## Chapter 1

# Introduction

## 1.1. Context of this thesis

Fiber optic telecommunication systems have been shown to be suitable for the transport of data rates exceeding 10 Gb/s (gigabits per second) over a single fiber. These bit rates are feasible when transported in several parallel streams through multichannel systems[1], or truly sequentially through single channel systems[2] using ultra fast opto-electronic components.

The relevance of particular system performance specifications, such as bandwidth, sensitivity and distortion, is of course application dependent.

- Bandwidth is a measure for transport capacity. Bandwidth is applicable in (1) trunk lines (point to point links) for the transport of high volumes of data and in (2) networks where the medium must be shared[3] by multiple users, nodes and/or subscribers.
- Sensitivity is a measure for the maximum distance that can be bridged in a trunk line or the maximum number of subscribers that can be simultaneously connected to passive optical networks [103].
- Link distortion leads to intermodulation that limits the performance and the number of TV-channels in analog lightwave video links [106]. In digital links, distortion deteriorates the bit error rate and burst-performance of the system [108].

System performance requirements set high demands on lightwave transmitters and receivers. In subscriber networks, the use of expensive exotic components for meeting performance requirements is viable only on the local exchange side. This is because investments at this side of the network are shared with multiple subscribers. On the other hand, the costs on the subscriber side of the lightwave network are decisive for the economical viability of the network. This justifies the in-depth investigation of low-cost lightwave receiver and transmitter realizations, while optimizing performance [101].

Improved performance, realized using low-cost technology, increases the economical feasibility of lightwave subscriber networks. This can be illustrated as follows.

- Similar performance, realized with cheaper components, reduces overall system cost.
- Increasing sensitivity while maintaining system cost increases the number of subscribers that can be simultaneously connected to passive optical networks, This better shares system investments.
- Increasing bandwidth while maintaining equal cost reduces the number of lightwave channels (fibers or wavelengths) needed to fulfill system transport capacity

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[1] As in wavelength division multiplex systems (WDM) or in coherent systems [105,107].

[2] As in direct detection systems [102].

[3] Electrical and optical ATM networks (asynchronous transfer mode) are examples of networks sharing transport capacity [104].

requirements. This increases access to sophisticated services for the majority of users.

The tools and methods described in this manuscript facilitate the design of wideband amplifiers with optimal performance. Although the examples are focused on lightwave receiver design, and the design examples are realized using discrete components mounted on low-cost glass-epoxy prints, the methods and tools are more widely applicable.

## 1.2. State of the art

The present trend in lightwave transmission systems to increasingly broader bandwidths places unique demands on the design and realization of the associated electronics. The symbiotic melding of techniques, drawn from traditional analog electronics as well as microwave circuits, forms the primary terrain of this study. It resulted in a new field we have chosen to call *wideband*[4] *electronics*.

A seamless integration of analog and microwave electronics is not as simple as one might expect since both disciplines use different approaches. In practice, microwave engineers and analog electronic engineers speak different 'languages'. Recent developments, however, in automated (vector) network analyzers and microwave circuit simulators have significantly simplified this integration, stimulated by the present trend in lightwave transmission systems.

This section provides a short overview of these fields and discusses state-of-the-art aspects of wideband characterization and feedback design.

### *1.2.1. Evolution of various fields of study*

The problems attendant to the development of large scale telephone links in the 1920's stimulated the systematic study of electronic systems. Voltage, current, and wave concepts, as well as circuit theory, transmission line theory and feedback theory, are all known aspects of electronic design. The complexity of electronic application led to the rise of many different fields of study, focusing on specialized topics. Examples are analog electronics, microwave electronics, circuit simulation, opto-electronics, etc.

Since an exact definition of each field of study does not exist, this section tends to be descriptive of trends.

***Analog electronics*** forms the basis for many aspects of electronic design. This discipline has affinity with the type of analog circuits used in various audio and video applications. Analog engineers are well acquainted with feedback loops at the circuit level.

The in-depth study of feedback amplifiers, first introduced in 1934 by Black [401], has resulted in a variety of basic feedback theories. These theories include the general feedback theory of Bode [403], developments in the early 1950's of root-locus analysis

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[4] The words *wideband* and *broadband* are synonymous.

methods[5], compensation of loop stability using phantom zeros [404] in 1961, and the structured design (synthesis) of feedback amplifiers proposed by Nordholt [406] in 1983. Many applications of feedback are focused on frequencies below 100 MHz and share more than a decade in bandwidth. The first column of figure 1.1 shows a survey of characteristic aspects, tools and techniques drawn from practice.

| **analog electronics** | **microwave electronics** |
|---|---|
| ***typical aspects*** | ***typical aspects*** |
| many applications below 100 MHz | many applications above 1 GHz |
| many applications more than a decade bandwidth | many applications within an octave bandwidth |
| many application using feedback | many applications using resonators |
| feedback usually covering several stages | feedback usually avoided |
| voltages and currents preferred | waves preferred |
| Z-, Y-, H-parameters often used | S-, T-parameters often used |
| sources with zero or infinite impedances | sources with matched impedances |
| lumped[6] elements preferred | distributed[7] elements often used |
| ***powerful tools and techniques*** | ***powerful tools and techniques*** |
| circuit simulator Spice/Pspice/.... | Touchstone/Libra/MDS/SuperCompact |
| structured synthesis of feedback amplifiers | network analyzer |
| pole-zero patterns | stability circles in Smith charts |
| root-locus analysis | measurements relative to reference planes |
| | full two-port transfer parameter analysis |
| | full two-port noise parameter analysis |
| | microstrip and stripline print layout |

