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RF/MICROWAVE CIRCUIT DESIGN FOR WIRELESS APPLICATIONS

RF/MICROWAVE CIRCUIT DESIGN FOR WIRELESS APPLICATIONS

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To Professor Vittorio Rizzoli

who has been instrumental in the development of the powerful harmonic-balance analysis tool, specifically Microwave Harmonica, which is part of Ansoft's Serenade Design Environment. Most of the success enjoyed by Compact Software, now part of Ansoft, continues to be based on his far-reaching contributions.

CONTENTS

Foreword	xiii
Preface	xv
1 Introduction to Wireless Circuit Design	1
1-1 Overview / 1	
1-2 System Functions / 3	
1-3 The Radio Channel and Modulation Requirements / 5	
1-3-1 Introduction / 5	
1-3-2 Channel Impulse Response / 7	
1-3-3 Doppler Effect / 13	
1-3-4 Transfer Function / 14	
1-3-5 Time Response of Channel Impulse Response and Transfer Function / 14	
1-3-6 Lessons Learned / 17	
1-3-7 Wireless Signal Example: The TDMA System in GSM / 18	
1-4 About Bits, Symbols, and Waveforms / 29	
1-4-1 Introduction / 29	
1-4-2 Some Fundamentals of Digital Modulation Techniques / 38	
1-5 Analysis of Wireless Systems / 47	
1-5-1 Analog and Digital Receiver Designs / 47	
1-5-2 Transmitters / 58	
1-6 Building Blocks / 81	
1-7 System Specifications and Their Relationship to Circuit Design / 83	
1-7-1 System Noise and Noise Floor / 83	
1-7-2 System Amplitude and Phase Behavior / 88	
1-8 Testing / 114	
1-8-1 Introduction / 114	
1-8-2 Transmission and Reception Quality / 114	
1-8-3 Base-Station Simulation / 118	
1-8-4 GSM / 118	

1-8-5 DECT / 118

1-9 Converting C/N or SNR to E_b/N_0 / 120**2 Models for Active Devices****123**

2-1 Diodes / 124

2-1-1 Large-Signal Diode Model / 124

2-1-2 Mixer and Detector Diodes / 128

2-1-3 PIN Diodes / 135

2-1-4 Tuning Diodes / 153

2-2 Bipolar Transistors / 198

2-2-1 Transistor Structure Types / 198

2-2-2 Large-Signal Behavior of Bipolar Transistors / 199

2-2-3 Large-Signal Transistors in the Forward-Active Region / 209

2-2-4 Effects of Collector Voltage on Large-Signal Characteristics in the Forward-Active Region / 225

2-2-5 Saturation and Inverse Active Regions / 227

2-2-6 Small-Signal Models of Bipolar Transistors / 232

2-3 Field-Effect Transistors / 237

2-3-1 Large-Signal Behavior of JFETs / 246

2-3-2 Small-Signal Behavior of JFETs / 249

2-3-3 Large-Signal Behavior of MOSFETs / 254

2-3-4 Small-Signal Model of the MOS Transistor in Saturation / 262

2-3-5 Short-Channel Effects in FETs / 266

2-3-6 Small-Signal Models of MOSFETs / 271

2-3-7 GaAs MESFETs / 301

2-3-8 Small-Signal GaAs MESFET Model / 310

2-4 Parameter Extraction of Active Devices / 322

2-4-1 Introduction / 322

2-4-2 Typical SPICE Parameters / 322

2-4-3 Noise Modeling / 323

2-4-4 Scalable Device Models / 333

2-4-5 Conclusions / 348

2-4-6 Device Libraries / 359

2-4-7 A Novel Approach for Simulation at Low Voltage and Near Pinchoff Voltage / 359

2-4-8 Example: Improving the BFR193W Model / 370

3 Amplifier Design with BJTs and FETs**375**

3-1 Properties of Amplifiers / 375

3-1-1 Introduction / 375

3-1-2 Gain / 380

3-1-3 Noise Figure (NF) / 385

3-1-4 Linearity / 415

3-1-5 AGC / 431

3-1-6 Bias and Power Voltage and Current (Power Consumption) / 436

- 3-2 Amplifier Gain, Stability, and Matching / 441
 - 3-2-1 Scattering Parameter Relationships / 442
 - 3-2-2 Low-Noise Amplifiers / 448
 - 3-2-3 High-Gain Amplifiers / 466
 - 3-2-4 Low-Voltage Open-Collector Design / 477
- 3-3 Single-Stage FeedBack Amplifiers / 490
 - 3-3-1 Lossless or Noiseless Feedback / 495
 - 3-3-2 Broadband Matching / 496
- 3-4 Two-Stage Amplifiers / 497
- 3-5 Amplifiers with Three or More Stages / 507
 - 3-5-1 Stability of Multistage Amplifiers / 512
- 3-6 A Novel Approach to Voltage-Controlled Tuned Filters Including CAD Validation / 513
 - 3-6-1 Diode Performance / 513
 - 3-6-2 A VHF Example / 516
 - 3-6-3 An HF/VHF Voltage-Controlled Filter / 518
 - 3-6-4 Improving the VHF Filter / 521
 - 3-6-5 Conclusion / 521
- 3-7 Differential Amplifiers / 522
- 3-8 Frequency Doublers / 526
- 3-9 Multistage Amplifiers with Automatic Gain Control (AGC) / 532
- 3-10 Biasing / 534
 - 3-10-1 RF Biasing / 543
 - 3-10-2 dc Biasing / 543
 - 3-10-3 dc Biasing of IC-Type Amplifiers / 547
- 3-11 Push–Pull/Parallel Amplifiers / 547
- 3-12 Power Amplifiers / 550
 - 3-12-1 Example 1: 7-W Class C BJT Amplifier for 1.6 GHz / 550
 - 3-12-2 Impedance Matching Networks Applied to RF Power Transistors / 565
 - 3-12-3 Example 2: Low-Noise Amplifier Using Distributed Elements / 585
 - 3-12-4 Example 3: 1-W Amplifier Using the CLY15 / 589
 - 3-12-5 Example 4: 90-W Push–Pull BJT Amplifier at 430 MHz / 598
 - 3-12-6 Quasiparallel Transistors for Improved Linearity / 600
 - 3-12-7 Distribution Amplifiers / 602
 - 3-12-8 Stability Analysis of a Power Amplifier / 602
- 3-13 Power Amplifier Datasheets and Manufacturer-Recommended Applications / 611

4 Mixer Design

636

- 4-1 Introduction / 636
- 4-2 Properties of Mixers / 639
 - 4-2-1 Conversion Gain/Loss / 639
 - 4-2-2 Noise Figure / 641
 - 4-2-3 Linearity / 645
 - 4-2-4 LO Drive Level / 647

x CONTENTS

- 4-2-5 Interport Isolation / 647
- 4-2-6 Port VSWR / 647
- 4-2-7 dc Offset / 647
- 4-2-8 dc Polarity / 649
- 4-2-9 Power Consumption / 649
- 4-3 Diode Mixers / 649
 - 4-3-1 Single-Diode Mixer / 650
 - 4-3-2 Single-Balanced Mixer / 652
 - 4-3-3 Diode-Ring Mixer / 659
- 4-4 Transistor Mixers / 678
 - 4-4-1 BJT Gilbert Cell / 679
 - 4-4-2 BJT Gilbert Cell with Feedback / 682
 - 4-4-3 FET Mixers / 684
 - 4-4-4 MOSFET Gilbert Cell / 693
 - 4-4-5 GaAsFET Single-Gate Switch / 694

5 RF/Wireless Oscillators

716

- 5-1 Introduction to Frequency Control / 716
- 5-2 Background / 716
- 5-3 Oscillator Design / 719
 - 5-3-1 Basics of Oscillators / 719
- 5-4 Oscillator Circuits / 735
 - 5-4-1 Hartley / 735
 - 5-4-2 Colpitts / 735
 - 5-4-3 Clapp–Gouriet / 736
- 5-5 Design of RF Oscillators / 736
 - 5-5-1 General Thoughts on Transistor Oscillators / 736
 - 5-5-2 Two-Port Microwave/RF Oscillator Design / 741
 - 5-5-3 Ceramic-Resonator Oscillators / 745
 - 5-5-4 Using a Microstrip Inductor as the Oscillator Resonator / 748
 - 5-5-5 Hartley Microstrip Resonator Oscillator / 756
 - 5-5-6 Crystal Oscillators / 756
 - 5-5-7 Voltage-Controlled Oscillators / 758
 - 5-5-8 Diode-Tuned Resonant Circuits / 765
 - 5-5-9 Practical Circuits / 771
- 5-6 Noise in Oscillators / 778
 - 5-6-1 Linear Approach to the Calculation of Oscillator Phase Noise / 778
 - 5-6-2 AM-to-PM Conversion / 788
 - 5-6-3 Nonlinear Approach to the Calculation of Oscillator Phase Noise / 798
- 5-7 Oscillators in Practice / 813
 - 5-7-1 Oscillator Specifications / 813
 - 5-7-2 More Practical Circuits / 814
- 5-8 Design of RF Oscillators Using CAD / 825
 - 5-8-1 Harmonic-Balance Simulation / 825
 - 5-8-2 Time-Domain Simulation / 831

