Preface

Feedback Networks: Theory and Circuit Applications is not an explicit circuit design text, but it is very much a text that forges a foundation for the creative design of electronic circuits and systems. A circuit design initiative that culminates by responding positively to the demanding performance specifications of modern data processing, information transmission, and communication systems is a challenging and often daunting undertaking. The acquisition of design skills is complicated by the curious fact that computational precision is not the primary objective of design-oriented circuit analysis. Rather, the purpose of analyses undertaken in support of a design venture is to gain insights into the theoretic and phenomenological underpinnings of the mathematical solutions for the electrical responses of electronic networks. An insightful understanding is cultivated by solutions — albeit approximate solutions premised on clearly understood engineering presumptions — cast in forms that highlight circuit attributes, limitations, best case operating features, and worst case performance shortfalls. In short, design skills, methodologies, and guidelines are not necessarily nurtured by elegant and mathematically satisfying circuit solutions. They are more likely to derive from approximate circuit solutions that, when properly interpreted in light of given applications, paint an understandable engineering picture of pertinent circuit dynamics. A fundamental objective of this textbook is to paint compelling analytical images that support the innovative design of high frequency and high speed integrated electronics.

Two engineering reasons justify the obvious "feedback" focus of this textbook. The first of these reasons is that feedback signal flow paths are pervasive of all electronic networks. These feedback paths are either purposefully implemented or parasitically incurred and in many active networks destined for high frequency or high speed signal processing applications, both purposeful and parasitic feedback prevails. Included among the numerous advantages of feedback incorporated explicitly as a design vehicle is the realization of electronic circuits and systems exuding broadbanded steady state frequency responses, suitable impedance levels at input and output network ports, and acceptable desensitization of input-to-output transfer characteristics with respect to vagarious circuit elements or active device parameters. When feedback is not overtly adopted, it nonetheless prevails, generally in the form of undesirable capacitive coupling between device terminals or network node pairs, parasitic magnetic coupling between network branches, or unwanted conductive coupling between device terminals. For example, when an impedance is inserted in series with the source lead of a common source amplifier, the transistor channel resistance, which is not very large in deep submicron device technologies, is a bilateral, nonglobal feedback element interconnecting the drain and source terminals of the device. Rarely is parasitic feedback advantageous to circuit design objectives. Indeed, it commonly incurs degradation of the forward signal transmission characteristics, poor transient responses, difficulties in achieving maximum signal power gain, and in extreme cases, outright circuit instability.

A second reason for the expressed focus of this textbook is that the analysis of feedback networks is invariably cumbersome, particularly if attention is directed to high frequency circuit performance. As a result, definitive manual analyses are obviated in favor of only computer-based investigations that may not impart the circuit insights supportive of accurate, reliable, and reproducible circuit design. When manual analyses are executed, their value is often limited by unrealistic approximations and assumptions that either mask requisite insights or produce results that are incapable of mirroring engineering reality. In this textbook, a systematic analysis methodology for feedback electronics (which is actually a superfluous phrase, since feedback is pervasive of all electronics) is developed and ultimately applied to the design-oriented analysis of practical electronic networks. Aside from merely applying the new feedback analysis techniques to the standard cells of analog electronic systems, the new procedure actually facilitates circuit broadbanding innovations, as is demonstrated in the final chapter. In addition to rendering feedback network analysis less daunting and more practical than might be traditionally expected, the new methodology implicitly accounts for the facts that the feedback paths of interest may not be global and that purposefully implemented or parasitically encountered feedback is invariably bilateral in nature.

Feedback Networks: Theory and Circuit Applications is principally an advanced circuits and systems analysis text that forges a strong analytical foundation for more design-intensive analog and mixed signal integrated circuits and systems classes. It teaches students computationally efficient manual methods, complemented by meaningful computer-aided assessment and verification strategies, for analyzing the electrical dynamics of active networks destined for monolithic realization in silicon-germanium (SiGe) heterostructure bipolar, and principally complementary metal-oxide-semiconductor (CMOS) technologies. More than teaching mere analytical problem solving techniques, the text couches analyses in forms that foster the engineering insights underpinning a meaningful characterization and performance assessment of active circuits embedded in high frequency and/or high speed system applications. These insights are fundamental to consistently creative circuit and system design, for they enable realistic comparisons among candidate active devices and among plausible circuit architectures. They are also indispensable to the omnipresent design problem of mitigating the deleterious effects that parasitic energy storage and other high order device and circuit phenomena have on such performance metrics as bandwidth, signal delay in both time and frequency domains, gain and phase margins, phase noise, distortion, and transient step and impulse responses. In short, the formulation of insightful design-oriented analysis strategies commensurate with the realization of modern integrated circuits, and particularly analog high performance integrated circuits and systems, is the primary focus of this work.

