Electromagnetic Field Interaction with Transmission Lines

WIT*PRESS*

WIT Press publishes leading books in Science and Technology. Visit our website for the current list of titles. www.witpress.com

WIT*eLibrary*

Home of the Transactions of the Wessex Institute, the WIT electronic-library provides the international scientific community with immediate and permanent access to individual papers presented at WIT conferences. Visit the WIT eLibrary at http://library.witpress.com

Advances in Electrical Engineering and Electromagnetics

Associate Editors

R. Belmans Katholieke Universiteit Leuven Belgium

A.R. Bretones University of Granada Spain

R. Gomez Martin University of Granada Spain

K. Hameyer Katholieke Universiteit Leuven Belgium

L. Haydock Newage International Limited UK

A. Konrad University of Toronto Canada

A. Kugi Johannes Kepler University Austria

F. Lattarulo Politecnico di Bari Italy

G Manara University of Pisa Italy **E.K. Miller** Lincoln USA

T. Miyoshi Kobe University Japan

O.A. Mohammed Florida International University USA

G. Molinari University of Genoa Italy

B. Notaros University of Massachusetts USA

G. Pelosi University of Florence Italy

D. Poljak University of Split Croatia

F. Rachidi EMC Group Switzerland

T. Rang Tallinn Technical University Estonia **B. Ribas** Ministry of Health Spain

K. Richter Graz University of Technology Austria

V. Roje University of Split Croatia

S. Russenchuck European Laboratory for Particle Physics Switerland

H. Ryssel Fraunhofer Institute for Integrated Circuits Germany

A. Savini Universita de Pavia Italy

N. Takahashi Okayama University Japan **C.Y. Tham** Tunku Abdul Rahman University Malaysia

A.G. Tijhuis Technische Universiteit Eindhoven The Netherlands

S. Tkachenko Otto-von-Guericke-University of Magdeburg Germany

T. Tsiboukis Aristotle University of Thessaloniki Greece

P. Vas Unversity of Aberdeen Scotland

S. Walker Imperial College London UK

K. Zakrzewski Politechnika Lodzka Poland

Electromagnetic Field Interaction with Transmission Lines

From classical theory to HF radiation effects

Edited by

F Rachidi & S Tkachenko





Editors:

F. Rachidi Swiss Federal Institute of Technology, Switzerland

S.V. Tkachenko

Otto-von-Guericke-University, Germany

Published by

WIT Press

Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK Tel: 44 (0) 238 029 3223; Fax: 44 (0) 238 029 2853 E-Mail: witpress@witpress.com http://www.witpress.com

For USA, Canada and Mexico

WIT Press

25 Bridge Street, Billerica, MA 01821, USA Tel: 978 667 5841; Fax: 978 667 7582 E-Mail: infousa@witpress.com http://www.witpress.com

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available from the British Library

ISBN: 978-1-84564-063-7 ISSN: 1742-3783

Library of Congress Catalog Card Number: 2007922339

The texts of the papers in this volume were set individually by the authors or under their supervision.

No responsibility is assumed by the Publisher, the Editors and Authors for any injury and/ or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. The Publisher does not necessarily endorse the ideas held, or views expressed by the Editors or Authors of the material contained in its publications.

© WIT Press 2008

Printed in Great Britain by Athenaeum Press Ltd.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the Publisher.

To Mojgan

To Victoria, Natalie and Anna

Contents

Preface

xv

PART I: CLASSICAL TRANSMISSION LINE THEORY

Cł	apt	ter	1

De	erivat	ion of t	elegrapher's equations and field-to-transmission line	2	
С.	A. Nu	cci, F. I	Rachidi & M. Rubinstein	5	
1	Tran	smissio	n line approximation	3	
2	Single-wire line above a perfectly conducting ground				
	2.1	Taylor	r, Satterwhite and Harrison model	6	
		2.1.1	Derivation of the first field-to-transmission line		
			coupling (generalized telegrapher's) equation	6	
		2.1.2	Derivation of the second field-to-transmission line		
			coupling equation	8	
		2.1.3	Equivalent circuit	9	
	2.2	Agraw	/al, Price and Gurbaxani model	10	
	2.3	Rachie	di model	11	
3	Cont	ribution	n of the different electromagnetic field components	12	
4	Inclu	ision of	losses	13	
5	Case	of mul	ticonductor lines	15	
6	Time	e-domai	in representation of the coupling equations	17	
7	Frequency-domain solutions				
	7.1	Green	's functions	18	
	7.2	BLT e	equations	19	
8	Time	e-domai	in solutions	20	
9	Cone	clusions	3	21	