5-9	Phase-Noise Improvements of Integrated RF and Millimeter-Wave Oscillators / 831	
5-9-1	Introduction / 831	
5-9-2	Review of Noise Analysis / 831	
5-9-3	Workarounds / 833	
5-9-4	Reduction of Flicker Noise / 834	
5-9-5	Applications to Integrated Oscillators / 835	
5-9-6	Summary / 842	
6	Wireless Synthesizers	848
6-1	Introduction / 848	
6-2	Phase-Locked Loops / 848	
6-2-1	PLL Basics / 848	
6-2-2	Phase/Frequency Comparators / 851	
6-2-3	Filters for Phase Detectors Providing Voltage Output / 863	
6-2-4	Charge-Pump-Based Phase-Locked Loops / 867	
6-2-5	How to Do a Practical PLL Design Using CAD / 876	
6-3	Fractional- N -Division PLL Synthesis / 880	
6-3-1	The Fractional- N Principle / 880	
6-3-2	Spur-Suppression Techniques / 882	
6-4	Direct Digital Synthesis / 889	
APPENDIXES		
A	HBT High-Frequency Modeling and Integrated Parameter Extraction	900
A-1	Introduction / 900	
A-2	High-Frequency HBT Modeling / 901	
A-2-1	dc and Small-Signal Model / 902	
A-2-2	Linearized T Model / 904	
A-2-3	Linearized Hybrid- π Model / 906	
A-3	Integrated Parameter Extraction / 907	
A-3-1	Formulation of Integrated Parameter Extraction / 908	
A-3-2	Model Optimization / 908	
A-4	Noise Model Validation / 909	
A-5	Parameter Extraction of an HBT Model / 913	
A-6	Conclusions / 921	
B	Nonlinear Microwave Circuit Design Using Multiharmonic Load-Pull Simulation Technique	923
B-1	Introduction / 923	
B-2	Multiharmonic Load-Pull Simulation Using Harmonic Balance / 924	
B-2-1	Formulation of Multiharmonic Load-Pull Simulation / 924	
B-2-2	Systematic Design Procedure / 925	

xii CONTENTS

- B-3 Application of Multiharmonic Load-Pull Simulation / 927
 - B-3-1 Narrowband Power Amplifier Design / 927
 - B-3-2 Frequency Doubler Design / 933
- B-4 Conclusions / 937
- B-5 Note on the Practicality of Load-Pull-Based Design / 937

INDEX

939

FOREWORD

One of the wonderful things about living in these times is the chance to witness, and occasionally be part of, major technological trends with often profound impacts on society and people's lives. At the risk of stating the obvious, one of the greatest technological trends has been the growth of wireless personal communication—the development and success of a variety of cellular and personal communication system technologies, such as GSM, CDMA, and Wireless Data and Messaging, and the spreading of the systems enabled by these technologies worldwide. The impact on people's lives has been significant, not only in their ability to stay in touch with their business associates and with their families, but often in the ability to save lives and prevent crime. On some occasions, people who have never before used a plain old telephone have made their first long distance communication using the most advanced satellite or digital cellular technology. This growth of wireless communication has encompassed new frequencies, driven efforts to standardize communication protocols and frequencies to enable people to communicate better as part of a global network, and has encompassed new wireless applications. The wireless web is with us, and advances in wireless global positioning technology are likely to provide more examples of lifesaving experiences due to the ability to send help precisely and rapidly to where help is urgently needed.

RF and microwave circuit design has been the key enabler for this growth and success in wireless communication. To a very large extent, the ability to mass produce high quality, dependable wireless products has been achieved through the advances of some incredible RF design engineers, sometimes working alone, oftentimes working and sharing ideas as part of a virtual community of RF engineers. During these past few years, these advances have generated a gradual demystification of RF and microwave circuitry, moving RF techniques ever so reluctantly from “black art” to science. Dr. Ulrich Rohde has long impressed many of us as one of the principal leaders in these advances.

In this book, *RF/Microwave Circuit Design for Wireless Applications*, Dr. Rohde helps clarify RF theory and its reduction to practical applications in developing RF circuits. The book provides insights into the semiconductor technologies, and how appropriate technology decisions can be made. Then, the book discusses—first in overview, then in detail—each of the RF circuit blocks involved in wireless applications: the amplifiers, mixers, oscillators, and frequency synthesizers that work together to amplify and extract the signal from an often hostile environment of noise and reflected signals. Dr. Rohde's unique expertise in VCO and PLL design is particularly valuable in these unusually difficult designs.

It is a personal pleasure to write this foreword—Dr. Rohde has provided guest lectures to engineers at Motorola, and provided suggestions on paths to take and paths to avoid to several design engineers. The value his insights have provided are impossible to measure, but are so substantial that we owe him a “thanks” that can never be expressed strongly enough. I believe that his impact on the larger RF community is even more substantial. This book helps share his expertise in a widely available form.

ERIC MAASS
Director of Operations, Wireless Transceiver Products
Motorola, SPS

PREFACE

When I started two years ago to write a book on wireless technology—specifically, circuit design—I had hoped that the explosion of the technology had stabilized. To my surprise, however, the technology is far from settled, and I found myself in a constant chase to catch up with the latest developments. Such a chase requires a fast engine like the Concorde.



In the case of this somewhat older technology, its speed still has not been surpassed by any other commercial approach. This tells us there is a lot of design technology that needs to be understood or modified to handle today's needs. Because of the very demanding calculation effort required in circuit design, this book makes heavy use of the most modern CAD tools. Hewlett-Packard was kind enough to provide us with a copy of their Advanced Design System (ADS), which also comes with matching synthesis and a wideband CDMA library. Unfortunately, some of the mechanics of getting us started on the software collided with the already delayed publication schedule of this book, and we were only in a position to reference their advanced capability and not really demonstrate it. The use of this software,

including the one from Eagleware, which was also provided to us, needed to be deferred to the next edition of this book. To give a consistent presentation, we decided to stay with the Ansoft tools. One of the most time-consuming efforts was the actual modeling job, since we wanted to make sure all circuits would work properly. There are too many publications showing incomplete or nonworking designs.

On the positive side, trade journals give valuable insight into state-of-the-art designs, and it is recommended that all engineers subscribe to them. Some of the major publications include:

*Applied Microwave & Wireless
Electronic Design
Electronic Engineering Europe
Microwave Journal
Microwaves & RF
Microwave Product Digest (MPD)
RF Design
Wireless Systems Design*

There are also several conferences that have excellent proceedings, which can be obtained either in book form or on CD:

GaAs IC Symposium (annual; sponsored by IEEE-EDS, IEEE-MTT)
IEEE International Solid-State Circuits Conference (annual)
IEEE MTT-S International Microwave Symposium (annual)

There may be other useful conferences along these lines that are announced in the trade journals mentioned above. There are also workshops associated with conferences, such as the recent "Designing RF Receivers for Wireless Systems," associated with the IEEE MTT-S.

Other useful tools include courses, such as *Introduction to RF/MW Design*, a four-day short course offered by Besser Associates.

Wireless design can be split into a digital part, which has to do with the various modulation and demodulation capabilities (advantages and disadvantages), and an analog part, the description of which comprises most of this book.

The analog part is complicated by the fact that we have three competing technologies. Given the fact that cost, space, and power consumption are issues for handheld and battery-operated applications, CMOS has been a strong contender in the area of cordless telephones because of its relaxed signal-to-noise-ratio specifications compared with cellular telephones. CMOS is much noisier than bipolar and GaAs technologies. One of the problems then is the input/output stage at UHF/SHF frequencies. Here we find a fierce battle between silicon-germanium (SiGe) transistors and GaAs technology. Most prescalers are bipolar, and most power amplifiers are based on GaAs FETs or LDMOS transistors for base stations. The most competitive technologies are the SiGe transistors and, of course, GaAs, the latter being the most expensive of the three mentioned. In the silicon-germanium area, IBM and Maxim seem to be the leaders, with many others trying to catch up.

Another important issue is differentiation between handheld or battery-operated applications and base stations. Most designers, who are tasked to look into battery-operated devices, ultimately resort to using available integrated circuits, which seem to change every six to nine months, with new offerings. Given the multiple choices, we have not yet seen a

systematic approach to selecting the proper IC families and their members. We have therefore decided to give some guidelines for the designer applications of ICs, focusing mainly on high-performance applications. In the case of high-performance applications, low power consumption is not that big an issue; dynamic range in its various forms tends to be more important. Most of these circuits are designed in discrete portions or use discrete parts. Anyone who has a reasonable antenna and has a line of sight to New York City, with the antenna connected to a spectrum analyzer, will immediately understand this. Between telephones, both cordless and cellular, high-powered pagers, and other services, the spectrum analyzer will be overwhelmed by these signals. IC applications for handsets and other applications already value their parts as “good.” Their third-order intercept points are better than -10 dBm, while the real professional having to design a fixed station is looking for at least $+10$ dBm, if not more. This applies not only to amplifiers but also to mixer and oscillator performance. We therefore decided to give examples of this dynamic range. The brief surveys of current ICs included in Chapter 1 were assembled for the purpose of showing typical specifications and practical needs. It is useful that large companies make both cellular telephones and integrated circuits or their discrete implementation for base stations. We strongly believe that the circuits selected by us will be useful for all applications.

Chapter 1 is an introduction to digital modulation, which forms the foundation of wireless radiocommunication and its performance evaluation. We decided to leave the discussion of actual implementation to more qualified individuals. Since the standards for these modulations are still in a state of flux, we felt it would not be possible to attack all angles. Chapter 1 contains some very nice material from various sources including tutorial material from my German company, Rohde & Schwarz in Munich—specifically, from the digital modulation portion of their 1998 *Introductory Training for Sales Engineers* CD. *Note:* On a few rare occasions, we have used either a picture or an equation more than once so the reader need not refer to a previous chapter for full understanding of a discussion.

Chapter 2 is a comprehensive introduction to the various semiconductor technologies to enable the designer to make an educated decision. Relevant material such as PIN diodes have also been covered. In many applications, the transistors are being used close to their electrical limits, such as a combination of low voltage and low current. The f_T dependence, noise figure, and large-signal performance have to be evaluated. Another important application for diodes is their use as switches, as well as variable capacitances frequently referred to as tuning diodes. In order for the reader to better understand the meaning of the various semiconductor parameters, we have included a variety of datasheets and some small applications showing which technology is best for a particular application. In linear applications, noise figure is extremely important; in nonlinear applications, the distortion products need to be known. Therefore, this chapter includes not only the linear performance of semiconductors, but also their nonlinear behavior, including even some details on parameter extraction. Given the number of choices the designer has today and the frequent lack of complete data from manufacturers, these are important issues.

Chapter 3, the longest chapter, has the most detailed analysis and guidelines for discrete and integrated amplifiers, providing deep insight into semiconductor performance and circuitry necessary to get the best results from the devices. We deal with the properties of the amplifiers, gain stability, and matching, and we evaluate one-, two-, and three-stage amplifiers with internal dc coupling and feedback, as are frequently found in integrated circuits. In doing so, we also provide examples of ICs currently on the market, knowing that every six months more sophisticated devices will appear. Another important topic in this chapter is the choice of bias point and matching for digital signal handling, and we provide

insight into such complex issues as the adjacent channel power ratio, which is related to a form of distortion caused by the amplifier in its particular operating mode. To connect these amplifiers, impedance matching is a big issue, and we evaluate some couplers and broadband matching circuits useful at these high frequencies, as well as providing a tracking filter as preselector, using tuning diodes. Discussion of differential amplifiers, frequency doublers, AGC, biasing and push-pull/parallel amplifiers comes next, followed by an in-depth section on power amplifiers, including several practical examples and an investigation of amplifier stability analysis. A selection of power-amplifier datasheets and manufacturer-recommended applications rounds out this chapter.

