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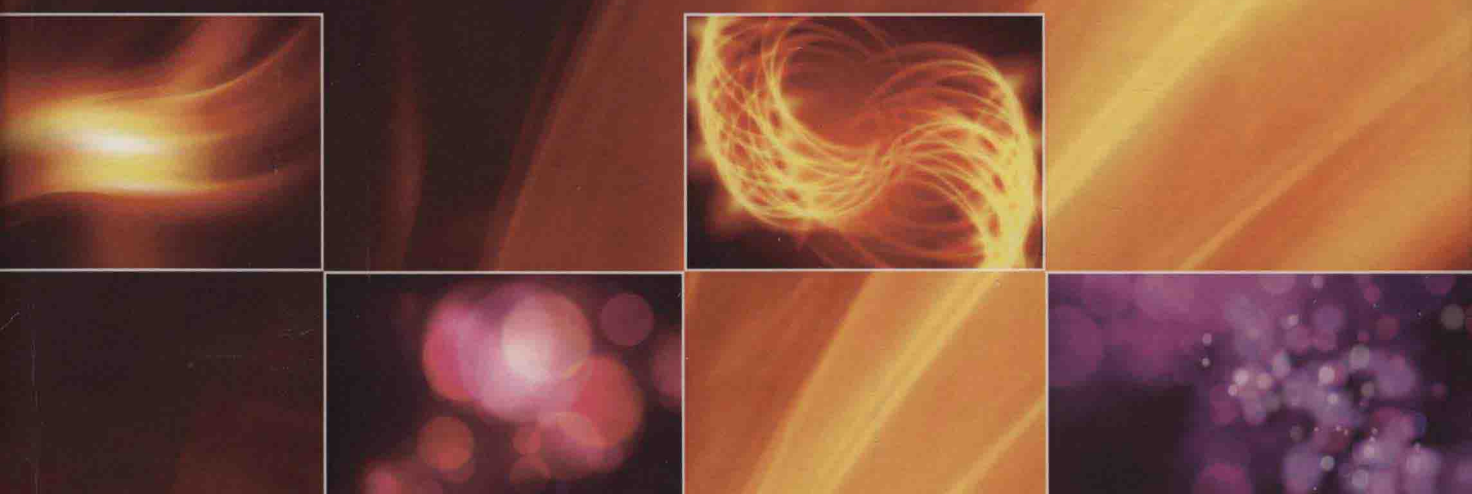
SECOND EDITION

MICROWAVE/RF APPLICATORS AND PROBES

FOR MATERIAL HEATING, SENSING, AND PLASMA GENERATION

A DESIGN GUIDE



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Second Edition

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Microwave/RF Applicators and Probes for Material Heating, Sensing, and Plasma Generation

To my mother, and the memory of my father for their nurturing persistence; and to my wife for her patience and active help in preparing the manuscript.

Preface

Interactions of electromagnetic fields with materials at high frequencies have given rise to a vast array of practical applications in industry, science, medicine, and consumer markets. Applicators or probes, which are the front end of these systems, provide the field that interacts with the material. Devices as diverse as the domestic microwave oven, medical therapeutic applicators, industrial microwave sensors, RF/microwave plasma applicators, and numerous others fall in the general category of near field applicators or probes.

While these devices are diverse in configuration, size, and applications, principally they share much in common; and to properly categorize them one must look beyond the specific application for which they are designed. Much of the existing literature in this area, however, is written by the experts in specific application areas; and there have been few attempts at bringing that knowledge together. Due to the fragmented nature of work in this area, practitioners report new findings in publications within their own fields. Furthermore, in classical electrical engineering curricula, components such as resonant cavities are treated for their external frequency selective properties, and little is covered for cases where they are used for the interaction of fields with materials.

This book is written with three goals in mind. First, to bring together the overall area of high frequency applicators and probes for material interactions as an integrated science. Second, and even more important, it aims to be a useful reference to those who design these devices, and finally to provide an update on the most recent trends and findings in this area.

Above all, my ultimate goal has been to make this volume a comprehensive and useful source where the reader can find design rules and principles of high frequency applicators and probes for material processing and sensing applications. The reader will find that the key design principles of applicators and probes for diverse applications are often quite similar, and once understood can be applied readily, and a great deal of design trial and error can be avoided.

Application areas where these applicators and probes are used are growing, and they have plenty of room for further expansion. More innovation is needed to foster this growth, which requires intuitive and phenomenological understanding on the part of the researchers and designers. Complex mathematical derivations, as well as modern numerical analysis techniques are useful in their own right, and tend to produce accurate results. In this book, however, the emphasis has been placed on producing an intuitive grasp of the subject matter using phenomenological explanations and well annotated figures. Mathematical expressions are provided as design tools, and are often simplified using curve-fitting techniques so that a practicing designer can rely on handheld calculators when possible. In cases where such simplification does not apply, Mathematica™ software by Wolfram Research is used, and the codes (notebooks) are included as Appendices.

The text is written to be useful for both expert and non-expert. For the expert, useful equations and worked out examples, using situations encountered in practice, are offered. For the non-expert, explanations of the phenomena involved are made without the usage of hard-to-follow mathematical derivations. In order to keep the book less cluttered, when rigorous derivations are needed, they are included as appendices.

