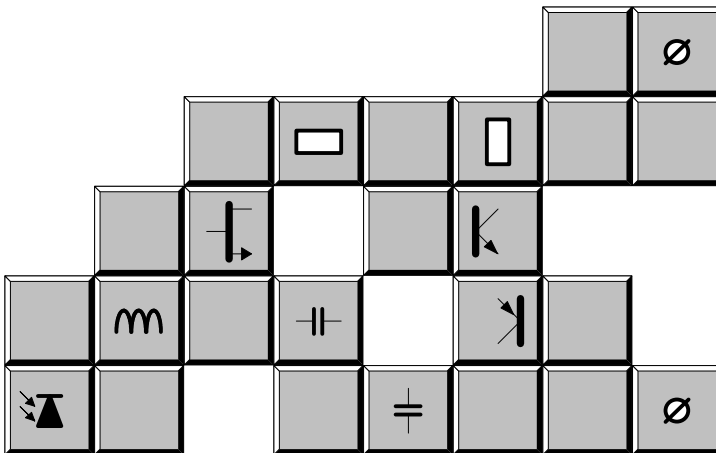

Rob van den Brink

Low-noise Wideband Feedback Amplifiers

an integrated approach to
characterization and design using
microwave and lightwave techniques



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design using microwave and lightwave
techniques

ruisarme, breedbandig tegengekoppelde versterkers
een geïntegreerde aanpak van karakteriseren en ontwerpen
op basis van microgolf en optische technieken

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft
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door het College van Dekanen aangewezen,
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door

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Contents

CONTENTS	0-1
Summary in English.....	0-6
Summary in Dutch	0-8
INTRODUCTION	1-1
1.1. Context of this thesis	1-1
1.2. State of the art.....	1-2
1.2.1. Evolution of various fields of study	1-2
1.2.2. State-of-the-art methods for wideband characterization.....	1-4
1.2.3. State-of-the-art methods for wideband feedback design	1-6
1.3. Essentials of this thesis: <i>back to basics</i>	1-9
1.3.1. Characterization	1-9
1.3.2. Feedback design.....	1-10
1.3.3. Overall structure.....	1-11
1.4. Spin-off of this thesis.....	1-12
1.4.1. High performance lightwave receivers.....	1-12
1.4.2. SABEL-CAE design environment.....	1-13
1.4.3. Microwave concepts applied to acoustic applications.....	1-14
1.5. Publications and patents resulting from this work	1-15
FORMAL DESCRIPTION OF TRANSFER.....	2-1
2.1. Signal flow observed relative to reference planes.....	2-2
2.1.1. Signal definition in paired conductor links.....	2-4
2.1.2. Equivalent load models	2-6
2.1.3. Equivalent source models.....	2-7
2.1.4. Interconnection transformation of waves	2-8
2.1.5. Conclusions	2-9
2.2. Blackbox representation of multi-port networks.....	2-10
2.2.1. Multi-port matrix parameters	2-11
2.2.2. Multi-port matrix properties.....	2-13
2.2.3. Multi-port matrix reduction algorithm	2-15
2.2.4. Application of multi-port transfer matrices in circuit simulators.....	2-16
2.2.5. Conclusions	2-17
2.3. Two-port transfer parameters.....	2-18
2.3.1. Two-port matrix parameters.....	2-18
2.3.2. Two-port virtual circuit parameters.....	2-20
2.3.3. Conclusions	2-24