Chapter 4 is a detailed analysis of the available mixer circuits that are applicable to the wireless frequency range. The design and the necessary mathematics to calculate the difference between insertion loss and noise figure are both presented. The reader is given insight into the differences between passive and active mixers, additive and multiplicative mixers, and other useful hints. We have also added some very clever circuits from companies such as Motorola and Siemens, as they are available as ICs.

Chapter 5, on oscillators, is a logical next step, as many amplifiers turn out to oscillate. After a brief introduction explaining why voltage-controlled oscillators (VCOs) are needed, we cover the necessary conditions for oscillation and its resulting phase noise for various configurations, including microwave oscillators and the very important ceramic-resonator-based oscillator. This chapter walks the reader through the various noise-contributing factors and the performance differences between discrete and integrated oscillators and their performance. Here too, a large number of novel circuits are covered.

Chapter 6 deals with the frequency synthesizer, which depends heavily on the oscillators shown in Chapter 5 and different system configurations to obtain the best performance. All components of a synthesizer, such as loop filters and phase/frequency discriminators, are evaluated along with their actual performance. Included are further applications for commercial synthesizer chips. Of course, the principles of the direct digital frequency synthesizer, as well as the fractional- N -division synthesizer, are covered. The fractional- N -division synthesizer is probably one of the most exciting implementations of synthesizers, and we have added patent information for those interested in coming up with their own designs.

The book then ends with two appendixes. Appendix A is an exciting approach to high-frequency modeling and integrated parameter extraction for HBTs. An enhanced noise model has been developed that gives significant improvement in the accuracy of determining the performance of these devices.

Appendix B is another CAD-based application for determining circuit performance—specifically, how to implement load-pulling simulation.

Appendix C is an electronic reproduction of a manual for a GSM handset application board that can be downloaded via web browser or ftp program from Wiley's public ftp area at <ftp://ftp.wiley.com/public/sci-tech-med/microwave>. It is probably the most exciting portion for the reader who would like to know how everything is put together for a mobile wireless application. Again, since every few months more clever ICs are available, some of the power consumption parameters and applications may vary relative to the system discussed, but all new designs will certainly be based on its general principles.

We would like to thank the many engineers from Ansoft, Alpha Industries, Motorola, National Semiconductor, Philips, Rohde & Schwarz, and Siemens Semiconductor (now Infineon Technologies) for supplying current information and giving permission to reproduce some excellent material.

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system or to affect its safety or effectiveness.

I am also grateful to John Wiley & Sons, specifically George Telecki, for tolerating the several slips in schedule, which were the result of the complexity of this effort.

ULRICH L. ROHDE

*Upper Saddle River, New Jersey
March, 2000*

RF/MICROWAVE CIRCUIT
DESIGN FOR WIRELESS
APPLICATIONS

INDEX

- Abrupt junction, 155–157
- Abrupt-junction diode, capacitance versus total junction, 155–156
- Acceptor, 140
- Access burst, 28, 29
- Acoustic measurements, 115
- AD7008 DDS modulator, 892–893
- Additive JFET mixer, 691, 693
- Additive mixing:
 - BJT, 637
 - MOSFET, 638, 691
- Adjacent-channel power ratio, 103–104, 114
 - high-gain amplifiers, 470
- AGC, 431, 433–436
- AlGaAs/InGaAs HEMT, 313–317
- Alloyed diodes, distortion product reduction, 170
- Alternating voltage, modulating diode capacitance by, 186
- Amplifiers
 - adjacent-channel power ratio as function of RF source power, 429
 - AGC, 431, 433–436
 - biasing, *see* Biasing
 - BJT, 439, 441
 - class A, B, and C operation, 375–376
 - compression, 415, 417
 - constant-gain circles, 446
 - differential, 522–525
 - distributed, 378–379
 - dynamic range, 415, 417
 - emitter–ground connection, 436
 - figure of merit, 446
 - frequency doublers, 526–532
 - gain, 380–385
 - intermodulation distortion, 415, 417
 - linearity
 - analysis, 420–429
 - requirements for digital modulation, 417
 - low-voltage open-collector design, 477–490
 - collector–emitter voltage, 480, 482
 - dc load line, 480, 482
 - flexible matching circuit, 488–490
 - open collector with inductor, 483–486
 - open collector with inductor and R_{LOAD} , 487–489
 - open collector with R_{LOAD} , 481–482, 484
 - R_C as source resistor, 477–478
 - transistor analysis, 477, 479
 - multistage, 507–512
 - with automatic gain control, 532–534
 - noise factor, 386
 - noise figure, 377–378, 385–415
 - bias-dependent noise parameters, 403–405
 - cascaded networks, 396
 - determining noise parameters, 414–415
 - influence of external parasitic elements, 399–405
 - measurements, 389–391
 - noise circles, 405–408
 - noise correlation in linear two-parts using correlation matrices, 408–412
 - noisy two-port, 391–396
 - signal-to-noise ratio, 387–389
 - test equipment, 412–414
 - output, modulation signal, 423
 - $\pi/4$ -DQPSK, circuit analysis, 429–432
 - potentially unstable, design, 451
 - power consumption, 436–442
 - properties, 375–380
 - push–pull/parallel, 547–550
 - single-stage feedback, 490–497
 - S parameter relationships, 442, 444–447
 - stability factor, 381–382

- Amplifiers (*continued*)
 - time-domain magnitude of complex modulation signal, 429–429
 - transducer power, 445–446
 - two-stage, 497–507
 - voltage gain, 445
 - see also* High-gain amplifiers; Low-noise amplifiers; Power amplifiers
- Amplitude-imbalance errors, 672
- Amplitude linearity, issues, 89, 91
- Amplitude nonlinearity, 88–89
- Amplitude shift keying, *see* ASK
- Amplitude stability, oscillators, 731
- AM-to-PM conversion, 101–102, 788–797
- Analog FM, 62
- Analog modulation:
 - single-sideband, 62–63
 - spectral considerations, 89–90
- Analog receiver:
 - C/N, 47–48
 - design, 47–49
 - selectivity measurement, 109
- Angelov FET model, dc I - V curves, 365
- Ansoft physics-based MESFET model, 335
- AP-to-PM distortion, 101
- ASK:
 - bit error rate, 40–41
 - in frequency domain, 38–39
 - in I/Q plane, 38–39
 - in time domain, 38
- AT21400 chip, 784–785
- AT-41435 silicon tripolar transistor, noise parameters versus feedback, 402
- Attenuation, versus angular frequency, 581–582
- Automatic gain control, 148

- BA243/244, specifications, 194
- BA110 diode, capacitance/voltage characteristic, 173
- Baluns, 713
- Bandpass filter:
 - conversion of low-pass filter into, 582–583
 - networks, broadband matching using, 578, 580–585
- Band spreading, 17–18
- Bandwidth, effect on fading, 16
- Barkhausen criteria, 720
- Barrier height, Schottky diode, 133–134
- Barrier potential, 127
- Baseband modulation inputs, SA900, 64
- Baseband waveforms, mapping data onto, 34–35
- Base current, 222–223
- Base-station
 - identification code, 28
 - simulation, 118
- Base transport factor, 224
- BAT 14-099, 654–657
- BB141, capacitance/voltage characteristic, 174–175
- BB142, capacitance/voltage characteristic, 174–175
- BCR400 bias controller, 440–441, 546
- BF995, 281–290
- BF999, 276–280
- BFG235, 472, 474
- BFP420, 442–443
 - transistors in parallel, 492–493
- BFP420 matched amplifier, 460–461
 - narrowband, 462–466
 - frequency-dependent gain, matching, and noise performance, 462, 468
 - frequency response, 464, 466
 - inductance for resonance, 462
 - input filter, 464–465
 - schematic, 463
- BFP420 transistor, noise parameters, 403–405
- BFP450 amplifier, 586–589
 - with distributed-element matching, 587–588
- BFR193W, 370–371
- Biasing, amplifiers, 436–439, 534–547
 - correction elements, 541–542
 - dc, 543–547
 - IC-type, 546–547
 - Lange coupler, 539
 - multiple coupled lines element, 539–540
 - OPEN element, 541–542
 - radial stubs, 540–541
 - RF, 543
 - STEP element, 541–542
 - T junction, cross, and Y junction, 536–538
 - transmission line, 534, 536
 - via holes, 540–541
- Binary phase shift keying, *see* BPSK
- Bipolar devices, scaling, 333
- Bipolar junction transistor, *see* BJT
- Bipolar transistors, 198–236
 - base current, 222–223
 - efficiency, 201–202
 - electrical characteristics, 202–218
 - ac characteristics, 203–218
 - collector–base capacitance, 208
 - collector–base time constant, 208
 - dc characteristics, 202–203
 - maximum frequency of oscillation, 208–209
 - reverse I - V characteristics, 202–203
 - S parameter, 203–206
 - transition frequency, 206–208
 - emitter current, 223
 - inverse current gain, 230
 - large-signal, forward-active region, 209, 219–224
 - collector voltage effects, 225–227
 - large-signal behavior, 199–209
 - leakage current effect, 229, 231–232
 - noise factor, 200–201, 341
 - n pn planar structure, 219–220
 - output characteristics, 226
 - performance characteristics, 200–202

