

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

X-Parameters

This is the definitive guide to X-parameters, written by the original inventors and developers of this powerful new paradigm for nonlinear RF and microwave components and systems.

Learn how to use X-parameters to overcome intricate problems in nonlinear RF and microwave engineering, as the general theory behind X-parameters is carefully and intuitively introduced, and then simplified down to specific, practical cases, providing you with useful approximations that will greatly reduce the complexity of measuring, modeling, and designing for nonlinear regimes of operation.

Containing real-world case studies, definitions of standard symbols and notation, detailed derivations within the appendices, and exercises with solutions, this is the definitive stand-alone reference for researchers, engineers, scientists, and students looking to remain on the cutting edge of RF and microwave engineering.

David E. Root is an Agilent Research Fellow at Agilent Technologies. He co-led the Agilent research and technical development of X-parameters through its commercialization. He is a Fellow of the IEEE, and co-editor of *Nonlinear Transistor Model Parameter Extraction Techniques* (2011).

Jan Verspecht is a Master Research Engineer at Agilent Technologies. He invented X-parameters in 1996, and is a Fellow of the IEEE.

Jason Horn is an Expert Design Engineer at Agilent Technologies, who has been heavily involved in the development of X-parameter measurements.

Mihai Marcu is a Senior Consultant at Agilent Technologies, who is deeply involved in the development and application of X-parameters for nonlinear modeling.

Cambridge University Press
978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components
David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu
Frontmatter
[More information](#)

The Cambridge RF and Microwave Engineering Series

Series Editor

Steve C.ripps, Distinguished Research Professor, Cardiff University

Peter Aaen, Jaime Plá and John Wood, *Modeling and Characterization of RF and
Microwave Power FETs*

Dominique Schreurs, Máirtín O'Droma, Anthony A. Goacher and Michael Gadringer,
RF Amplifier Behavioral Modeling

Fan Yang and Yahya Rahmat-Samii, *Electromagnetic Band Gap Structures in Antenna
Engineering*

Enrico Rubiola, *Phase Noise and Frequency Stability in Oscillators*

Earl McCune, *Practical Digital Wireless Signals*

Stepan Lucyszyn, *Advanced RF MEMS*

Patrick Roblin, *Nonlinear RF Circuits and the Large-Signal Network Analyzer*

Matthias Rudolph, Christian Fager and David E. Root, *Nonlinear Transistor Model
Parameter Extraction Techniques*

John L. B. Walker, *Handbook of RF and Microwave Solid-State Power Amplifiers*

Anh-Vu H. Pham, Morgan J. Chen and Kunia Aihara, *LCP for Microwave Packages
and Modules*

Sorin Voinigescu, *High-Frequency Integrated Circuits*

Richard Collier, *Transmission Lines*

Valeria Teppati, Andrea Ferrero and Mohamed Sayed, *Modern RF and Microwave
Measurement Techniques*

Nuno Borges Carvalho and Dominique Schreurs, *Microwave and Wireless
Measurement Techniques*

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu, *X-Parameters*

Forthcoming

Richard Carter, *Theory and Design of Microwave Tubes*

Hossein Hashemi and Sanjay Raman, *Silicon mm-Wave Power Amplifiers and
Transmitters*

Earl McCune, *Dynamic Power Supply Transmitters*

Isar Mostafanezad, Olga Boric-Lubecke and Jenshan Lin, *Medical and Biological
Microwave Sensors*

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu
Frontmatter

[More information](#)

X-Parameters

Characterization, Modeling, and Design of
Nonlinear RF and Microwave Components

DAVID E. ROOT

Agilent Technologies, Inc.

JAN VERSPECHT

Agilent Technologies, Inc.

JASON HORN

Agilent Technologies, Inc.

MIHAI MARCU

Agilent Technologies, Inc.



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components
David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu
Frontmatter
[More information](#)

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Published in the United States of America by Cambridge University Press, New York

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9780521193238

© Cambridge University Press 2013

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

First published 2013

Printing in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalog record for this publication is available from the British Library

Library of Congress Cataloging in Publication data

Root, David E.

X-parameters : characterization, modeling, and design of nonlinear RF and microwave components / David E.
Root, Agilent Technologies Inc., Jan Verspecht, Agilent Technologies Inc., Jason Horn, Agilent Technologies
Inc., Mihai Marcu, Agilent Technologies Inc.

pages cm – (The Cambridge RF and microwave engineering series)

Includes bibliographical references.

ISBN 978-0-521-19323-8 (Hardback)

1. Microwave circuits—Design and construction—Mathematics. 2. Electric circuits, Nonlinear—Design and
construction—Mathematics. 3. Parametric devices—Design and construction—Mathematics.