EXTRACTION OF TRANSFER PARAMETERS.....	3-1
3.1. One-port model extraction methods for linear synthesis.....	3-2
3.1.1. Elementary extraction methods of analytical transfer functions.....	3-2
3.1.2. Extraction methods for equivalent circuit elements.....	3-4
3.1.3. Extraction of adequate photo-diode impedance-models.....	3-5
3.1.4. Conclusions.....	3-8
3.2. Two-port extraction methods for transistor models.....	3-10
3.2.1. Virtual circuit parameters as device representation method.....	3-11
3.2.2. Extraction of transistor parameters using Taylor series expansion.....	3-14
3.2.3. Extraction of parameters with delay using Taylor series expansion.....	3-16
3.2.4. Conclusions.....	3-17
3.3. Discussion on commonly used transistor models.....	3-18
3.3.1. Discussion on base resistance versus emitter inductance.....	3-18
3.3.2. Discussion on current transport function vs. diffusion capacitance.....	3-19
3.3.3. Conclusions.....	3-22
FORMAL DESCRIPTION OF FEEDBACK.....	4-1
4.1. Superposition analysis of feedback amplifiers.....	4-3
4.1.1. Superposition model parameters.....	4-3
4.1.2. Superposition flow parameters.....	4-7
4.1.3. Example of the extraction of superposition parameters.....	4-9
4.1.4. Conclusions.....	4-10
4.2. Superposition parameter calculation.....	4-11
4.2.1. Calculation of loop gain, forward gain and feedback factor.....	4-11
4.2.2. Calculation of asymptotic and virtual gain and forward leakage.....	4-14
4.2.3. Conclusions.....	4-15
4.3. Loop gain estimation using single-cut methods.....	4-16
4.3.1. One-cut loop gain estimation using two-port parameters.....	4-17
4.3.2. One-cut loop gain estimation using open voltage and current gain.....	4-20
4.3.3. Conclusions.....	4-22
4.4. Loop gain representation by poles and zeros.....	4-23
4.4.1. The purpose of pole-zero patterns.....	4-23
4.4.2. Strategy of pole-zero extraction methods.....	4-23
4.4.3. Practical demonstration of the pole-zero extractor.....	4-25
4.4.4. Interpretation of pole-zero patterns.....	4-27
4.4.5. Conclusions.....	4-28
4.5. Loop gain deflation algorithms.....	4-29
4.5.1. Manual deflation using pseudo delay.....	4-29
4.5.2. Automated deflation by pole-zero cancellation.....	4-31
4.5.3. Automated deflation using dominant singularities.....	4-32
4.5.4. Automated overall deflation.....	4-34
4.5.5. Conclusions.....	4-34
WIDEBAND FEEDBACK SYNTHESIS.....	5-1
5.1. Aperture analysis of feedback amplifiers.....	5-3
5.1.1. Definition of virtual-aperture and effective-aperture.....	5-3
5.1.2. Bandwidth analysis.....	5-6
5.1.3. Bandpass analysis.....	5-9

5.1.4. Conclusions	5-12
5.2. Compensation techniques for feedback amplifiers	5-13
5.2.1. Profiled compensation techniques in the forward amplifier	5-14
5.2.2. Profiled compensation techniques with intertwined solutions.....	5-16
5.2.3. Phantom compensation techniques in the feedback network.....	5-18
5.2.4. Conclusions	5-21
5.3. Compensation synthesis for feedback amplifiers	5-22
5.3.1. Bandpass synthesis.....	5-22
5.3.2. Compensation algorithm	5-25
5.3.3. Examples of loops with full compensation.....	5-29
5.3.4. Examples of loops with dominant compensation	5-33
5.3.5. Conclusions	5-35

FEEDBACK DESIGN EXAMPLE: LIGHTWAVE RECEIVERS 6-1

6.1. Lightwave receiver configurations.....	6-2
6.1.1. Conventional receiver front-ends	6-3
6.1.2. Improved receivers with current-current feedback.....	6-4
6.1.3. Implementation of receivers using current-current feedback	6-6
6.2. Iterative synthesis focused on maximal bandwidth.....	6-8
6.2.1. Quantifying parasitic effects using circuit stripping techniques	6-9
6.2.2. Cumulative quantification of parasitics using pole-zero techniques.....	6-12
6.2.3. Bandwidth performance of current-current feedback receivers.....	6-13
6.3. Iterative synthesis focused on minimal noise.....	6-14
6.3.1. Noise optimization in the absence of tuning.....	6-15
6.3.2. Noise tuning in absence of overall feedback	6-16
6.3.3. Noise tuning in combination with overall feedback	6-20
6.3.4. Noise performance of current-current feedback receivers.....	6-21
6.3.5. The role of noise measurements in an iterative synthesis	6-22
6.4. Conclusions	6-24

FORMAL DESCRIPTION OF NOISE 7-1

7.1. Definitions of signal and noise spectra	7-3
7.1.1. Spectral identification of random signals	7-4
7.1.2. Spectral correlation between random signals	7-6
7.1.3. Analytical noise analysis using complex noise spectra	7-7
7.2. Blackbox representation of noisy multi-port networks	7-8
7.2.1. Description of multi-port circuits including deterministic sources.....	7-8
7.2.2. Description of noisy multi-ports using correlation matrices.....	7-10
7.2.3. Reduction of correlation matrix dimension of noisy multi-ports.....	7-12
7.2.4. Application of noise correlation matrices in circuit simulators.....	7-13
7.2.5. Generalized thermal noise theorem for multi-port networks	7-14
7.2.6. Conclusions	7-15
7.3. Two-port noise parameters	7-17
7.3.1. Matrix noise parameters, dedicated to two-ports.....	7-17
7.3.2. Conventional spot noise parameters for two-ports	7-21
7.3.3. Autonomous noise parameters for two-ports.....	7-24
7.3.4. Conclusions	7-26

