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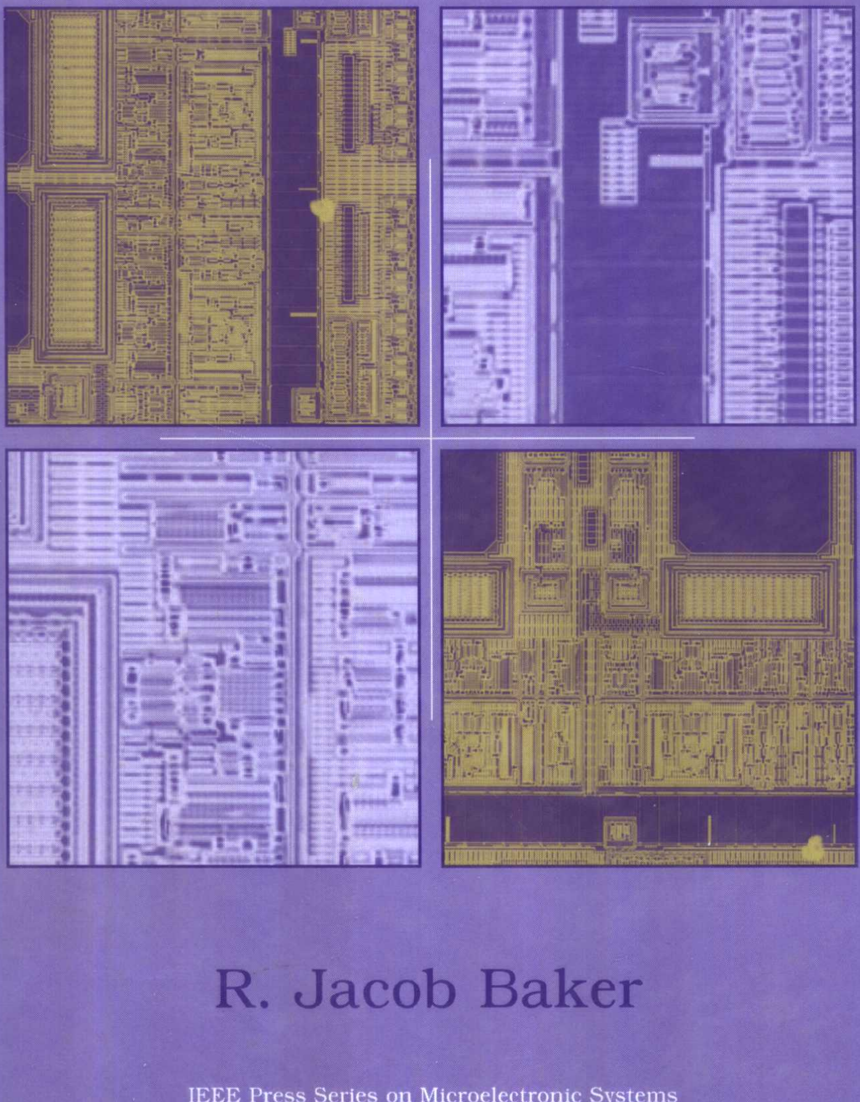

R. Jacob Baker

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CMOS
Mixed-Signal Circuit Design

R. Jacob Baker

Volume II of CMOS: Circuit Design, Layout, and Simulation

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To

Julie, Kyri, and Josh

Preface to Volume II

Why a second volume? Why not write a separate, unassociated, book covering mixed-signal circuit design? The answer to these questions comes from my desire to keep from duplicating material available in *CMOS Circuit Design, Layout, and Simulation* (the, sometimes affectionately called, "purple" book containing the first 29 chapters). My goal, when writing this second volume, was to provide a quality textbook and reference that contains material that isn't covered in other textbooks and to couple this material with online learning aids. The supporting companion website, **http://cmosedu.com**, provides worked solutions to the problems, SPICE simulation netlist examples, and discussions concerning mixed-signal circuit design.

Book Organization

The power of a mixed-signal circuit design, and perhaps the reason they are replacing analog-only designs in the implementation of analog interfaces, comes from the marriage of analog circuits with digital signal processing. Chapter 30 uses the topic of data converter modeling as a vehicle to illustrate some fundamental signal processing topics. In addition, models are developed to aid in the understanding of quantization noise. Chapter 31 discusses signal-to-noise ratio (SNR) and ways of improving SNR using filtering (averaging). The chapter provides a practical discussion of some of the basic tools the mixed-signal designer uses to improve SNR. Decimation, interpolation, and feedback (and the concept of pushing quantization noise to higher-frequencies, i.e., noise-shaping, so that it can be filtered out using a digital filter) are also discussed. Because of the importance of noise-shaping to the design of analog interfaces Ch. 32 is devoted entirely to noise-shaping data converters (often called delta-sigma or sigma-delta data converters). The presentation mixes theory with practical implementations and examples to illustrate the operation of these data converters.