***Fig 1.1*** *Some typical aspects of analog and microwave electronics. Both disciplines are well-acquainted with ABCD parameters.*

***Microwave electronics*** is a specialized discipline, having its origin in the application of extraordinarily high frequencies. A different type of engineering was required to handle these frequencies. The invention of the radar just prior to World-War II was based on the application of resonance techniques and power matching.

Powerful design concepts that are often used in this field are waves related to well-defined reference planes and scattering parameters (s-parameters). The growing interest in microwaves resulted in 1939 in the development of the Smith Chart at Bell Laboratories by Philip Smith. In the years 1942 to 1946 a rather intensive and systematic exploitation of microwave problems was carried out at the Radiation Laboratory of MIT. In the years 1946-1952 these studies led to a series of 28 volumes dealing with microwave and related techniques, including [203,204].

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[5] Although loop gain variation is most widely used in root-locus analysis, there is no good criterion for selecting this parameter for the best available choice. Variation of circuit element values (pole-zero position diagrams) is another possibility.

[6] A *lumped* element is an element, so small that wave propagation effects may be ignored. It is modeled as if it has zero 'volume'.

[7] A *distributed* element is an element in which wave propagation effects cannot be ignored. An example is a transmission line. The volume of distributed elements cannot be ignored with respect to the wavelength of interest.

The increasing application of s-parameters prompted Deschamps [212] for development of a graphical method for the extraction of s-parameters from reflection measurement data. In 1965, Kurokawa [210,211] published a generalized s-parameter theory and two years later the first automatic network analyzer [213,214] was introduced for directly measuring two-port s-parameters. This seminal design remained in production for about twenty years. In the 1980's the popularity of s-parameters increased because of the appearance of new network analyzers which performed s-parameter measurements with ease.

Many microwave applications are focused on frequencies above 1 GHz, and are concentrated in octave bandwidths. Although *absolute bandwidths* may exceed several GHz, *relative bandwidths* in most applications are quite small.

The second column of figure 1.1 surveys microwave aspects, tools and techniques drawn from practice.

***Circuit simulators*** have been developed for specific analog electronic applications as well as specific microwave applications. Since the mid-1970's a number of computer programs for circuit simulation have become commercially available. The SPICE family [127] with many members [407] is probably the most well-known family of simulators. This family supports linear analysis as well as non-linear analysis using time-domain analysis. The analysis is based on equivalent circuit models of semiconductor devices [303]. Recent developments in symbolic circuit simulators enable automated design of analog integrated circuits [511,513].

Microwave applications require another approach. In general, models tend to fail when the frequency of interest increases, due to unknown parasitic effects. The development of simulators combining device models with device measurements (s-parameters in tabular form) resulted in typical microwave simulators. Examples are Super-Compact/Harmonica, Touchstone/Libra [124,125] and MDS [126].

These commercially available microwave simulators are more powerful than SPICE in that (1) they give full-support to the application of s-parameters in tabular form and distributed elements, and that (2) they facilitate iterative optimization of circuit parameters, guided by user-defined design goals. Harmonic-balance algorithms are used for non-linear steady-state analysis to reduce the overall calculation effort (compared to time domain analysis).

Microwave simulators are equipped with extensive libraries of models of microstrip and stripline elements. These models facilitate the simulation of planar microwave structures. More recently, the development of two- and three-dimensional EM-field solvers has significantly broadened the scope of these in essence physical simulations.

### 1.2.2. State-of-the-art methods for wideband characterization

Over the years, the increasing transition frequency of semiconductor devices has shifted amplifier and lightwave receiver[8] bandwidths beyond 1 GHz. Designing low-noise wideband circuits, for use at high frequencies, requires reliable knowledge of parasitic effects. This holds for transfer as well as noise aspects.

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[8] State-of-the-art examples are lightwave receivers, such as the commercially available HP70810b, ranging from 100kHz–22GHz.

Desired effects as well as parasitics are quantified using techniques which we have chosen to call *characterization*. Characterization starts with measurements on devices or subcircuits, relative to well-defined reference planes (see section 2.1). The required information is subsequently reconstructed from the measurement data by transforming it into a most appropriate form, followed by extraction of the parameters of interest. Examples of these parameters are (1) element values of equivalent circuit models and (2) poles and zeros of equivalent transfer functions (see chapter 3).

This section 1.2.2 considers in short parasitics, high frequencies, and state-of-the-art characterization methods.

### *What are parasitic effects?*

An exact definition of parasitic effects does not exist in our case. It is a collective term for all frequency-dependent effects in a circuit that are undesired by the designer. As a rule of the thumb, all equivalent circuit elements that change a transfer function of interest are parasitic elements when the change is undesired by the designer. Deleterious parasitics are parasitics for which the change in transfer exceeds predefined quality limits.

