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Built-in-Self-Test and Digital Self-Calibration for RF SoCs

 Springer

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To my loving family

Sleiman Bou-Sleiman

*To the memory of my father,
Ismail El-Naggar*

Mohammed Ismail

Preface

Single-chip radio systems, or Radio Frequency System-on-Chips (RF SoC), have become increasingly popular in recent years driven by the many aspects and intersections of technology, market demands, and consumer needs. Consumers now expect flawless and seamless communication capabilities in their increasingly connected world. Satisfying these demands is contingent on the abilities of scientists and engineers to continually advance the state-of-the-art in microelectronics processes and circuit designs. On the technology side, the improvements in silicon MOS have enabled high performance and highly integrated circuits, taking CMOS from a purely digital to a mixed-mode technology. For companies, the ability to provide platforms and systems built around a common technology, in smaller form factors and with more horsepower is a critical aspect of their survival in a deeply competitive market. The successful merge of the latest technology with the best design practices is the catalyst to first time design success.

The continual physical shrinking of device dimensions is allowing for more integration between the previously segmented digital logic, memory, analog, and radio frequency domains. While this co-existence may indicate a cost reduction on paper, in reality it might well turn out in the red. The smaller device sizes, while faster, are becoming increasingly unreliable. Although able to meet the performance requirements for high-speed analog and RF, the devices are not guaranteed to always run at their typical sweet spot. The drifts from the optimal operation are due to many factors related to the silicon process and its response to changes in voltage and temperature, or what is collectively named *PVT* (Process, Voltage, Temperature) variations. These variations are a problem in all the integrated domains of the chip; however, RF and millimeter-wave (mm-wave) circuits fail, in a more disproportionate manner, at sustaining proper operation over *PVT*. The reason being that RF devices, unlike digital circuits, do not function exclusively as on-off switches at either edges of operation but also exercise all the continuous states in between, and at very high frequencies. This makes them more prone to performance degradations and loss of yield when fabricated, in contrast to digital chips that can achieve near perfect yield. Putting both RF and digital together on a single chip, the hybrid system obviously inherits the lower yield, negating all the integration advantages.

Therefore, the RF portions, in a sense, represent the SoC's Achilles' heel; in essence, an overly powerful and densely integrated chip can be made useless by a smaller underperforming portion of the chip.

The ultimate goal is to increase the functional yield of the RF blocks by actively maintaining them in their optimal operating region. This proves to be a non-trivial task, as the operating conditions of the system at all times need to be known. While fabrication testing is one way to test how a chip performs after production, it cannot be all-inclusive of all operating conditions. Moreover, it is quite costly to fully verify each single chip rendering the validation task quite prohibitive. A solution would be to build self-testing, and eventually self-healing, systems. However, this demands a shift in design paradigms to include testing, early on, in the design phase, or what is dubbed as Design-for-Testability (DfT). While DfT's primary goal is to ease external testing of complex chips, an additional upgrade is highly desirable: the integration of the full testing functionality on-chip.

Built-in-Self-Test (BiST) techniques have already established themselves in the validation of digital blocks but are now becoming an increasingly active domain of research and development in RF. The notion of migrating RF test functionality to inside the chip brings us one step closer to cognitive-like radios. Self-awareness in RF systems is therefore a product of efficient on-chip test generation and result acquisition and interpretation. If RF/mm-wave blocks and systems can test for, and extract, their performance, then the ability to calibrate and cancel discrepancies can also be built into the system. Hence, Built-in-Self-Calibration (BiSC) can be layered on top of BiST to result in auto-correcting RF impairments at the block and system levels.

In this book, we discuss both BiST and BiSC in the context of RF SoCs. In Chapter 1, we describe CMOS' roadmap towards RF and mm-wave capabilities. The beneficial and adverse effects of technology scaling are highlighted showing the possibilities of increased integration as well as the problems associated with decreased device and circuit robustness. Chapter 2 describes the basics of communication systems and transceivers, while highlighting the most critical performance issues. System- and block-level metrics are presented along with RF built-in-testing schemes to reduce the costs of production testing. In Chapter 3, we express the requirements for building efficient true self-test mechanisms using on-chip resources not only as value-added elements but also as necessary components for successful first-pass success of RF and mm-wave SoCs. Simple additional circuits for test are therefore desirable; however, on-chip testing of radio frequency signal needs special attention, as these signals' properties are not easily interpretable. Hence, an efficient RF detector is presented with different implementations covering the RF and mm-wave spectra. In Chapter 4, the detector is used under different built-in-test schemes for parametric extraction of RF blocks. The self-testing of metrics such as gain, linearity, and quadrature mismatch is described with example test-benches and circuits. Chapter 5 takes the proposed on-chip test implementations and uses them to aid in the development of calibration techniques. These techniques aim at leveraging the strengths of the more robust parts of the system to cover up the weaknesses of the others. Therefore, the digital domain is fully

exploited to augment the capabilities of RF circuits by providing them with the digital notion of programmability: an added degree of flexibility and tunability with the goal of enabling performance steering capabilities. Examples of RF Built-in-Self-Calibration using DSP-driven approaches are briefly highlighted and shown to re-adjust a failing circuit's operating conditions.