Su	rge p	ropaga	tion and crosstalk in multiconductor transmission	
lin	es ab	ove gro	ound	23
Ne	lson T	Theetha	yi & Rajeev Thottappillil	
1	Intro	duction	1	23
2	Tele	grapher	's or transmission line equations for MTL systems	24
	2.1	Expres	ssions for internal impedance of wires	27
	2.2	Extern	al impedance and admittance of wires above	
		finitel	v conducting ground	27
		2.2.1	Carson's ground impedance expression for	
			low-frequency pulse propagation studies	31
		2.2.2	Sunde's ground impedance expression for	
			high-frequency pulse propagation studies	33
		2.2.3	Asymptotic nature of ground impedance and	
			the concept of penetration depth of fields in the ground	34
		2.2.4	Limits of transmission line approximation for	
			overhead wires	37
		2.2.5	Ground admittance for above ground wires	37
	2.3	Comp	lete per unit transmission line representation and	
		the ser	nsitivity of each transmission line parameters	39
2.4 Transmission line equations time domain for wires abo		nission line equations time domain for wires above		
		ground	d	41
		2.4.1	Time domain transient ground impedance	42
3	Time	e domai	n numerical solutions for transmission line equations	45
	3.1	Finite	difference time domain method	45
	3.2	Freque	ency domain solutions for MTL systems	50
	3.3	Comp	arison between direct frequency domain solutions and	
		FDTD	method	52
4	Cros	stalk in	MTL systems	54
	4.1	Crosst	alk under weak coupling conditions and for electrically	
		short l	ines	55
		4.1.1	Crosstalk due to common impedance coupling	55
		4.1.2	Crosstalk due to capacitive coupling	57
		4.1.3	Crosstalk due to inductive coupling	60
		4.1.4	Capacitive and inductive crosstalk combinations	63
	4.2	Crosst	alk under strong coupling conditions	67
		4.2.1	Case 1: influence of receptor height	71
		4.2.2	Case 2: influence of finitely conducting ground	72
		4.2.3	Case 3: influence of receptor terminal loads	73
5	Conc	cluding	remarks	74

Su	rge p	opagation in multiconductor transmission lines	
be	low g	ound	79
Ne	lson	heethayi & Rajeev Thottappillil	
1	Intro	luction	79
2	Tele	rapher's or transmission line equations for the buried wires	81
	2.1	Ground impedance for buried wires	83
		2.1.1 Asymptotic analysis	86
	2.2	Ground admittance for buried wires	87
3	Poss	ble limits of transmission line approximation for buried wires	91
4	Cou	ling to cable core through cable shields	93
	4.1	Generalized double shield three-core cable	95
		4.1.1 Telegrapher's equations for shielded cables	95
		4.1.2 Transmission line impedance and admittance	
		parameters for shielded cables	97
	4.2	An example of RG-58 cable 1	01
	4.3	Influence of shield thickness in the coupling phenomena 1	05
	4.4	A simple measurement for estimating inductance and	
		capacitance matrix elements for internal conductors of cables 1	07
		4.4.1 MTL capacitance matrix estimation 1	08
		4.4.2 MTL inductance matrix estimation 1	08
5	Som	additional cases of ground impedance based on wire geometry 1	09
	5.1	Impedance with wires on the ground 1	09
	5.2	Mutual impedance with one wire above ground and the	
		other below the ground 1	11
6	Som	examples 1	11
	6.1	Time domain simulation of pulse propagation in bare and	
		insulated wires 1	11
	6.2	A practical crosstalk problem 1	13
7	Con	uding remarks 1	18

