

ANALOG INTEGRATED

CIRCUIT

DESIGN

SECOND EDITION

Tony Chan Carusone | David A. Johns | Kenneth W. Martin



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To Soo, Brayden, Teague, and Senna
To Cecilia, Christopher, Timothy, and Victoria
To Elisabeth and Jeremy

Preface

It has long been predicted that there would soon be little need for analog circuitry because the world increasingly relies on digital signals, yet the need for good analog circuit design remains strong. Many applications have indeed replaced analog circuitry with their digital counterparts (such as digital audio). However, when digitizing physical signals, analog-to-digital and digital-to-analog converters are always needed, together with their associated anti-aliasing and reconstruction filters. In addition, new applications continue to appear; their requirements demand the use of high-performance analog front ends, such as digital communication over wireline and wireless channels and microsensor interfaces. Also, as integrated circuits integrate more functionality, it is much more likely that at least some portion of a modern integrated circuit will include analog circuitry to interface to the real world. Moreover, the continued scaling of digital circuits has led to the emergence of new problems that require analog solutions, such as on-chip power management and the generation of stable clock signals. Although it may constitute only a small portion of total chip area, analog circuitry is often the limiting factor on overall system performance and the most difficult part of the IC to design. As a result, a strong industrial need for analog circuit designers continues. The purpose of this book is to help develop excellent analog circuit designers by presenting a concise treatment of the wide array of knowledge required by an integrated circuit designer.

This book strives to quash the notion that the design and test of high-performance analog circuits are “mystical arts.” Whereas digital design is relatively systematic, analog design appears to be much more based upon intuition and experience. Analog testing may sometimes seem to depend more upon the time of day and phase of the moon than on concrete electrical properties. But these thoughts about analog circuits usually occur when one is not familiar with the many fundamentals required to create high-performance analog circuits. This book helps to take the mystery out of analog integrated circuit design. Although many circuits and techniques are described, the most important design principles are emphasized throughout this book. Physical and intuitive explanations are given, and although mathematical quantitative analyses of many circuits have necessarily been presented, one must not miss seeing the forest for the trees. In other words, this book attempts to present the critical underlying concepts without becoming entangled in tedious and overcomplicated circuit analyses.

NEW TO THIS EDITION

This, the second edition of *Analog Integrated Circuit Design*, has new material to make it more accessible to beginners in the field while retaining the depth, detail, and intuitive approach that made the first edition a favorite reference among experienced designers. Two new chapters have been added early in the text: Chapter 4, dedicated to the frequency response of analog integrated circuits, provides a review of frequency-domain analysis and single-stage amplifier response; Chapter 5 covers the basic theory of feedback amplifiers. The conventional categorization and dissection of feedback amplifiers according to their topology is by and large forgone in favor of an intuitive, practical, yet analytical approach that is based on the practices of experienced analog designers. These new chapters make the second edition well-suited to the teaching of analog integrated circuit design at both the undergraduate and graduate levels, while still allowing it to serve as a comprehensive reference for practicing engineers.

The first edition of *Analog Integrated Circuit Design* was written roughly 15 years before the second, and the field changed considerably in the intervening years necessitating significant updates to reflect advances in

technology and engineering practice. For example, material on CMOS integrated circuit device modeling, processing, and layout in Chapters 1 and 2 has been updated and expanded to cover effects that are of tremendous importance to analog designers using modern fabrication technologies. New and expanded topics include modeling MOS subthreshold operation and mobility degradation in Chapter 1, and proximity effects and mismatch both covered under the subheading “Variability” in Chapter 2. Also in Chapter 1, the increasingly important role of simulation in the early phases of analog design is reflected by relating MOS parameters to the results of practical simulations. Simulation examples have been added throughout the text, particularly in the early chapters. Circuits and architectures whose fundamental importance have emerged over the past decade have been added such as voltage regulators (in Chapter 7) and the 1.5-bit-per-stage pipelined A/D converter (in Chapter 17). New circuit topologies specifically suited to low-voltage operation are presented, such as a low-voltage bandgap reference circuit in Chapter 7. Nonlinearity and dynamic range are now presented in Chapter 9 alongside noise, highlighting their fundamental interrelationship. New study problems have been added throughout the text and numerical examples have been updated to reflect the realities of modern fabrication technologies.

This edition has also been updated to accommodate today’s varying pedagogical approaches toward the teaching of bipolar devices and circuits. Material on bipolar devices and circuits, which was scattered over several chapters of the first edition, has been combined into Chapter 8 of this edition. The reorganization permits undergraduate-level instructors and readers to either incorporate or omit the material at their discretion. In the later chapters, readers are assumed to have experience with analog design, hence bipolar and BiCMOS circuits are presented alongside CMOS circuits, as in the first edition.

Finally, Chapter 19 on phase-locked loops (PLLs) has been rewritten. When the first edition was released, it was one of the first analog circuit texts to elucidate the design of integrated circuit PLLs. Today, fully-integrated PLLs have become a basic building block of both analog and mostly-digital integrated circuits. As such, the material has become standard fare at the graduate level, and increasingly at the undergraduate level too. Chapter 19 now provides a thorough treatment of jitter and phase noise, major performance metrics in the design of modern PLLs and clocked systems.

