Advances in Microwave and Radio Frequency Processing
Monika Willert-Porada (Ed.)

Advances in Microwave and Radio Frequency Processing

Report from the 8th International Conference on Microwave and High Frequency Heating held in Bayreuth, Germany, September 3–7, 2001

With 469 Figures
Preface

Prometheus brought fire to mankind
Arthur R. von Hippel “Dielectrics and Waves”, 1954
Our contribution?

There are only few areas of research and development of a comparable scientific and technological extension as microwave and high frequency processing. “Processing” means not only application of radiation of 300 MHz to 300 GHz frequency to synthesis, heating or ionisation of matter but also generation, transmission and detection of microwave and radio frequency radiation.

Microwave and high frequency sources positioned in the orbit are the foundation of modern satellite telecommunication systems, gyrotron tubes being presently developed in different countries all over the world will most probably be the major devices to open up a new era of energy supply to mankind be means of fusion plasma. Although initiated by military purposes during the Second World War (RADAR, Radio Detection and Ranging), microwave and high frequency utilisation has spread over almost every important aspect of normal day life since than, from individual mobile phones and kitchen microwave ovens to industrial food processing, production of composites as sustainable building materials, green chemistry, medical applications and finally infrastructure installations like GPS and Galileo, to name only few examples.

These different areas of microwave and high frequency radiation application can not be unified within one group of scientists and technologists. There are several distinguished communities active e.g., in the area of telecommunication systems, strong microwaves for fusion plasma or plasma based materials processing. Research to improve fundamental knowledge leading to new non-military applications of high frequency technology, to support necessary regulations and to provide long term development of commodity and industrial applications as well as to improve the knowledge about these new technologies within the society is less well covered by scientific or professional organizations. In order to close this gap and provide a forum for fruitful discussions a group of researchers from academia and industry started to organize Microwave and High Frequency Heating Conferences in 1986, which take place every 2 years in a different European country. In 1993 AMPERE, Association for Microwave Power in Europe for Research and Education (www.ampereeeurope.org) was established and the conferences were organized on behalf of AMPERE since than. In addition to the regular conference schedule Microwaves in Chemistry meetings were added 1998 and 2000.

Conference activities in the field of microwave and RF-applications show a remarkable growth: up to mid-80 of the 20th century IMPI (International Microwave Power Institute, USA) almost exclusively covered the organized activities in the field. The widespread availability of kitchen microwave ovens as well as the development of powerful microwave sources within national fusion programmes fa-
cilitated use of this “cold” radiation for chemical syntheses and materials processing, with often quite unexpected results. Therefore professional organizations like e.g., the American Ceramic Society and the Materials Research Society established Microwave Symposia within their regular conferences in the period 1988-1996. Numerous Symposia Proceedings volumes came out of these conferences (e.g., MRS Proc. Vol. 124, 189, 269, 347, 430 and Ceram. Trans. Vol. 21, 36, 59, 80), including publications from the 1st and 2nd World Congress on Microwave and Radio Frequency Processing. New professional associations enter the scene, like e.g., the Microwave Working Group in the USA, and different Societies in Japan and China.

The overview and technical papers contained in this book reflect the major areas of activity not only of AMPERE members but also of a representative group of other researchers worldwide. The topics were selected from contributions of the 8th International Conference on Microwave and High Frequency Heating, organised by AMPERE and held in September 2001 in Bayreuth, Germany. The papers were refereed by major specialists in the respective field.

The book is intended to provide non-specialists an overview of the State of the Art in the field of microwave and high frequency hardware, measurement and modelling as well as to give the specialists insight into the most advanced R&D topics of microwave and high frequency radiation application in different disciplines.

Many experts and colleagues contributed to this book. I am particularly indebted to (in alphabetical order):

J.P. Bernard, France; J. Binner, UK; J. Booske, USA; S. Bradshaw, South Africa; A. Breccia, Italy; M. Brito, Japan; J.M. Catalá-Civera, Spain; T. Gerdes, Germany; J. Gerling, USA; W. Jansen, Netherlands; W. Van Loock, Belgium; R. Metaxas, UK; A. Mavretic, USA; T. Ohlsson, Sweden; P. Püschner, Germany; E. de los Reyes, Spain; A. Rosin, Germany; G. Roussy, France; A. Schmidt, Germany; V. Semenov, Russia; M. Thumm, Germany; N. Tran, Australia.

My deep thanks go to the authors for their patience and effort to collect excellent papers; to colleagues for valuable suggestions and to my co-workers for many hours of work to fit the individual contributions into a book.

Hopefully this book will facilitate further development of the fascinating field of microwave and high frequency processing, in a synergetic effort of many groups all over the world.