PART II: ENHANCED TRANSMISSION LINE THEORY

Hi ele S. V	gh-fro ctrod 7. Tka	equency electromagnetic coupling to transmission lines: ynamics correction to the TL approximation chenko, F. Rachidi & J.B. Nitsch	123
1	Intro	duction	123
2	High	-frequency electromagnetic field coupling with a straight wire	
	abov	e a perfectly conducting ground	124
	2.1	Derivation of an electric field integral equation in a TL-like	
		form for a straight thin wire of finite length	124
	2.2	Iterative solution of the coupling equations in frequency-domain	129

	2.3	Coupling of a plane wave to an infinite wire: exact and iterative	
		solutions	131
	2.4	Correction to the reflection coefficient for a semi-infinite	
		open-circuit line	134
	2.5	Iterative solution of the coupling equations for a	
		finite-length straight line in time-domain	138
	2.6	Discussion of the convergence of the procedure for a finite line	141
3	Prop	agation of high-frequency current waves through a line bend	145
	3.1	Statement of the problem	145
	3.2	Characterization of the line bend: derivation of the	
		electric field integral equations	146
	3.3	Iterative solutions of the electric field integral equation	150
	3.4	Validation of the proposed method	152
	3.5	Radiated power	154
4	Conc	lusion	155

Hi	gh-fre	equenc	y electromagnetic field coupling to long loaded		
no	n-uni	form li	nes: an asymptotic approach	159	
<i>S. V</i>	⁷ . Tka	chenko,	F. Rachidi & J.B. Nitsch		
1	Intro	duction		159	
2	High	-freque	ncy electromagnetic field coupling to a long loaded line	161	
	2.1	Asym	ptotic approach	161	
		2.1.1	Solution for the induced current in the asymptotic region	161	
		2.1.2	Expression for the induced current at the line terminals		
			(regions I and III)	166	
		2.1.3	Summary of the proposed procedure to determine the		
			induced current along the line and at the line terminals	168	
	2.2	Accura	acy of the proposed three-term expression for the		
		induce	d current along the asymptotic region of the line	168	
	2.3	Applic	ation: response of a long terminated line to an external		
		plane	wave	169	
3	Asyn	nptotic	approach for a non-uniform transmission line	172	
4	Conc	lusion		178	
	Appendix 1: Determination of coefficients R_+ , R , C_+ , C as a function				
	of co	efficie	the I_1 and I_2	179	
	Appe	endix 2	Derivation of analytical expressions for the coefficients		
	C_+ ar	nd C_{-} for	or a semi-infinite open-circuited line, using the iterative		
	meth	od pres	ented in Chapter 4	180	
	Appe	endix 3	Analytical expression for the induced current along the		
	asym	ptotic 1	region of the line containing a lumped impedance	182	

Tra	ansm	ission line models for high-speed conventional interconnects	
ano A.C	<mark>d met</mark> G. Chi	allic carbon nanotube interconnects iariello, A. Maffucci, G. Miano & F. Villone	187
1	Intro	duction and historical background	187
2	Gene	ral integral formulation and derivation of transmission	
	line r	nodels	190
	2.1	Integral formulation	190
	2.2	Transmission line equations	192
3	Tran	smission line model for conventional conductors	195
	3.1	A cylindrical pair	195
	3.2	A coupled microstrip	197
4	Trans	smission line model for CNT interconnects	199
	4.1	A fluid model for CNTs	201
	4.2	A transmission line model for a SWCNT above a ground plane	202
5	Exan	nples and applications	205
	5.1	Finite length and proximity effect	205
	5.2	High-frequency losses	207
	5.3	High-frequency crosstalk and mode-conversion	211
	5.4	A comparison between CNT and copper interconnects for	
		nanoelectronic applications	213
6	Conc	lusions	217

Th	ie elec	tromagnetic field coupling to buried wires: frequency		
an	and time domain analysis			
D.	Polja	k		
1	Intro	duction	221	
2	The f	frequency domain approach	223	
	2.1	Formulation in the frequency domain	223	
	2.2	Numerical solution of the integro-differential equation	226	
	2.3	The calculation of a transient response	228	
	2.4	Numerical results	229	
3	Time	domain approach	231	
	3.1	Formulation in the time domain	232	
	3.2	Time domain energy measures	238	
	3.3	Time domain numerical solution procedures	239	
	3.4	Alternative time domain formulation via a simplified		
		reflection/transmission coefficient	243	
	3.5	Computational examples	244	