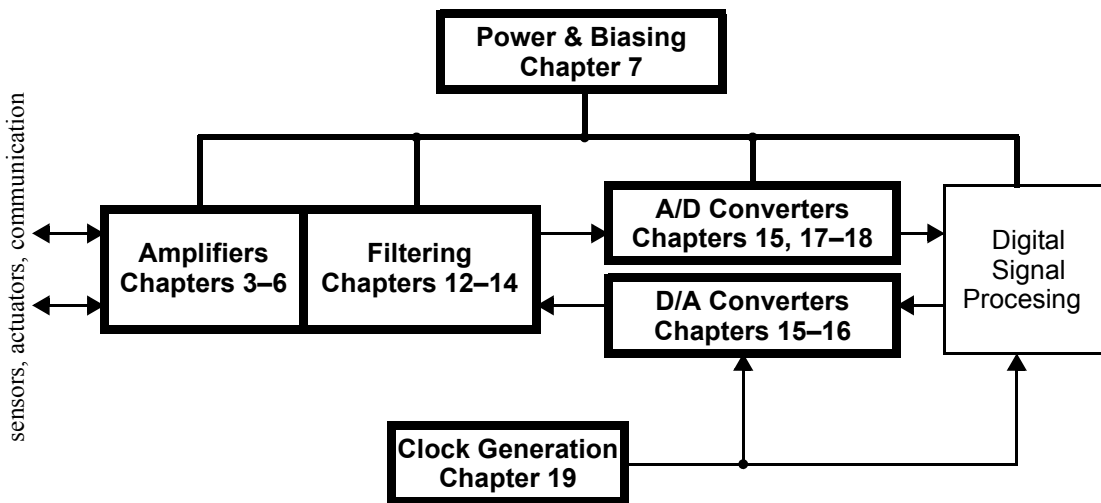
INTENDED AUDIENCE

This book is intended for use as a senior-undergraduate and graduate-level textbook, and as a reference for practicing engineers. To appreciate the material in this book, it is expected that the reader has had at least one basic introductory course in electronics. Specifically, the reader should be familiar with the concept of small-signal analysis and have been exposed to basic transistor circuits. In addition, the reader should have been exposed to Fourier and Laplace transforms. Some prior knowledge of discrete-time signal processing is important for the later chapters. Although all of these topics are reviewed, background in these areas will benefit the reader significantly.

The chapters of this book have intentionally been made mostly independent so that some chapters can be covered while others are skipped. Also, it has been found to be very easy to change the order of presentation. For example, if readers have a good modelling background they might skip Chapter 1, and if their discrete-time knowledge is good Chapter 13 might be assigned only as review. We believe that such flexibility is essential in presenting textbooks for the later years of study.

The material in this book can be used for a few courses. A second undergraduate course in electronics typically has frequency response and feedback, as its major topics. For such a course, Chapters 1, 3, 4 and 5 may be assigned. Some advanced modeling from Chapter 1 may be omitted and replaced with selected topics from Chapters 2 and 6 at the instructor’s discretion. A senior-level undergraduate course in analog integrated circuits assigns Chapters 1, 2, 6, and 7, with Chapters 3–5 serving as a useful reference for those students requiring extra review. Chapter 8 may be included in any course that covers bipolar processing and devices.

A senior undergraduate or entry-level graduate course on analog signal processing may use Chapters 9–14. A graduate-level course on data converters will focus upon Chapters 15–18, drawing upon the earlier chapters as



needed for supplementary material. Finally, Chapter 19 may be used for a graduate level course on phase locked loops. Naturally there is considerable variability in the specific readings assigned by different instructors, particularly at the graduate level. This variability is recognized in the basic organization of the book.

A secondary audience for this book includes recently graduated electrical engineers who wish to rapidly increase their knowledge of modern analog circuit design techniques. In fact, much of the material covered in this text was originally taught and refined over many years in popular short courses offered to working engineers who realized the importance of upgrading their knowledge in analog circuit design. For this audience, we have put effort into highlighting the most important considerations when designing the various circuits. We have also tried to include modern, well-designed examples and references to primary sources for further study.

TEXT OUTLINE

Analog integrated circuits are critical blocks that permeate complex electronic systems. Analog circuits inevitably arise whenever those systems must interact with the analog world of sensors or actuators (including antennas, cameras, microphones, speakers, displays, lighting, motors, and many others), and when they must communicate using anything but the most rudimentary digital signals. A typical system is illustrated in the figure. The blocks covered in some detail in this text are highlighted, and the corresponding chapters referenced. Chapters describing the design of amplifiers, and all chapters not explicitly referenced in the figure, are foundational and relevant to the implementation of many analog and mixed-signal systems. The table of contents provides a catalog of the book's main topics. What follows here is a very brief summary of each chapter.

In Chapter 1, the basic physical behavior and modelling of diodes, MOS transistors, and integrated circuit capacitors and resistors are covered. Here, many of the modelling equations are derived to give the reader some appreciation of model parameters and how they are affected by processes parameters. Diode and MOSFET models are summarized in a table format for quick reference.

