Stefan Lindenmeier
Robert Weigel *Editors*

Electromagnetics and Network Theory and their Microwave Technology Applications

A Tribute to Peter Russer

Springer

Stefan Lindenmeier • Robert Weigel
Editors

Electromagnetics and Network Theory and their Microwave Technology Applications

A Tribute to Peter Russer

Springer

Editors
Prof. Dr.-Ing. habil. Stefan Lindenmeier
Universität der Bundeswehr München
Institut für Hoch- und
Höchstfrequenztechnik
Werner-Heisenberg-Weg 39
85577 Neubiberg
Germany
stefan.lindenmeier@unibw.de

Prof. Dr.-Ing. Dr.-Ing. habil. Robert Weigel
Universität Erlangen-Nürnberg
Lehrstuhl für Technische Elektronik
Cauerstr. 9
91058 Erlangen
Germany
r.weigel@ieee.org

ISBN 978-3-642-18374-4 e-ISBN 978-3-642-18375-1
DOI 10.1007/978-3-642-18375-1
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2011931676

Cover design: eStudio Calamar S.L.

The printing of this volume has been sponsored by GAUSS INSTRUMENTS GmbH

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Electromagnetics and Network Theory and their Microwave Technology Applications

Preface

On October 8–9, 2008, we organized an IEEE MTT-S International Mini-Symposium on Electromagnetics and Network Theory and its Microwave Applications at Munich University of Technology (TUM), Munich, Germany. This symposium was dedicated to Peter Russer on the occasion of his 65th birthday and his retirement. During his career as researcher in the field of Electromagnetics and Network Theory Peter Russer achieved not only a multitude of outstanding scientific results but he also had the special gift to bring researchers together and to build up an international network of scientists in this field. This network was base of the successful symposium which provided an international forum for the discussion of the challenges and perspectives of electromagnetics and network theory and their microwave applications in various aspects. Invited presentations have been given by Josef A. Nossek of TUM, President of Association for Electrical, Electronic & Information Technologies, VDE, Franz X. Kärtner of Massachusetts Institute of Technology, MIT, and of course by Peter Russer, TUM. In oral sessions and an interactive forum 48 reviewed scientific contributions were presented. Half of those contributions have been further extended now to be combined in this book in order to give a compact overview about actual research in the field of Electromagnetics and Network Theory and its Microwave Applications.

The book is subdivided into basic topics of applications and theory in this field as there are antennas and wave propagation, microwave- and communication-systems and methods for the numerical modelling of components, networks and structures being part of these systems. In a first section an actual state of research in antennas and propagation is given since the description of antennas as well as wave propagation in RF-lines and electric networks is crucial for the investigation of microwave systems like radar-, radio-location- and communication-systems.

Especially in mobile applications, radar-, radio-location- and navigation-systems as well as microwave sensors are more and more in use. An actual state of research in this field is given in the second section. Actual results of research on such systems are shown for automotive radar, a high precision radio-location-system, RF-sensors and RF-measurement technologies. The wide field of communication systems is discussed in the third section where an overview about further progress in mobile communication and wireless data transmission is given and results of actual research are shown.

In the fourth section actual numerical methods are discussed which are essential for the estimation of electromagnetic effects in all the applications shown previously. In the scope between the treatment of very tiny structures and very large structures new ways are shown for the numerical modelling of the electromagnetic field in nanostructures as well as in macrostructures and large periodic structures. In the last chapter we present the autobiography of Peter Russer which shows in a very good example, that the combined treatment of all the aspects mentioned above leads to achievements which may seem almost impossible. But, speaking with his words, the impossible just takes longer.

At this point we would like to take the occasion to give a brief summary on the very successful scientific work history and Peter Russer's extraordinary achievements – both as an outstanding researcher and as a distinguished educator. Peter Russer was born in Vienna, Austria in 1943, during World War II. After finishing elementary school and gymnasium in Vienna, he studied Electrical Engineering at the Vienna University of Technology where he received the Dipl.-Ing. degree in 1967. He continued at his Alma Mata and became a young research assistant working towards the doctoral degree under the supervision of the late Professor Hans Pötzl on "Josephson electronics", for which he received the Dr. techn. degree in 1971. Shortly after (1971) he joined the AEG-Telefunken Research Institute in Ulm, Germany, where, for ten years, he worked on fibre optic communication, solid-state electronic circuits, noise analysis, laser modulation and fibre optic gyroscopes. At the young age of 38 (in 1981), he was offered a Full Professorship at the TUM and to become Director of the Institute of High Frequency Engineering, where he has been since. His service to TUM was only briefly interrupted from 1992 to 1995 when he was selected the Founding Director of the Ferdinand Braun Institute in Berlin, Germany, a position which was also associated with a Guest Professorship at the Technical University of Berlin. In September 1995 he returned to TUM, and from 1997 to 1999 he served as Dean of the Faculty of Electrical and Information Engineering.

