

TN431.1
L192

9561542

DESIGN OF ANALOG INTEGRATED CIRCUITS AND SYSTEMS

Kenneth R. Laker

University of Pennsylvania

Willy M. C. Sansen

Katholieke Universiteit Leuven

Belgium



E9561542

McGraw-Hill, Inc.

New York St. Louis San Francisco Auckland Bogotá Caracas
Lisbon London Madrid Mexico City Milan Montreal
New Delhi San Juan Singapore Sydney Tokyo Toronto

This book was set in Times Roman by Electronic Technical Publishing Services.
The editors were George T. Hoffman and John M. Morriss;
the production supervisor was Richard A. Ausburn.
The cover was designed by Carla Bauer.
Project supervision was done by Electronic Technical Publishing Services.
Arcata Graphics/Martinsburg was printer and binder.

DESIGN OF ANALOG INTEGRATED CIRCUITS AND SYSTEMS

Copyright © 1994 by McGraw-Hill, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.



This book is printed on recycled, acid-free paper containing a minimum of 50% total recycled fiber with 10% postconsumer de-inked fiber.

1 2 3 4 5 6 7 8 9 0 AGM AGM 9 0 9 8 7 6 5 4

ISBN 0-07-036060-X

Library of Congress Cataloging-in-Publication Data

Laker, Kenneth R., (date).

Design of analog integrated circuits and systems / Kenneth R.

Laker, Willy M. C. Sansen.

p. cm. — (McGraw-Hill series in electrical and computer engineering. Electronics and VLSI circuits)

Includes bibliographical references (p.) and index.

ISBN 0-07-036060-X

1. Linear integrated circuits—Design and construction.

I. Sansen, Willy M. C. II. Title. III. Series.

IN PROCESS

621.3815—dc20

93-49574

**DESIGN OF ANALOG
INTEGRATED CIRCUITS
AND SYSTEMS**

McGraw-Hill Series in Electrical and Computer Engineering

Senior Consulting Editor

Stephen W. Director, Carnegie Mellon University

Circuits and Systems

Communications and Signal Processing

Computer Engineering

Control Theory

Electromagnetics

Electronics and VLSI Circuits

Introductory

Power and Energy

Radar and Antennas

Previous Consulting Editors

Ronald N. Bracewell, Colin Cherry, James F. Gibbons, Willis W. Harman, Hubert Heffner, Edward W. Herold, John G. Linvill, Simon Ramo, Ronald A. Rohrer, Anthony E. Seigman, Charles Susskind, Frederick E. Terman, John G. Truxal, Ernst Weber, and John R. Whinnery

Electronics and VLSI Circuits

Senior Consulting Editor

Stephen W. Director, Carnegie Mellon University

Consulting Editor

Richard C. Jaeger, Auburn University

Colclaser and Diehl-Nagle: *Materials and Devices for Electrical Engineers and Physicists*

DeMicheli: *Synthesis and Optimization of Digital Circuits*

Elliott: *Microolithography: Process Technology for IC Fabrication*

Fabricius: *Introduction to VLSI Design*

Ferendeci: *Physical Foundations of Solid State and Electron Devices*

Fonstad: *Microelectronic Devices and Circuits*

Franco: *Design with Operational Amplifiers and Analog Integrated Circuits*

Geiger, Allen, and Strader: *VLSI Design Techniques for Analog and Digital Circuits*

Grinich and Jackson: *Introduction to Integrated Circuits*

Hodges and Jackson: *Analysis and Design of Digital Integrated Circuits*

Huelsman: *Active and Passive Analog Filter Design: An Introduction*

Ismail and Fiez: *Analog VLSI: Signal and Information Processing*

Laker and Sansen: *Design of Analog Integrated Circuits and Systems*

Long and Butner: *Gallium Arsenide Digital Integrated Circuit Design*

Millman and Grabel: *Microelectronics*

Millman and Halkias: *Integrated Electronics: Analog, Digital Circuits, and Systems*

Millman and Taub: *Pulse, Digital, and Switching Waveforms*

Offen: *VLSI Image Processing*

Roulston: *Bipolar Semiconductor Devices*

Ruska: *Microelectronic Processing: An Introduction to the Manufacture of Integrated Circuits*