In Chapter 2, issues associated with the manufacturing of an integrated circuit are discussed. Emphasis is placed on CMOS fabrication. In addition to the provided background, issues that are of particular importance to analog designers are emphasized, such as variability (including random mismatch) layout rules and best practices.

Fundamental building blocks of analog integrated circuits are discussed in Chapter–3, specifically, MOS current mirrors and single-stage amplifiers, concluding with the basic MOS differential pair. A point to note here is that only active-load amplifiers are considered since these are prevalent in integrated circuits.

Chapter 4 provides an introductory view of the frequency response of electronic circuits. It begins with fundamental material on frequency response, establishing definitions and notation for the following chapters. Then, the frequency response of elementary CMOS analog building blocks is presented. Along the way, fundamental topics are presented including the Miller effect and the method of zero-value time-constants.

Feedback amplifiers are introduced in Chapter 5. Loop gain and phase margin are defined. Basic concepts are illustrated using generic analyses of first- and second-order feedback systems. At the end of the chapter, the analysis is applied to common CMOS feedback circuits.

In Chapter 6, the fundamental principles of basic opamp design are presented. To illustrate many of these principles, the design of a classic two-stage CMOS opamp is first thoroughly discussed. Proper biasing and device sizing strategies are covered. Compensation is introduced and a systematic procedure for compensation is described. Then, advanced current-mirror approaches are discussed, followed by two opamps that make use of them: the folded-cascode and current mirror opamps. Finally, fully differential opamps are presented, as they are used in many modern industrial applications where high speed and low noise are important considerations.

Biasing, reference, and regulators are presented in Chapter 7. Any reader that wishes to design a real and complete opamp circuit should be aware of the attendant issues covered here. The later sections on bandgap references and voltage regulators may not be essential to all readers.

Chapter 8 provides a comprehensive summary of bipolar devices and circuits. It includes the basics of device modeling, fabrication, and fundamental circuit blocks such as current mirrors and gain stages. The reader may wish to read sections of this chapter alongside the corresponding material for MOS transistors presented in Chapters 1–7.

Noise analysis and modelling and linearity are discussed in Chapter 9. Here, we assume the reader has not previously been exposed to random-signal analysis, and thus basic concepts in analyzing random signals are first presented. Noise models are then presented for basic circuit elements. A variety of circuits are analyzed from a noise perspective giving the reader some experience in noise analysis. Finally, the concept of dynamic range is introduced as a fundamental specification of most any analog circuit, and the basic measures of linearity are defined.

In Chapter 7, comparator design is discussed. Comparators are perhaps the second most common analog building block after opamps. Here, the practical limitations of comparators are described as well as circuit techniques to improve performance. In addition, examples of modern high-speed comparators are presented.

In Chapter 11, some additional analog building blocks are covered. Specifically, sample-and-hold circuits and translinear gain and multiplier circuits are presented. By the end of this chapter, all the main analog building blocks have been covered (with the possible exception of voltage-controlled oscillators) and the remaining material in the text deals with more system-level analog considerations.

Continuous-time filters are the focus of Chapter 12. After a brief introduction to first- and second-order filters, transconductance-C filters are described. CMOS, bipolar, and BiCMOS approaches are covered. Active-RC filters are then presented, followed by some tuning approaches. Finally, a brief introduction to complex analog signal processing and complex filters is included.

The basics of discrete-time signals and filters are presented in Chapter 13. This material is essential for understanding the operation of many analog circuits such as switched-capacitor filters and oversampling converters. The approach taken here is to show the close relationship between the Z-transform and the Laplace transform, thereby building on the reader's experience in the continuous-time domain.

In Chapter 14, the basics of switched-capacitor circuits are described. Switched-capacitor techniques are a common approach for realizing integrated filters due to their high degree of accuracy and linearity. The chapter concludes with a description of other switched-capacitor circuits, such as gain stages, modulators, and voltage-controlled oscillators.

In Chapter 15, the fundamentals of data converters are presented. Ideal converters and the properties of quantization noise are discussed first. Signed codes are then presented, and the chapter concludes with a discussion of performance limitations and metrics.

Popular Nyquist-rate D/A architectures are discussed in Chapter 16 and various approaches for realizing Nyquist-rate A/D converters are described in Chapter 17. The importance of data converters cannot be overemphasized in today's largely digital world, and these two chapters discuss the main advantages and design issues of many modern approaches.

Oversampling converters are presented separately in Chapter 18 due to the large amount of signalprocessing concepts needed to properly describe these converters. Here, digital issues (such as decimation filters) are also presented since good overall system knowledge is needed to properly design these types of converters. In addition, practical issues and advanced approaches (such as the use of bandpass and multibit converters) are also discussed. This chapter concludes with a third-order A/D converter example.

Finally, the text concludes with phase-locked loops (PLLs) in Chapter 19. The chapter first provides a big-picture overview of PLLs. A more rigorous treatment follows, including small-signal analysis and noise analysis in both the time domain (jitter) and frequency domain (phase noise). Performance metrics and design procedures are included.