This book is intended for RF design engineers, system-on-chip design engineers as well as graduate students and researchers in the field. The material strives to present an approach and a description of a process that fits perfectly into the premise of, and promise of, highly performing first-time-right design of RF SoC moving into the nanometer regimes.

The work in this book has its roots in the PhD work of the first author at the Analog VLSI Lab at the Ohio State University. Both authors would like to acknowledge the support of colleagues at the Analog VLSI Lab and Electroscience Laboratory at the Ohio State University.

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Contents

1	Introduction and Motivation.....	1
1.1	The Need for Robust RF and mm-Wave ICs	2
1.1.1	Integration Trends in CMOS.....	2
1.1.2	CMOS Scaling Effects	4
1.1.3	Cost Factors.....	8
1.2	Aim and Scope of this Book	10
	References.....	11
2	Radio Systems Overview: Architecture, Performance, and Built-in-Test.....	13
2.1	Transceiver Architectures	13
2.1.1	Basic Communication System Architecture	14
2.1.2	Heterodyne and Homodyne Configurations.....	15
2.1.3	Quadrature Signal Processing	18
2.1.4	Transceiver Architecture for Multi-Band Multi-Standard SoCs.....	19
2.2	RF System and Block Performance	20
2.2.1	System Metrics.....	20
2.2.2	Component Metrics.....	24
2.3	Integrated Radio and System-on-Chip Testing	30
2.3.1	Built-in-Test Techniques	31
2.4	Summary	34
	References.....	34
3	Efficient Testing for RF SoCs.....	35
3.1	On-Chip Test Migration and Portability	36
3.2	A BiST-Ready RF SoC	38

3.3	RF Amplitude Detectors for RF BiST	40
3.3.1	Detector Requirements.....	40
3.3.2	Detector Architectures	41
3.3.3	Proposed Detector Design.....	41
3.3.4	Implementations for RF and mm-Wave BiST.....	46
3.4	Summary	54
	References.....	54
4	RF Built-in-Self-Test	57
4.1	Specification-based Tests Using the RF Amplitude Detector.....	57
4.1.1	Gain.....	59
4.1.2	Compression Point	60
4.1.3	Intermodulation Distortion.....	60
4.1.4	Quadrature Mismatch.....	61
4.1.5	Isolation and Feedthrough.....	62
4.2	Built-in-Self-Test Demonstration.....	64
4.2.1	Detector Test-Benches	64
4.2.2	LNA as Circuit-Under-Test	66
4.3	Summary	70
	References.....	71
5	RF Built-in-Self-Calibration	73
5.1	RF Block and System Self-Awareness.....	74
5.1.1	Digital Solutions to Analog Impairments	75
5.1.2	Enabling Built-in-Self-Calibration.....	75
5.2	Circuit-Level Tuning.....	78
5.2.1	LNA Calibration.....	78
5.2.2	Mixer Calibration.....	81
5.2.3	IQ Imbalance Calibration.....	82
5.3	Summary	85
	References.....	85
6	Conclusions	87

List of Figures

Fig. 1.1	System-on-Chip: Single-chip radio systems with RF, analog, memory and digital	2
Fig. 1.2	Data rates and ranges of various wireless standards	3
Fig. 1.3	Transistor cut-off frequencies for different processes and geometry nodes	5
Fig. 1.4	Intrinsic and parasitic channel capacitance and resistance per technology node	6
Fig. 1.5	The many contributors to variability in nanometer CMOS technologies	7
Fig. 1.6	The effects of variability and tighter specifications and requirements on yield	8
Fig. 1.7	Moore's observation on the relative manufacturing cost and number of integrated components	9
Fig. 1.8	The opposing trends in transistor cost and lithography tool cost	9
Fig. 2.1	Basic communication system and its constituent blocks	14
Fig. 2.2	The mixer as a frequency conversion block	14
Fig. 2.3	Homodyne and heterodyne frequency conversion	15
Fig. 2.4	The image problem and the need for image rejection	16
Fig. 2.5	An example signal band with dc-free encoding	17
Fig. 2.6	Image problem in direct-conversion architectures	17
Fig. 2.7	Constellation diagrams for various complex modulation schemes	18
Fig. 2.8	Direct conversion transceiver architecture	19
Fig. 2.9	BER versus SNR for various modulation schemes	21
Fig. 2.10	IQ plane with ideal and measured symbol locations	21
Fig. 2.11	Two-tone intermodulation spectrum	23
Fig. 2.12	Linearity characteristics	24
Fig. 2.13	Ideal and nonlinear amplifier effects	25
Fig. 2.14	Nonideal mixer effects	26