- power gain, 200
- power output, 201
- saturation and inverse active regions, 227–232
- sign convention, 199
- small-signal models, 232–236
- Bit error rate, 114
 - after channel equalizer, 12
 - noise and, 85–86
 - Rayleigh channel, 7–8
- Bit synchronization, 24
- BJT:
 - additive mixing, 637
 - amplifiers, 439, 441
 - Colpitts oscillator, input impedance, 721–722
 - high-frequency, noise factor, 396–397
 - noise model, 326–328
 - 90-W push–pull amplifier, 598–600
- BJT amplifier, 7-W class, 550–564
 - conducting angle, 551
 - dc I – V curves, 556, 559
 - efficiency, 552–553
 - frequency response, 556, 558
 - gain, 556, 558
 - as function of drive, 556, 563
 - heat sink, thermal resistance, 553
 - input matching network, 554
 - large-signal S parameters, 563
 - load line, 556, 559
 - output, 556, 560–562
 - matching network, 555
 - schematic, 557
- BJT-based oscillators:
 - microwave, phase noise, 828
 - with noise feedback, 837–838
- BJT DRO, 828–831
- BJT Gilbert cell:
 - advantages, 679
 - with feedback, 682–690
 - validation circuit, 680
- BJT microwave oscillator, 827–828
- BJT model, 232–236
- BJT oscillator, phase noise, 814, 819, 817, 824
 - as function of supply voltage, 812
- BJT RF amplifier:
 - with distributed elements, 535, 543
 - with lumped elements, 535
- Blocking, 92
 - dynamic range, 92
- Bode equation, 581
- Bode plot, phase-locked loops, 878–879
- Body effect, 262
- Boltzmann approximation, Fermi–Dirac distribution function, 220
- BPF450 amplifier:
 - frequency-dependent responses, 591–592
 - schematic, 590–591
- BPSK, 669
 - bandwidth requirements, 40, 42
 - bit error rate, 40–41, 43
 - constellation diagram, 40, 42
 - in frequency domain, 38–39
 - maximum interference voltages, 40, 42
- Breakdown voltage:
 - versus capacitance ratio, testing, 162
 - PIN diodes, 142–143
 - testing, 180–181
- Broadband matching:
 - single-stage feedback amplifiers, 496–497
 - using bandpass filter networks, 578, 580–585
- Broadband modulation, 17
- Burst:
 - structures, 23–29
 - bit synchronization, 24
 - compensation of multipath reception, 25–26
 - delay correction, 26–28
 - guard period, 26–27
 - information bits, 23–25
 - training sequence, 24–26
 - types, 28–29
- Burst noise, JFET, 254
- Capacitance:
 - adding across tuning diode, 794
 - connected in parallel or series with tuner diode, 183–186, 767–768
 - gate–source, MOS, 264
 - microstrip, 752
 - minimum, determining, 184–185
 - PIN diodes, 143–145
 - RF power transistors, 566–567
 - temperature coefficient, 162–164
 - testing, 174–177
 - as function of junction temperature, 175–176
 - modulating by applied ac voltage, 186
- Capacitance diodes, 513–514
 - equivalent circuits, 174
- Capacitance equations, MESFETs, 341–342
- Capacitance ratio, 764, 767
 - determining, 184–185
 - testing, 167
- Capacitors, interdigital, 539–540
- Carrier concentrations, saturated *npn* transistor, 227
- Carrier rejection, 672–674
- Carrier-to-noise ratio, converting to energy per bit/normalized noise power, 119
- Cascade amplifier, 497, 500–502
- Cascaded networks, noise figure, 88, 396–399
- Cascaded sigma-delta modulator, power spectral response, 884
- CDMA, advantages and disadvantages, 20–21
- CDMA signal, 17
- CD4046 phase/frequency comparator, 858–860
- Cellular telephone:
 - growth, 1

- Cellular telephone (*continued*)
 - parameters, 56
 - standard, 55
 - system functions, 3–5
- Ceramic-resonator oscillators, equivalent circuit
 - calculation, 747–750
- CFY77, 313–317
- CGY94 GaAs MMIC power amplifier, 419–420
 - simulated signal, 423–428
- CGY96 GaAs MMIC power amplifier, 417–418
- CGY121A, 435–439
 - application circuit and parts list, 437–438
 - block diagram, 436
 - gain versus V_{control} , 439
- Channel impulse response, 7–13, 26
 - delay spread, 9
 - echoes, 8–10
 - equalization, 9, 11–12
 - estimation, 11
 - time response, 14–16
- Charge pump, 848, 853
 - external, 868, 870–872
- Charge-pump-based phase-locked loops, 867–868, 870–876
- Clapp–Gouriet oscillator, 730, 736–737
- Clock recovery circuitry, 51, 53
- CLY10, 927
- CLY15, 317–321
 - output and power characteristics, 592–593
 - 1-W amplifier, 589, 591–598
- CLY15 amplifier:
 - frequency-dependent responses, 595, 598
 - schematic, 597
- CMOS, 255
- CMY91, 705, 708
- CMY210, circuit, 698, 708
- Code-division multiple access, *see* CDMA
- Coherence bandwidth, 14
- Coherent demodulation, 37–38
- Collector–base capacitance, 208
- Collector–base time constant, 208
- Collector current, saturation region, 229–230
- Collector efficiency, 202
- Collector–emitter voltage, amplifiers, low-voltage
 - open-collector design, 480, 482
- Collector voltage, effects on large-signal bipolar transistors, 225–227
- Colpitts oscillator, 725–727, 735–736, 773–775, 778
 - using RF negative feedback, 804, 806
- Compression, amplifiers, 415, 417
- Compression point, 1-dB, mixers, 645
- Conduction angle, low-noise amplifiers, 448–449
- Congruence transformation, 411
- Constant-gain circles, 446
- Contact potential, 132–133
- Conversion gain/loss, mixers, 639–640
- Cordless telephone:
 - parameters, 56
 - standards, 55
- Correlation admittance, 393–394
- Correlation matrix:
 - from *ABCD* matrix, 411–412
 - noise correlation in linear two-ports, 408–412
- Correlation receiver, 36–37
- Cross, 537
- Cross-modulation, 99–100
 - PIN diodes, 149
 - testing, 168–170, 188–190
- Crystal oscillators, 66, 716–717, 756–763
 - abbreviated circuit, 803–804
 - Colpitts, 758
 - electrical equivalent, 757
 - input impedance, 759
 - noise-sideband performance, 797
 - output, 761
 - parameters, 757
 - phase noise, 760, 763
 - phase noise versus reference frequency, 877
 - ultra-low-phase-noise applications, 762
- Curtice cubic model, NE71000, 352
- Cutoff frequency, 164
 - testing, 179–180
- Damping factor, 864–865
- Databank, generating for parameter extraction, 334
- dc biasing, 543–547
 - IC-type amplifiers, 546–547
- dc-coupled oscillator, 771–772, 775
- dc models, comparison, 348–350
- dc offset, mixers, 647
- dc polarity, mixers, 649
- dc-stabilized oscillator, 776–778
- DECT, testing, 118–119
- Delay correction, 26–28
- Delay line, principles, 834–835
- Delay spread, 9
- Demodulation, digitally modulated carriers, 36–38
- Depletion FETs, 309–310
- Depletion zone, 143–144
- Desensitization, 92
- Desensitization point, 1-dB, mixers, 645
- Detector diodes, 128–135
- Device libraries, FETs, 359–361
- Differential amplifiers, 522–525
- Differential gain, 385
- Differential group delay, 103–104
- Differential phase, 385
- Differential phase modulation, 38
- Diffusion charge, 127
- Diffusion current density, 220
- Digital FM, 62
- Digital I/Q modulator, 33

- Digital modulation:
 - linearity requirements, 417
 - spectral considerations, 89–90
 - techniques, 38–46
- Digital modulator, 30
- Digital radiocommunication tester, 116–117
- Digital receivers, selectivity measurement, 109
- Digital recursion relation, 891
- Digital tristate comparators, 855–863
- Diode attenuator/switch, 670–671
- Diode diffusion capacitance, 640
- Diode loss, testing, 163–168
- Diode mixers, 649–678
 - BAT 14-099, 654–657
 - diode-ring mixer, *see* Diode-ring mixer
 - single-balanced, 652–653, 658–660
 - single-diode, 650–653
 - subharmonically pumped single-balanced mixer, 659, 661
 - 20 GHz, 706–708
- Diode noise model, 323, 325–326
- Diode-ring mixer, 659–660, 662–678
 - abode-cathode voltage, 666, 668
 - binary phase shift keying modulator, 669
 - conversion gain and noise figure, 662–663
 - diode attenuator/switch, 670–671
 - IF-output voltage, 667
 - image-reject mixer, 670–671
 - in-phase/quadrature modulator, 671–677
 - output, 664–665
 - phase detector, 669
 - quadrature IF mixer, 670
 - quadrature phase sift keying modulator, 669–670
 - responses for LO levels, 666
 - Rohde & Schwarz subharmonically pumped DBM, 677–678
 - schematic, 662
 - single-sideband modulator, 671–677
 - termination-insensitive mixer, 668–669
 - triple-balanced mixer, 676–677
 - two-tone testing, 666–667
- Diode rings, phase/frequency comparators, 851–852
- Diodes, 124–197
 - capacitance, 513–514
 - modeling, 124–125, 127
 - capacitance–voltage characteristic, 764
 - detector, 128–135
 - diffusion charge, 127
 - double-balanced mixer, noise figure and conversion gain versus LO power, 644
 - equivalent noise circuit, 325
 - hyperabrupt-junction, 516–518
 - I – V curves, 128
 - junction capacitance, 132–133
 - versus frequency, 134–136
 - large-signal model, 124–128
 - linear model, 135, 137
 - mixer, 128–135, 137
 - noise figure versus LO power, 134
 - performance, 513–516
 - Schottky barriers, electrical characteristics and physics, 128–130
 - silicon versus GaAs, 134
 - small-signal parameters, 131–132
 - SPICE parameters, 126
 - see also* PIN diodes; Testing
- Diode switch, 191–197
 - as bandswitch, 193–196
 - data, 193–194
 - resonant circuits incorporating, 193–196
 - technology, 191–193
 - use in television receiver, 197
- Diode-tuned resonant circuits, 765–769, 771
- Direct digital synthesis, 889, 891–896
 - block diagram, 892–894
 - design guidelines, 891
 - digital recursion relation, 891
 - low-power, drawback, 892
- Distortion, effects, power amplifiers, 416–420
- Distortion ratio, 94–95
- Distribution amplifiers, 602
- DMOS, cross section, 269–270
- Donor, 140
- Dopants, 140
- Doppler effect, 13–14
 - phase uncertainty, 16
- Double-balanced mixers:
 - interport isolation, 660, 662–663
 - Rohde & Schwarz subharmonically pumped, 677–678
- Doubly balanced “star” mixer, 708
- Drain current, KGF1608, 357
- Drain–source voltage, FET, 420–421, 423
- Dual-conversion receiver, block diagram, 108
- Dual-downconversion receiver, schematic, 47
- Dual-gate MOS/GaAs mixers, 692, 694
- DUALTX output matching network, 67–68
- Dummy burst, 28–29
- Dynamic measure, 96–99
- Dynamic range, 96, 111
 - mixers, 645
- Early voltage effect, 484–485
- Ebers–Moll equations, 230–231
- Echo profiles, 8–9, 13
- Edge-triggered JK master–slave flip-flops,
 - phase/frequency comparators, 852–855
- Efficiency, bipolar transistors, 201–202
- EG8021 monolithic amplifier, 376–378
- Electrical properties, testing, 178–181
- Emitter current, 223
 - saturation region, 229–230
- Enhancement FETs, 309–310
- Envelope delay, 103–104