USING THE BOOK AND WEBSITE

SPICE simulation examples are an important feature of the book. Passages annotated with the boxed icon shown here indicate that a SPICE simulation may be performed either as an essential part of the problem, or to corroborate the results of a hand analysis. Many of the problems and examples in this book rely upon the fictitious CMOS process technologies whose parameters are summarized in Table 1.5. SPICE model files corresponding to each of these fictitious technologies are provided on the companion website, www.analogicdesign.com. Also there are many netlists that may be used for the simulations. The results they provide should roughly corroborate hand analyses performed using the parameters in Table 1.5. However, simulation results *never* provide precise agreement. In fact, simulated results may differ from the results of a hand analysis by as much as 50%! This is a reality of analog design, and the SPICE examples in this book are no exception. This is, of itself, a valuable lesson to the student of analog design. It illustrates, through practice, those tasks to which hand analysis and simulation are best suited.



End-of-chapter problems are organized by the subsection to which they pertain. For example, if one wishes to practice only those problems pertaining to current mirror opamps, one may proceed directly to Section 6.11.5.

Key points throughout the text are emphasized using highlighted boxes in the margins, as shown here. These key points are collected and listed at the end of each chapter.

Key Point: *Key points throughout the text are emphasized using separate highlighted boxes in the margins. These key points are collected and listed at the end of each chapter as a study aid.*

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Contents

CHAPTER 1	INTEGRATED-CIRCUIT DEVICES AND MODELLING	1
1.1	Semiconductors and pn Junctions	1
1.1.1	Diodes	2
1.1.2	Reverse-Biased Diodes	4
1.1.3	Graded Junctions	7
1.1.4	Large-Signal Junction Capacitance	9
1.1.5	Forward-Biased Junctions	10
1.1.6	Junction Capacitance of Forward-Biased Diode	11
1.1.7	Small-Signal Model of a Forward-Biased Diode	12
1.1.8	Schottky Diodes	13
1.2	MOS Transistors	14
1.2.1	Symbols for MOS Transistors	15
1.2.2	Basic Operation	16
1.2.3	Large-Signal Modelling	21
1.2.4	Body Effect	24
1.2.5	p-Channel Transistors	24
1.2.6	Low-Frequency Small-Signal Modelling in the Active Region	25
1.2.7	High-Frequency Small-Signal Modelling in the Active Region	30
1.2.8	Small-Signal Modelling in the Triode and Cutoff Regions	33
1.2.9	Analog Figures of Merit and Trade-offs	36
1.3	Device Model Summary	38
1.3.1	Constants	38
1.3.2	Diode Equations	39
1.3.3	MOS Transistor Equations	40
1.4	Advanced MOS Modelling	42
1.4.1	Subthreshold Operation	42
1.4.2	Mobility Degradation	44
1.4.3	Summary of Subthreshold and Mobility Degradation Equations	47
1.4.4	Parasitic Resistances	47
1.4.5	Short-Channel Effects	48
1.4.6	Leakage Currents	49
1.5	SPICE Modelling Parameters	50
1.5.1	Diode Model	50
1.5.2	MOS Transistors	51
1.5.3	Advanced SPICE Models of MOS Transistors	51
1.6	Passive Devices	54
1.6.1	Resistors	54
1.6.2	Capacitors	58

1.7	Appendix	60
1.7.1	Diode Exponential Relationship	60
1.7.2	Diode-Diffusion Capacitance	62
1.7.3	MOS Threshold Voltage and the Body Effect	64
1.7.4	MOS Triode Relationship	66
1.8	Key Points	68
1.9	References	69
1.10	Problems	69

CHAPTER 2 PROCESSING AND LAYOUT**73**

2.1	CMOS Processing	73
2.1.1	The Silicon Wafer	73
2.1.2	Photolithography and Well Definition	74
2.1.3	Diffusion and Ion Implantation	76
2.1.4	Chemical Vapor Deposition and Defining the Active Regions	78
2.1.5	Transistor Isolation	78
2.1.6	Gate-Oxide and Threshold-Voltage Adjustments	81
2.1.7	Polysilicon Gate Formation	82
2.1.8	Implanting the Junctions, Depositing SiO ₂ , and Opening Contact Holes	82
2.1.9	Annealing, Depositing and Patterning Metal, and Overglass Deposition	84
2.1.10	Additional Processing Steps	84
2.2	CMOS Layout and Design Rules	86
2.2.1	Spacing Rules	86
2.2.2	Planarity and Fill Requirements	94
2.2.3	Antenna Rules	94
2.2.4	Latch-Up	95
2.3	Variability and Mismatch	96
2.3.1	Systematic Variations Including Proximity Effects	96
2.3.2	Process Variations	98
2.3.3	Random Variations and Mismatch	99
2.4	Analog Layout Considerations	103
2.4.1	Transistor Layouts	103
2.4.2	Capacitor Matching	104
2.4.3	Resistor Layout	107
2.4.4	Noise Considerations	109
2.5	Key Points	113
2.6	References	114
2.7	Problems	114

CHAPTER 3 BASIC CURRENT MIRRORS AND SINGLE-STAGE AMPLIFIERS**117**

3.1	Simple CMOS Current Mirror	118
3.2	Common-Source Amplifier	120
3.3	Source-Follower or Common-Drain Amplifier	122

3.4	Common-Gate Amplifier	124
3.5	Source-Degenerated Current Mirrors	127
3.6	Cascode Current Mirrors	129
3.7	Cascode Gain Stage	131
3.8	MOS Differential Pair and Gain Stage	135
3.9	Key Points	138
3.10	References	139
3.11	Problems	139