4. Differential equations. I. Verspecht, Jan. II. Horn, Jason. III. Marcu, Mihai. IV. Title.

TK7876.R66 2013

621.3841'2—dc23 2013013915

“X-parameters” is a trademark of Agilent Technologies, Inc.

ISBN 978-0-521-19323-8 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of
URLs for external or third-party internet websites referred to in this publication,
and does not guarantee that any content on such websites is, or will remain,
accurate or appropriate.

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

**For Marilyn, with thanks for her patience, support, and, most of all, her love.
David**

**In memory of Petrus Verspecht.
Jan**

**To Jessica, Jonathan, and Elise, my inspiration.
Jason**

**To Domnica, for the patience shown in the many evenings and weekends
that I have spent away from her.
Mihai**

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

“Just as the S-parameters revolutionized linear microwave circuit engineering nearly 60 years ago, the relatively new development of the X-parameters and the mixer-based VNA provides a truly scientific approach to nonlinear RF and microwave circuit design. This book, written by experts, contains a wealth of information about the characterization and modeling of nonlinear components as well as their applications to various types of designs. I can only wish that such capability and textbook had been available when I was a design engineer.”

Les Besser

Founder of Compact Software and Besser Associates

“S-parameters revolutionized linear RF and Microwave design in the 1970s and X-parameters are doing the same for non-linear design today. Starting with the familiar foundation of S-parameters, the text guides the reader through the additional non-linear terminology needed to provide a clear and practical view of X-parameters. Many practical examples show how to apply them in real world designs and answers are provided to some of the more subtle concepts of cross-frequency phase and memory effects. In a world where wireless is proliferating, this book will be an invaluable reference for any RF designer to reduce design turns and improve their first-pass designs.”

Mark Pierpont

Agilent Technologies

Contents

	<i>Preface</i>	<i>page</i> xiii
	<i>Acknowledgments</i>	xv
1	S-parameters – a concise review	1
	1.1 Introduction	1
	1.2 S-parameters	1
	1.3 Wave variables	2
	1.4 S-parameter measurement	5
	1.5 S-parameters as a spectral map	7
	1.6 Superposition	8
	1.7 Time invariance of components described by S-parameters	10
	1.8 Cascadability	11
	1.9 DC operating point	12
	1.10 S-parameters of a nonlinear device	12
	1.11 Additional benefits of S-parameters	15
	1.11.1 S-parameters are applicable to distributed components at high frequencies	15
	1.11.2 S-parameters are easy to measure at high frequencies	15
	1.11.3 Interpretation of two-port S-parameters	15
	1.11.4 Hierarchical behavioral design with S-parameters	16
	1.12 Limitations of S-parameters	16
	1.13 Summary	18
	Exercises	18
	References	18
	Additional reading	19
2	X-parameters – fundamental concepts	20
	2.1 Overview	20
	2.2 Nonlinear behavior and nonlinear spectral mapping	20
	2.3 Multi-harmonic spectral maps	22
	2.4 Load- and source-mismatch effects	25
	2.5 Cascading DUTs	25
	2.6 Example: cascading two RF power amplifiers with independent bias	27

2.7	Relationship to harmonic balance	29
2.8	Cross-frequency phase	30
2.8.1	Commensurate signals	30
2.8.2	Definition of cross-frequency phase	30
2.9	Basic X-parameters for multi-harmonic multi-port stimulus	34
2.9.1	Time invariance and related properties of $F_{p,k}(\cdot)$ functions	35
2.9.2	Definition of X-parameters and X-parameter behavioral model	36
2.9.3	Example: a set of X-parameters	37
2.10	Physical meaning of the basic X-parameters	38
2.10.1	Reference stimulus and response	38
2.10.2	Physical interpretation	39
2.11	Using the X-parameter behavioral model	39
2.11.1	Example: amplifier with source and load mismatch	40
2.12	Summary	43
	Exercises	44
	References	44
	Additional reading	44
3	Spectral linearization approximation	45
3.1	Simplification of basic X-parameters for small mismatch	45
3.1.1	Non-analytic maps	46
3.1.2	Large-signal operating point	48
3.2	Adding small-signal stimuli (linearized nonlinear spectral mapping)	50
3.2.1	Small-signal interactions: the RF terms	51
3.2.2	Small-signal interactions: the DC terms	52
3.3	Physical meaning of the small-signal interaction terms	55
3.4	Discussion: X-parameters and the spectral Jacobian	60
3.5	X-parameters as a superset of S-parameters	60
3.6	Two-stage amplifier design	64
3.7	Amplifier matching under large-signal stimulus	68
3.7.1	Output matching and hot- S_{22}	69
3.7.2	Input matching	78
3.8	Practical application – a GSM amplifier	80
3.9	Summary	84
	Exercise	84
	References	87
	Additional reading	87
4	X-parameter measurement	88
4.1	Measurement hardware	88
4.1.1	Hardware requirements	88
4.1.2	Mixer-based systems	88