Schilling and Belove: *Electronic Circuits: Discrete and Integrated*

Seraphim: *Principles of Electronic Packaging*

Singh: *Physics of Semiconductors and Their Heterostructures*

Singh: *Semiconductor Devices: An Introduction*

Smith: *Modern Communication Circuits*

Sze: *VLSI Technology*

Taub: *Digital Circuits and Microprocessors*

Taub and Schilling: *Digital Integrated Electronics*

Tsividis: *Operation and Modeling of the MOS Transistor*

Wait, Huelsman, and Korn: *Introduction to Operational and Amplifier Theory Applications*

Yang: *Microelectronic Devices*

Zambuto: *Semiconductor Devices*

Also Available from McGraw-Hill

Schaum's Outline Series in Electronics & Electrical Engineering

Most outlines include basic theory, definitions and hundreds of example problems solved in step-by-step detail, and supplementary problems with answers.

Related Titles on the Current List Include:

Analog & Digital Communications
Basic Circuit Analysis
Basic Electrical Engineering
Basic Electricity
Basic Mathematics for Electricity & Electronics
Digital Principles
Electric Circuits
Electric Machines & Electromechanics
Electric Power Systems
Electromagnetics
Electronic Circuits
Electronic Communication
Electronic Devices & Circuits
Electronics Technology
Engineering Economics
Feedback & Control Systems
Introduction to Digital Systems
Microprocessor Fundamentals

Schaum's Solved Problems Books

Each title in this series is a complete and expert source of solved problems with solutions worked out in step-by-step detail.

Related Titles on the Current List Include:

3000 Solved Problems in Calculus
2500 Solved Problems in Differential Equations
3000 Solved Problems in Electric Circuits
2000 Solved Problems in Electromagnetics
2000 Solved Problems in Electronics
3000 Solved Problems in Linear Algebra
2000 Solved Problems in Numerical Analysis
3000 Solved Problems in Physics

Available at most college bookstores, or for a complete list of titles and prices, write to:

Schaum Division
McGraw-Hill, Inc.
Princeton Road, S-1
Hightstown, NJ 08520

TO OUR FAMILIES
Mary Ellen, John, Chris, and Brian
Hadewych, Katrien, Sara, and Marjan

PREFACE

In the short span of twenty five years, the field of analog integrated circuits and systems has developed and matured. During this same period, much has been made of the competition between analog and digital system design strategies. Advances in digital VLSI has enabled microprocessors and digital-signal processors to assume roles largely filled in the past by analog systems. However, there are three facts that render analog integrated circuits and systems increasingly important. First, the natural world is analog. Thus, analog systems are needed in information acquisition systems in order to prepare analog information for conversion to digital format. Second, there remain many important applications that are best addressed by mixed analog/digital VLSI systems. That is, analog and digital VLSI circuits coexist on the same die. Third, demanding digital systems can exhibit analog circuit qualities. Thus, a good grasp of analog IC design techniques is a valuable asset in the design and debugging of digital systems. The advances in both analog and digital VLSI has profoundly changed the way systems are partitioned to optimize integration and cost.

Much of the analog design during the 1960s and 1970s was done in bipolar and hybrid technologies. During this time, the operational amplifier emerged as an important subsystem. During subsequent years, the operational amplifier has been optimized and scaled to the degree that it is now considered a common component, like a resistor or capacitor. The 1980s was an era of rapid evolution of MOS analog integrated circuits, in particular CMOS. During the 1990s, we have seen the BICMOS technology (incorporating both bipolar and CMOS devices on the same die) emerge as a serious contender to the original technologies. Although somewhat more expensive to fabricate (e.g., more mask levels) than CMOS, BICMOS allows the designer to use both bipolar and MOS devices to their best advantage. At the same time, we have seen a proliferation of mixed analog/digital VLSI integrated circuits realized in

state-of-the-art digital CMOS technologies to optimize cost and power dissipation in consumer products, many of which are pocket size and battery powered. For very high performance applications, BICMOS offers the opportunity to mix analog circuits on the same die with high-speed ECL digital circuits and dense CMOS logic.

It has become increasingly important for analog circuit designers to have a thorough appreciation of the similarities and differences between MOS and bipolar devices, and to be able to design with either, where appropriate. The same argument can be made for sampled-data and continuous-time design techniques. Thus, in this book, we combine the consideration of CMOS and bipolar circuits into a unified treatment. We also include combined CMOS-bipolar circuit realizations made possible by BICMOS technology. The text progresses smoothly from MOS and bipolar device modeling, to simple one- and two-transistor building block circuits (e.g., amplifiers, active loads, and sources). We then follow with a thorough treatment of the design of operational and transconductance amplifiers. The final two chapters present a unified coverage of sample-data and continuous-time signal processing systems. Earlier in the text, we thoroughly cover the concepts of feedback and sensitivity. These important topics, along with noise, nonlinear distortion, and power supply rejection are integrated, as needed, throughout the text.