Monika Willert-Porada, Editor

Bayreuth, first half of the first decade of the 21st century
Contents

PART I: HARDWARE
Understanding Microwave Heating Systems: A Perspective on State-of-the-Art .................................................................3
H. C. Reader

Millimeter-Wave-Sources Development: Present and Future .............15
Manfred Thumm and Lambert Feher

3.5 kW 24 GHz Compact Gyrotron System for Microwave Processing of Materials ........................................................................24
Yu. Bykov, G. Denisov, A. Eremeev, M. Glyavin, V. Holoptsev,
I. Plotnikov, V. Pavlov

Design Guidelines for Applicators Used in the Microwave Heating of High Losses Materials .........................................................31
Juan V. Balbastre, E. de los Reyes, M. C. Nuño and P. Plaza

Design Parameters of Multiple Reactive Chokes for Open Ports in Microwave Heating Systems ..................................................39
J. M. Catalá-Civera, P. Soto, V.E. Boria, J. V. Balbastre and E. de los Reyes

Microwave High-Power Four Post Auto-Matching System .................48
Pedro Plaza, Antoni J. Canós, Felipe L. Penaranda-Foix and Elias de los Reyes

Design of an Applicator for Processing of Nanoscale Zeolite/Polymer Composites with Superposed Static Magnetic Field .................................................................56
Ralph Schertlen, Stefan Bossmann, Werner Wiesbeck

PART II: MEASUREMENT TECHNIQUES AND REGULATIONS
Measurement Techniques for Microwave and RF Processing .............65
Georges Roussy

Dielectric Characterisation of High Loss and Low Loss Materials at 2450 MHz .................................................................77
Andrew Y.J Lee and V. Nguyen Tran

European Regulations, Safety Issues in RF and Microwave Power .................................................................85
Walter Van Loock
FUTURE PROSPERITY OF INDUSTRIAL, SCIENTIFIC AND MEDICAL (ISM) APPLICATIONS OF MICROWAVES ................................................................. 92
David Sánchez-Hernández and José M. Catalá-Civera

ELECTRIC FIELD MEASUREMENTS FOR COMMERCIALLY-AVAILABLE MOBILE PHONES ................................................................................. 103
Antonio Martínez-González, Ángel Fernández-Pascual and David Sánchez-Hernández

USE OF THE DIELECTRIC PROPERTIES TO DETECT PROTEIN DENATURATION ........................................................................................................ 107
S. A. Barringer and C. Bircan

SANDALWOOD MICROWAVE CHARACTERISATION AND OIL EXTRACTION .......... 119
V. Nguyen Tran

DIELECTRIC SPECTROSCOPY AND PRINCIPAL COMPONENT ANALYSIS AS A METHOD FOR OIL FRACTION DETERMINATION IN OIL-IN-WATER-EMULSIONS WITH VARYING SALT CONTENT ................................................. 129
M. Regier, X. Yu, S. Ghio, T. Danner, H. Schubert

MICROWAVE NON-DESTRUCTIVE EVALUATION OF MOISTURE CONTENT IN LIQUID COMPOSITES IN A CYLINDRICAL CAVITY AT A SINGLE FREQUENCY ........................................................................................................ 138
J. M. Catalá-Civera, A. J. Canós, F. Peñaranda-Foix and E. de los Reyes

MILLIMETER WAVE SPECTROSCOPY OF ALUMINA-ZIRCONIA SYSTEM .......... 149
Saburo Sano, Akihiro Tsuzuki, Kiichi Oda, Toshiyuki Ueno, Yukio Makino and Shoji Miyake

A MODIFIED CAVITY PERTURBATION TECHNIQUE FOR MEASUREMENT OF THE DIELECTRIC CONSTANT OF HIGH PERMITTIVITY MATERIALS. ............... 155
Sheila Oree

PART III: MODELLING

FINITE ELEMENTS IN THE SIMULATION OF DIELECTRIC HEATING SYSTEMS ........................................................................................................ 167

EXAMINATION OF CONTEMPORARY ELECTROMAGNETIC SOFTWARE CAPABLE OF MODELING PROBLEMS OF MICROWAVE HEATING ........................................................................................................ 178
Vadim V. Yakovlev