CHAPTER 4 FREQUENCY RESPONSE OF ELECTRONIC CIRCUITS 144

4.1	Frequency Response of Linear Systems	144
4.1.1	Magnitude and Phase Response	145
4.1.2	First-Order Circuits	147
4.1.3	Second-Order Low-Pass Transfer Functions with Real Poles	154
4.1.4	Bode Plots	157
4.1.5	Second-Order Low-Pass Transfer Functions with Complex Poles	163
4.2	Frequency Response of Elementary Transistor Circuits	165
4.2.1	High-Frequency MOS Small-Signal Model	165
4.2.2	Common-Source Amplifier	166
4.2.3	Miller Theorem and Miller Effect	169
4.2.4	Zero-Value Time-Constant Analysis	173
4.2.5	Common-Source Design Examples	176
4.2.6	Common-Gate Amplifier	179
4.3	Cascode Gain Stage	181
4.4	Source-Follower Amplifier	187
4.5	Differential Pair	193
4.5.1	High-Frequency T-Model	193
4.5.2	Symmetric Differential Amplifier	194
4.5.3	Single-Ended Differential Amplifier	195
4.5.4	Differential Pair with Active Load	196
4.6	Key Points	197
4.7	References	198
4.8	Problems	199

CHAPTER 5 FEEDBACK AMPLIFIERS 204

5.1	Ideal Model of Negative Feedback	204
5.1.1	Basic Definitions	204
5.1.2	Gain Sensitivity	205
5.1.3	Bandwidth	207
5.1.4	Linearity	207
5.1.5	Summary	208
5.2	Dynamic Response of Feedback Amplifiers	208
5.2.1	Stability Criteria	209
5.2.2	Phase Margin	211

5.3	First- and Second-Order Feedback Systems	213
5.3.1	First-Order Feedback Systems	213
5.3.2	Second-Order Feedback Systems	217
5.3.3	Higher-Order Feedback Systems	220
5.4	Common Feedback Amplifiers	220
5.4.1	Obtaining the Loop Gain, $L(s)$	222
5.4.2	Non-Inverting Amplifier	226
5.4.3	Transimpedance (Inverting) Amplifiers	231
5.5	Summary of Key Points	235
5.6	References	235
5.7	Problems	236
CHAPTER 6	BASIC OPAMP DESIGN AND COMPENSATION	242
6.1	Two-Stage CMOS Opamp	242
6.1.1	Opamp Gain	243
6.1.2	Frequency Response	245
6.1.3	Slew Rate	249
6.1.4	n -Channel or p -Channel Input Stage	252
6.1.5	Systematic Offset Voltage	252
6.2	Opamp Compensation	254
6.2.1	Dominant-Pole Compensation and Lead Compensation	254
6.2.2	Compensating the Two-Stage Opamp	255
6.2.3	Making Compensation Independent of Process and Temperature	259
6.3	Advanced Current Mirrors	261
6.3.1	Wide-Swing Current Mirrors	261
6.3.2	Enhanced Output-Impedance Current Mirrors and Gain Boosting	263
6.3.3	Wide-Swing Current Mirror with Enhanced Output Impedance	266
6.3.4	Current-Mirror Symbol	267
6.4	Folded-Cascode Opamp	268
6.4.1	Small-Signal Analysis	270
6.4.2	Slew Rate	272
6.5	Current Mirror Opamp	275
6.6	Linear Settling Time Revisited	279
6.7	Fully Differential Opamps	281
6.7.1	Fully Differential Folded-Cascode Opamp	283
6.7.2	Alternative Fully Differential Opamps	284
6.7.3	Low Supply Voltage Opamps	286
6.8	Common-Mode Feedback Circuits	288
6.9	Summary of Key Points	292
6.10	References	293
6.11	Problems	294
CHAPTER 7	BIASING, REFERENCES, AND REGULATORS	302
7.1	Analog Integrated Circuit Biasing	302
7.1.1	Bias Circuits	303

7.1.2	Reference Circuits	305
7.1.3	Regulator Circuits	306
7.2	Establishing Constant Transconductance	307
7.2.1	Basic Constant-Transconductance Circuit	307
7.2.2	Improved Constant-Transconductance Circuits	309
7.3	Establishing Constant Voltages and Currents	310
7.3.1	Bandgap Voltage Reference Basics	310
7.3.2	Circuits for Bandgap References	314
7.3.3	Low-Voltage Bandgap Reference	319
7.3.4	Current Reference	320
7.4	Voltage Regulation	321
7.4.1	Regulator Specifications	322
7.4.2	Feedback Analysis	322
7.4.3	Low Dropout Regulators	324
7.5	Summary of Key Points	327
7.6	References	327
7.7	Problems	328