The design of analog circuits relies heavily on insight gained from hand calculations based on first-order models. However, many important details of circuit behavior, such as precise gain, DC offsets, distortion, and noise, depend on second-order device characteristics that cannot be included in hand calculations. We use computer analysis the way it is most commonly employed in the engineering design process: as a tool to verify detailed circuit behavior beyond the scope of hand analysis. The circuit simulator called SPICE is the standard CAD tool for verifying integrated circuit performance. SPICE is available in a variety of forms on UNIX-based workstations and all popular PC platforms. With these thoughts in mind, we focus much of the text on the development of design intuition through hand calculations. Extensive use of SPICE is included throughout the text, particularly as part of examples in the problem sets. The problem sets also include several open-ended design problems that expose the reader to practical situations.

Both authors have had extensive industrial experience in integrated-circuit (IC) design, as well as in the teaching of academic courses on this subject. The choice of the material covered in the body of the text and the problem sets is a reflection of our collective experience. We believe it to be a valuable resource for both IC designers and users. An understanding of the IC structure is extremely useful in evaluating the relative desirability of different designs. In addition, the IC user is in a much better position to interpret a manufacturer's data if he or she has a working knowledge of the internal operation of the integrated circuit in question.

This text was written to be used both as a text for students and as a reference book for practicing engineers. For class use, there are numerous worked problems in each chapter; the problem sets at the end of each chapter illustrate the practical applications of the material in the text. The contents of this book originated largely for the purpose of serving two courses on analog integrated circuit design offered at

the University of Pennsylvania and the Katholieke Universiteit Leuven. The first of these is a senior level elective and the second is a first year graduate course. The book is structured so that it can be used as the basic text for such a two-course sequence. An outline of each chapter will follow shortly, together with suggestions for material to be covered in each course. We assume that each course consists of three hours of lecture per week over a 15-week semester. The users of this text are assumed to have a working knowledge of Laplace transforms and frequency-domain circuit analysis. We also assume that the readers have had an introductory course in electronics, such as that based on the text *Microelectronic Circuits* by A. Sedra and K. C. Smith. Thus, we expect readers to be familiar with the principles of transistor operation and with the functioning of simple analog circuits. We also expect that readers have an introductory knowledge of probability and statistics. We take advantage of the fact that an increasing number of students are exposed to sampled-data systems and the z -transform in their undergraduate curriculum. For those readers who have not been exposed to this material, and for those who wish to revitalize this knowledge, an introduction to sampled-data signals and systems is included in Appendix 7-1 at the end of Chapter 7.

The outline of the text is as follows:

Chapters 1 and 2 contain summaries of MOS and bipolar transistor models, respectively. This material is quite important in IC design because there is significant interaction between circuit and device design, as will be seen in later chapters. The components that are most crucial in achieving an accurate SPICE simulation are the device models. Thus, a thorough understanding of the influence of device fabrication on device characteristics and their models is essential. Both chapters in their entirety are required reading for both the undergraduate and graduate courses. We suggest spending one to two weeks on selected topics from these chapters, with the choice of topics depending on the background of the students.

Chapter 3 introduces the reader to the important concepts of feedback and sensitivity. Also included are the effects of feedback on transient response of second- and third-order systems. Some of this material will be review for some students, particularly at the graduate level. Particularly novel in this chapter is the inclusion of two powerful tools for designing feedback circuits, namely, Blackman's impedance relation and the asymptotic gain relation. In the undergraduate course, this chapter should be covered in full. It will require no more than two weeks to cover. For the graduate course, selected topics can be treated in class and the balance of the chapter as home reading. One week is allowed for this chapter in the graduate course.

Chapter 4 involves the use of transistors to construct elementary amplifier stages, buffers, impedance converter, active loads, and current sources. AC, DC, and transient performances are considered. Capacitances (both intentional and parasitic) give rise to poles and zeros that modify the input, output, and transfer relationships versus frequency. In all sections, the parallel between MOS and bipolar transistor stages is maintained; and the differences are highlighted. The configurations in this chapter represent the basic building blocks of modern analog IC design. Thus, in both courses this material should be covered in full with the exception of the appendices. A thorough

treatment of this chapter will require three weeks. We recommend coverage of the full chapter for the undergraduate course and selected topics for the graduate course. For the graduate course, coverage is reduced to two weeks.