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

4.1.3	Sampler-based systems	91
4.1.4	Stimulus requirements	93
4.2	Calibration	93
4.2.1	Scalar-loss correction	94
4.2.2	S-parameter calibration	94
4.2.3	NVNA calibration	96
4.3	Phase references	97
4.3.1	Phase-reference signals	97
4.3.2	Measurement considerations	99
4.3.3	Practical phase references	100
4.4	Measurement techniques	101
4.4.1	Large-signal response measurements	101
4.4.2	Small-signal response measurements	101
4.4.3	Practical measurement considerations	105
4.4.4	Simulation-based extraction	106
4.5	X-parameter files	106
4.5.1	Structure	107
4.5.2	Naming conventions	107
4.5.3	Example file	108
4.6	Summary	110
	References	110
	Additional reading	111
5	Multi-tone and multi-port cases	112
5.1	Introduction	112
5.2	Commensurate signals – large $A_{1,1}$ and large $A_{2,1}$: load-dependent X-parameters	113
5.2.1	Time invariance, phase normalization, and commensurate two-tone LSOP	114
5.2.2	Spectral linearization	115
5.3	Establishing the LSOP using a load tuner: passive load pull	116
5.4	Additional considerations for commensurate signals	118
5.4.1	Extraction of X-parameter functions under controlled loads	118
5.4.2	Harmonic superposition	118
5.4.3	Limitations of passive load pull for load-dependent X-parameters	119
5.4.4	Sampling of the three-RF-variable space defining the <i>refLSOPS</i>	119
5.4.5	Hardware setup for load-dependent X-parameters	119
5.4.6	Calibrating out uncontrolled harmonic impedances	119
5.5	Arbitrary load-dependent X-parameters of a GaAs FET	120
5.5.1	Load-dependent X-parameter model of a GaN HEMT: estimating the effect of independent harmonic impedance tuning	123

5.6	Design example: Doherty power amplifier design and validation	129
5.6.1	Doherty power amplifier	129
5.6.2	X-parameter characterization of the transistors	130
5.6.3	X-parameter model validation	132
5.6.4	Doherty power amplifier design using X-parameters	135
5.6.5	Results	136
5.7	Incommensurate signals	138
5.7.1	Notation for incommensurate two-tone X-parameters	138
5.7.2	Time invariance for incommensurate two-tone X-parameters	140
5.7.3	Reference LSOP	141
5.7.4	Spectral linearization	141
5.7.5	Discussion	143
5.7.6	When intermodulation frequencies are negative	143
5.7.7	X-parameter models of mixers	144
5.8	Summary	147
	Exercises	148
	References	148
	Additional reading	148
6	Memory	150
6.1	Introduction	150
6.2	Modulated signals: the envelope domain	151
6.3	Quasi-static X-parameter evaluation in the envelope domain	151
6.3.1	Quasi-static two-tone intermodulation distortion from a static one-tone X-parameter model	152
6.3.2	ACPR estimations using quasi-static approach	159
6.3.3	Limitations of quasi-static approach	160
6.3.4	Advantages of quasi-static X-parameters for digital modulation	161
6.4	Manifestations of memory	161
6.5	Causes of memory	163
6.5.1	Self-heating	163
6.5.2	Bias modulation	163
6.6	Importance of memory	167
6.6.1	Modulation-induced baseband memory and carrier memory	167
6.6.2	Dynamic X-parameters	168
6.6.3	Identification of the memory kernel: conceptual motivation	171
6.6.4	Step response of the memory kernel	172
6.6.5	Application to real amplifier	173
6.6.6	Validation of memory model	175
6.6.7	Interpretation of dynamic X-parameters	181
6.6.8	Wide-band X-parameters (X_{WB})	182
	References	187
	Additional reading	188

Appendix A: Notations and general definitions	189
A.1 Sets	189
A.2 Vectors and matrices	189
A.3 Signal representations	190
A.3.1 Time-domain representation (real signal)	190
A.3.2 Complex representation (complex envelope signal)	190
A.4 Fourier analysis	191
A.5 Wave definitions	192
A.5.1 Generalized power waves	192
A.5.2 Voltage waves	194
A.6 Linear network matrix descriptions	194
A.6.1 S-parameters	195
A.6.2 Z-parameters	195
A.6.3 Y-parameters	195
References	195
Appendix B: X-parameters and Volterra theory	196
B.1 Introduction	196
B.2 Mathematical notation and problem definition	196
B.3 Application of the Volterra theory	197
B.4 Derivation of the McLaurin series	198
B.5 McLaurin series for the DC output	200
B.6 Conclusions	200
References	201
Appendix C: Parallel Hammerstein symmetry	202
References	203
Appendix D: Wide-band memory approximation	204
Appendix E: Solutions to exercises	206
<i>Index</i>	216