If parasitic effects are harmful or not, is application dependent. This 'definition' is obvious when parasitics prevent feedback amplifiers from stable operation. In the case that parasitics introduce additional ripple in the overall transfer, the quality requirements of the application determine whether these parasitic effects are harmful or not.

### *What are high frequencies?*

A similar discussion holds for terms such as *low* frequencies, *high* frequencies, *narrowband* and *wideband*. In this study, we relate these concepts to deleterious parasitic effects because most parasitic effects increase with frequency. The various impedance[9] values, the mechanical construction as well as the complexity of a circuit are decisive whether high-frequent aspects play a role or not. For example, a poorly designed print layout may suffer from deleterious parasitics above 1 MHz, while proper redesign may shift this limit to above 100 MHz. In the first example, 10 MHz would then be a 'high' frequency and in the second example a 'low' frequency[10].

In this study, the word *wideband* is reserved for frequency ranges involving high frequencies, that range over more than a *decade*. The word *narrowband* is reserved[11] for frequency ranges less than an *octave*.

### *State-of-the-art transfer characterization*

Two-port transfer measurements, relative to well-defined reference planes, have become relatively simple since modern intelligent microwave network analyzers (mid 1980's) and lightwave component analyzers (early 1990's) have become commercially available

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[9] For instance, a current to voltage conversion using a resistor R is considered to be a low-frequency application for frequencies $\omega \ll 1/(RC)$, in which C denotes a parasitic shunt capacitance. It means that when C=1 pF, the conversion is a high-frequency one above 1 MHz when R=100kΩ. On the other hand, the application is a low-frequency one up to 1 GHz when R=100 Ω

[10] Some microwave engineers refer in waveguide applications to all signals below 1 GHz as "dc", since it is simple to transport them via wires. This illustrates how relative the notions "low" and "high" frequency are.

[11] In classical microwave applications, bandwidth of more than say 20% of the center frequency are usually referred to as *wideband*. This illustrates how relative the notions "narrowband" and "wideband" are.

and. They cover a wide range of frequencies. Network analyzers usually measure two-port parameters in terms of s-parameters.

Currently, many manufacturers are specifying their semiconductor devices on the basis of s-parameter measurements. An increasing number of manufacturers provide SPICE parameter sets as well. They represent the parameters of equivalent transistor models, applicable in SPICE family of circuits simulators.

A variety of similar transistor models for circuit *analysis* are described in the literature. In general, these models are inconvenient for circuit *synthesis*[12]. The complexity of synthesis forces the use of models that are *as simple as possible*. It requires models with a minimum number of parameters, yet still adequate over the full frequency band of interest.

Prior to this study, a structured method for extracting these synthesis models was lacking. Our techniques for transforming measured s-parameters into more dedicated formats (see chapter 2, virtual circuit parameters) and pole-zero techniques (see chapter 3) have proven to be successful in practice for this purpose.

> *This work introduces general methods for extracting a minimum number of poles, zeros and model parameters from device measurement.*

***State-of-the-art noise characterization***

The ease of transfer measurements, relative to well-defined reference planes, does not hold for similar two-port noise measurements.

Currently, instruments for measuring (electrical) input noise level under matched impedance conditions are commercially available covering a wide range of frequencies. Some setups for full two-port (electrical) noise measurements are commercially available, however they focus on the microwave frequency band. Prior to this study, instruments for reliable optical noise measurements on lightwave receivers were lacking. For this reason, our study of noise characterization was mainly focused on the measurement of noise. Noise modeling and low noise design aspects are not discussed in great detail.

> *This work introduces an innovative lightwave noise source and various calibration and measurement methods for input noise measurements on lightwave receivers and two-port noise measurements on electrical amplifiers.*

### 1.2.3. State-of-the-art methods for wideband feedback design

Feedback loops facilitate the stabilization of gain in amplifiers over several frequency decades. The greater the bandwidth, or the number of cascaded amplifier stages covered by a single loop, the more effective this stabilization may be. On the other hand, deleterious parasitic effects prevent the circuit from proper operation, especially when designing higher order feedback loops for high frequencies. These obstacles make wideband feedback design complicated and a specialist discipline.

This section 1.2.3 considers higher order feedback loops, and state-of-the-art feedback design methods.

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[12] The purpose of analysis is to find the properties of an extant circuit. Circuit simulations as well as measurements are adequate methods. The purpose of synthesis is to find a circuit that meets a set of pre-defined conditions. This is the reverse problem.

***What are higher order feedback loops?***

Feedback enables the stabilization of gain by using passive linear components, to improve the overall transfer function. The more amplifying stages are covered by an overall feedback loop, the more effective this stabilization will be.

The order of a feedback loop equals the dominant transfer order of the loop gain. The more amplifying stages in the loop, the higher the feedback order is, and the more complicated the design will be to ensure stable operation of the loop. Therefore the loop order in wideband circuits is in practice kept as low as possible, usually covering a single amplifying stage. To simplify matters, feedback loops can be divided into first-order and higher-order loops.