Chapter 5 is concerned with the modeling of operational and transconductance amplifier-based circuits from a behavioral point of view. A strong behavioral understanding is a prerequisite to undertaking the transistor level design of these amplifiers and/or the synthesis of higher level circuits that use them as components. The designer can greatly simplify the analysis and design of complex analog systems by using models for the amplifiers derived from behavioral descriptions rather than circuit schematics. Behavioral models developed in this chapter are used extensively in the analysis and design of analog signal processing systems in Chapters 7 and 8. Moreover, they are used in Chapter 6 to map detailed specifications to the attributes of transistor level circuit schematics. We recommend full coverage of this chapter in both courses, requiring two weeks.

Chapter 6 considers the transistor level analysis and design of several operational (op amp) and transconductance (OTA) amplifier schemes. They are developed by first considering the differential amplifier with active load, the simplest complete OTA. Succeeding schemes for CMOS, bipolar, and BICMOS, are developed with this basic OTA as a kernel. Fully differential or balanced schemes are also considered. Design plans are applied to all schemes, paying considerable attention to symmetry and matching, and also to other second-order effects (e.g., transient response, noise, nonlinearities, power supply rejection, offsets, common mode rejection, temperature effects), leading to a full set of specifications. Several design examples are worked in detail and important design tradeoffs are discussed. A thorough treatment of this chapter will require three weeks. We recommend coverage of the full chapter for both the undergraduate and graduate courses.

Chapter 7 is devoted to reviewing the fundamentals of linear active filtering in the continuous-time and sampled-data domains. For those readers who need to refresh their understanding of sampled-data systems, and z -transform, a brief review of these subjects is provided in Appendix 7-1. The fundamental schemes for integrated analog filters are introduced. Various performance requirements and methods for synthesizing efficient numerical transfer functions are considered. Models developed in Chapter 3 are used to estimate sensitivity and yield. A hybrid of discrete-time and analog circuit concepts are developed to facilitate the symbolic analysis and design of switched-capacitor circuits. A thorough treatment of this chapter requires three weeks. If Appendix 7-1 is reviewed in class, it can be adequately covered in two lectures. For the undergraduate course we recommend emphasizing continuous-time filters, providing an introduction to switched-capacitor filters. This involves all of Sections 7-1, 7-2, and 7-4, and parts of Sections 7-3, 7-5, and 7-6. This entire chapter is to be covered in the graduate course.

Chapter 8 builds on the materials in Chapters 5–7 to design and implement practical continuous-time and sampled-data integrated active filters. We consider concepts, circuit designs, circuit schematics, and design lore that have been found to result in robust integrated filters. Continuous-time and sampled-data realizations are con-

sidered with equivalent emphasis. Design and implementation is based on modular structures, where op amps, OTAs, and the passive structures are the building blocks. All schemes are analyzed, paying considerable attention to parasitics and matching, and also to other second-order effects (e.g., transient response, noise, nonlinearities, power supply rejection, and DC offsets). A thorough treatment of this chapter requires three weeks. There remains one week in the undergraduate course to cover selected sections. We recommend the coverage of Sections 8-1–8-3. The entire chapter is to be covered in the graduate course.

This book was conceived during W. Sansen's sabbatical leave with K. Laker at the University of Pennsylvania. The book was further developed during K. Laker's subsequent sabbatical leave at the Katholieke Universiteit Leuven. The funding for both sabbatical leaves were provided by the Penn-Leuven Faculty Exchange program. We are indeed grateful for this support. We wish to thank our students, colleagues, and the following reviewers for their careful evaluation of this book and their thoughtful comments: Stanley G. Burns, Iowa State University; L. Richard Carley, Carnegie Mellon University; Sherif Embabi, Texas A & M University; Sergio Franco, San Francisco State University; Edwin Greeneich, Arizona State University; Frank H. Hielscher, Lehigh University; Andrew L. Robinson, University of Michigan; Mani Soma, University of Washington; Bang-Sup Song, University of Illinois at Urbana-Champaign; and Gary Tuttle, Iowa State University. In particular, we wish to acknowledge the helpful suggestions from Professor Jan Van der Spiegel, University of Pennsylvania; Dr. T. R. Viswanathan, AT&T Microelectronics, Professor Michel Steyaert, Katholieke Universiteit Leuven, and Mr. A. Ganesan, Crystal Semiconductor.