CHAPTER 8 BIPOLAR DEVICES AND CIRCUITS**331**

8.1	Bipolar-Junction Transistors	331
8.1.1	Basic Operation	331
8.1.2	Analog Figures of Merit	341
8.2	Bipolar Device Model Summary	344
8.3	SPICE Modeling	345
8.4	Bipolar and BiCMOS Processing	346
8.4.1	Bipolar Processing	346
8.4.2	Modern SiGe BiCMOS HBT Processing	347
8.4.3	Mismatch in Bipolar Devices	348
8.5	Bipolar Current Mirrors and Gain Stages	349
8.5.1	Current Mirrors	349
8.5.2	Emitter Follower	350
8.5.3	Bipolar Differential Pair	353
8.6	Appendix	356
8.6.1	Bipolar Transistor Exponential Relationship	356
8.6.2	Base Charge Storage of an Active BJT	359
8.7	Summary of Key Points	359
8.8	References	360
8.9	Problems	360

CHAPTER 9 NOISE AND LINEARITY ANALYSIS AND MODELLING**363**

9.1	Time-Domain Analysis	363
9.1.1	Root Mean Square (rms) Value	364
9.1.2	SNR	365
9.1.3	Units of dBm	365
9.1.4	Noise Summation	366

9.2	Frequency-Domain Analysis	367
9.2.1	Noise Spectral Density	367
9.2.2	White Noise	369
9.2.3	1/f, or Flicker, Noise	370
9.2.4	Filtered Noise	371
9.2.5	Noise Bandwidth	373
9.2.6	Piecewise Integration of Noise	375
9.2.7	1/f Noise Tangent Principle	377
9.3	Noise Models for Circuit Elements	377
9.3.1	Resistors	378
9.3.2	Diodes	378
9.3.3	Bipolar Transistors	380
9.3.4	MOSFETS	380
9.3.5	Opamps	382
9.3.6	Capacitors and Inductors	382
9.3.7	Sampled Signal Noise	384
9.3.8	Input-Referred Noise	384
9.4	Noise Analysis Examples	387
9.4.1	Opamp Example	387
9.4.2	Bipolar Common-Emitter Example	390
9.4.3	CMOS Differential Pair Example	392
9.4.4	Fiber-Optic Transimpedance Amplifier Example	395
9.5	Dynamic Range Performance	397
9.5.1	Total Harmonic Distortion (THD)	398
9.5.2	Third-Order Intercept Point (IP3)	400
9.5.3	Spurious-Free Dynamic Range (SFDR)	402
9.5.4	Signal-to-Noise and Distortion Ratio (SNDR)	404
9.6	Key Points	405
9.7	References	406
9.8	Problems	406

CHAPTER 10 COMPARATORS

413

10.1	Comparator Specifications	413
10.1.1	Input Offset and Noise	413
10.1.2	Hysteresis	414
10.2	Using an Opamp for a Comparator	415
10.2.1	Input-Offset Voltage Errors	417
10.3	Charge-Injection Errors	418
10.3.1	Making Charge-Injection Signal Independent	421
10.3.2	Minimizing Errors Due to Charge-Injection	421
10.3.3	Speed of Multi-Stage Comparators	424
10.4	Latched Comparators	426
10.4.1	Latch-Mode Time Constant	427
10.4.2	Latch Offset	430

10.5	Examples of CMOS and BiCMOS Comparators	431
10.5.1	Input-Transistor Charge Trapping	435
10.6	Examples of Bipolar Comparators	437
10.7	Key Points	439
10.8	References	440
10.9	Problems	440
CHAPTER 11 SAMPLE-AND-HOLD AND TRANSLINEAR CIRCUITS		444
11.1	Performance of Sample-and-Hold Circuits	444
11.1.1	Testing Sample and Holds	445
11.2	MOS Sample-and-Hold Basics	446
11.3	Examples of CMOS S/H Circuits	452
11.4	Bipolar and BiCMOS Sample-and-Holds	456
11.5	Translinear Gain Cell	460
11.6	Translinear Multiplier	462
11.7	Key Points	464
11.8	References	465
11.9	Problems	466
CHAPTER 12 CONTINUOUS-TIME FILTERS		469
12.1	Introduction to Continuous-Time Filters	469
12.1.1	First-Order Filters	470
12.1.2	Second-Order Filters	470
12.2	Introduction to G_m -C Filters	471
12.2.1	Integrators and Summers	472
12.2.2	Fully Differential Integrators	474
12.2.3	First-Order Filter	475
12.2.4	Biquad Filter	477
12.3	Transconductors Using Fixed Resistors	479
12.4	CMOS Transconductors Using Triode Transistors	484
12.4.1	Transconductors Using a Fixed-Bias Triode Transistor	484
12.4.2	Transconductors Using Varying Bias-Triode Transistors	486
12.4.3	Transconductors Using Constant Drain-Source Voltages	491
12.5	CMOS Transconductors Using Active Transistors	493
12.5.1	CMOS Pair	493
12.5.2	Constant Sum of Gate-Source Voltages	494
12.5.3	Source-Connected Differential Pair	495
12.5.4	Inverter-Based	495
12.5.5	Differential-Pair with Floating Voltage Sources	497
12.5.6	Bias-Offset Cross-Coupled Differential Pairs	499
12.6	Bipolar Transconductors	500
12.6.1	Gain-Cell Transconductors	500
12.6.2	Transconductors Using Multiple Differential Pairs	501