Peter Russer is a renowned scholar and highly respected teacher who is devoted to his students. He has developed and taught a large variety of courses in RF techniques, microwaves, quantum electronics and optical communications. His scripts and monographs are superb teaching tools and have served as basis for a couple of distinguished textbooks. Peter Russer was also the mastermind behind the international Master of Science in the Microwave Engineering curriculum at the TUM which is running very successfully since eight years. His fine teaching skills have attracted a great number of young talents to become his Master and Ph.D. students. Over the years he has graduated a total of nearly 500 students of which about 70 received their doctoral degree. Many of his students have started successful careers in industry and academia and continue to keep close ties with their mentor and 'Doktorvater'. Quite a high number of his Ph.D. students like Erwin Biebl, Franz X. Kärtner, Gerhard Fischerauer, Gerd Scholl, Josef Hausner, Sebastian Sattler and ourselves have become University Professors, respectively at TUM, Massachusetts University of Technology, University of Bayreuth, Hamburg University of federal armed forces, University of Bochum, Munich University of federal armed forces, and University of Erlangen-Nuremberg; and these so-called "Peter's Boys" have greatly contributed to a special journal issue published in summer of 2008 (Peter's Boys – Making Frequencies Think, Frequenz – Journal of RF-Engineering and Telecommunications, vol. 62, no. 7–8, July/August 2008, pp. 153–207).

Peter Russer is well known internationally for his many innovative and significant contributions to Josephson electronics, fibre optic communication and gyroscopes, laser modulation, solid-state electronics, noise analysis techniques, Bragg cell-based spectrum analyzers, integrated optics, surface acoustic waves, hyperthermia, microwave superconductivity, linear/nonlinear circuit design methods, design of integrated microwave and millimetre-wave circuits, numerical techniques in computational electromagnetics, and lately also to electromagnetic compatibility (EMC). In most of these fields, Peter Russer has clearly pioneered the research from numerous points of view. Let us give just three examples: (1) The publication *H. Hillbrand, P. Russer, "An Efficient Method for Computer Aided Noise Analysis of Linear Amplifier Networks", IEEE Transactions on Circuits and Systems, vol. 23, no. 4, April 1976, pp. 235–238* laid the basis for the theoretical foundation for the noise analysis of two-ports using correlation matrices, a technique which meanwhile is being used in nearly all network analysis computer codes. (2) On December 21, 1978, Erich Kasper and Peter Russer, who in those days were colleagues at AEG-Telefunken in Ulm published their patent (Germany, no. DE2719464) entitled *Verfahren zur Herstellung von Hochfrequenztransistoren* which describes the invention of the SiGe heterobipolar transistor (HBT), a semiconductor device which is crucial for the implementation of silicon integrated millimetre-wave circuits (SIMMWICs) which nowadays are very successfully applied in communications, sensing and radar at millimetre-wave frequencies. (3) Peter Russer's pioneering work on the foundations of the Transmission Line Matrix (TLM) modelling of electromagnetic fields has been widely acclaimed as the most rigorous approach to put this technique on solid ground. In all his research areas, Peter Russer's work demonstrates an exceptional quality, originality, and technical impact. Many times he has been able to transfer his scientific results into innovative application beneficial for the economy and for the society. To this date, Peter Russer has authored and co-authored more than 140 refereed journal publications, more than 500 conference papers, 6 books and 20 book chapters. The impact of his academic work is complemented by the numerous novel ideas and approaches he developed for industry as evidenced by the more than 50 patents he holds or has applied for. Reflecting on all these merits, it is no surprise that Peter Russer has received several high-ranking awards and honours including the 1979 NTG award for his seminal paper "Electronic circuits for high-bit rate digital fibre optic communication systems". In 1994 he was elected IEEE Fellow for his fundamental contributions to noise analysis and low-noise optimization of linear electronic circuits with general topology. In 2006, he received the IEEE Microwave Theory and Techniques-Society Distinguished Educator Award, also in 2006 the Fellowship of the Council for Technical Sciences in Germany (ACATECH), and in 2007 the Honorary Doctoral degree from the Moscow State University of Aviation.