Kenneth R. Laker
Willy M. C. Sansen

CONTENTS

Preface	xix
1 MOS Transistor Models	1
Introduction	1
1-1 MOSFET and Junction FET	2
1-1-1 JFET	2
1-1-2 MOST	2
1-1-3 <i>n</i> MOST and <i>p</i> MOST	4
1-2 Capacitances and MOST Threshold Voltages	5
1-2-1 MOS Capacitance	5
1-2-2 Junction Capacitance	6
1-2-3 MOST and JFET	7
1-2-4 MOST Threshold Voltage	9
1-2-5 Enhancement and Depletion MOST	12
1-3 MOST Linear Region and Saturation Region	14
1-3-1 Large v_{GS} , Small v_{DS} , and Zero v_{BS}	14
1-3-2 Large v_{GS} , Large v_{DS} , and Zero v_{BS}	15
1-3-3 Large v_{GS} , Small v_{DS} , and Large v_{BS}	17
1-4 MOST Current-Voltage Characteristics	17
1-4-1 Linear Region	17
1-4-2 Linear Region: First-Order Model	18
1-4-3 MOST in Saturation: First-Order Model	19
1-4-4 Parameters K' and n	20
1-4-5 Plots of i_{DS} versus v_{GS} and v_{BS}	22
1-4-6 Effective Channel Length and Width	23
1-5 Small-Signal Model in Saturation	23
1-5-1 Transconductance g_m	25

1-5-2	Bulk Transconductance g_{mb}	26
1-5-3	Output Resistance r_o	26
1-6	Weak Inversion and Velocity Saturation	27
1-6-1	MOST in Weak Inversion	27
1-6-2	Transconductance-Current Ratio	29
1-6-3	Transition Weak-Strong Inversion	30
1-6-4	MOST in Velocity Saturation	32
1-7	Examples of Small-Signal Analysis	32
1-7-1	Example of Transconductance Amplifier	32
1-7-2	Example of Voltage Amplifier with Active Load	33
1-7-3	Example of a MOST Diode	35
1-7-4	Example of Source Follower	36
1-7-5	Example of MOST as a Switch with Resistive Load	38
1-7-6	Example with a MOST as a Switch with Capacitive Load	41
1-8	Capacitances	43
1-8-1	MOST: Oxide Capacitance C_{ox}	45
1-8-2	MOST Junction Capacitances	45
1-8-3	MOST Junction Leakage Currents and Capacitances	47
1-8-4	Interconnect Capacitances	47
1-8-5	Bonding Pad Capacitance	49
1-8-6	Package Pin Capacitance	49
1-8-7	Protection Network Capacitance	50
1-8-8	Total Capacitance Configurations	50
1-9	Higher-Order Models	51
1-9-1	VT0-KP-GAMMA-LAMBDA or TOX-PHI-NSUB-NSS?	52
1-9-2	Parasitic Resistances	52
1-9-3	Mobility Degradation Due to Longitudinal Electric Field	53
1-9-4	Mobility Degradation Due to Transverse Electric Field	55
1-9-5	Channel Width Factor DELTA	56
1-9-6	Static Feedback Effect Parameter ETA	57
1-9-7	Onset of Short-Channel Effects	58
1-9-8	Punchthrough and Substrate Currents	58
1-10	Design Example	60
1-11	Junction FETs	62
1-11-1	JFET Pinchoff Voltage	62
1-11-2	JFET DC Model	65
1-11-3	JFET: DC Model in Linear Region	66
1-11-4	JFET DC Model: Onset of Saturation	67
1-11-5	JFET DC Model in Saturation	69
1-11-6	Model for Wide-Channel JFETs	69
1-11-7	JFET DC Model in Saturation: Subthreshold Region	71
1-11-8	JFET Small-Signal Models	71
1-11-9	JFET Example: MESFET	73
1-11-10	JFET Design Example	74
1-12	Noise Sources in FET	74
1-12-1	Thermal or Johnson Noise	77
1-12-2	Shot Noise	78
1-12-3	$1/f$ Noise or Flicker Noise	79