LIGHTWAVE BASED ELECTRICAL NOISE MEASUREMENTS	8-1
8.1. The art of measuring noise.....	8-3
8.1.1. Pitfalls while measuring noise.....	8-3
8.1.2. Accuracy limits when measuring noise	8-4
8.1.3. Basic definitions.....	8-5
8.2. Multi-level noise source with lightwave noise-tee.....	8-6
8.2.1. Circuit diagram of a noise-tee	8-6
8.2.2. Variable noise source based on a matched noise-tee configuration	8-7
8.2.3. Output noise level of a matched noise-tee configuration.....	8-8
8.2.4. Output impedance variation of a noise-tee configuration.....	8-9
8.2.5. Conclusions	8-11
8.3. Calibration of synthetic noise	8-12
8.3.1. Definition of (spectral) noise-current ratio for synthetic noise.....	8-12
8.3.2. Calibration of synthetic noise with calibrated noise sources	8-13
8.3.3. Calibration of synthetic noise, with shot-noise.....	8-15
8.3.4. Transformation of calibrated noise to arbitrary reference planes	8-21
8.3.5. Mathematical halving of the noise-tee.....	8-23
8.3.6. Conclusions	8-26
8.4. Noise level measurements using matched sources.....	8-27
8.4.1. Basic principles and definitions	8-27
8.4.2. Extraction of input noise level using hot/cold noise sources.....	8-29
8.4.3. Extraction of input noise level using multi-level noise sources.....	8-29
8.4.4. Measurement of lightwave receiver noise	8-32
8.4.5. Alternative lightwave receiver noise measurements.....	8-36
8.4.6. Conclusions	8-38
8.5. Noise parameter measurements	8-39
8.5.1. State-of-the-art measurement methods	8-39
8.5.2. Proposed improvements to state-of-the-art noise measurements.....	8-43
8.5.3. Input noise measurements for mismatched source admittances.....	8-45
8.5.4. Extraction of device noise-parameters	8-47
8.5.5. Extraction of input noise level for arbitrary source admittances	8-49
8.5.6. Conclusions.....	8-50
 LIGHTWAVE SYNTHETIC NOISE GENERATION	 9-1
9.1. Basic principles of synthetic noise generation	9-4
9.1.1. Delayed self-homodyne principle with FM modulation	9-4
9.1.2. Example of a practical synthetic noise generator	9-7
9.1.3. Conclusions	9-10
9.2. Practical analysis of synthetic noise generation.....	9-11
9.2.1. Analysis of the spectral envelope of the synthetic noise	9-11
9.2.2. Spectral ripple reduction by noise injection	9-14
9.2.3. Power analysis of synthetic noise	9-20
9.2.4. Statistical analysis of synthetic noise	9-22
9.2.5. Conclusions	9-25
9.3. Theoretical analysis of synthetic noise generation.....	9-26
9.3.1. Time domain analysis of the synthetic noise signal.....	9-26
9.3.2. Incoherence analysis	9-29
9.3.3. Spectral analysis far above incoherence threshold	9-34

9.3.4. Statistical analysis far above incoherence threshold.....	9-38
9.3.5. Conclusions.....	9-39

APPENDIX	@-1
A. Transformation rules for two-port parameters	@-1
B. Algorithms for overdetermined matrix divisions	@-2
C. Algorithm for polynomial curve fits.....	@-5
D. Algorithm for rational curve fits	@-6
E. Algorithm for rational magnitude fit.....	@-8
F. Algorithm for rational delay fit	@-9
G. Algorithm for weighed polynomial division	@-10
H. Algorithm for dominant deflation of transfer order.....	@-11
I. Bessel, Butterworth and Chebyshev transfer functions	@-13
J. Algorithm for feedback compensation synthesis.....	@-16
K. Definitions of spectra and integral transformations.....	@-18
L. Algorithm for extraction of equivalent input noise	@-22
M. Noise parameter extraction using hot and cold sources	@-24
N. Noise parameter extraction using paired hot and cold sources	@-27
O. Acknowledgments.....	@-29
P. Bibliography of the author	@-30
Q. References.....	@-31
R. Index	@-37

Summary

Summary in English

The design of wideband amplifiers with ultimate performance requires a radical change of approach. The cumulation of all minor imperfections of individual devices often causes a dramatic reduction of the overall performance. These imperfections (parasitics) are taken into account from the very beginning; so definitely not marginally as it is commonly done.