12.7	BiCMOS Transconductors	506
12.7.1	Tunable MOS in Triode	506
12.7.2	Fixed-Resistor Transconductor with a Translinear Multiplier	507
12.7.3	Fixed Active MOS Transconductor with a Translinear Multiplier	508
12.8	Active RC and MOSFET-C Filters	509
12.8.1	Active RC Filters	510
12.8.2	MOSFET-C Two-Transistor Integrators	512
12.8.3	Four-Transistor Integrators	515
12.8.4	R-MOSFET-C Filters	521
12.9	Tuning Circuitry	516
12.9.1	Tuning Overview	517
12.9.2	Constant Transconductance	519
12.9.3	Frequency Tuning	520
12.9.4	Q-Factor Tuning	522
12.9.5	Tuning Methods Based on Adaptive Filtering	523
12.10	Introduction to Complex Filters	525
12.10.1	Complex Signal Processing	525
12.10.2	Complex Operations	526
12.10.3	Complex Filters	527
12.10.4	Frequency-Translated Analog Filters	528
12.11	Key Points	531
12.12	References	532
12.13	Problems	534

CHAPTER 13 DISCRETE-TIME SIGNALS**537**

13.1	Overview of Some Signal Spectra	537
13.2	Laplace Transforms of Discrete-Time Signals	537
13.2.1	Spectra of Discrete-Time Signals	540
13.3	z-Transform	541
13.4	Downsampling and Upsampling	543
13.5	Discrete-Time Filters	545
13.5.1	Frequency Response of Discrete-Time Filters	545
13.5.2	Stability of Discrete-Time Filters	548
13.5.3	IIR and FIR Filters	550
13.5.4	Bilinear Transform	550
13.6	Sample-and-Hold Response	552
13.7	Key Points	554
13.8	References	555
13.9	Problems	555

CHAPTER 14 SWITCHED-CAPACITOR CIRCUITS**557**

14.1	Basic Building Blocks	557
14.1.1	Opamps	557

14.1.2	Capacitors	558
14.1.3	Switches	558
14.1.4	Nonoverlapping Clocks	559
14.2	Basic Operation and Analysis	560
14.2.1	Resistor Equivalence of a Switched Capacitor	560
14.2.2	Parasitic-Sensitive Integrator	560
14.2.3	Parasitic-Insensitive Integrators	565
14.2.4	Signal-Flow-Graph Analysis	569
14.3	Noise in Switched-Capacitor Circuits	570
14.4	First-Order Filters	572
14.4.1	Switch Sharing	575
14.4.2	Fully Differential Filters	575
14.5	Biquad Filters	577
14.5.1	Low-Q Biquad Filter	577
14.5.2	High-Q Biquad Filter	581
14.6	Charge Injection	585
14.7	Switched-Capacitor Gain Circuits	588
14.7.1	Parallel Resistor-Capacitor Circuit	588
14.7.2	Resettable Gain Circuit	588
14.7.3	Capacitive-Reset Gain Circuit	591
14.8	Correlated Double-Sampling Techniques	593
14.9	Other Switched-Capacitor Circuits	594
14.9.1	Amplitude Modulator	594
14.9.2	Full-Wave Rectifier	595
14.9.3	Peak Detectors	596
14.9.4	Voltage-Controlled Oscillator	596
14.9.5	Sinusoidal Oscillator	598
14.10	Key Points	600
14.11	References	601
14.12	Problems	602

CHAPTER 15 DATA CONVERTER FUNDAMENTALS**606**

15.1	Ideal D/A Converter	606
15.2	Ideal A/D Converter	608
15.3	Quantization Noise	609
15.3.1	Deterministic Approach	609
15.3.2	Stochastic Approach	610
15.4	Signed Codes	612
15.5	Performance Limitations	614
15.5.1	Resolution	614
15.5.2	Offset and Gain Error	615
15.5.3	Accuracy and Linearity	615
15.6	Key Points	620
15.7	References	620
15.8	Problems	620

CHAPTER 16 NYQUIST-RATE D/A CONVERTERS**623**

- 16.1 Decoder-Based Converters 623
 - 16.1.1 Resistor String Converters 623
 - 16.1.2 Folded Resistor-String Converters 625
 - 16.1.3 Multiple Resistor-String Converters 625
 - 16.1.4 Signed Outputs 627
- 16.2 Binary-Scaled Converters 628
 - 16.2.1 Binary-Weighted Resistor Converters 629
 - 16.2.2 Reduced-Resistance-Ratio Ladders 630
 - 16.2.3 R-2R-Based Converters 630
 - 16.2.4 Charge-Redistribution Switched-Capacitor Converters 632
 - 16.2.5 Current-Mode Converters 633
 - 16.2.6 Glitches 633
- 16.3 Thermometer-Code Converters 634
 - 16.3.1 Thermometer-Code Current-Mode D/A Converters 636
 - 16.3.2 Single-Supply Positive-Output Converters 637
 - 16.3.3 Dynamically Matched Current Sources 638
- 16.4 Hybrid Converters 640
 - 16.4.1 Resistor-Capacitor Hybrid Converters 640
 - 16.4.2 Segmented Converters 640
- 16.5 Key Points 642
- 16.6 References 643
- 16.7 Problems 643