- Epitaxial-collector, 199
- Equivalent noise conductance, 394–395
- ESH2/ESH3 test receiver, 769, 771
- Excess noise, 398
- Excess noise ratio, 413
- Exponential transmission lines, 578
- Eye diagrams, 422–423
 - $\pi/4$ -DQPSK, 429–430
- Fading, 5–6
 - effect of bandwidth, 16
 - simulator, 12
- FDMA, advantages and disadvantages, 18–19
- Feedback amplifier, elements, 494
- Feedback oscillator, 733
- Fermi–Dirac distribution function, Boltzmann approximation, 220
- FET amplifier, 381–383
 - circuit diagram, 381
 - single-tone RF power sweep analysis, 420–421
- FETs, 237–321
 - device libraries, 359–361
 - drain current, 556, 564
 - drain–source voltage, 420–421, 423
 - equivalent noise circuit, 251, 253
 - forward-based gate model, 342
 - linear model, 251
 - models
 - ac errors, 359
 - dc errors, 348
 - modified Materka model, dc I – V curves, 367–368
 - MOSFETs, 254–262
 - noise modeling, 323, 325–333
 - operating parameters, 237, 240
 - parameter extraction, 338–339, 341
 - generating databank, 334–337
 - scalable device models, 333–334
 - short-channel effects, 266–271
 - simulation at low voltage and near pinchoff
 - voltage, 359, 365–370
 - SPICE parameters, 322–325
 - types, 237–239
- Field-effect transistors, *see* FETs
- Figure of merit:
 - amplifiers, 446
 - amplitude linearity, 89, 91
 - dynamic measure, 96–99
 - error vector magnitude, 111–113
 - 1-dB compression point, 92
 - intermodulation intercept point, 93–95
 - maximum frequency of oscillation, 208–209
 - noise figure, *see* Noise figure
 - noise power ratio, 100–101
 - transition frequency, 206–208
 - triple-beat distortion, 99–100
- Film resistor, equivalent model, 79
- Filter attenuator, π -mode, 150–151
- Filters:
 - frequency response/phase-noise analysis graph, 883
 - phase detectors providing voltage output, 863–870
 - phase-locked loops, passive, 872–876
 - voltage-controlled tuned, 513–522
- Flicker corner frequency, 326–327, 329, 332
- Flicker noise, 782, 784
 - cleaning up, 834, 836
 - effect on noise-sideband performance, 789–790
 - integrated RF and millimeter-wave oscillators, 834–835, 837–838
- Flicker noise coefficient, 326–327, 329, 332
- Forward current, as function of diode voltage, 134–135
- Forward error correction, 114
- Forward transconductance curve, 246–247
- Four-reactance networks, 573–578
- Fractional- N -division PLL synthesis, 880–890
 - spur-suppression techniques, 882–890
- Fractional- N -division synthesizer, phase noise, 886–887
- Fractional- N principle, 880–882
- Fractional- N synthesizer, block diagram, 884
- Frequency shift keying, 35
- Frequency correction burst, 28
- Frequency-division duplex transceiver, 63
- Frequency-division multiple access, *see* FDMA
- Frequency doubler:
 - circuit topology, 934
 - conversion purity, 935–936
 - dc I – V curves, 531–532
 - design, using multiharmonic load-pull simulation, 933–937
 - frequency-dependent gain, 529–530
 - input and output voltage waveforms, 935, 937
 - output spectrum, 529, 531
 - schematic, 526–527
 - spectral purity, 934–936
- Frequency doublers, 526–532
- Frequency pushing, 813
- Frequency ratio, output voltage as function of, 857–858
- Frequency shift, testing, 188
- Frequency synthesizer, block diagram, 717
- Fukui's expression, 408
- Fundamental angle-modulation theory, 46
- GaAs, testing, 158–159
- GaAsFET amplifier, dc-coupled, 502–503, 506–507
- GaAsFET feedback amplifier, 466–468
- GaAsFET single-gate switch, 694–713
 - circuit, 695
 - physical layout of, 696
- GaAsFET wideband amplifiers, 382–385
- GaAs MESFETs, 325
 - datasheet, 317–321
 - disadvantages, 303

- extrinsic model, 305
- large-signal behavior, 301, 303–310
- large-signal equations, 304, 306–307
- linear equivalent circuit, 310–311
- modified Materka-Kacprzak model, 304, 307–309
- noise model, 328–330
- package model, 305
- small-signal model, 310–321
- structure, 302
- types, 309–310
- GaAs MMIC, 699–704
- Gain:
 - amplifiers, 380–385
 - circles, 406
 - compression, 92–93
 - multiple-signal, 100
 - definitions, 383
 - differential, 385
 - as function of drive, 556, 563
 - saturation, 92
- Gaussian minimum shift keying, 35, 62
- GMSK, 35, 62
- Graded junction, 513–514
- Group delay, 103–104
- Groupe Special Mobile:
 - pulsed signal, 432
 - testing, 118
 - see also* TDMA, in GSM
- Guard period, 26–27
- Gummel–Poon BJT model, 209, 219, 326

- Handheld transceiver, block diagram, 3–4
- Harmonic-balance simulation, 923–924
 - multiharmonic load-pull simulation using, 924–927
 - RF oscillators, 825–282
- Harmonic distortion, testing, 170–171
- Harmonic generation, 188
- Harmonic intermodulation products, mixers, 645–646
- Harmonic mixing, 674
- Hartley microstrip resonator oscillator, 756
- Hartley oscillator, 725–726, 735–736
- Health effects, potential, 1–2
- Heat sink, thermal resistance, 553
- Heterojunction bipolar transistors, 900–921
 - integrated parameter extraction, 907–909
 - intrinsic noise parameters, 907
 - model
 - dc and small-signal, 902–904
 - dc I - V curves, 914
 - equivalent circuit, 901–902
 - linearized hybrid- π , 906–907
 - linearized T, 904–906
 - noise figures, 918–920
 - optimization, 908–909
 - parameter extraction, 913–920
 - S parameters, 915–918
 - modeling, 901–907
 - noise figure, 904–905
 - noise model, validation, 909–913
 - package parasitics, 902
- HF/VHF voltage-controlled filter, 518–521
- High-frequency field, PIN diodes applications, 147–148
- High-frequency signals, amplitude control, PIN diodes, 148, 150–151
- High-gain amplifiers, 466, 468–477
 - adjacent-channel power ratio, 470
 - BFG235, 472, 474
 - class A, B, and C operation, 466, 468–469
 - dc I - V curves, 469–470
 - noise figure, 469
 - third-order intercept point, 470–471
 - three-tone analysis, 470–471, 473
 - tuned circuits, 468
- Hopf bifurcation, 608
- Hybrid synthesizer, 893, 896
- Hyperabrupt-junction diode, 158–159
- Hyperabrupt-junction tuning diodes, 516–518

- ICOM IC-736 HF/6-meter transceiver, 893–894
- IC-type amplifiers, dc biasing, 546–547
- IF image, 636–637
- Image-reject mixer, 670–671
- Impact ionization, 273–274
- Impedance:
 - input
 - Colpitts oscillator, 721–722
 - crystal oscillator, 759
 - negative-resistance oscillator, 728–729
 - RF power transistors, 565–566
 - junction, 191–192
 - output
 - matching, SA900, 67–68
 - RF power transistors, 565–567
 - transformation equation, 380
- Impedance inverters, 582, 584
- Impedance matching networks, applied to RF power transistors, 565–585
 - broadband matching using bandpass filter networks, 578, 580–585
 - exponential lines, 578
 - four-reactance networks, 573–578
 - matching networks using quarter-wave transformers, 578–580
 - three-reactance matching networks, 570–574
 - two-resistance networks, 567–570
 - use of transmission lines and inductors, 570–571
- Inductors, printed, 536, 538
- Information channel, 31
- In-phase/quadrature modulator, 671–677
- Input matching network, CLY15, 592–593, 595–596
- Input selectivity, 108

- Integrated parameter extraction, HBT:
 - formulation, 908
 - model optimization, 908–909
- Integrated RF and millimeter-wave oscillators:
 - flicker noise reduction, 834–835, 837–838
 - phase-noise improvements, 831–842
 - applications, 835, 838–842
 - workarounds, 833–836
- Interdigital capacitors, 539–540
- Intermodulation:
 - large-signal effects, 100, 102
 - PIN diodes, 149
 - testing, 170
- Intermodulation distortion, 92–96
 - amplifiers, 415, 417
 - mixers, 646–647
 - quasiparallel transistors, 600–602
- Intermodulation intercept point, 93–95
- Intersymbol interference, 26
- Inverse current gain, 230
- I/Q generator, digital FM baseband, 62
- I/Q modulation, 34
 - transmitters, 58–63
- I/Q modulator:
 - equations, 76–77
 - mathematical representation, 58–59
- IS-54 front-end chipset, 63–65
- IS-54 handsets, configurations, 66
- ISM band application, SA900, 73, 76
- Isolation, mixers, 647–648

- JFETs:
 - burst noise, 254
 - datasheet, 241–245
 - large-signal behavior, 246–250
 - lowest-noise, 784
 - modified Materka model, 246
 - noise characteristics, 253
 - noise model, 328–330
 - nonlinear model, 250
 - small-signal behavior, 249, 251–254
 - static characteristics, 246–247
 - structure, 302
- Johnson noise, resistor, 387–388
- Jones cell, 710
- Junction capacitance:
 - versus frequency, 134–136
 - range versus voltage, 134–136
 - Schottky barrier chip, 132–133
- Junction field-effect transistor, *see* JFETs
- Junction impedance, 191–192

- Ka-band MMIC voltage-controlled oscillator, 838, 840–841
- KGF1608, 348, 354–358
 - dc I - V curves, 356
 - drain current, 357
 - output power, 358
- Kirchhoff's equations, 468