During his professional career, Peter Russer was not only very active in research and teaching, he has also greatly contributed time and talent to the well-being of the scientific community. He is a member of IEEE, EuMA, URSI, ITG, DPG and ÖPG. Besides serving as chairman, organizer, member of technical program and steering committees of numerous conferences, workshops, society chapters, sessions etc., he also serves the scientific community as reviewer for national and international journals, conferences and research foundations. Just to note a few of these activities: Peter Russer organized and chaired the European Microwave Conference in Munich in 1999, has been chair of the German IEEE MTT/AP Joint Chapter, has been chair of URSI's commission D – Electronics and Photonics, has been a member of the German Science Foundation's (DFG) senate board for collaborative research centres, has been Associate Editor of the IEEE Transactions on Microwave Theory and Techniques, has been chair of the IEEE MTT-Society's Technical Committee on Field Theory, and has been a member of the EuMA board of directors.

It always was and still is an honour to know Peter Russer personally and for so many years. He has now moved into his status of an Emeritus of Excellence which has been awarded to him by his university TUM and which shows, that his university still counts on his very valuable contributions. We are sure he will go on in continuing his service to the scientific society and we are looking forward to it.

We cordially thank Dr. Daniel Brenk of the University of Erlangen-Nuremberg and Carmen Wolf of Springer who wisely supervised the edition of this book.

Munich
Erlangen
July 2011

Stefan Lindenmeier
Robert Weigel

Contents

Part IV Numerical Methods for Electromagnetic Field Modeling

Part I
Antennas and Propagation

Chapter 1
A Hybrid MoM/UTD Method for the Analysis of a Monopole Antenna in an Aperture

Christoph Ullrich and Peter Russer

Automotive antennas are usually realized as conformal antennas that are placed on the car glazing. Therefore they reside in the apertures of the metallic car body. In a simplified representation the passenger cabin is an absorbing cavity which features one or more apertures.

The coupling of an electromagnetic wave through an aperture into a cavity is a well-known problem in electromagnetic compatibility as it describes the shielding effectiveness of a metal encasing. This problem has already been successfully solved with the Method of Moments (MoM) [2, 12, 23]. A modified version of this problem are apertures that are penetrated by a wire [4]. However, in these cases from literature the aperture is excited by an incident wave whereas the model of an automotive antenna has to be excited by a source in the aperture plane. A source model for this excitation in the aperture plane is given in this work.

First a simple model of an automotive antenna is created: the outer shell of the car body with the window opening is represented by a metal screen with an aperture. The passenger compartment with lossy interior materials is simplified to an absorber-clad cavity. A representation of this model is given in Fig. 1.1.

1.1 Method of Moments with Magnetic Current Density

1.1.1 Integral Equations with Magnetic Charge

In order to calculate the field distribution in the aperture we introduce a fictitious magnetic charge $\underline{\mathcal{Q}}_m$ in addition to the electric charge $\underline{\mathcal{Q}}_e$ and electric current $\underline{\mathcal{I}}_e$.

C. Ullrich (✉)
AUDI AG, 85045 Ingolstadt, Germany
e-mail: christoph.ullrich@audi.de

P. Russer
Technische Universität München, Arcisstraße 21, 80333 Munich, Germany
e-mail: russer@tum.de

S. Lindenmeier and R. Weigel (eds.), *Electromagnetics and Network Theory and their Microwave Technology Applications*, DOI 10.1007/978-3-642-18375-1_1,

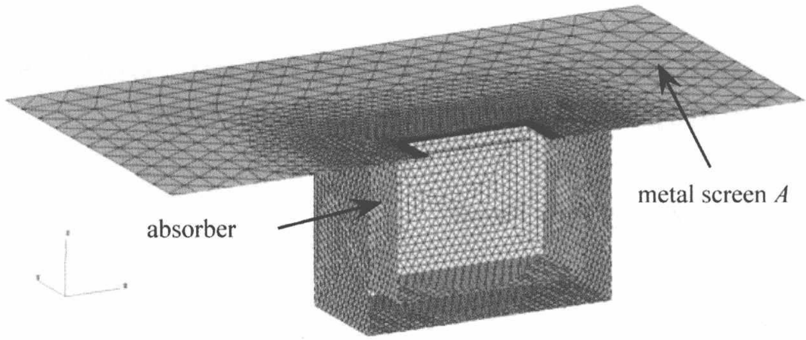

Fig. 1.1 Mesh of an aperture antenna backed by an absorbing body

Moving magnetic charges lead to a magnetic current $\underline{\mathscr{J}}_m$. Then we can write the Maxwell's equations [18] in the following form