CHAPTER 17 NYQUIST-RATE A/D CONVERTERS**646**

- 17.1 Integrating Converters 646
- 17.2 Successive-Approximation Converters 650
 - 17.2.1 DAC-Based Successive Approximation 652
 - 17.2.2 Charge-Redistribution A/D 653
 - 17.2.3 Resistor-Capacitor Hybrid 658
 - 17.2.4 Speed Estimate for Charge-Redistribution Converters 658
 - 17.2.5 Error Correction in Successive-Approximation Converters 659
 - 17.2.6 Multi-Bit Successive-Approximation 662
- 17.3 Algorithmic (or Cyclic) A/D Converter 662
 - 17.3.1 Ratio-Independent Algorithmic Converter 662
- 17.4 Pipelined A/D Converters 665
 - 17.4.1 One-Bit-Per-Stage Pipelined Converter 667
 - 17.4.2 1.5 Bit Per Stage Pipelined Converter 669
 - 17.4.3 Pipelined Converter Circuits 672
 - 17.4.4 Generalized k-Bit-Per-Stage Pipelined Converters 673
- 17.5 Flash Converters 673
 - 17.5.1 Issues in Designing Flash A/D Converters 675
- 17.6 Two-Step A/D Converters 677
 - 17.6.1 Two-Step Converter with Digital Error Correction 679
- 17.7 Interpolating A/D Converters 680

17.8	Folding A/D Converters	683
17.9	Time-Interleaved A/D Converters	687
17.10	Key Points	690
17.11	References	691
17.12	Problems	692

CHAPTER 18 OVERSAMPLING CONVERTERS**696**

18.1	Oversampling without Noise Shaping	696
18.1.1	Quantization Noise Modelling	697
18.1.2	White Noise Assumption	697
18.1.3	Oversampling Advantage	699
18.1.4	The Advantage of 1-Bit D/A Converters	701
18.2	Oversampling with Noise Shaping	702
18.2.1	Noise-Shaped Delta-Sigma Modulator	703
18.2.2	First-Order Noise Shaping	704
18.2.3	Switched-Capacitor Realization of a First-Order A/D Converter	706
18.2.4	Second-Order Noise Shaping	706
18.2.5	Noise Transfer-Function Curves	708
18.2.6	Quantization Noise Power of 1-Bit Modulators	709
18.2.7	Error-Feedback Structure	709
18.3	System Architectures	711
18.3.1	System Architecture of Delta-Sigma A/D Converters	711
18.3.2	System Architecture of Delta-Sigma D/A Converters	713
18.4	Digital Decimation Filters	714
18.4.1	Multi-Stage	715
18.4.2	Single Stage	717
18.5	Higher-Order Modulators	718
18.5.1	Interpolative Architecture	718
18.5.2	Multi-Stage Noise Shaping (MASH) Architecture	719
18.6	Bandpass Oversampling Converters	721
18.7	Practical Considerations	722
18.7.1	Stability	722
18.7.2	Linearity of Two-Level Converters	723
18.7.3	Idle Tones	725
18.7.4	Dithering	726
18.7.5	Opamp Gain	726
18.8	Multi-Bit Oversampling Converters	727
18.8.1	Dynamic Element Matching	727
18.8.2	Dynamically Matched Current Source D/S Converters	728
18.8.3	Digital Calibration A/D Converter	728
18.8.4	A/D with Both Multi-Bit and Single-Bit Feedback	729
18.9	Third-Order A/D Design Example	730
18.10	Key Points	732
18.11	References	734
18.12	Problems	735

CHAPTER 19 PHASE-LOCKED LOOPS**738**

- 19.1 Basic Phase-Locked Loop Architecture 738
 - 19.1.1 Voltage Controlled Oscillator 739
 - 19.1.2 Divider 740
 - 19.1.3 Phase Detector 741
 - 19.1.4 Loop Filter 746
 - 19.1.5 The PLL in Lock 747
- 19.2 Linearized Small-Signal Analysis 748
 - 19.2.1 Second-Order PLL Model 749
 - 19.2.2 Limitations of the Second-Order Small-Signal Model 751
 - 19.2.3 PLL Design Example 754
- 19.3 Jitter and Phase Noise 756
 - 19.3.1 Period Jitter 760
 - 19.3.2 P-Cycle Jitter 761
 - 19.3.3 Adjacent Period Jitter 761
 - 19.3.4 Other Spectral Representations of Jitter 762
 - 19.3.5 Probability Density Function of Jitter 764
- 19.4 Electronic Oscillators 765
 - 19.4.1 Ring Oscillators 766
 - 19.4.2 LC Oscillators 771
 - 19.4.3 Phase Noise of Oscillators 772
- 19.5 Jitter and Phase Noise in PLLS 777
 - 19.5.1 Input Phase Noise and Divider Phase Noise 777
 - 19.5.2 VCO Phase Noise 778
 - 19.5.3 Loop Filter Noise 779
- 19.6 Key Points 781
- 19.7 References 782
- 19.8 Problems 782

INDEX**787**

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