- Lange coupler, 539
 - four-strip version, 548–549
- Large-signal diode model, 124–128
- Large-signal effects, 100, 102
- LDMOS FETs, 270–271, 325, 612–616, 693, 819
- Leakage current, testing, 180–181
- Leeson equation, 736–737
- Lifetime, 141
- Linear digital modulation, 60–62
- Linear diode model, 135, 137
- Linear distortion, 88
- Linearized hybrid- π model, 906–907
- Linearized T model, 904–906
- Linearly graded junction, testing, 156–158
- Linear modulations, 34–35
- LMX2350-based synthesizer, 888–890
- LO drive level, mixers, 647
- Load-pull technique, 923–938
- Logical symbols, 30
- LO harmonics, 48–49
- Loop-filter design, improper, 106
- LO outputs, 64, 66
- LO power, versus noise figure, diodes, 134
- Lossless feedback, single-stage feedback amplifiers, 495–496
- Low-noise amplifiers, 448–468
 - BFP420 amplifier
 - matched, 460–461
 - narrowband, 462–466
 - conduction angle, 448–449
 - design guidelines, 451–452
 - effective FR voltage, 451
 - fundamental and harmonic currents, 450–451
 - GaAsFET feedback amplifier, 466–468
 - NE68133 matched amplifier, 452–459
 - power gain, 448
 - saturation voltage, 448
 - using distributed elements, 585–592
 - push-pull BJT amplifier, 598–600
 - 1-W amplifier using CLY15, 589, 591–598
- Low-pass filter, conversion into bandpass filter, 582–583
- Lumped-resonator oscillator, 744–745

- Maas mixer, 707
- Mapping equation, 925
- M -ary phase shift keying modulation, *see* MPSK
- Materka FET, scaling, 334
- Materka FET model, modified, dc I - V curves, 367–368
- Materka-Kacprzak model, modified, GaAs MESFETs, 304, 307–309
- Materka model:
 - modified, 246
 - NE71000, 351

- Maxim Integrated Products, 77, 79
- Maximum available gain, 200
- Maximum frequency of oscillation, 208–209
- MBE MESFET, 362–364
- MC1350/1490, 532–534
- MC 12040 phase/frequency comparator, 858, 860
- MC12148 ECL oscillator, 815, 817, 822–823
- MC13109FB, test circuit, 78–79
- MC13143, frequency responses, 683
- MC13144, 501–504
- Mesa processing, 159–160
- MESFET doubler:
 - gain comparison, 335–336
 - layout, 337
- MESFETs, 927–929
 - capacitance equations, 341–342
 - circuit partitioned into linear and nonlinear subcircuits, 826
 - GaAs, *see* GaAs MESFETs
 - intrinsic model and complete chip/package model, 340
 - parameter extraction, 340–348
 - physics-based modeling, 359, 362–364
 - R_{DS} , 369
- MEXTRAM, 556, 563
- MGA64135 MMIC amplifier, 472, 475–477
- Microstrip inductor:
 - high-Q, 751–753
 - as oscillator resonator, 748–756
- Microwave diode, scaling, 333
- Miller effect, 586
- Minimum detectable signal, 83
- Minimum shift keying, 35
- Minority-carrier charge, 221–222
- Minority-carrier concentration, saturated transistor, 227–229
- Mixed-mode MFSK communication system, 50–57
 - baseband circuitry, 50, 52
 - BER versus SNR, 51, 54
 - block diagram, 50
 - clock recovery circuitry, 51, 53
 - PLL CAD simulation, 51, 53–57
 - received signal, 51, 53
 - RF section, 51–52
- Mixer diodes, 128–135, 135, 137
 - equivalent circuit, 640
- Mixers, 636–713
 - conversion gain/loss, 639–640
 - dc offset, 647
 - dc polarity, 649
 - dynamic range, 645
 - harmonic intermodulation products, 645–646
 - intermodulation distortion, 646–647
 - interport isolation, 647–648
 - linearity, 645–647
 - LO drive level, 647
 - noise figure, 641–645
 - port VSWR, 647, 649
 - power consumption, 649
 - SSB versus DSB noise figure, 645
 - see also* Diode mixers; Transistor mixers
- Mobile station, synchronization, 27
- Modulation noise analysis, 803
- Modulator, cascaded sigma-delta modulator, power spectral response, 884
- MOS:
 - devices, transfer characteristics, 255–261
 - electron drift velocity versus tangent electric field, 266–267
 - gate–source capacitance, 264
 - I – V characteristics, 259, 261
 - small-signal model in saturation, 262–265
 - threshold voltage, 258
 - voltage limitations, 261–262
- MOSFET Gilbert cell, 693–694
- MOSFET oscillator, phase noise, 814, 819
- MOSFETs:
 - additive mixing, 638, 691
 - equivalent noise circuit, 331
 - f_T , 265
 - large-signal behavior, 254–262
 - model of velocity saturation, 268
 - multiplicative mixing, 638
 - noise model, 331–333
 - structure, 302
 - substrate flow, 273–274
 - subthreshold conduction, 271–273
- MPSK, 15–16
- MRF186, 617–623
- MRF899, 625–630
- MRF5003, 291–300
- MSA-0375 MMIC amplifier, 501, 505
- Multiharmonic load-pull simulation, 923–937
 - circuit topology, 924–925, 927
 - design procedure using, 926
 - formulation, 924–925
 - frequency doubler design, 933–937
 - narrowband power amplifier design, 927–934
 - output power spectrum, 931, 933
 - practicality, 937
 - second-harmonic, 931–932
 - systematic design procedure, 925–927
- Multipath reception, compensation, 25–26
- Multiplicative mixing, MOSFET, 638
- Multistage amplifiers, 507–512
 - with automatic gain control, 532–534
 - stability, 512
- Narrowband modulation, 17
- Narrowband power amplifier, design, 927–934
- NE67300, nonlinear device library datasheet, 360–361
- NE71000:
 - Curtice cubic model, 352
 - dc I – V curves, 343

- NE71000 (*continued*)
 - Materka model, 351
 - S parameters, 344–348
 - TOM model, 353
- NE42484A, 786–787
- NE5204A IC, 512
- NEC UPC2749, 507–509
- Negative-resistance oscillator, input impedance, 728–729
- NE68133 matched amplifier, 452–459
 - circles for gain, noise figure, and source and load-plane stability, 453, 455
 - input matching-network extraction, 455–456
 - intermodulation distortion outputs, 458
 - optimized performance, 456–457
 - output constellation, 458–459
 - output matching-network extraction, 455–456
- NE/SA5204A amplifier, 508–509
- N-JFET mixer, 691, 693
- NMOS:
 - with bias voltages applied, 258–259
 - depletion region, 255, 257
 - enhancement-mode structure, 255–258
 - transfer characteristic, 271–273
- Noise:
 - conversion analysis, 801, 803
 - excess, 398
 - mechanisms, 800–801
 - modeling, 323, 325–333
 - in oscillators, 778–812
 - AM-to-PM conversion, 788–797
 - causes, 782
 - generation, 798
 - sideband, 789–790
 - sources, 393–394
 - see also* Phase noise; Signal-to-noise ratio; System noise
- Noise analysis, review, 831–833
- Noise bandwidth, 388–389
- Noise circles, 405–408
- Noise correlation, linear two-ports, using correlation matrices, 408–412
- Noise correlation matrix, 906
- Noise equivalent resistance, 394
- Noise factor, 86–88
 - amplifiers, 386
 - bipolar transistors, 200–201, 341
 - mixer, exact mathematical nonlinear approach, 642–644
 - in terms of correlation matrix, 412
- Noise figure, 86–88, 201
 - amplifiers, 377–378
 - for antennas and antenna systems, 87
 - cascaded networks, 88, 396–399
 - as function of external feedback, 402–403
 - HBT, 904–905, 918–920
 - high-gain amplifiers, 469
 - versus LO power, diodes, 134
 - lowest, 585–586
 - mixers, 641–645
 - SSB versus DSB, 645
 - temperature dependency, 913
 - test equipment, 412–414
 - see also* Amplifiers, noise figure
- Noise floor, 83
- Noiseless feedback, single-stage feedback amplifiers, 495–496
- Noise matrix, transformation, 410–411
- Noise model:
 - bijunction transistor, 326–328
 - GaAs MESFETs, 328–330
 - JFET, 328–330
 - MOSFET, 331–333
 - validation, HBT, 909–913
- Noise parameters:
 - bias-dependent, 403–405, 911–913
 - determining, 414–415
 - transformation matrix, 400–401
- Noise performance, RF oscillators, 736
- Noise power, thermal, 386
- Noise power ratio, 100–101
- Noise-sideband:
 - crystal oscillator, 797
 - as function of flicker frequency, 789–790
 - influence of tuning diodes, 791–792
 - power, 112
- Noise temperature, 88
- Noisy nonlinear circuit, equivalent representation, 798–799
- Noisy two-port, 391–396
 - ABCD*-matrix description, 392
 - cascaded, 396–399
 - noise correlation using correlation matrices, 408–412
 - S-parameter form, 392–393
- Nonlinear distortion, 88
- npn*, 198
- NPN silicon RF power transistor, 625–630
- Nyquist criterion, 720
- Nyquist's equation, 394, 788
- Nyquist stability analysis, power amplifiers, 603, 606–607
- NZA, datasheet, 241–245
- Offset QPSK, 45–46
- On-chip clocks, 68, 70
- Oscillating amplifier, phase noise, 608–610
- Oscillation:
 - approximate frequency, 606, 608–610
 - where it begins, 608, 610–611
- Oscillators:
 - ac load line, 810
 - amplitude stability, 731
 - background, 716, 718

- Barkhausen criteria, 720
- block diagram, 719
- with capacitive voltage divider, 720–722
- Clapp–Gouriet, 730, 736–737
- coarse and fine tuning, 769–771, 775
- Colpitts, 725–727, 735–736
- conversion noise analysis, 801, 803
- dc I – V curves, 810
- design, 719–735
- equivalent representation, noisy nonlinear circuit, 798–799
- experimental variations, 803–805
- feedback, 733
- frequency conversion approach, 798–802
- Hartley, 725–726, 735–736
- input impedance, 721–722
- lumped-resonator, 744–745
- modulation noise analysis, 803
- NE42484A, 786–787
- noise, 105
- Nyquist criterion, 720
- output, 808–809
- phase noise
 - causes, 782–783
 - comparison between predicted and measured, 807
 - equivalent feedback models, 780–782
 - linear approach to calculating, 778–788
 - nonlinear approach to calculating, 798–812
 - optimization, 805, 811–812
- phase stability, 731–735
- practical circuits, 814–824
- push–pull, 814, 817
- short-term frequency stability, 732
- silicon/GaAs-based integrated VCOs, 817–822, 825
- specifications, 813–814
- three-reactance oscillators, 723–728
- two-port oscillator, 728–731
- types, 716
- see also* Integrated RF and millimeter-wave oscillators; Noise, in oscillators; RF oscillators
- Output impedance matching, SA900, 67–68
- Output load, RF power transistors, 566–567
- Output matching network, CLY15, 592, 594–596
- Output power, KGF1608, 358