1-12-4	Other Noise Sources	81
1-12-5	Total Noise	81
1-12-6	FET Noise Models	83
1-12-7	$1/f$ Noise in SPICE	84
1-12-8	Equivalent Input Noise Current	85
1-12-9	Gate Leakage Noise	86
	Summary	86
	Exercises	86
	Appendix 1-1: Notation of Symbols	90
	References	91
2	Bipolar Transistor Models	92
2-1	Bipolar Transistor Operation	92
2-1-1	Structure	92
2-1-2	Depletion Layers	96
2-1-3	Base Doping	96
2-1-4	Forward Biasing	96
2-1-5	Base Transit Time	100
2-2	The Transistor Beta (β)	101
2-2-1	Beta Caused by Injection in the Emitter β_{IE}	102
2-2-2	Beta Caused by Recombination in the Base β_{RB}	102
2-2-3	Beta Caused by Recombination in the EB Space Charge Layer	102
2-2-4	AC Beta β_{AC}	103
2-3	The Hybrid- π Small-Signal Model	106
2-3-1	Transconductance g_m	106
2-3-2	Input Resistance r_π	106
2-3-3	Output Resistance r_o	107
2-3-4	Voltage Gain of Small-Signal Gain Stage	110
2-3-5	Junction Capacitances	110
2-3-6	Diffusion Capacitance C_D	112
2-3-7	Common-Emitter Configuration with Current Drive	112
2-3-8	Common-Emitter Configuration with Voltage Drive	116
2-3-9	Common-Collector and Common-Base Configurations	117
2-4	The Ohmic Resistances	121
2-4-1	The Base Resistance	121
2-4-2	Extrinsic Base Resistance	121
2-4-3	Intrinsic Base Resistance	121
2-4-4	The Collector Resistances	125
2-4-5	The Emitter Resistance	126
2-5	High-Injection and Other Second-Order Effects	126
2-5-1	High-Injection Effects in the Base	127
2-5-2	High-Injection Model of Beta	130
2-5-3	Base Resistance Effects	131
2-5-4	Graded Base	131
2-5-5	Collector Current Spreading	131
2-5-6	High-Injection Effects in the Collector	132
2-5-7	Bipolar Transistors for VLSI	132
2-6	Lateral pnp Transistors	134
2-6-1	Substrate pnp Transistors	134

2-6-2	Lateral <i>pnp</i> Transistors	137
2-6-3	Base Width, Early Voltage, and Punchthrough	139
2-6-4	Base Resistance and Emitter Crowding	139
2-6-5	Applications with <i>pnp</i> 's	139
2-7	Noise	142
2-7-1	Input Noise Sources	142
2-7-2	Equivalent Input Noise Sources	143
2-7-3	Noise Figure	144
2-7-4	Optimum R_S	145
2-7-5	Optimum NF	146
2-7-6	Optimum I_C	146
2-8	Design Example	147
2-9	Other Components	147
2-9-1	Base Diffusion Resistors	147
2-9-2	Other Resistors	149
2-9-3	Temperature Coefficient	150
2-9-4	Voltage Coefficient	151
2-9-5	Frequency Dependence	151
2-9-6	Absolute and Relative Accuracy	152
2-9-7	Resistors in a CMOS Process	153
2-9-8	Thin Film Resistors	153
2-9-9	Capacitors	153
2-9-10	Inductors	155
2-10	Comparison between MOSTs and Bipolar Transistors	156
2-10-1	Input Current	157
2-10-2	DC Saturation Voltage	157
2-10-3	Transconductance-Current Ratio	159
2-10-4	Design Planning	160
2-10-5	Current Range	160
2-10-6	Maximum Frequency of Operation	160
2-10-7	Noise	161
	Summary	162
	Exercises	162
	Appendix 2-1	164
	References	169
3	Feedback and Sensitivity in Analog Integrated Circuits	170
	Introduction	170
3-1	Feedback Theory	172
3-1-1	Basic Feedback Concepts and Definitions	177
3-1-2	Feedback Configurations and Classifications	185
3-2	Analysis of Feedback Amplifier Circuits	188
3-2-1	Analysis When the Feedback Network is One of the Four Basic Configurations in Fig. 3-7	189
3-2-2	Blackman's Impedance Relation	194
3-2-3	The Asymptotic Gain Relation	198
3-3	Stability Considerations in Linear Feedback Systems	200
3-3-1	Effect of Feedback on the System Natural Frequencies	202
3-3-2	The Use of Bode Plots in Stability Analysis	212