10 detail the major source groups.

We express our thanks and appreciation for the help of our colleagues in the preparation of this book:

Gregory Benford	Steven Gold
Dominic Benford	Bill Prather
David Price	Edward Goldman
Keith Kato	David Giri
Carl Baum	William Radasky
Jerry Levine	Douglas Clunie
Kevin Parkin	Charles Reuben
Bob Forward	Richard Dickinson
George Caryotakis	Bob Gardner
Mike Haworth	Daryl Sprehn

Yuval Carmel
Mike Cuneo
Larry Altgilbers
Sid Putnam
Ron Gilgenbach

Special thanks go to Hilary Benford, who tirelessly compiled the manuscript and figures.

James Benford
John Swegle
Edl Schamiloglu
July 2006

Authors

James Benford is president of Microwave Sciences, Inc., in Lafayette, California. He does contracting and consulting in high power microwaves (HPM). His interests include HPM systems from conceptual designs to hardware, microwave source physics, electromagnetic power beaming for space propulsion, experimental intense particle beams, and plasma physics. He earned a Ph.D. in physics at the University of California–San Diego. He is an IEEE fellow and an EMP fellow. He has taught 25 courses in HPM in nine countries.

John A. Swegle, a staff member at Lawrence Livermore National Laboratory and formerly a staff member at Sandia National Laboratories, also works as an independent consultant in the field of HPM. He has taught short courses on HPM in the U.S., Europe, and China, and his previous research work included HPM sources, magnetic insulation in pulsed power systems, and particle beam transport. His current work in the field concentrates on the analysis of HPM systems. He earned a Ph.D. in applied physics at Cornell University.

Edl Schamiloglu is the Gardner-Zemke Professor of Electrical and Computer Engineering at the University of New Mexico. His interests include the research and development of intense beam-driven HPM sources, in addition to their effects on networked infrastructure. He is an IEEE fellow and an EMP fellow.

Contents

1

Introduction

This new edition of *High Power Microwaves* is a substantial departure from the 1992 first edition.[1] That work was a technical monograph that reflected the activities and trends up to that time. High power microwaves (HPM) has moved from being a promising technology to implementation in several applications. HPM systems are being built, studied, and applied not only in the U.S., Russia, and Western European countries such as the U.K., France, Germany, and Sweden, but also in China and developing nations such as India, Taiwan, and South Korea.

In this new volume, we have adopted a *systems point of view.* A significant change in the HPM community has been increasing emphasis on optimizing the entire system. It is widely realized in the HPM community that only by viewing HPM systems as integrated devices may the output of sources exceed present levels of power and pulse energy. Further, the community of potential HPM users demands it. One can no longer separate the system into discreet constituent components and optimize them separately. In adopting a systems point of view, one begins with a basic understanding of the constraints imposed by the application. Then one identifies subsystem component classes and how they interact and properly takes account of the requirements of ancillary equipment.

To get the flavor of this new approach, we advise the reader to begin by reading two chapters before reading the specific technical chapters that follow. Chapter 2, on HPM systems, describes how to conceptualize an HPM system by making choices of components based on a standard methodology. Chapter 3, on HPM applications, sets out the requirements for such systems.

Another major difference between the two editions is that this edition is a textbook intended to be used by students in HPM courses or for self-study by the technically trained. Therefore, we have introduced problems for most of the chapters. (Readers who wish to acquire solutions for these problems, or additional problems, should contact the authors at http://home.earthlink.net/~jbenford/index.html.)

There are several other innovations:

- An HPM formulary giving rules of thumb that the authors have found useful
- A new chapter on ultrawideband systems