Preface

The evaluation of electromagnetic field coupling to transmission lines is an important problem in electromagnetic compatibility. Customarily, use is made of the transmission line (TL) approximation which applies to uniform transmission lines with electrically-small cross-sectional dimensions, where the dominant mode of propagation is transverse electromagnetic (TEM). Antenna-mode currents and higher-order modes appearing at higher frequencies are neglected in the classical TL theory.

Since the development of the TL theory and the derivation of the so-called telegrapher's equations by Oliver Heaviside in the late 19th century, significant progress has been achieved in the understanding of wave propagation along transmission lines. In 1965, Taylor, Satterwhite and Harrison extended the classical TL equations to include the presence of an external electromagnetic field. Their field-to-transmission coupling equations – as well as their equivalent formulations derived later – have been successfully applied to solve a large range of problems dealing with EMP and lightning interaction with power and telecommunication lines.

The unabated increase in the operating frequency of electronic products and the emergence of sources of disturbances with higher frequency content (such as High Power Microwave and Ultra-Wide Band systems) have led to a breakdown of the TL approximation's basic assumptions for a number of applications. In the last decade or so, the generalization of the TL theory to take into account high frequency effects has emerged as an important topic of study in electromagnetic compatibility. This effort resulted in the elaboration of the so-called 'generalized' or 'full-wave' TL theory, which incorporates high frequency radiation effects, while keeping the relative simplicity of TL equations.

This book covers both the classical transmission line theory as well as its recent enhancements. It is intended for graduate students, researchers and engineers interested in the transmission line theory and electromagnetic field interaction with transmission lines, with special emphasis on high frequency effects. The text is organized in two main parts containing a total of seven chapters.

Part I presents the consolidated knowledge of classical transmission line theory and different field-to-transmission line coupling models.

Chapter 1 discusses the assumptions of the TL theory and presents the derivation of the field-to-transmission line coupling equations. Three different but

completely equivalent approaches that have been proposed to describe the coupling of electromagnetic field coupling to transmission lines are also presented and discussed. Chapters 2 and 3, deal, respectively, with the specific cases of overhead multiconductor lines and buried cables. Various factors influencing the pulse propagation and crosstalk along multiconductor systems are discussed, and methods for the calculation of the line longitudinal and transverse line parameters are presented.

Part II presents different approaches developed to generalize the TL theory in order to include high frequency effects.

In Chapter 4, a TL-like pair of equations is derived under the thin-wire approximation for evaluating currents and potentials induced by external electromagnetic fields on a wire of a given geometric form above a perfect conducting ground. Based on perturbation theory, an iterative procedure is proposed to solve the derived coupling equations, where the zero-iteration term is determined by using the classical TL approximation. Chapter 5 presents an efficient hybrid method to compute high frequency electromagnetic field coupling to long, loaded lines including lumped discontinuities. Chapter 6 shows that the classical TL theory may be included in a more general model based on an integral formulation of the general full-wave problem. The derived general model is applied to conventional high-speed microelectronics, as well as to nanoelectronics applications. Chapter 7 deals specifically with high frequency domain based on the Pocklington's integral equation, and the other in the time domain using the Hallen integral equation, are proposed and discussed.

Although the chapters follow a logical order and a novice reader is advised to read the book sequentially, an effort has been made to make each chapter as independent of the others as possible. Therefore, readers interested in a particular aspect of the subject dealt with in one chapter do not need to consult other chapters of the book.

This book is the result of the authors' activities in the area of electromagnetic field-to-transmission line interactions. The authors are indebted to many individuals for their support, advice, and guidance. Special thanks are due to Michel Ianoz, Juergen Nitsch and Fred M. Tesche, and to all the authors of the chapters for their precious contributions.

Farhad Rachidi and Sergei Tkachenko