Fig. 2.15	PLL block diagram	27
Fig. 2.16	Jitter and phase noise	28
Fig. 2.17	Effects of phase noise on mixing	28
Fig. 2.18	IQ demodulator: effects of amplitude and phase mismatch.....	29
Fig. 2.19	Phase and amplitude imbalance effects on image rejection.....	30
Fig. 2.20	Loopback testing configuration.....	32
Fig. 2.21	Alternate testing: parameter, signature, and specification spaces and their mapping	33
Fig. 2.22	Digitally-assisted analog/RF circuit.....	33
Fig. 3.1	A BiST-ready RF SoC.....	38
Fig. 3.2	RF-to-dc curves for various detectors in literature	43
Fig. 3.3	Proposed detector architecture.....	43
Fig. 3.4	Proposed detector characteristics	44
Fig. 3.5	One- and two-tone transient responses with all tones having same amplitude	45
Fig. 3.6	Pseudo-differential RF amplitude detector core	47
Fig. 3.7	Two-bit programmable voltage bias source	47
Fig. 3.8	Response of microwave amplitude detector at 2.5 GHz	48
Fig. 3.9	Combined continuous linear response of the detector for input frequencies between 0.5 and 9 GHz	48
Fig. 3.10	Square-law and linear regions of the detector response at low RF signal amplitudes.....	48
Fig. 3.11	Deviations of the detector's response due to temperature and process variations	49
Fig. 3.12	Zero-RF re-referencing to increase measurement accuracy	50
Fig. 3.13	mm-Wave amplitude detector core and bias circuits	50
Fig. 3.14	mm-Wave sub-ranged amplitude detector characteristics.....	51
Fig. 3.15	Self-adjusting RF amplitude detector	52
Fig. 3.16	Self-adjusting RF detector modes under different temperature and process variations	53
Fig. 3.17	Maximum detection errors (Monte Carlo simulations) across the amplitude range.....	53
Fig. 4.1	BiST-ready SoC architecture with the important measurement points along the transceiver.....	58
Fig. 4.2	Setup for one-tone test for gain measurement	59
Fig. 4.3	Two-tone test setup and IM3 measurement	61
Fig. 4.4	Quadrature amplitude and phase mismatch measurement.....	62
Fig. 4.5	Downconversion mixer test setup for LO to RF port isolation	63
Fig. 4.6	Upconversion mixer test setup for LO feedthrough.....	64
Fig. 4.7	RF detector output and mapped output amplitude in response to a two-tone input with varying IM3 component	65
Fig. 4.8	Predicted versus actual IM3 amplitude.....	66
Fig. 4.9	Phase imbalance prediction versus the actual imbalance (<i>left axis</i>); prediction error in degrees (<i>right axis</i>)	67

Fig. 4.10	2.4 GHz LNA gain extraction: actual versus predicted gain curve	67
Fig. 4.11	60 GHz LNA used for mm-wave BiST.....	68
Fig. 4.12	Effect of the mm-wave detectors on the LNA characteristics: with and without	68
Fig. 4.13	Actual and predicted gain curve after one-tone test sweep.....	69
Fig. 4.14	Third order intermodulation extraction and IIP3 measurement.....	70
Fig. 5.1	Self-calibration loop and its components.....	76
Fig. 5.2	Digitally-assisted RF and mm-wave circuits implemented with wide operation flexibility and ranges always containing the optimal operation point	77
Fig. 5.3	Iterative calibration algorithm with changing PVT conditions.....	77
Fig. 5.4	LNA with digital calibration for input match and output load tuning	80
Fig. 5.5	Transient snapshot of LNA calibration routine and the corresponding RF amplitude detector dc output	81
Fig. 5.6	Double-balanced CMOS mixer with digital tuning knobs for gain and linearity calibration	82
Fig. 5.7	Basic farrow filter structure.....	84
Fig. 5.8	Mixed-mode IQ imbalance compensation	84
Fig. 5.9	Test tone demodulation: quadrature phase mismatch before and after compensation	84

List of Tables

Table 1.1	CMOS technology roadmap	5
Table 1.2	Threshold voltage variability	7
Table 3.1	Important transceiver parameters to measure	39
Table 3.2	RF detectors in literature	42
Table 3.3	Comparison of the implemented RF amplitude detectors	54
Table 4.1	Test setups for the various RF blocks	58
Table 4.2	Actual versus predicted parameters for the 60 GHz LNA.....	70