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Chapter 33 covers circuit design using submicron CMOS devices. This chapter was born, in part, after I was asked, "Why didn't you use a more modern CMOS process in the purple book?" Submicron devices don't follow the square-law MOSFET model and so hand calculations based on equations derived from the square-law models are somewhat meaningless. I quickly realized, however, that many designers don't do hand calculations and so the significant deviations between long- and short-channel behavior aren't readily apparent. Similarly, students are often asked to compare their hand calculations to SPICE simulation results using the level 1 model. Of course, the simulations and hand calculations match but have little, if anything, to do with the performance of the submicron CMOS circuits in actual silicon.

At the risk of stating the obvious, accurate models for submicron CMOS devices are extremely important. In Ch. 33 the EKV model is used. The EKV model does a good job of modeling the device's transition from weak to strong inversion. This is important when simulating modern data converter or mixed-signal circuits where the threshold voltage doesn't scale with the power supply voltage (i.e., the circuitry is operating a larger percentage of the time in the subthreshold region). As seen in Ch. 33, hand calculations can be performed with transconductance or output resistance values read off of plots generated experimentally or from simulations using the accurate EKV model.

Chapter 34 covers the implementation of data converters. Its purpose is to provide ideas and discussions for implementing the data converter topologies discussed in Ch. 29. Matching, offsets, gains, bandwidths, and topologies are discussed to provide insight into the design of Nyquist rate data converters.

Chapter 35 covers the design of integrated filters. This topic is a book in itself so I've picked the most relevant subjects and attempted to provide practical insight useful when implementing the filters in CMOS technology. The material is complete and useful enough so that, once the material in the chapter is understood, the reader should have little difficulty understanding the merits or trade-offs of any filtering topology. A special twist on the material is the way the topic of digital filtering is presented (hopefully, it is very practical).

Significant effort, in these first six chapters, has been put into integrating theory and examples with simulation results (using actual numbers, i.e., not just symbolic representations). The reader serious about learning the material will find the ability to modify a simulation netlist (downloaded from http://cmosedu.com) and look at the resulting output a very useful learning tool. However, while hand calculations and simulations are very important when learning and designing CMOS circuits, equally, if not more, important is the actual building and testing of the mixed-signal circuits. Chapter 36 provides some examples of actual circuits built "at the bench" to provoke thought and interest. The hope is that instead of just simulating a design, the engineer/student may also want to build and test a representation of the circuit using discrete components. While these discrete circuits won't provide an exact representation of the actual integrated circuits, they can provide insight into the limitations of a particular design. They can also be used to get aquainted with the test equipment and the possible loading that might be introduced into the circuit when probing.

Acknowledgments

Finally, and perhaps most importantly, I would like to thank the reviewers, contributors, colleagues, and (especially!) students who helped make this book possible: Jake Anderson, Brian Bergeson, Tom Bernhard, Kurt Beigel, Jan Bissey, Bill Black, Ken Boorom (special thanks for the very detailed reviews), Dave Boyce, Liz Brauer, Joe Brewer, Curtis Cahoon, Mansun Chan, John Chen, Cathy Faduska, Chris Fayomi, Ed Fong, Dan Foty, Rich Friel, Paul Furth, Randy Geiger, David Goldman, Neil Goldsman, Tyler Gomm, Mike Green, John Griffin, Joe Hartman, Francis Heck, Rick Hilton, Gexin Huang, Glen Hush, Pandurang Irkar, Alok Jain, Brent Keeth, Christy Kuhnen, Harry Li, Yantao Ma, Paul Mason, Mary Miller, Bob Moehrke, Ken Moore, Sugato Mukherjee, Fred Perner, Adrian Ong, Zuxu Qin, Jeremy Rice, Ben Rivera, Brandon Roth, Savang Sengkhamyong, Mir Seyyedy, Brian Shirley, Joseph P. Skudlarek, Jim Slupe, Ken Smith, Mike Smith (special thanks for WinSPICE), Liu Song, Stuart Tewksbury, Lisa Van Horn, Tony VenGraitis, and Tom Voshell.

