## Design of CMOS Phase-Locked Loops

Using a modern, pedagogical approach, this textbook gives students and engineers a comprehensive and rigorous knowledge of CMOS PLL design for a wide range of applications. It features intuitive presentation of theoretical concepts, built up gradually from their simplest form to more practical systems; broad coverage of key topics, including oscillators, phase noise, analog PLLs, digital PLLs, RF synthesizers, delay-locked loops, clock and data recovery circuits, and frequency dividers; tutorial chapters on high-performance oscillator design, covering fundamentals to advanced topologies; and extensive use of circuit simulations to teach design mentality, highlight design flaws, and connect theory with practice. Offering over 200 thought-provoking examples that demonstrate best practices and common pitfalls, 250 end-of-chapter homework problems to test and enhance the readers' understanding, and solutions and lecture slides for instructors, this is the perfect text for senior undergraduate and graduate-level students and professional engineers who want an in-depth understanding of PLL design.

**Behzad Razavi** is Professor of Electrical Engineering at The University of California, Los Angeles. He has received numerous teaching and education awards, and is a member of the US National Academy of Engineering and a Fellow of the IEEE. His previous textbooks include *Fundamentals of Microelectronics, RF Microelectronics* and *Design of Analog CMOS Integrated Circuits.*

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## From Circuit Level to Architecture Level

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**To my brother Hossein,**
**who has always been there for me**

# Contents

# Preface

A quick search on Google brings up nearly two dozen books on PLLs. So why another one? This book addresses the need for a text that methodically teaches modern CMOS PLLs for a wide range of applications. The objective is to teach the reader how to approach PLLs from transistor-level design to architecture development.

Based on 25 years of teaching courses on the subject and the latest trends in industry, this book deals with oscillators, phase noise, analog phase-locked loops, digital phase-locked loops, RF synthesizers, delay-locked loops, clock and data recovery circuits, and frequency dividers. The objective is to reach a broad spectrum of readers while maintaining a cohesive flow.

As with my past writings, I have implemented a multitude of pedagogical tools to help the reader learn efficiently—and experience the pleasure of learning. One principle that I uphold in writing is to start with the simplest possible arrangement, teach how it works and what shortcomings it has, and then add components to it to improve its performance. This approach allows the reader to see how a basic architecture evolves to a complex system. After laying the theoretical foundation for each topic, I present a step-by-step design flow and proceed to design the circuit.

And not all design efforts are successful. The reader can clearly see how certain decisions lead to a dead end and how we revise these decisions to reach a new, more practical solution. This exploratory mentality not only makes the process of learning more exciting but also helps the reader see why each component is necessary, what criteria govern its choice, and what not to do.

A unique aspect of this book is its extensive use of simulations to teach design and investigate agreement between theory and practice. For each design, I use the theoretical basis to choose certain parameters and predict the performance, and then I simulate the circuit. If the simulation results do not agree with the predictions, I delve into the details and determine why. Another unique aspect of this book is that it leverages concepts from one field (e.g., wireless technology) to another (e.g., wireline communications) by bringing the vast knowledge in these fields under one roof.

A website for the book provides additional resources for readers and instructors, including Powerpoint slides and a solutions manual.

Behzad Razavi
September 2019

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My wife, Angelina, typed the entire book. I am very grateful to her.

Behzad Razavi

# About the Author

Behzad Razavi received the BSEE degree from Sharif University of Technology in 1985 and the MSEE and PhDEE degrees from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since 1996, he has been Associate Professor and subsequently Professor of electrical engineering at University of California, Los Angeles. His current research includes wireless and wireline transceivers and data converters.

Professor Razavi was an Adjunct Professor at Princeton University from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committees of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and VLSI Circuits Symposium from 1998 to 2002. He has also served as Guest Editor and Associate Editor of the *IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems,* and *International Journal of High Speed Electronics*. He presently serves as the Editor-in-Chief of the *IEEE Solid-State Circuits Letters*.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC, the best paper award at the 1994 European Solid-State Circuits Conference, the best panel award at the 1995 and 1997 ISSCC, the TRW Innovative Teaching Award in 1997, the best paper award at the IEEE Custom Integrated Circuits Conference in 1998, and the McGraw-Hill First Edition of the Year Award in 2001. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He received the Lockheed Martin Excellence in Teaching Award in 2006, the UCLA Faculty Senate Teaching Award in 2007, and the CICC Best Invited Paper Award in 2009 and in 2012. He was the co-recipient of the 2012 and the 2015 VLSI Circuits Symposium Best Student Paper Awards and the 2013 CICC Best Paper Award. He was also recognized as one of the top 10 authors in the 50-year history of ISSCC. He received the 2012 Donald Pederson Award in Solid-State Circuits. He was also the recipient of the American Society for Engineering Education PSW Teaching Award in 2014. Professor Razavi is a member of the US National Academy of Engineering. He received the 2017 IEEE CAS John Choma Education Award.

Professor Razavi has served as an IEEE Distinguished Lecturer and is a Fellow of IEEE. He is the author of *Principles of Data Conversion System Design* (IEEE Press, 1995), *RF Microelectronics* (Prentice Hall, 1998, 2012) (translated to Chinese, Japanese, and Korean), *Design of Analog CMOS Integrated Circuits* (McGraw-Hill, 2001, 2016) (translated to Chinese, Japanese, and Korean), *Design of Integrated Circuits for Optical Communications* (McGraw-Hill, 2003, Wiley, 2012), and *Fundamentals of Microelectronics* (Wiley, 2006) (translated to Korean, Portuguese, and Turkish), and the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* (IEEE Press, 1996), and *Phase-Locking in High-Performance Systems* (IEEE Press, 2003).