This textbook is suitable for use in a senior elective circuits course whose students have successfully completed courses in basic circuit analysis, basic linear systems, and an introductory electronics course featuring exposure to linear electronics exploiting bipolar and MOS technology devices. It can also be used as a graduate level core course for the electronic circuits and systems arena. Students using this textbook should be comfortable with using one of the many available versions of SPICE computer-aided analysis software, such as HSPICE, PSPICE, TOPSPICE, Tanner SPICE, or the circuit analysis tools implicit to the CADENCE design suite.

Chapter 1 on *Circuit and System Fundamentals* offers the student an overview of the basic theoretic concepts traditionally addressed in sophomore and junior level circuits and linear systems classes. Although the issues covered in this chapter should not be foreign to senior and graduate level electrical engineering students, their interpretation in light of a variety of conventional circuit design requirements may comprise new material for neophyte electronic circuit design students. For example, the well-known theorems of Thévenin and Norton are reviewed and thence used directly to define the basic terminal characteristics of the four types of amplifiers encountered in modern electronic systems. Second order circuits are studied thoroughly in both the frequency and the time domains. In a representative graduate electrical engineering class, the instructor may elect to ignore Chapter 1 and proceed directly to Chapter 2. In such an event, the student is nonetheless strongly encouraged to read Chapter 1 and to attempt several of the Exercises at its conclusion to assess his/her ability to utilize fundamental theoretic detail in practical problems.

In Chapter 2 on *Two-Port Network Models and Analysis*, the models and analysis procedures surrounding the four fundamental types of two-port network characterizations are studied in detail. In the course of this study, the underpinnings of circuit feedback are introduced through the introduction of the concepts of open loop and loop gains. Computationally efficient methods of studying interconnections of two-port networks are developed, and power gain in active networks is defined and assessed. The concepts of potential network instability and unconditional network stability are introduced. Chapter 3 on *Scattering Parameters* embellishes the contents of Chapter 2 by considering the scattering parameter characterization of linear two-port networks. These scattering parameters are carefully interpreted and thence applied to the problem of designing lossless filters, which are commonly deployed in both narrowband and wideband electronics earmarked for high frequency communication systems.

Chapters 4, 5, and 6 collectively comprise a reasonably exhaustive treatise on the analysis of feedback networks. Chapter 4 on *Feedback Circuit and System Theory* addresses first order, second order, and multi-order feedback networks from the perspectives, of gain, transfer function sensitivity to critical parameters, bandwidth, gain-bandwidth product, and other performance metrics. Useful expressions for the gain and phase margins of second order networks are propounded, and the problems of overshoot, settling time, and delay time surrounding feedback network responses to transient step and impulsive inputs are thoroughly examined. Chapter 5, which considers *Signal Flow Methods of Feedback Network Analysis*, offers a general, tractable, and insightful method for analyzing both single loop and dual loop feedback amplifiers. The theoretic detail underpinning this analytical method, which embodies the analytical notions of null gain, return ratio, and null return ratio, is applied to the problem of definitively assessing the performance attributes and shortfalls indigenous to several types of traditionally encountered amplifiers. Chapter 6 on *Multiloop Feedback Amplifiers* complements the considerations of Chapter 5 by providing the reader with enhanced mathematical rigor. It also embellishes the dual loop discourse of Chapter 5 by developing a generalized and powerful mathematical technique for analyzing multiloop feedback circuits.

Chapter 7 on *Analog MOS Technology Circuits* exploits the theoretic disclosures proffered in preceding chapters by studying the canonic MOS technology analog cells at both low and high signal frequencies. In advance of these circuit studies, the circuit level models of MOS transistors, inclusive of deep submicron technologies, are studied in reasonably complete detail so that the circuit assessments developed in the chapter can be interpreted in terms device phenomenological issues and monolithic processing constraints. Chapter 8 on *MOS Technology Operational Amplifiers* builds on its predecessor chapter by studying, and developing design methodologies for, single stage and two-stage operational amplifiers destined for utilization in monolithic mixed signal applications.

In Chapter 9, *Broadband and Radio Frequency MOS Technology Amplifiers*, the feedback tools developed earlier are applied to the problem of optimizing amplifier performance at high signal frequencies. The circuit broadbanding schemes addressed include resistance-capacitance degeneration, shunt peaking, multi-order series peaking, and series-shunt peaking. In the course of these discussions, a new broadbanding scheme, premised on the realization of constant resistance compensation filters, is proposed. Impedance matching in tuned radio frequency amplifiers is discussed and critically assessed.

Almost all of the material included in this textbook has been used several times by Prof. Choma in a graduate level core course on electronic circuits at the University of Southern California Viterbi School of Engineering. To this end, the text benefits from the critique and constructive criticisms of many Viterbi School of Engineering graduate students and particularly, those unselfishly offered by Mr. Jonathan Roderick, who is scheduled to complete his electrical engineering doctorate early in 2006. Prof. Choma also wishes to acknowledge the enormous benefits gleaned from numerous technical exchanges he enjoyed with his faculty colleague, Prof. Hossein

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