- Parallel-resonant circuit:
 - testing, 181–183
 - tuning range, 769, 771
- Parameter extraction:
 - generating databank, 334–337
 - MESFETs, 340–348
 - test setup, 338
- Parasitic effects, amplifiers, 399–405
- Phase-cancellation network, 672
- Phase constellation, 112–113

- Phase detectors:
 - diode-ring mixer, 669
 - providing voltage output, filters, 863–870
- Phase errors, 111–112
- Phase feedback loop, closed-loop response, 781
- Phase/frequency comparators, 851–863
 - with antibracklash circuit, 862–863
 - digital tristate, 855–863
 - diode rings, 851–852
 - edge-triggered JK master–slave flip-flops, 852–855
- Phase-imbalance errors, 672
- Phase-locked loops, 848–880
 - basics, 848–851
 - Bode plot, 878–879
 - charge-pump-based, 867–868, 870–876
 - damping factor, 864–865
 - design using CAD, 876–880
 - external charge pump, 868, 870–872
 - filter
 - passive, 872–876
 - for phase detectors providing voltage output, 863–870
 - fractional- N -division synthesis, 880–890
 - linearized model, 850
 - nonlinear, 850
 - phase/frequency comparators, 851–863
 - second-order, 864
 - third-order, 866
 - reference-energy suppression, 873–874
 - transient response, 867–870
 - VCO operation, 850
- Phase-locked-loop synthesizer, 748, 750
 - block diagram, 848–849
- Phase-locked loop system, CAD-based, 51, 53–57
 - block diagram, 51, 54
 - phase noise, 51, 53–55
- Phase noise, 111–112
 - added to carrier, 778–779
 - BJT oscillator, 817, 824
 - ceramic-resonator-based oscillator, 749–750
 - comparison of BJT and MOSFET oscillators, 814, 819
 - crystal oscillator, 760, 763
 - effects, 103, 105–107
 - fractional- N -division synthesizer, 886–887
 - as function of supply voltage, 812
 - microwave BJT oscillator, 828
 - modeled by noise-free amplifier and phase modulator, 780
 - oscillating amplifier, 608–610
 - with oscillator output, 734–735
 - oscillators
 - causes, 782–783
 - comparison between predicted and measured, 807
 - equivalent feedback models, 780–782

- Phase noise (*continued*)
 - oscillators (*continued*)
 - linear approach to calculating, 778–788
 - nonlinear approach to calculating, 798–812
 - optimization, 805, 811–812
 - versus reference frequency, 877
 - RF oscillators, 738–739
 - Siemens IC oscillator, 816
 - spectral density, 780–781
 - two-differential-amplifier oscillator circuit, 821
 - VCO, 774, 777, 831–832
 - optimization and, 805, 811
- Phase nonlinearity, 88–89
- Phase perturbation, 782, 784
- Phase response, issues, 103
- Phase-shift analysis, parallel tuned circuit, 732
- Phase shift keying, 38–39
- Phase stability, oscillators, 731–735
- Phase uncertainty, Doppler effect, 16
- $\pi/4$ -DQPSK:
 - baseband generator, 60
 - circuit analysis, 429–432
 - eye diagram, 429–430
 - signal constellation, 60–61
- Pinched-FET model, 342
- Pinchoff voltage, 246
- PIN diodes, 135–153
 - amplitude control of high-frequency signals, 148, 150–151
 - applications, 146–153
 - breakdown voltage, 142–143
 - capacitance, 143–145
 - cross-modulation, 149
 - current versus voltage, 143
 - dopants, 140
 - equivalent series circuit, 145
 - figure of merit, 145
 - insertion loss versus frequency, 145, 147
 - intermodulation, 149
 - large-signal model, 136–138
 - lifetime, 141
 - model keywords, 139
 - π network for TV tuners, 151–153
 - resistance, 141
 - forward, versus forward current, 148
 - as function of dc, 137, 139
 - reverse series, 145–146
 - reverse shunt, 147
 - series, as function of bias, 142
 - variable, 138, 140–142
 - ring, 670–671
 - scaling, 333
- π network, TV tuners, PIN diodes, 151–153
- Planar, 198
- Planar process, 159–160
- Plessey SL610 wideband amplifier with AGC, 433–435
- PMOS, 255
- Post-tuning drift, 167–168
- Power amplifiers, 416–420, 550–611
 - BJT amplifier, 7-W class, 550–564
 - classes, 550
 - distribution amplifiers, 602
 - impedance matching networks, *see* Impedance matching networks, applied to RF power transistors
 - low-noise amplifier, using distributed elements, 585–592
 - MRF186, 617–623
 - MRF899, 625–630
 - Nyquist stability analysis, 603, 606–607
 - oscillation
 - approximate frequency, 606, 608–610
 - where it begins, 608, 610–611
 - output current, 550–551
 - PTF 10009, 612–616
 - quasiparallel transistors, improved linearity, 600–602
 - small-signal ac analysis, 603–605
 - stability analysis, 601–611
 - unstable, 606–608
- Power consumption:
 - mixers, 649
- Power gain, bipolar transistors, 200
- Power ON time, SA900, 73, 75
- Power output, bipolar transistors, 201
- Power ratios–voltage ratios, 380
- Printed inductors, 536, 538
- PSK, 38–39
- PTF 10009, 612–616
- Punchthrough, 157
 - voltage, 144
- Push–pull BJT amplifier, 598–600
- Push–pull oscillator, 814, 817
 - using LDMOS FETs, 819
- Push–pull/parallel amplifiers, 547–550
- QAM, 43, 46
- Q factor, 142–146
 - versus bias, 166
 - definitions, 163–165
 - testing, 163–168, 177–178
- QPSK:
 - band-limited signal, 44, 46
 - bandwidth requirements, 40, 42
 - baseband generator, 60
 - bit error rate, 40–41, 43
 - constellation diagram, 40, 42
 - maximum interference voltages, 40, 42
 - modulation in time and frequency domains, 40–41
 - modulator, 40
 - serial-to-parallel conversion, 60–61
 - signal constellation, 60–61
 - spectrum, 40–41

- pseudorandom binary sequence data, 44, 46
- Quad-D circuit, 858
- Quadrature amplitude modulation, 43, 46
- Quadrature IF mixer, 670
- Quadrature phase sift keying modulator, 669–670
- Quadrature phase shift keying, *see* QPSK
- Quality factor, “wide” microstrip, 752
- Quarter-wave transformers, matching networks using, 578–580
- Quasiparallel transistors, 600–602

- Radial bend, 537
- Radial stubs, 540–541
- Radiation, “harmful,” 2
- Radio channel, characteristics, 5–7
- Rayleigh channel, bit error rate, 7–8
- Rayleigh distribution, 6–7
- RC filter, schematic, 863–864
- Receive signal, as a function of time or position, 6–7
- Reception quality, 114–117
- Reciprocal mixing, 105, 107–111
- Reflection coefficient, 396
 - between transformed load and generator, 580
 - input, 445
 - output, 408, 445
- Resistor, Johnson noise, 387–388
- Resonant circuits:
 - diode-tuned, *see* Testing
 - incorporating diode switches, 193–196
- RF amplifier, with active biasing, 544–545
- RF biasing, 543
- RF carrier:
 - digitally modulated
 - demodulation, 36–38
 - spectrum, 36
 - modulated
 - generation, 33–34
 - waveform, 31–33
- RF harmonics, 48–49
- RFICs, selector guide, 79–82
- RF image, 636–637
- RF oscillators, 736–778
 - buffered, 741–743
 - ceramic-resonator oscillators, 745–750
 - coarse and fine tuning, 769–771, 775
 - Colpitts, 773–775, 778
 - crystal oscillators, 756–763
 - dc-coupled, 771–772, 775
 - dc-stabilized, 776–778
 - design flowchart, 744
 - design using CAD, 825–831
 - harmonic-balance simulation, 825–828
 - time-domain simulation, 828–831
 - diode-tuned resonant circuits, 765–769, 771
 - Hartley microstrip resonator oscillator, 756
 - increasing loaded Q, 749–751
 - microstrip inductor, as oscillator resonator, 748–756
 - noise performance, 736
 - phase noise, 738–739
 - two-port microwave/RF oscillator, 741–745
 - UHF VCO using the tapped-inductor differential oscillator, 753–756
 - voltage-controlled oscillators, 758, 764–766
 - see also* Integrated RF and millimeter-wave oscillators
- RF parameters, versus local-oscillator drive level, 135–136
- RF power FETs, 291–300, 617–623
- RF power transistors:
 - frequency response, 567–568
 - impedance matching networks, *see* Impedance matching networks, applied to RF power transistors
 - input impedance, 565–566
 - output impedance, 565–567
 - output load, 566–567
 - termination reactance compensation, 569–570
- RF source power, adjacent-channel power ratio as function of, 429
- Rice distribution, 6–7
- Richardson equation, 129–130
- Rohde & Schwarz radiocommunication tester, 115–116
- Rohde & Schwarz SMDU signal generator, 739–741
- Rohde & Schwarz subharmonically pumped DBM, 677–678
- Roll-off compensation network, 583, 585

- SA620, 749, 751–752
 - schematic, 755
- SA900, 58–59
 - amplitude and phase imbalance, 72
 - architecture, 63–64
 - baseband I/Q inputs, 64
 - crystal oscillator, 66
 - designing with, 64, 66–69
 - ISM band application, 73, 76
 - modes of operation, 68
 - on-chip clocks, 68, 70
 - output impedance matching, 67–68
 - output matching using *S* parameters, 68–69
 - performance, 70–71
 - power ON time, 73, 75
 - spectral mask, 73–75
 - transmit local oscillator, 64, 66
 - transmit modulator, 58–59
 - VCO, 66–67
- Saturation voltage, low-noise amplifiers, 448
- Scaling, FETs, 333–334
- Schottky barrier chip, junction capacitance, 132–133
- Schottky barriers, electrical characteristics and physics, 128–130