$$\mathrm{d}\underline{\mathscr{E}} = -j\omega\underline{\mathscr{B}} + \underline{\mathscr{J}}_m \tag{1.1a}$$

$$\mathrm{d}\underline{\mathscr{H}} = j\omega\underline{\mathscr{D}} + \underline{\mathscr{J}}_e \tag{1.1b}$$

$$\mathrm{d}\underline{\mathscr{D}} = \underline{\mathscr{Q}}_e \tag{1.1c}$$

$$\mathrm{d}\underline{\mathscr{B}} = \underline{\mathscr{Q}}_m \ . \tag{1.1d}$$

In this form Maxwell's equations show almost perfect symmetry. Therefore solutions that were developed to calculate the electric current density on electric conductors can directly be applied to solve magnetic currents in an aperture. At this point it should be noted that magnetic charge and magnetic current do not necessarily exist physically but are solely used as a means to simplify the solution.

Let the metal screen A be of infinite extension. Then we cover the aperture with a perfect magnetic conductor (PMC). We use the equivalence principle [6] to replace the electromagnetic sources that cause the radiation from the aperture by an equivalent magnetic current on both sides of the PMC. This impressed magnetic current must cause the same field distribution in the both half spaces that are separated by the metal screen as if no PMC were present.

From the magnetic current $\underline{\mathscr{J}}_m$ we can derive the magnetic surface current density on the PMC $\underline{\mathscr{J}}_m^{PMC}$ and from this the desired value of the electric field in the aperture $\underline{\mathscr{E}}^{Aperture}$ [3]:

$$\mathsf{n} \wedge \underline{\mathscr{E}}^{Apertur} = -\mathsf{n} \wedge \underline{\mathscr{J}}_m^{PMC} \tag{1.2}$$

The electromagnetic field which is excited by $\underline{\mathscr{J}}_m$ can only be derived from a scalar potential if the field is irrotational in the considered domain. By introducing a potential partitioning surface (PPS) the space surrounding the conductor is separated in such a way that all possible integration paths encircling the conductor are cut

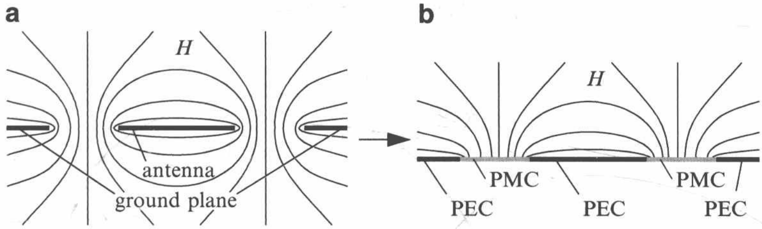

Fig. 1.2 Separation of possible integration paths by a PPS

by a PPS [13]. The PMC covering the aperture divides the problem space in two subspaces each with an irrotational magnetic field. Therefore the PMC also acts as PPS as shown in Fig. 1.2. A solution of the problem can be found by first solving the subproblems in the subspaces and then matching the field at the PMC boundary.

Furthermore, on the surface of the PMC we have $\underline{\mathcal{J}} = 0$ and $\underline{\mathcal{Q}_e} = 0$. Therefore the electrical current density is divergence free. Hence in analogy to the derivation of the EFIE [24] we can develop the magnetic field $\underline{\mathcal{H}}$ in dependance to the magnetic current $\underline{\mathcal{J}_m}$ [21]:

$$\underline{\mathcal{H}} = j\omega\varepsilon \int_V \underline{\mathcal{G}_m} \wedge \underline{\mathcal{J}_m} \tag{1.3}$$

$\underline{\mathcal{G}_m}$ itself is defined as the Green's dyad

$$\underline{\mathcal{G}_m} = (1 - \frac{1}{k^2} \mathrm{d} \star \mathrm{d}\star) G_{m0} \mathcal{I}. \tag{1.4}$$

Here it should be mentioned that in comparison to the Green's dyad in [24] we have a sign change of the second term which can be traced back to the remaining asymmetry of the signs in the Maxwell's equations as given in (1.1).