This thesis introduces innovative methods and tools to facilitate the application of *higher-order* feedback, over *several* amplifying stages, in the presence of deleterious parasitics. Much attention is paid on (1) formal descriptions of transfer, feedback and noise, (2) characterization methods of devices and sub-circuits and (3) design methods for compensation networks in feedback loops.

Formal description of transfer, feedback and noise

The formal descriptions provide unambiguous definitions of (a) multi-port y-, z- and s-parameters, (b) superposition parameters of feedback loops, such as loopgain and aperture, (c) noise spectra and (d) noise parameters. Signal representations, in terms of voltages, currents or waves, are discussed simultaneously.

The concept of virtual circuits is formalized for transfer as well as noise to simplify parameter extraction of device models. Algorithms are described for analyzing transfer and noise properties of arbitrary linear networks. We illustrate, for instance, how to calculate the thermal noise levels in *multi-port* networks from transfer measurements.

Characterization of transfer

Characterization enables the quantification of parasitic effects in terms of (a) multiport transfer parameters, (b) equivalent circuit models, and (c) poles and zeros. This thesis describes methods for measuring these device parameters between well-defined reference planes. A structured method is discussed for tracing relevant parasitics using these measurements (circuit stripping).

Algorithms have been developed for (a) extracting poles and zeros from transfer functions, and (b) reconstructing equivalent circuit models from full one- or two-port measurements.

These algorithms demonstrate that adequate (linear) modeling of transistors does not necessarily result in exotic and complicated transistor models. This approach has, for instance, resulted in a new (small-signal) bipolar transistor model, that is more appropriate to wideband analysis and synthesis than the well-known hybrid- Π model.

Characterization of noise

The development of a new instrument, a lightwave *synthetic noise generator*, has facilitated the application of new methods of noise characterization. Our source generates white noise using *lightwave* principles, and has many advantages with respect

to conventional 50 Ω noise sources. The noise bandwidth of this source can be varied simply, exceeding 10 GHz in bandwidth (hundreds of GHz are feasible).

Novel instruments, principles and algorithms have been developed for (a) calibration of noise sources, (b) noise measurement of electrical and *optical* receivers, and (c) measurement of transistor noise parameters. The feasibility of our measurement methods is demonstrated in practice.

Feedback design

Parasitic effects degrade the dominant behavior of feedback loops. Characterization supplies the parameters for analyzing this degradation, e.g. in a circuit simulator. Adequate compensation networks can minimize this degradation. There is, however, in general no all-embracing answer to the question of how to design these compensation networks, particularly not in combination with harmful parasitics.

This thesis study resulted in robust algorithms for predicting the frequency response of these compensation networks, in terms of poles and zeros. These algorithms are suitable for implementation in (future) circuit simulators. Realistic examples up to 3 GHz demonstrate the effectiveness of our approach.

An integrated approach

All of these methods and tools have contributed to a closer integration of the fields of analog electronics and microwave techniques. The need for an integrated approach to characterization and design finds its origin in the fact that well-known suppression methods of parasitic effects become ineffective in the case of wide bandwidths. It required an in-depth *return to the basics* to combine various methods.

We have carried out an in-depth study of wideband lightwave receivers, resulting in various low-noise receivers using discrete 'low-cost' components. Overall feedback loops spanning two and even three amplifier stages, have been realized with bandwidths exceeding 1 GHz. The applicability of the methods proposed in this thesis have hereby been proven in practice.

(328 pages)

Summary in Dutch

Het ontwerpen van breedbandige versterkers tot op de rand van hetgeen fysisch haalbaar is vereist een radicale verandering van aanpak. De optelsom van alle kleine onvolkomenheden in individuele componenten veroorzaakt vaak een dramatische reductie van de totale kwaliteit. Deze onvolkomenheden (parasiteiten) dienen vanaf het eerste begin volledig in rekening gebracht te worden; dus zeker niet marginaal zoals meestal gedaan wordt.

Dit proefschrift introduceert innovatieve methoden en gereedschappen om *hogere-orde* tekenkoppeling in praktijk te brengen, dus over meerdere versterker trappen tegelijk, onder invloed van hinderlijke parasieten. Veel aandacht is besteed aan (1) formele beschrijvingen van overdracht, tegenkoppeling en ruis, (2) karakterisatie methoden van componenten en sub-circuits, en (3) ontwerp methoden voor compensatie netwerken in tegenkoppellussen.