- Schottky diodes, 640
 - band diagrams, 133
 - barrier height, 133–134
 - chip cross section, 129
 - diode mixers, 652–653
 - as noise generator, 641
 - silicon versus GaAs, 134
- Scout program, 338, 526
 - user interface, 338–339
- Selectivity curves, four-reactance networks, 575–577
- Sensitivity, 84–85
- Series inductance, testing, 178–180
- Series resistance, testing, 177–178
- Series resonant frequency, testing, 178–180
- Shockley equation, 124
- Short-channel effects, FETs, 266–271
- Siemens IC oscillator, 814–815
- Siemens NPN silicon RF transistor, 210–218
- Sigma-delta modulator, cascaded, power spectral response, 884
- Signal generator, phase noise, 107
- Signal representation, different forms, 33
- Signal-to-noise ratio, 84–85
 - amplifiers, 387–389
 - converting to energy per bit/normalized noise power, 119
 - measurement, 389
- Silicon, 198
 - testing, 158–159
- Silicon-based BiCMOS, 835, 838–839
- Silicon dual gate mixer, 710
- Silicon dual Schottky diode, 654–657
- Silicon/GaAs-based integrated VCOs, 817–822, 825
- Silicon inductor, 526, 528–529
- Silicon N channel MOSFET tetrode, 281–290
- Silicon N channel MOSFET triode, 276–280
- SINAD ratio, 85
- Single-balanced mixer, 652–653, 658–660
 - subharmonically pumped, 659, 661
- Single-BJT mixer, 678–679
- Single-diffused diodes, distortion product reduction, 171
- Single-diode mixer, 650–653
 - conversion gain and noise figure, 651
 - output spectrum, 651
- Single-loop synthesizer, block diagram, 848–849
- Single-sideband:
 - noise figure, measurements, 413–414
 - signal-to-noise ratio, 788
 - suppression contours, 73
- Single-sideband AM, 62–63
- Single-sideband modulator, 671–677
 - return loss, 678
- Single-sideband phase noise, 105
- Single-stage feedback amplifiers, 490–497
 - broadband matching, 496–497
 - lossless or noiseless feedback, 495–496
 - transconductance, 493–494
 - voltage gain, 490
- Single-tone gain-compression factor, 92
- Small-signal ac analysis, power amplifiers, 603–605
- Smith charts, 444
- Smith diagram, 585–586
- S parameters, 203–206
 - amplifiers, relationships, 442, 444–447
 - BFP420, 443
 - HBT, 915–918
 - KGF1608, 355
 - linear noisy two-port, 392–393
 - NE71000, 344–348
 - two-port oscillators, 743
- Spectral mask, SA900, 73–75
- Spectral regrowth, 90, 103
- SPICE noise model, enhanced, 328–329, 332
- SPICE parameters, 322–325
 - BFR193W, 370
 - diodes, 126
- SPICE shot noise model, 910
- Splatter, 114
- Spur-suppression techniques, 882–890
- Stability analysis, power amplifier, 601–611
- Stability factors, 381–382
 - two-port oscillators, 743
- Stanford Microdevices, 77
- Subharmonically pumped single-balanced mixer, 659, 661
- Subharmonic mixing, 674
- Substrate flow, MOSFETs, 273–274
- Subthreshold conduction, MOSFETs, 271–273
- Super low noise pseudomorphic HJ FET, 786–787
- Switching FET mixer, simplified, 696–697
- Synchronization burst, 28
- System noise, 83–88
 - bit error rate and, 85–86
 - sensitivity, 84–85
 - SINAD ratio, 85
- Tapped-microstrip resonator, differential oscillator, 753–756
- TDA1053, internal circuitry, 151
- TDMA:
 - advantages and disadvantages, 19–20
 - in GSM, 21–29
 - burst structures, 23–29
 - frame and multiframe, 21–23
 - RF data, 21–22
 - timers, 22–24
- Television receiver, diode switch use, 197
- Television tuners, π network, PIN diodes, 151–153
- Temperature coefficient of capacitance, testing, as
 - function of reverse voltage, 175, 177
- Temperature-compensation circuit, 186–187
- Termination-insensitive mixer, 668–669

- Testing, 114
- abrupt junction, 155–157
 - acoustic measurements, 115
 - base-station simulation, 118
 - breakdown voltage, 180–181
 - capacitance, 174–177
 - as function of junction temperature, 175–176
 - modulating by applied ac voltage, 186
 - temperature coefficient, 162–164
 - capacitance ratio, 160–162, 167
 - capacitances connected in parallel or series, 183–186
 - comparative, 167
 - compensating temperature dependence, 186–187
 - cross-modulation, 168–170, 188–190
 - current/voltage and capacitance/voltage characteristics, 173–174
 - cutoff frequency, 179–180
 - DECT, 118–119
 - differential forward resistance as function of forward current, 192–193
 - diode switch, 191–197
 - distortion products, 168–174
 - reduction, 170–174
 - dynamic stability, 187–190
 - electrical properties, 178–181
 - equivalent circuit, 174
 - equivalent shunt resistance, 182
 - frequency shift, 188
 - generating tuning voltage, 190–191
 - GSM, 118
 - harmonic distortion, 170–171
 - harmonic generation, 188
 - hyperabrupt junction, 158–159
 - intermodulation, 170
 - IS-95 parameters, 115
 - leakage current, 180–181
 - linearly graded junction, 156–158
 - matching, 181
 - parallel-resonant circuit, 181–183
 - physics, 155–160
 - planar versus mesa construction, 159–160
 - post-tuning drift, 167–168
 - Q factor, 163–168, 177–178
 - series inductance, 178–180
 - series resistance, 177–178
 - series resonant frequency, 178–180
 - silicon versus GaAs, 158–159
 - slope as function of the reverse voltage, 175–176
 - temperature coefficient of capacitance, as function of reverse voltage, 175, 177
 - tracking, 185–186
 - tuning range, 185
- Thermal noise power, 386
- Three-reactance matching networks, 570–574
- Three-reactance oscillators, 723–728
- Three-tone analysis, high-gain amplifiers, 470–471, 473
- Time-division duplex transceiver, 63–64
- Time-division multiple access, *see* TDMA
- Time-domain simulation, RF oscillators, 828–831
- Timing advance, 28
- T junction, 537
- TMOS, 269–270
- TOM model, NE71000, 353
- Tracking, 185–186, 771
- Transceiver:
 - handheld, block diagram, 3–4
 - single-chip direct-conversion, 5
- Transconductance:
 - differential amplifier, 522
 - single-stage feedback amplifiers, 493–494
- Transfer characteristic, filter, 863–864
- Transfer function, 14–15
 - time response, 15–16
- Transformation equation, 380
- Transformation matrix parameters, 400–401
- Transformation paths, four-reactance networks, 575–576
- Transient response, phase-locked loops, 867–870
- Transistor mixers, 678–713
 - BJT Gilbert cell, 679–682
 - with feedback, 682–690
 - CMY210, 699–704
 - FET mixers, 684, 691–694
 - GaAsFET single-gate switch, 694–713
 - MC13143, 685–690
 - MOSFET Gilbert cell, 693–694
- Transistor oscillators, 736–741
- Transistors:
 - equivalent circuit, 399
 - with lowest noise figure, 783–784
 - structure types, 198–199
 - see also* specific types of transistors
- Transition frequency, 206–208
- Transmission line, 534, 536
 - RF power transistors, 570–571
- Transmission quality, 114–117
- Transmit local oscillator, 64, 66
- Transmitters, 58–77
 - I/Q modulation, 58–63
 - I/Q modulator equations, 76–77
 - system architecture, 63–66
 - see also* SA900
- Triple-balanced mixer, 676–677
- Triple-beat distortion, 99–100
- Tristate comparators, 855–863
- Tristate detector, with antibacklash circuit, 862
- Tuned filters, voltage-controlled, 513–522
 - diode performance, 513–516
 - HF/VHF, 518–521
 - third-order intercept point, 519–521
 - VHF

- Tuned filters, voltage-controlled (*continued*)
 - example, 516–518
 - improving, 521–522
- Tuning diodes, 153–197, 765
 - ac load line, 791, 793–796
 - capacitance
 - adding, 794
 - connected in parallel or series with, 767–768
 - influence on noise-sideband performance, 791–792
 - noise influence, 784
 - in parallel-resonant circuit, 765–767
- Tuning range, 185
 - parallel-resonant circuit, 769, 771
- Tuning voltage, generating, 190–191
- Turbocharged, 601
- Two-differential-amplifier oscillator, phase noise, 821
- Two-port microwave/RF oscillator, 741–745
- Two-port nonlinear circuit, schematic, 925–926
- Two-port oscillator, 728–731
- Two-ports:
 - parallel combination, 409
 - unconditionally stable, 447
- Two-stage amplifiers, 497–507
- TXLO inputs, 64, 66

- UHF VCO using the tapped-inductor differential oscillator, 753–756
- Ultra-high-frequency/super-high-frequency, *see* UHF/SHF
- Ultra low power DC-2.4 GHz linear mixer, 685–690
- UMA1018M dual-synthesizer chip, 867–870
- UPC2710 electrical specifications, 508, 510–511

- UPC2749 MMIC, 508

- Varactors, 153
- Varactor tuning diodes, 513–515
- Varicaps, 153
- VCO, 66–67
 - phase-locked loops, 850
 - phase noise, 774, 777, 831–832
 - optimization and, 805, 811
 - schematic, 791, 793
 - silicon/GaAs-based integrated, 817–822, 825
 - very-low-phase-noise, 776
- VHF filter, 516–518
 - improving, 521–522
- Via holes, 540–541
- Viterbi algorithm, 11
- VMOS:
 - cross section, 269–270
- Voltage-controlled oscillator, 716, 719
- Voltage gain, amplifiers, 445
- VSWR, Lo-port, 647, 649

- Wilkinson divider/combiners, 549
- Wilkinson power dividers, 602
- Wireless synthesizers, 848–896
 - direct digital synthesis, 889, 891–896
 - hybrid, 893, 896
 - see also* Phase-locked loops

- Y junction, 538

- Zener diode, 190–191

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