G_{m0} is given by

$$G_{m0} = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi\mu|\mathbf{r}-\mathbf{r}'|} \tag{1.5}$$

and $\mathcal{I}$ denotes the unit double one-form [18]. With (1.4) and (1.5) we can write (1.3) as

$$\underline{\mathcal{H}} = j\omega\varepsilon\mu \int G_{m0}\mathcal{I} \wedge \underline{\mathcal{J}_m} - \frac{j}{\omega} \mathrm{d} \star \mathrm{d} \star \int G_{m0}\mathcal{I} \wedge \underline{\mathcal{J}_m}. \tag{1.6}$$

Considering the Lorenz gauge $\star\, \mathrm{d} \star \underline{\mathcal{A}}^e = j\omega\varepsilon\mu\Phi^e$ this can be shortened to

$$\underline{\mathcal{H}} = j\omega\underline{\mathcal{A}}^e + \mathrm{d}\Phi^e, \tag{1.7}$$

where $\underline{\mathcal{A}}^e$ and Φ^e denote the *electric* vector potential

$$\underline{\mathcal{A}}^e = \varepsilon\mu \int G_{m0}\mathcal{I} \wedge \underline{\mathcal{J}_m} \tag{1.8}$$

and the *magnetic* scalar potential

$$\Phi^e = -\frac{j}{\omega} \int \star \mathrm{d} \star G_{m0} \mathscr{I} \wedge \underline{\mathscr{J}}_m. \tag{1.9}$$

1.1.2 Calculation of Magnetic Currents Using the MoM

In order to solve (1.6) we apply the Method of Moments [6, 22]. To this end we expand the unknown magnetic current $\underline{\mathscr{J}}_m$ in the aperture into

$$\underline{\mathscr{J}}_m(\mathbf{r}) = \sum_n^N V_n \mathsf{f}_n(\mathbf{r}), \tag{1.10}$$

where V_n denote generalized voltage amplitudes and $\mathsf{f}_n(\mathbf{r})$ denotes a suitable basis one-form [1, 22]. We insert (1.10) into (1.6) and test the resulting equation with f_m in an application of the Galerkin method. After partial integration we yield:

$$\begin{aligned} \int_S \mathsf{f}_m \wedge \underline{\mathscr{H}} = \quad & j\omega\varepsilon\mu \int_S \mathsf{f}_m \wedge \int_S' G_{m0} \mathscr{I} \wedge \textstyle\sum_n^N V_n \mathsf{f}_n \\ & -\tfrac{j}{\omega} \int_S \mathrm{d}\mathsf{f}_m \wedge \int_S' \star \mathrm{d} \star G_{m0} \mathscr{I} \wedge \textstyle\sum_n^N V_n \mathsf{f}_n \end{aligned} \tag{1.11}$$

Consideration of the boundary conditions for the tangential magnetic field on the surface of the PMC $\underline{\mathscr{H}}^{tan}$ for an incident magnetic field $\underline{\mathscr{H}}^{in}$ yields

$$\mathsf{n} \wedge \underline{\mathscr{H}}^{in} = -\mathsf{n} \wedge \underline{\mathscr{H}}^{tan}. \tag{1.12}$$

When the basis one-forms f_n are defined on the surface of the PMC, we can write the left side of (1.11) as

$$-\int_S \mathsf{f}_m \wedge \underline{\mathscr{H}}^{tan}. \tag{1.13}$$

The resulting equation can be written as a system of linear equations of dimension $N \times N$:

$$\mathbf{I} = \mathbf{YV} \tag{1.14}$$

The N-dimensional vectors $\mathbf{I}$ and $\mathbf{V}$ aggregate the generalized excitation currents I_n and generalized voltage amplitudes V_n that have been introduced in (1.10). The coefficients of $\mathbf{Y}$ can be calculated very similar to the coefficients of $\mathbf{Z}$ in [17]. With (1.14) and (1.11) we can write

$$Y_{mn} = j\omega\mu\varepsilon \int_S \mathsf{f}_m \wedge \int_S' G_{m0} \mathscr{I} \wedge \mathsf{f}_n - \frac{j}{\omega} l_m \int_S' \star \mathrm{d} \star G_{m0} \mathscr{I} \wedge \mathsf{f}_n. \tag{1.15}$$