Formele beschrijving van overdracht, tegenkoppeling en ruis

De formele beschrijvingen leveren ondubbelzinnige definities op van (a) multipoort y -, z - en s -parameters, (b) superpositie parameters van tegenkoppellussen, waaronder lusversterking en apertuur, (c) ruispectra en (d) ruisparameters. Signaal representaties, in termen van spanningen, stromen en golven zijn simultaan besproken.

Het concept van virtuele circuits is geformaliseerd voor zowel overdracht als ruis om parameter extractie van transistormodellen te vereenvoudigen. Algoritmen zijn ontwikkeld voor het analyseren van overdracht- en ruiseigenschappen van willekeurige lineaire netwerken. Zo laten we bijvoorbeeld zien hoe thermische ruisniveaus in multipoort netwerken berekend kunnen worden uit overdrachtsmetingen.

Karakterisatie van overdracht

Karakterisatie maakt het mogelijk parasitaire effecten te kwantificeren in termen van (a) multipoort overdrachts parameters, (b) equivalente circuit modellen, en (c) polen en nulpunten. Dit proefschrift beschrijft methoden voor het meten van deze parameters tussen goed gedefinieerde referentievlakken. Een gestructureerde methode is besproken voor het opsporen van relevante parasieten op basis van deze meetmethoden (circuit stripping).

Er zijn algoritmen ontwikkeld voor (a) het extraheren van polen en nulpunten uit overdrachtsfuncties, en (b) voor het reconstrueren van equivalente circuit modellen uit volledige een- of tweepoort metingen. Deze algoritmen laten zien dat een goede (lineaire) modelering van transistoren niet noodzakelijk resulteert in exotische en gecompliceerde transistor modellen. Deze aanpak heeft bijvoorbeeld een nieuw (klein-signaal) bipolair transistor model opgeleverd, dat veel beter geschikt is voor breedbandige analyse en synthese dan het bekende hybride-II model.

Karakterisatie van ruis

De ontwikkeling van een nieuw instrument, een *synthetische ruisgenerator*, heeft de toepassing van nieuwe ruiskarakterisatie methoden mogelijk gemaakt. Onze bron genereert witte ruis op basis van *optische* principes, en heeft vele voordelen ten opzichte van conventionele 50 Ω ruisbronnen. Zo is de ruisbandbreedte van deze bron eenvoudig te variëren, tot meer dan 10 GHz bandbreedte (vele honderden GHz zijn mogelijk).

Nieuwe instrumenten, principes en algoritmen zijn ontwikkeld voor (a) het calibreren van ruisbronnen, (b) ruismetingen aan elektrische en *optische* ontvangers, en (c) het meten van transistor ruisparameters. De toepassing van onze meetmethoden is in de praktijk getoetst.

Ontwerp van tegenkoppelingen

Parasitaire effecten degraderen het dominante gedrag van tegenkoppelingen. Karakterisatie levert de parameters voor het analyseren van deze degradatie, bijvoorbeeld met een circuitsimulator. Goede compensatie netwerken kunnen deze degradatie minimaliseren. Er bestaat echter geen alomvattend antwoord op de vraag hoe deze compensatie netwerken ontworpen moeten worden, met name niet in combinatie met hinderlijke parasieten.

Dit promotieonderzoek heeft robuuste algoritmen voortgebracht voor het voorspellen van de frequentiecarakteristiek van compensatie netwerken, in termen van polen en nulpunten. Deze algoritmen zijn geschikt voor implementatie in (toekomstige) circuitsimulators. Realistische voorbeelden tot 3 GHz tonen de kracht van onze aanpak aan.

Een geïntegreerde aanpak

Al deze methoden en gereedschappen hebben de vakgebieden van analoge elektronica en microgolfttechniek dichter bij elkaar gebracht. De noodzaak van een geïntegreerde aanpak van karakteriseren en ontwerpen komt voort uit het feit dat bekende onderdrukings principes van parasitaire effecten tekort schieten bij het ontwerpen van zeer breedbandige schakelingen. Het vereiste een grondige *terug-naar-het-begin* aanpak om verschillende methoden te kunnen combineren.

We hebben veel onderzoek verricht naar breedbandige optische ontvangers, hetgeen geresulteerd heeft in verschillende ontvangers op basis van goedkope discrete componenten. Algehele tegenkoppeling, over twee tot drie versterkertrappen tegelijk, is gerealiseerd voor bandbreedtes tot voorbij 1 GHz. De methoden die ontwikkeld zijn in het kader van dit proefschrift hebben zich hiermee in de praktijk bewezen.

(328 pagina's)