- *First-order feedback loops* are simple in nature and usually cover one stage (local feedback). A stage can be a single transistor or a transistor decoupled by a common-base (gate) configuration[13]. This approach minimizes the transfer order of the loopgain and avoids the need for compensation. Therefore, ultra wideband first-order loops have been reported for lightwave receivers exceeding 10 GHz in bandwidth. An example is a 14 GHz (monolithic integrated) lightwave receiver [815], using local transimpedance feedback.
- *Higher-order feedback loops* require adequate compensation networks to prevent oscillatory behavior. They are fed back covering more than one amplifier stage (overall feedback), in which the gain of each individual stage is maximized by avoiding local feedback. The application of these loops is usually restricted to frequencies below 100 MHz. The wider the bandwidth of interest, the more the overall stability must rely on adequate compensation and the more sophisticated the loop will be.

Using higher-order feedback loops is advantageous because well-implemented loops improve the flatness and the linearity of the overall transfer function.

***State-of-the-art feedback design***

The use of higher order feedback loops places high demands on the circuit design. Therefore, many-ultra wideband receivers use no feedback at all, and rely on an established microwave approach based on carefully designed resonators and matching networks.

The use of higher-order feedback loops is a typical analog electronic design gambit. Nordholt [406], inspired by the work of Cherry and Hooper [405], developed a systematic and straightforward synthesis method to design amplifiers using higher-order feedback loops. It is a hierarchical design method, in which the overall circuit is developed in a series of design steps.

One aspect of this synthesis is that it suppresses deleterious parasitic effects introduced by additional circuitry, such as cascoded[14] amplifier stages or long-tailed[15] transistor pairs (active de-coupling). The advantage of this technique is that the designer may use

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[13] In general, a cascode stage neutralizes the parasitic 'Miller' capacitance, compared with a single transistor stage. It has inverted gain. A long-tailed pair is a transistor pair that has similar performance and non-inverted gain.

[14] A cascode configuration is a cascade of a CE - CB configuration (common Emitter, common Base).

[15] A long tailed pair a cascade of a CC - CB configuration (common Collector, common Base). In differential applications it is also called a balanced transistor pair.

simplified models for the individual circuit devices, to handle the complexity of the overall synthesis.

The above design approach is very effective for relatively low frequencies[16], up to say 1% of the transition frequency $f_T$ of the amplifying devices. Designers, well-skilled in the art, may even apply this approach for significantly higher frequencies, up to perhaps 10% of $f_T$. The influence of parasitics on the signal flowing through the individual devices, nevertheless, limits the designability of the overall feedback loop. This is because active decoupling tends to fail in wideband feedback loops, for instance, due to secondary parasitics introduced by the active decoupling circuits.

Many higher-order feedback amplifiers have been developed successfully for frequencies below 10 MHz using Nordholt's method. Higher-order feedback realizations exceeding 100 MHz in frequency are much less prevalent. Nevertheless, third order loops covering 500 MHz in bandwidth and second order loops exceeding 1 GHz in bandwidth are applicable, as is demonstrated in chapter 6.

### *Improved feedback analysis*

In general, the complexity of the overall design increases with frequency, so that it is a serious challenge to design *higher-order* feedback loops for multi-GHz amplifiers, in the presence of dominant parasitics. Microwave circuit simulators simplify the analysis of wideband circuits. They give full-support to the application of s-parameters and distributed elements, for analyzing the deterioration of overall performance by parasitic effects. However, full support for pole-zero analysis of loop gain and other superposition parameters (see chapter 4) is lacking in current microwave simulators. Additional analysis tools for the *synthesis* of wideband feedback circuits have been developed in the course of this study.

> *This work introduces various supplementary algorithms for (future) circuit simulators to analyze feedback loops in terms of superposition parameters and root locus plots.*

### *Improved feedback synthesis*

Nordholt's synthesis provides powerful methods for compensating feedback loops, in the case of unstability. When parasitics are dominant and their suppression using active decoupling fails, Nordholt's compensation synthesis may fail.

Prior to this study, the question of dealing with dominant parasitic effects in feedback loops, was an unanswered one. Computer assisted synthesis methods for the design of higher-order wideband feedback loops, in the presence of deleterious parasitics, are dealt with in depth in chapter 5.

> *This work introduces an innovative synthesis algorithm to synthesize the transfer function of compensating networks required for stable feedback loops.*

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[16] When designing amplifiers using transistors with 5 GHz transition frequency, 1% means 50 MHz bandwidth, and 10% means 500 MHz amplifier bandwidth.

## 1.3. Essentials of this thesis: *back to basics*

The design of wideband amplifiers with ultimate performance required a radical change of approach. The cumulation of all minor imperfections of individual devices often cause a dramatically reduction of the overall performance.
These imperfections (parasitics) had to be taken into account from the very beginning; so definitely not marginally as it is commonly done. This required an in-depth *return to the basics* to enable an *integrated approach* to characterization and design. It resulted in profound formal descriptions of transfer, feedback and noise.

Of particular importance is the emphasis on full *characterization* of devices and subcircuits. Measurements aren't just used for verifying performance when circuit design has completed. They form an integral part of the overall design procedure and are important for quantifying parasitics. These parasitics are identified by extraction from wideband full two-port measurements. This study has led to a variety of characterization methods for transfer as well as noise.