A HYBRID APPROACH FOR RESOLVING THE ELECTROMAGNETIC FIELDS INSIDE A WAVEGUIDE LOADED WITH A LOSSY MEDIUM ........................................ 191
Viktor Vegh, Ian W. Turner
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A NOVEL FDTD SYSTEM FOR MICROWAVE HEATING AND THAWING ANALYSIS WITH AUTOMATIC TIME-VARIATION OF ENTHALPY-DEPENDENT MEDIA PARAMETERS</td>
<td>199</td>
</tr>
<tr>
<td>Malgorzata Celuch-Marcysiak, Wojciech K. Gwarek, Maciej Sypniewski</td>
<td></td>
</tr>
<tr>
<td>SIMULATION OF MICROWAVE SINTERING WITH ADVANCED SINTERING MODELS</td>
<td>210</td>
</tr>
<tr>
<td>Hermann Riedel, Jiří Svoboda</td>
<td></td>
</tr>
<tr>
<td>FINITE ELEMENT MODELLING OF THIN METALLIC FILMS FOR MICROWAVE HEATING</td>
<td>217</td>
</tr>
<tr>
<td>R.A. Ehlers and A.C. Metaxas</td>
<td></td>
</tr>
<tr>
<td>ANALYSIS OF COUPLED ELECTROMAGNETIC AND THERMAL MODELING OF PRESSURE-AIDED MICROWAVE CURING PROCESSES</td>
<td>226</td>
</tr>
<tr>
<td>SELECTIVE HEATING AND MOISTURE LEVELLING IN MICROWAVE-ASSISTED DRYING OF LAMINAR MATERIALS: AN EXPLICIT MODEL</td>
<td>234</td>
</tr>
<tr>
<td>J. Monzó-Cabrera, A. Diaz-Morcillo, J. M. Catalá-Civera, E. de los Reyes</td>
<td></td>
</tr>
<tr>
<td>MICROWAVE HEATING OF READY MEALS – FDTD SIMULATION TOOLS FOR IMPROVING THE HEATING UNIFORMITY</td>
<td>243</td>
</tr>
<tr>
<td>B. Wäppling-Raaholt, P. O. Risman and T. Ohlsson</td>
<td></td>
</tr>
</tbody>
</table>

**PART IV: FOOD PROCESSING AND ENVIRONMENTAL ENGINEERING APPLICATIONS**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOVEL AND TRADITIONAL MICROWAVE APPLICATIONS IN THE FOOD INDUSTRY</td>
<td>259</td>
</tr>
<tr>
<td>H. Schubert and M. Regie</td>
<td></td>
</tr>
<tr>
<td>MICROWAVE DRYING: PROCESS ENGINEERING ASPECTS</td>
<td>271</td>
</tr>
<tr>
<td>SM Bradshaw</td>
<td></td>
</tr>
<tr>
<td>QUALITY OF MICROWAVE HEATED MULTICOMPONENT PREPARED FOODS</td>
<td>282</td>
</tr>
<tr>
<td>Savi Ryynänen</td>
<td></td>
</tr>
<tr>
<td>SENSORY EVALUATION OF DRIED BANANAS OBTAINED FROM AIR DEHYDRATION ASSISTED BY MICROWAVES</td>
<td>289</td>
</tr>
<tr>
<td>Sousa, W.A.; Pitombo, R.N.M.; Da Silva, M.A.A.P.; Marsaioli, Jr., A.</td>
<td></td>
</tr>
<tr>
<td>MICROWAVE METHOD FOR INCREASING THE PERMEABILITY OF WOOD AND ITS APPLICATIONS</td>
<td>303</td>
</tr>
<tr>
<td>G. Torgovnikov and P. Vinden</td>
<td></td>
</tr>
</tbody>
</table>
SELECTIVE HEATING OF DIFFERENT GRAIN PARTS OF WHEAT BY MICROWAVE ENERGY ..........................................................312
E. Pallai-Varsányi; M. Neményi; A. J. Kovács; E. Szijjártó

MICROWAVE IN SITU REMEDIATION OF SOILS POLLUTED BY VOLATILE HYDROCARBONS .........................................................321
D. Acierno, A. A. Barba, M. d’Amore, V. Fiumara, I. M. Pinto, A. Scaglione

BIO-DIELECTRIC SOIL DECONTAMINATION ........................................................................................................................329
J. P. M. Janssen-Mommen, W. J. L. Jansen

WASTE TREATMENT UNDER MICROWAVE IRRADIATION ......................................................................................................341

ENVIRONMENTAL ASPECTS OF MICROWAVE HEATING IN POLYELECTROLYTE SYNTHESIS ...........................................................................349
E. Mateescu, G. Craciun, D. Martin, D. Ighigeanu, M. Radoiu, I. Calinescu and H. Iovu

PART V: MICROWAVE APPLICATIONS IN CHEMISTRY

ROLE OF MICROWAVE RADIATION ON RADIOPHARMACEUTICALS PREPARATIONS ..................................................................................359
Enrico Gattavecchia, Elida Ferri, Biagio Esposito, Alberto Breccia