The purpose of the additions and changes for the second edition are threefold: To cover updates on recent advancements in the area, to expand the scope of the book, and incorporate what the reviewers and readers find important. Some of these changes and additions are

1. The addition of an introductory section, explaining the significance of the topics presented by pointing to vast applications of the subject matter.
2. The addition of a chapter on plasma applicators used for plasma activation (Chapter 10).
3. New topics and updates in most chapters, including those of references.

Finally, I am particularly interested in establishing contact with the users of this book, in order to improve and correct it for future editions and revisions; and to answer any questions. Please feel free to contact me with any comments or questions via email at: mehrdad@ieee.org.

Mehrdad Mehdizadeh, PhD
Wilmington, Delaware
2015

Acknowledgments

I would like to express my debt of gratitude to Dr Ronald J. Riegert who in many ways, directly, or indirectly contributed to this volume. Through many discussions over the years, his depth of knowledge in electromagnetic theory and modeling techniques has been instrumental in sharpening my understanding of many topics covered here. In addition, Dr Riegert has written or contributed effectively writing of the Mathematica™ codes that are included in the appendices in this volume.

I wish to thank the following reviewers for their helpful comments in preparing the manuscript for the second edition: Dr Sina Ebnesajjad, President of FluoroConsultants Group, LLC, Mr Tony Koral MBA, BSc, CEng, FIEE, Radio Frequency Heating Consultant, Dr Ronald J. Riegert, Research Physicist, DuPont Engineering Research & Technology, and Dr Jan Vrba, PhD., Professor of Microwave Engineering, Czech Technical University in Prague.

I would also like to thank Dr Sina Ebnesajjaad for encouraging me to write the original manuscript and for his guidance as an experienced author of several excellent technical books; and thanks are due to Dr James F. Ryley for many useful discussions on plasma science and applications. Furthermore, I would like to gratefully acknowledge the helpful comments and suggestions of a number of readers over the years since the publication of the first edition.

Introduction

Probes and applicators are, in essence, converters of electrical signals to electromagnetic fields, or vice versa. On one side, we have the material that is being interrogated or processed with the field that is imposed on it. On the other side, we have the electrical signal or power. When the material is being interrogated, the device is called a "probe" or a "sensor"; and when significant energy is imparted to the material, it is called an "applicator."

These devices serve a wide variety of applications in many diverse disciplines. While some of these applications are discussed, the book is really about the devices themselves. We will see the similarities and common design principles for applications with no apparent resemblance.

The significance of the subject matter is illustrated by an incomplete list of applications given here.

MICROWAVE/RADIOFREQUENCY (RF) NEAR FIELD SENSORS

- Microwave/RF moisture measurement or moisture sensing
- Microwave density sensors
- Microwave flow sensors

MAGNETIC RESONANCE

- Magnetic resonance
- Nuclear magnetic resonance (NMR)
- Magnetic resonance imaging (MRI)
- Electron spin (or paramagnetic) resonance (ESR or EPR)
- Nuclear quadropole resonance (NQR)

MICROWAVE HEATING

- Domestic microwave ovens
- Industrial microwave heating, defrosting, or drying
- Industrial RF heating or drying
- RF welding, bonding
- Microwave welding or bonding
- Microwave sterilization
- Microwave waste treatment

MICROWAVE-ASSISTED CHEMICAL LABORATORY METHODS

- Microwave-assisted organic chemistry
- Microwave digestion
- Microwave exfoliation
- Microwave sterilization

INDUSTRIAL RF PROCESSING

- RF plastics welding
- RF heating and drying

INDUCTION HEATING METHODS

- Metals processing (annealing, brazing, tempering, soldering, hardening, forging, heating, bonding)
- Cap sealing
- Susceptor-assisted heating, metal-organic chemical vapor deposition (MOCVD)
- Metal–glass sealing
- Curing of coatings
- Crystal growing for semiconductor industry
- Plastics reflow
- Catheter tipping
- Hyperthermia with nano-ferromagnetic liquids

RF HEATING

- Industrial drying
- Food industry—baking
- RF bonding/welding/tube sealing

RF/MICROWAVE–INDUCED PLASMAS

SEMICONDUCTOR/ELECTRONICS INDUSTRY

- Anisotropic etching in fabrication of microelectronic chips
- Deposition of silicon nitride for surface passivation and insulation
- Surface oxidation used in fabrication of silicon-based microelectronic circuits
- Chemical vapor deposition of amorphous silicon films used in solar cells
- Plasma sputtering deposition

LIFE SCIENCES AND MEDICINE

- Precision cleaning, activation, and decontamination of surfaces
- Plasma surface modification to enhance biomedical adhesion
- Inactivation of bacteria
- Surface modification of seeds for enhanced germination

POLYMERS/PLASTICS, ADVANCED MATERIALS MANUFACTURING

- Surface modification for adhesion promotion of encapsulants and adhesives
- Plasma-surface treatment for improved film adhesion to polymer surfaces
- Deposition of thin film diamond and synthetic diamond manufacturing
- Plasma-assisted manufacture of communication optical fibers
- Synthesis of ultrapure powders, nano powders, carbon nanotubes

WASTE TREATMENT/ENVIRONMENTAL ABATEMENT SURFACE CLEANING

- Plasma torch surface cleaning in various industries
- Municipal waste treatment

ANALYTICAL LABORATORIES

Inductive coupled plasmas (ICP) for mass spectroscopy

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