Of equal importance is the computer assisted *design* of feedback loops, taking full account of the parasitics. State-of-the-art design methods are applicable to the synthesis of an initial design from scratch. *Supplementary* to the methods of Nordholt [406], our algorithms provide, in the presence of dominant parasitics, the transfer functions of compensation networks required for stable feedback operation.

### *1.3.1. Characterization*

Back to basics meant in practice that most of this thesis is focused on *characterization*. Transfer measurements are discussed and demonstrated with devices mounted on standard printed circuit boards. For noise characterization (electrical and optical), a promising lightwave noise source has been developed, including innovative test setups and measurement protocols. New methods and algorithms are introduced for parameter extraction from transfer and noise measurements.
This work has dealt with various obstacles to state-of-the-art characterization:

- The use of formal descriptions of transfer, feedback and noise brought to light that often used concepts are ambiguous, mixed up, or restricted to limited conditions.
  Chapters 2, 4 and 7 provide unambiguous definitions, discuss voltages, currents and waves simultaneously, and describe the relationship between various equivalent parameter representations.
- The transfer measurements used have clearly demonstrated that commonly used hybrid-Π transistor models tend to fail above 10% of the transition frequency. This in turn has led to questions concerning the validity of the diffusion capacity concept in these models.
  Chapter 3, discusses extraction methods leading to more suitable transistor models. They demonstrate that adequate (linear) modeling of transistors does not necessarily result in exotic and complicated transistor models.
- Our noise measurements have confirmed how tricky it is to carry out meaningful noise measurements. Noise levels may in practice be as much as 5.5 dB too low: 2~2.5 dB when spectral measurements are only corrected for resolution bandwidth

effects and another 3 dB when double sided intensity spectra are measured without further notice. These are serious pitfalls because many publications on noise performance of lightwave receivers do not properly specify *what* noise quantity is measured and *how* its value is reconstructed from measurements. Universally accepted conventions on these topics are lacking.

Chapter 8 introduces innovative measurement methods for noise, based on the lightwave noise source discussed in chapter 9. These methods make feasible the development of simple and yet reliable noise models of semiconductor devices.

### 1.3.2. Feedback design

The hierarchical design method of Nordholt [406] follows a *top-down* approach. When parasitics are adequately suppressed by active decoupling, idealized block diagrams (superposition model) are adequate for describing transfer and noise performance of amplifiers.

This top-down approach is very effective in the initial design phase, although it may fail when active decoupling fails. These are typical obstacles when designing feedback amplifiers exceeding $f_T/100$ or $f_T/10$ in bandwidth. In general, designers get into trouble when suppression of parasitics becomes ineffective. The established approach is: keep it simple, avoid higher order feedback loops, use superior technology and accept limited performance.

We propose an additional *bottom-up* approach to handle higher order feedback loops when active decoupling fails. The resulting iterative improvement of the design, is illustrated in figure 1.2.

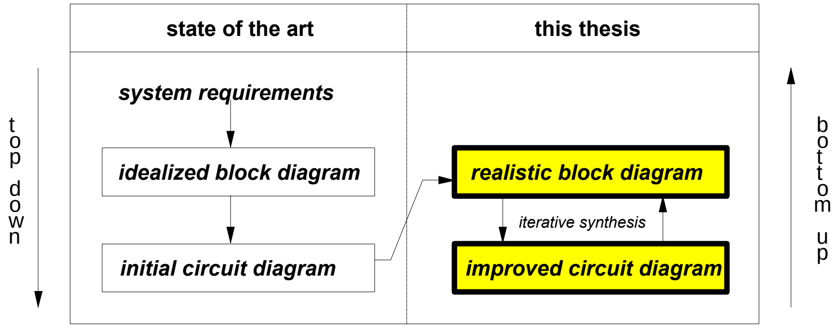

***Fig 1.2*** *A top-down design approach, using parameters of idealized block diagrams, is effective in the initial design phase. In wideband amplifiers, parasitics are harmful and require an additional iterative approach. In this approach, the parameters of realistic block diagrams are extracted from measurements and simulations, and used to improve the design.*

This study resulted in computer algorithms for extracting the parameters of a block diagram (superposition model) from first-try designed circuit diagrams. Parasitics are fully taken into account increasing the accuracy of extracted parameters.

These parameters are supplied to another algorithm that analyzes the loop stability and calculates the transfer function (in terms of poles and zeros) of adequate compensation networks. This is valuable information for designers, who can use this to improve their initial design.
Our approach is required when circuit analysis indicates that the overall circuit performance significantly deviates from using ideal block diagrams. Possible conditions include: oscillations, ringing, ripple, smaller bandwidths or higher noise levels.

### 1.3.3. Overall structure

This work is divided roughly in two parts: chapters 2 to 5 deal with various transfer aspects and chapters 7 to 9 with noise. Chapter 6 considers the application of our approach to the design of lightwave receivers, linking in effect the two parts.