Boise, ID, January 2002 R. Jacob (Jake) Baker

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Chapter 30

Data Converter Modeling

In this chapter we continue our discussion of data converters by discussing methods to model ideal data converters and their components using SPICE. The main goal of this chapter is to provide tools for evaluating mixed-signal designs with large complexity, which can be used in design evaluation and later in the book. In particular, we will generate SPICE models, using behavioral elements, for ideal analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) blocks. This allows us to analyze the performance of a mixed-signal circuit block in a SPICE simulation within a reasonable amount of time. For example, if we have designed a DAC at the transistor level and want to use SPICE to simulate its operation, under various temperatures and matching conditions, we may apply a digital input code generated from our ideal ADC with a sinewave input as seen in Fig. 30.1. Similarly, given a digital signal processing (DSP) system, we can drop our ideal DAC into the simulation at any point where there is a digital word and get an analog waveform output.

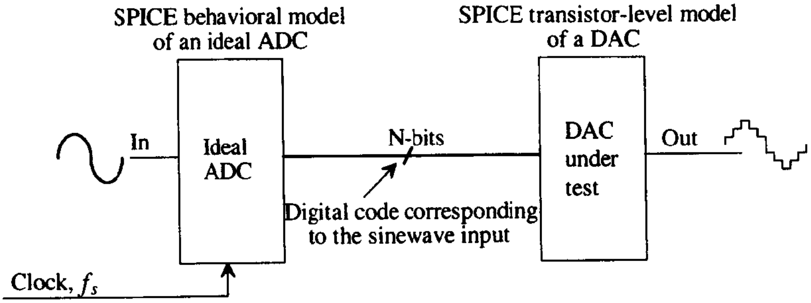


Figure 30.1 Generating the sinewave digital code for DAC simulation with an ideal ADC.

Also, in this chapter we look at how the analog-to-digital and digital-to-analog conversion process affects the signals in the system. Figure 30.2 shows the basic conversion process. We will make extensive use of the spectral analysis capability (discrete fourier transform or DFT) available in SPICE to look at the digital data (and analog signals) in the frequency domain.

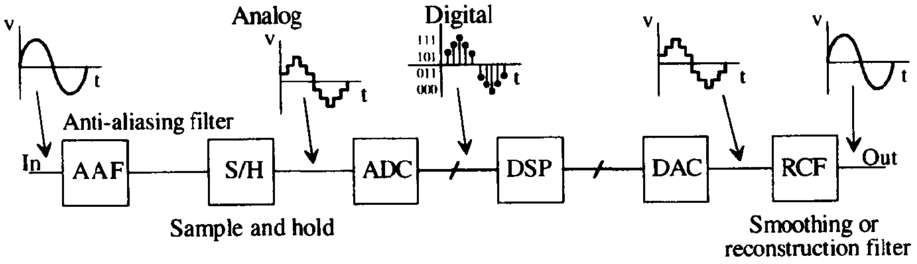


Figure 30.2 Signals resulting from A/D and D/A conversion in a mixed-signal system.

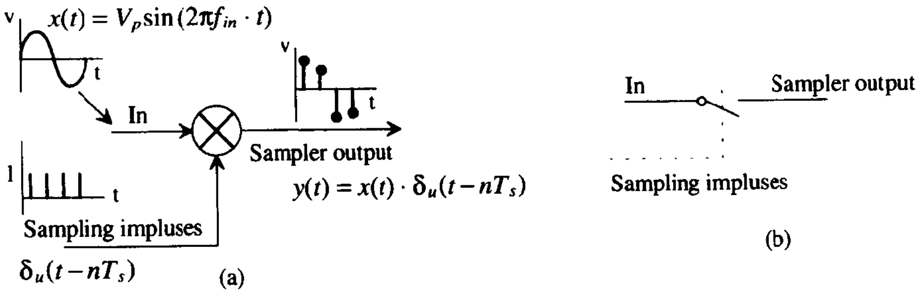
30.1 Sampling and Aliasing: A Modeling Approach

In this section we discuss how sampling a signal changes the signal's spectrum. We also discuss how to model the sampling process in SPICE.

30.1.1 Impulse Sampling

Consider the simple sampling gate shown in Fig. 30.3a. Let's assume we apply a sinewave input, $x(t)$, to this sampling gate of the form, $V_p \sin(2\pi f_{in} \cdot t)$ (for the moment, a single frequency input). The output of the sampling gate (a.k.a. sampler), $y(t)$, is the product of the input and a sampling unit impulse signal or

$$y(t) = \sum_{n=-\infty}^{\infty} V_p \sin(2\pi f_{in} \cdot nT_s) \cdot \delta_u(t - nT_s) \qquad (30.1)$$



(a) (b)

Figure 30.3 (a) Simple sampling gate and (b) SPICE implementation of a sampling gate.

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