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

Preface

The need for a rigorous, yet practical, framework for characterization, modeling, and design of nonlinear electronic components at high frequencies has never been more urgent. The communications revolution is inexorably forcing active devices into more and more strongly nonlinear regimes of operation. This is a consequence of the relentless drive for more efficiency in order to save power, extend battery life, and minimize cooling. The price for efficiency is nonlinearity. Dealing with nonlinearity means that new measurement instrumentation and new modeling and design methodologies are required that go far beyond linear S-parameters. Fortunately, there is an overarching, interoperable paradigm combining all these pieces of the nonlinear puzzle together, seamlessly. The new paradigm is called X-parameters,¹ and that is what this book is about.

The book is intended as a comprehensive introduction to X-parameters. It is aimed at a diverse audience with a wide range of backgrounds. This is quite a challenging undertaking! We are targeting professional microwave engineers, device modeling engineers and scientists, RF and microwave circuit designers, electronic and communications engineers, CAE professionals developing simulator algorithms, and microwave and RF professionals developing new high-speed instrumentation for a wide range of nonlinear characterization applications. The inherent interdisciplinary nature of X-parameters is the prime reason we seek to appeal to this broad audience. The practical solutions based on X-parameters deployed by industry over the past several years depend on contributions in all of these areas.

With this diverse audience in mind, we have chosen a particular sequence with which to introduce the subject. We start with a concise summary of the well-known time-invariant linear theory, namely S-parameters. We choose this context, familiar to many readers, to introduce more advanced concepts that will be needed for the remainder of the book. Chapter 2 introduces X-parameters, based on multi-tone nonlinear spectral maps defined on a harmonic grid, and goes into significant detail about the application and implications of the constraint of time invariance. Chapter 3 simplifies the general discussion to simple practical cases, based on the application of spectral linearization, a useful approximation that reduces complexity, enabling practical applications. Several examples are presented demonstrating the power, utility, and relative simplicity of these

¹ “X-parameters” is a trademark of Agilent Technologies, Inc.

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

simplest X-parameters. The origins of “conjugate” terms in the spectral linearization are discussed. Chapter 4 is devoted to how X-parameters are measured, and also to how they are computed (generated) from within a circuit simulator. The functional block diagram of the main instrument (the nonlinear vector network analyzer – NVNA) is discussed, and the application of measurements using a pulse generator phase reference to obtain the key X-parameter quantities is reviewed. Chapter 5 extends the treatment of X-parameters to multiple large signals and multiple ports, as is necessary in the treatment of many mixers, the treatment of intermodulation with phase, and the large-signal response of power amplifiers as nonlinear functions of both input power and reflections of electrical signals back into the device due to large mismatch, going beyond the first spectral linearization approximation of Chapter 3. Finally, Chapter 6 extends the treatment of X-parameters to dynamic “memory effects,” important phenomena exhibited by practical modern high-speed devices in response to wide-band communication signals, for example. Several appendices are provided for detailed derivations, standard symbol and notational definitions, and further elaboration of some parts of the main text to help serve as a reference for workers in the field.

The book is appropriate as a text for an advanced undergraduate or graduate course in electrical engineering. In fact, we perceive an acute need to make X-parameters a standard part of the electrical engineering curriculum. The book may also be appropriate for applied mathematicians and scientists with an interest in rigorous and practical foundations for applications to a wide range of nonlinear systems well beyond electronics.

The background needed by readers of this book is not much more than first-year calculus, basic circuit theory, and simple Fourier analysis. Rudimentary knowledge of electronic power amplifiers and transistors, S-parameter fundamentals, differential equations, circuit design, and circuit simulation would certainly be helpful.

Cambridge University Press

978-0-521-19323-8 - X-Parameters: Characterization, Modeling, and Design of Nonlinear RF
and Microwave Components

David E. Root, Jan Verspecht, Jason Horn and Mihai Marcu

Frontmatter

[More information](#)

Acknowledgments

The authors are profoundly grateful to our many dedicated and talented colleagues who collaborated with us to develop and deploy X-parameter technology, products, support, and services. We are grateful to our many customers, academic researchers, and practicing professionals for their thoughtful feedback, stimulating discussions, and creative applications of this technology. We thank Agilent management for their vital support. Finally, we thank the staff at Cambridge University Press for their commitment to this project, their cheerful professionalism, and their patience.