*(A) Transfer characterization and feedback design*:

- Chapter 2 starts with a formal description of electronic networks in terms of two-ports and multi-ports, and discusses appropriated measurement methods.
- Chapter 3 introduces innovative algorithms for extracting parameter sets of device models from two-port measurements using *poles and zero* techniques. This has led to an improved linear model for the bipolar junction transistor; simple and yet applicable up to the transition frequency $f_T$.
- Chapter 4 introduces algorithms for extraction of the *superposition parameters* in the presence of parasitic effects. The associated superposition model provides a realistic block diagram for the analysis of feedback amplifiers.

  Various algorithms are introduced in chapter 4 for evaluating the loop gain of feedback amplifiers, to represent them by pole-zero descriptions and to simplify this description to the dominant form.
- Chapter 5 discusses compensation methods for neutralizing dominant poles and zeros in feedback loops. This chapter introduces a powerful algorithm for the synthesis of compensation networks, in terms of poles and zeros.
- Chapter 6 illustrates the application of the tools of this study in the support of lightwave receiver design. These receivers have been constructed using second order feedback loops yielding bandwidths in excess of 1 GHz, and using third order feedback loops (500 MHz). This chapter discusses the discrepancy between measured and simulated receiver noise to illustrate the importance of reliable characterization of noisy devices.

*(B) Noise characterization:*

- Chapter 7 discusses the formal description of noisy devices in terms of two-port and multi-port noise parameters. This chapter relates *matrix noise parameters* (convenient for noise analysis) with *spot noise parameters* (commonly used to specify semiconductor devices) and introduces *autonomous noise parameters* (convenient for evaluating device models). Calculation methods and generalized methods for evaluating thermal noise in passive networks are discussed in detail.
- Chapter 8 introduces new methods for measuring electrical noise using lightwave principles. This chapter demonstrates the superior performance of our *noise-tee* compared to conventional 50Ω noise sources, and discusses methods for calibrating

the associated lightwave noise source. Methods for measuring lightwave receiver noise and measuring two-port noise parameters are demonstrated.

- Chapter 9 introduces the *lightwave synthetic noise source*, a new instrument for generating white electrical noise to support the measurement methods of chapter 8. One of the advantages of this lightwave source is that the noise is concentrated in a user definable bandwidth (ranging from tens of MHz to hundreds of GHz). This prevents overload problems to the device under test.

## 1.4. Spin-off of this thesis

The pole-zero extraction tools that have been developed in this study are more widely applicable than the field of wideband electronics. The transfer function of any (linearized) physical process can be reconstructed from measured data using these tools. In addition, our compensation algorithms yield poles and zeros that are applicable for controlling the stability of any linear feedback process.

Currently, our study has resulted in (1) high performance lightwave receivers, (2) a design environment, and (3) several acoustic applications.

### *1.4.1. High performance lightwave receivers*

This study resulted in various lightwave receivers using current-current feedback. Their advantages and performance are discussed in chapter 6.

We were the first to propose this feedback principle for wideband receiver design [608], and demonstrated the applicability of this concept for frequencies exceeding 1 GHz. Applications have been found in various lightwave transmission experiments, including the European projects ESPRIT 2054 (UCOL), RACE 2024 (BAF [108]) and PTT-Research projects such as COSNET [107].

Focusing on the ultimate performance of these receivers yielded the understanding that wideband synthesis must be based on sophisticated measurement techniques and powerful computer algorithms. This has resulted in tools and concepts that are more widely applicable than lightwave receiver design.

***The application of lightwave receivers using discrete components***

All design examples in this work are restricted to discrete components mounted on low-cost glass-epoxy printed circuit boards (PCB's). Integrated circuit solutions or thin film solutions have not been investigated, although our design theories and tools can also be applied to these technologies.

The wide bandwidth results of our receivers illustrate that it is not mandatory to use chip technology when designing wideband high-performance circuits. Nevertheless, significant improvements in performance are to be expected when using thin-film technology in combination with chip technology. This holds in particular when choosing a foundry processes with the highest $f_T$ available.

When bandwidth demands are fulfilled, low-cost aspects may be an argument for using chip technology. We note that it is, however, not so obvious that chip-technology is always pre-eminently suited for low-cost wideband applications. This is best illustrated as follows:

- Discrete SMD[17] components have been optimized for reduced costs when circuits are produced in high volumes. Consumer electronics, in fact, frequently uses discrete components in combination with ASIC's.
- Furthermore, discrete technology enables the combination of widely differing devices, such as GaAs FET's with PNP *and* NPN Si-BJT's. Therefore, a designer can take full advantage of this benefit and can combine the most suitable devices.

It is perhaps indicative that, as we enter the last quarter of 1994, fully integrated low-cost lightwave receivers are still commercially unattractive when compared with receivers using discrete technology. Commercially available monolithic transimpedance amplifiers (>1 GHz) are currently intended for use with photo diodes with relatively low capacitance (~0.3 pF). The price of these diodes ($\lambda$ = 1300-1500 nm) is often indicative for the price of the overall receiver. Our 1 GHz current-current feedback receivers enable the use of low-cost photo diodes with relatively high capacitance (~1.5 pF).

Moreover, state-of-the-art television tuners are produced in high volumes, and most of them use many discrete components. The above discussion indicates that discrete components and chips are competitive technologies when designing 1 GHz lightwave receivers. Therefore, restricting our use to discrete components is a realistic one, although we do not wish to exclude other technologies.