FAST SYNTHESIS OF BIODIESEL FROM TRIGLYCERIDES IN PRESENCE OF MICROWAVES ...........................................................................................370
C. Mazzocchia, A. Kaddouri, G. Modica, R. Nannicini

ALTERATION OF ESTERIFICATION KINETICS UNDER MICROWAVE IRRADIATION ..........................................................................................377
L. A. Jermolovicjus, B. Schneiderman and J. T. Senise

MULTISTEP MICROWAVE-ASSISTED SOLVENT-FREE ORGANIC REACTIONS: SYNTHESIS OF 1,6-DISUBSTITUTED-4-OXO-1,4-DIHYDRO-PYRIDINE-3-CARBOXYLIC ACID BENZYL ESTERS ................................................................................................................386
Mauro Panunzio, Maria Antonietta Lentini, Eileen Campana, Giorgio Martelli, Paola Vicennati

RECENT APPLICATIONS OF MICROWAVE POWER FOR APPLIED ORGANIC CHEMISTRY ........................................................................................................390
Bernd Ondruschka and Matthias Nüchter

LIQUID PHASE CATALYTIC HYDRODECHLORINATION OF CHLOROBENZENE UNDER MICROWAVE IRRADIATION ........................................398
Marilena T. Radoiu, Ioan Calinescu, Diana I. Martin, Rodica Calinescu
CONVENTIONAL AND NEW SOLVENT SYSTEMS FOR MICROWAVE CHEMISTRY .........................................................405
   Jens Hoffmann, Antje Tied, Matthias Nüchter and Bernd Ondruschka

PART VI: INDUSTRIAL MICROWAVE APPLICATIONS
STATE OF THE ART OF MICROWAVE APPLICATIONS IN THE FOOD INDUSTRY IN THE USA..........................417
   Robert F. Schiffmann
MICROWAVE VACUUM DRYING IN THE FOOD PROCESSING INDUSTRY .................................................426
   G. Ahrens, H. Kriszio, G. Langer
DEVELOPMENT OF AN INDUSTRIAL SOLID PHASE POLYMERIZATION PROCESS USING FIFTY-OHM RADIO FREQUENCY TECHNOLOGY .........................436
   Joseph W. Cresko, L. Myles Phipps, Anton Mavretic
RF WORLD TOUR ..................................................................................................................445
   Jean-Paul Bernard

PART VII: FUNDAMENTALS OF MICROWAVE APPLICATION TO MATERIALS PROCESSING
HOW THE COUPLING OF MICROWAVE AND RF ENERGY IN MATERIALS CAN AFFECT SOLID STATE CHARGE AND MASS TRANSPORT AND RESULT IN UNIQUE PROCESSING EFFECTS ..................461
   John H. Booske and Reid F. Cooper
ENHANCED MASS AND CHARGE TRANSFER IN SOLIDS EXPOSED TO MICROWAVE FIELDS ..........................................................................................472
   V.E. Semenov, K.I. Rybakov
THERMAL RUNAWAY AND HOT SPOTS UNDER CONTROLLED MICROWAVE HEATING ..................................482
   V.E. Semenov, N.A. Zharova
DENSIFICATION AND DIFFUSION PROCESSES IN THE BA,SR-TITANATE SYSTEM UNDER MICROWAVE SINTERING ..........................................................................491
   O.I. Getman, V. V. Panichkina, V. V. Skorokhod, E.A. Shevchenko, V. V. Holoptsev
OBSERVATION OF THE MICROWAVE EFFECT ON THE DIFFUSION BEHAVIOR IN 28 GHz MILLIMETER-WAVE SINTERED ALUMINA ........................................498
   Toshiyuki UENO, Yukio MAKINO and Shoji MIYAKE, Saburo SANO
DILATOMETER MEASUREMENTS IN A MM-WAVE OVEN .........................................................................506
   G. Link, S. Rhee, M. Thumm
IN SITU DETERMINATION OF SHRINKAGE UNDER MICROWAVE CONDITIONS.........................................................................................................514
J. Bossert, C. Ludwig, J.R. Opfermann

MULTISTABLE BEHAVIOUR IN MICROWAVE HEATING OF CERAMICS ..................521
J. R. Thomas, Jr., Xiaofeng Wu, W. A. Davis

PART VIII: MICROWAVE SINTERING OF CERAMICS AND METALS

MICROWAVE SINTERING OF SILICON NITRIDE CERAMICS........................................533
Kiyoshi Hirao, Mark I. Jones, Manuel E. Brito and M. Toriyama