### 1.4.2. SABEL-CAE design environment

The algorithms proposed in this work are implemented in software and tested using actual measured data. From the very beginning of this study (1985) we realized the importance of linking measurement instruments with simulation software. Over the years, we realized the SABEL-CAE[18] design environment [111].

A complete discussion of this environment is beyond the scope of this text. Some hardware aspects of this environment are shown in figure 1.3. This short overview is, furthermore, restricted to the description of self-made elements:

- *Copydata* is a Pascal program [111] for data acquisition. It links various instruments with a PC and provides the data in various file formats. It supports file formats, for signal processing with Matlab©[123], for linear circuit analysis with Touchstone© [124] and for non-linear circuit analysis with Libra©[125]. These three commercially available software tools are embedded in the design environment.
- *Locus* is a Pascal program for VAX-VMS to facilitate our study on feedback loops. Feedback analysis is discussed in chapter 4 and feedback synthesis in 5. The software facilitates (1) analytical circuit analysis for calculating poles and zeros, (2) pole-zero extraction from measured data using a mix of Marquardt iteration, and Gauss-Newton iteration, and (3) root-locus analysis for feedback systems. [113,114,115,116,117,118]
- Most algorithms described in this text are implemented as Matlab© applications (a fourth generation mathematical computer language). This has resulted in an extensive collection of general purpose data processing tools: the microwave toolbox *MW-tools*. [112]

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[17] SMD = surface mounted devices.

[18] SABEL-CAE = Synthesis and Analysis of Broadband Electronics using Computer Assisted Engineering

- The lightwave *noise testset* is an instrument that has evolved from our study on minimizing noise in lightwave receivers. Noise measurements are discussed in detail in chapter 8 and 9.

For more information on this environment see [101,109,111] and various related internal reports (see [111] for a complete overview).

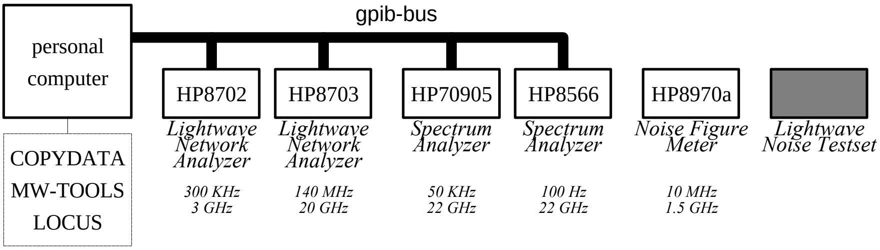

***Fig 1.3*** *Hardware part of the SABEL-CAE design environment.*

### *1.4.3. Microwave concepts applied to acoustic applications*

One of the basic concepts in this work is a blackbox description of devices and sub-circuits when adequate equivalent models are not available. This approach is not restricted to electrical application and is also applicable to a variety of other technical disciplines.

For instance, we have introduced two-ports and s-parameter concepts in acoustics [119], which can be regarded as a spin-off of this work. Furthermore, we have developed an *acoustic* network analyzer [120] and applied microwave calibration techniques to it [121,122]. The acoustic equivalent of shorts, opens and loads are respectively (1) pipes with covers, (2) open pipes and (3) pipes with absorbers.

We applied microwave measurement techniques to measure *acoustic* transmission in ducts (pipes). These methods were previously unknown in acoustics. Microwave simulators, such as Touchstone©[124], have proven to be valuable in designing matching networks in acoustical oscillators. Microwave matching techniques and microwave circuit simulators (linear or non-linear) have successfully used for designing thermo-acoustic energy converters. Other possible applications are acoustical filters in air conditioning systems, and exhaust systems for combustion engines.

This illustrates the power of an interdisciplinary design approach.

## 1.5. Publications and patents resulting from this work

***Patent applications***

[803] R.F.M. van den **Brink**: *Method for lightwave noise measurements*. Patent application, Europe: EP-0522614, USA, June 1991.

[901] R.F.M. van den **Brink**: *Lightwave noise source*. Patent application, The Netherlands: NL-9300347, Feb 1993.

***International publications (electronics)***

[608] R.F.M. van den **Brink**: *Optical receiver with third-order capacitive current-current feedback*, Electronics Letters, vol 24 no. 16, pp 1024-1025, Aug 1988.

[801] R.F.M. van den **Brink**, E.**Drijver**, M.O van **Deventer**: *Novel noise measurement setup with high dynamic range for optical receivers*, Electronics Letters, vol 28 no. 7, pp 629-630, March 1992.

[802] R.F.M. van den **Brink**: *Novel electrical noise source based on lightwave components*, Microwave and Optical technology letters, vol 5 no. 11, pp 549-553, Oct 1992.

[902] R.F.M. van den **Brink**,: *Improved lightwave synthetic noise generator using noise injection and triangular modulation*. IEEE Photonics technology letters, vol 6, no 4, pp579-582, April 1994.

[108] C.M. de **Blok**, R.F.M. van den **Brink**, M.J.M. van **Vaalen**, P.J.M. **Prinz**: *Fast low-cost feed-forward burst-mode optical receiver for 622 Mb/s*: EFOC & N'93 the Eleventh Annual Conference, June 30, 1993. PTT Research, NT-PU-93-1242.