NOVEL MATERIALS PROCESSING BY MILLIMETER-WAVE RADIATION - PRESENT AND FUTURE .................................................................541
Shoji Miyake

CORRELATION BETWEEN DENSIFICATION AND $\beta$ - PHASE FORMATION AT MICROWAVE SINTERING OF Si$_3$N$_4$ CERAMICS ....................................................553
O. I. Getman, V. V. Panichkina, V. V. Skorokhod, I. V. Plotnikov, V. V. Holoptsev

SINTERING BEHAVIOUR AND MECHANICAL PROPERTIES OF MICROWAVE SINTERED SILICON NITRIDE .................................................................562
Mark I. Jones, Maria-Cecilia Valecillos, Kiyoshi Hirao, Manuel E. Brito, Motohiro Toriyama

MILLIMETER-WAVE SINTERING OF HIGH PURE ALUMINA – MICROSTRUCTURE AND MECHANICAL PROPERTIES..............................................................570
Yukio Makino, Shoji Miyake, Saburo Sano, Hidenori Saito, Bunkei Kyoh, Hideki Kuwahara and Akinobu Yoshikawa

MICROWAVE SINTERING OF LARGE-SIZE CERAMIC WORKPIECES .......................577
S. V. Egorov, N. A. Zharova, Yu. V. Bykov, V. E. Semenov

MICROWAVE ASSISTED SINTERING OF Al$_2$O$_3$ ..................................................583
S. Leparoux, G. Walter; Th. Lampke, B. Wielage

ABSORPTION OF MILLIMETER WAVES IN COMPOSITE METAL-CERAMIC MATERIALS.................................................................591
A. G. Eremeev, I. V. Plotnikov, V. V. Holoptsev, K. I. Rybakov, A. I. Rachkovskii

MICROWAVE SINTERING OF PM STEELS ..............................................................598
F. Petzoldt, B. Scholz, H. S. Park, M. Willert-Porada

FORMATION OF FUNCTIONALLY GRADED CEMENTED CARBIDES BY MICROWAVE ASSISTED SINTERING IN REACTIVE ATMOSPHERES .........................609
R. Tap, M. Willert-Porada, K. Rödiger, R. Klupsch
PART IX: SYNTHESIS AND MICROWAVE PROCESSING OF POWDERS

MICROWAVE PLASMA SYNTHESIS OF CERAMIC POWDERS .....................................619
Dieter Vollath, D. Vinga Szabó

MICROWAVE AND CONVENTIONAL HYDROTHERMAL SYNTHESIS OF ZIRCONIA DOPED POWDERS ..............................................................627

MICROWAVE DECOMPOSITION OF METAL ALKOXIDES TO NANOPOROUS METAL OXIDES – A MECHANISTIC STUDY ................................633
F. Bauer, T. Schubert, M. Willert-Porada

CHARACTERIZATION OF SiC PRODUCED BY MICROWAVES ..................................645
Juan Aguilar, Zarel Valdez, Ubald Ortiz, Javier Rodríguez

MICROWAVE ASSISTED SYNTHESIS OF CATALYST MATERIALS FOR PEM FUEL CELLS .................................................................651
T. Schubert, M. Willert-Porada

EXCITATION OF SODIUM IN POWDERLIKE SILICATES BY MICROWAVE HEATING .................................................................661
M. Hasznos-Nezdei, E. Pallai-Varsányi, L. P. Szabó and S Szabó

PART X: NEW APPLICATIONS AND PROCESSES RELATED TO MICROWAVE AND RF HEATING

RF AND MICROWAVE RAPID MAGNETIC INDUCTION HEATING OF SILICON WAFERS .................................................................673
Keith Thompson, John Booske, Yogesh Gianchandani, Reid Cooper

INDUSTRIAL HIGHER FREQUENCY MICROWAVE PROCESSING OF COMPOSITE MATERIALS .................................................................681
Lambert Feher and Manfred Thumm

DRILLING INTO HARD NON-CONDUCTIVE MATERIALS BY LOCALIZED MICROWAVE RADIATION ..................................................687
E. Jerby and V. Dikhtyar

DESIGN OF AVIONIC MICROWAVE DE-/ANTI-ICING SYSTEMS ..............................695
Lambert Feher and Manfred Thumm

APPLICATION OF MICROWAVE TO GLAZE AND CERAMIC INDUSTRY ..................703
C. Leonelli, C. Siligardi, P. Veronesi, A. Corradi

MICROWAVE ASSISTED BINDER BURNOUT .............................................................710
J. Grosse-Berg, M. Willert-Porada, L. Eusterbrock, G. Ziegler