[107] **Labrujere**, **Deventer**, **Koning**, **Bekooij**, **Tan**, **Roelofsen**, **Lange**, **Boly**, **Berendschot-Aarts**, **Spruit**, **Nielen**, **Brink**, **Blok**, **Bochove**: *COSNET - a coherent optical subscriber network.* IEEE Journal of lightwave techn, vol 11, no 5/6, pp 865-874, May/June 1993.

***International publications (acoustics)***

[119] C.M.de **Blok**, R.F.M. van den **Brink**: *Full characterization of linear acoustic networks based on N-ports and s-parameters.* J. Audio Eng Soc., Vol 40 no. 6, pp 517-522, June 1992.

[120] C.M.de **Blok**, R.F.M. van den **Brink**: *Direct-reading one-port acoustic network analyzer.* J. Audio Eng Soc., Vol 41 no. 4, pp 231-238, April 1993.

[121] R.F.M. van den **Brink**, C.M.de **Blok**: *A one-port acoustic network analyzer with full error correction*. - to be published.

[122] R.F.M. van den **Brink**, C.M.de **Blok**: *Robust calibration methods for one-port acoustic network analyzers with multiple standard reflectors.* - to be published.

***National publications***

[109] R.F.M. van den **Brink**: *The characterization and modelling of opto-electronic devices*, Tijdschrift van het NERG, vol 57 no. 3, pp 103-108 (In Dutch), 1992, PTT-Research internal report NT-PU-92-1206.

[110] R.F.M. van den **Brink**: *Wideband print layout design; analog aspects in designing print layouts for digital circuits.* EMC in theory and practice, Holland Electronica / FME , The Netherlands, June 1993, (in Dutch) ISBN 96-71306-60-7, PTT internal: NT-PU-93-1234

[101] R.F.M. van den **Brink**: *Broadband analogue electronics*. PTT Research Yearbook 1989, Leidschendam the Netherlands

***ESPRIT reports***

[609] P.J.M. **Prinz**, R.F.M. van den **Brink**: *Report of first prototype of 900 MHz optical receiver preamplifier, deliverable 4.23*, PTT-Research, International ESPRIT 2054: UCOL report 938/90, Oct 1990.

[610] R.F.M. van den **Brink**: *Optical receivers with capacitive current-current feedback*, ESPRIT Conference/exhibition, PTT-Research, International ESPRIT 2054: UCOL report 1139/90, Nov 1990.

[612] P.J.M. **Prinz**, R.F.M. van den **Brink**: *Report of prototype of receiver preamplifier without tuning, deliverable 4.24*, PTT-Research, International ESPRIT 2054: UCOL report 483/91, April 1991.

[613] E. **Drijver**, R.F.M. van den **Brink**, H.J.T. van der **Vleut**, P.J.M. **Prinz**: *Report on Tuning, deliverable 4.39*, PTT-Research, International ESPRIT 2054: UCOL report NT-INT-91-1456, Dec 1991.

***PTT Research internal reports***

[606] R.F.M. van den **Brink**: *Noise Optimum of a fibre optic receiver pre-amplifier* PTT-Research, Memorandum 1391 DNL/86, Dec 1986

[607] M.J. van der **Pol**, R.F.M. van den **Brink**: *A wideband optical receiver using third order current-current feedback* (In Dutch), PTT-Research, Memorandum 1526 DNL/87, July 1987.

[111] R.F.M. van den **Brink**: *Handbook SABEL/CAE*. PTT-Research internal report NT-RAP-92-28, Jan 1992 (In Dutch) This is a complete overview of the system and refers to all relevant internal documents

[112] R.F.M. van den **Brink**: *SABEL/CAE: Microwave toolbox, users manual and theoretical backgrounds version 1.0.* PTT-Research internal report NT-ER-91-1298, Dec 1991 (In Dutch)

[113] R.F.M. van den **Brink**: *LOCUS Mathematics on some elementairy polynomial routines*. PTT-Research internal report 1538DNL/87, 1987 (In Dutch)

[114] R. **Robbertsen**, R.F.M. van den **Brink**: *LOCUS Mathematics on iteration routines for multi-variable functions (Levenberg-Marquardt iteration)*. PTT-Research internal report 1727DNL/88. (In Dutch)

[115] R.F.M. van den **Brink**: *LOCUS user's manual version 1.5*, PTT-Research internal report 110RNL/89. 1989 (In Dutch)

[116] T.A. van der **Laan**, R.F.M. van den **Brink**: *LOCUS algorithm for the determination of the frequency response of electrical circuits, in closed analytical form*. PTT-Research internal report 476RNL/89. 1989, (In Dutch)

[117] J.J. van **Wamel**, R.F.M. van den **Brink**: *LOCUS a study to automated compensation*. PTT-Research internal report 830RNL/89. 1989 (In Dutch)

[118] A.J. 't **Jong**, R.F.M. van den **Brink**: *LOCUS Analytical circuit simulation*. PTT-Research internal report 470/91. 1991 (In Dutch)