

 WILEY

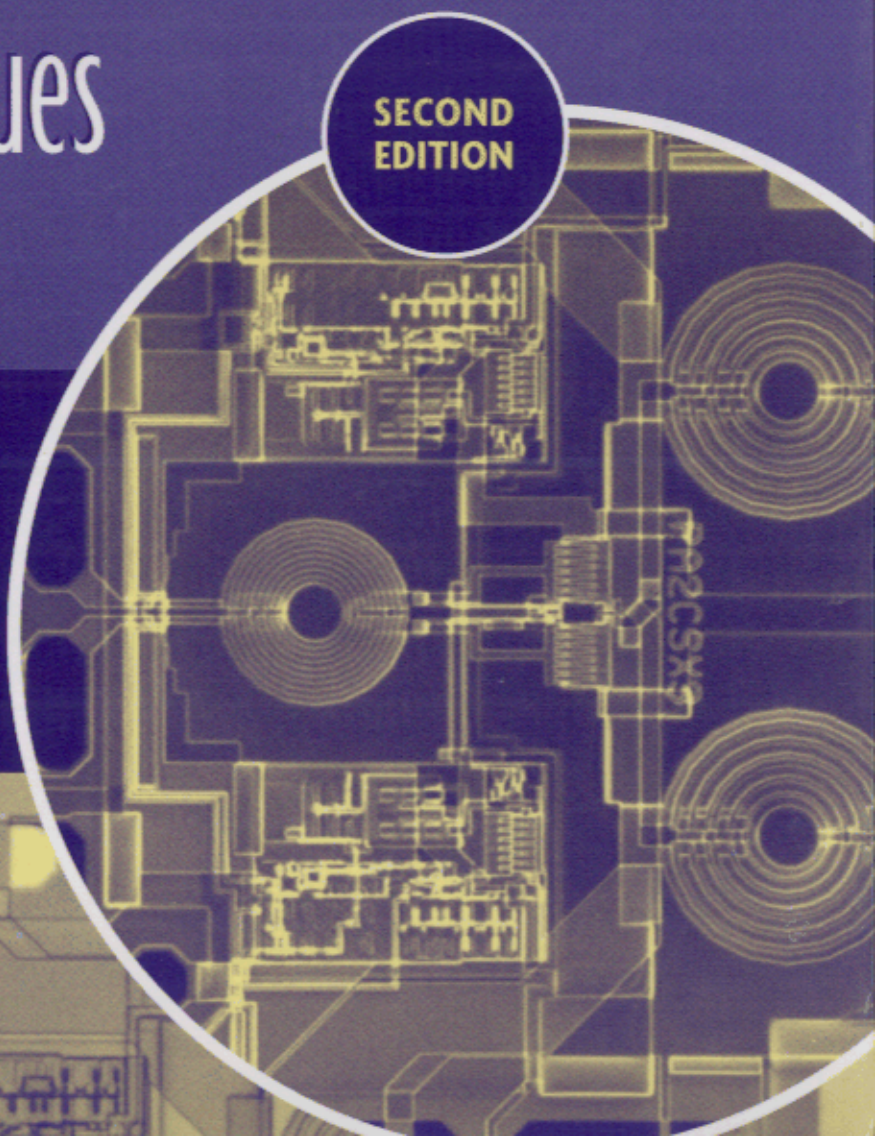
# Microwave Circuit Design Using Linear and Nonlinear Techniques

SECOND  
EDITION

GEORGE D. VENDELIN

ANTHONY M. PAVIO

ULRICH L. ROHDE



POWER IP VCCB VCCB

# CONTENTS

---

<b>FOREWORD</b>	<b>xv</b>
<i>ROBERT A. PUCEL</i>	
<b>PREFACE</b>	<b>xix</b>
<b>1 RF/MICROWAVE SYSTEMS</b>	<b>1</b>
1.1 Introduction / 1	
1.2 Maxwell's Equations / 10	
1.3 RF Wireless/Microwave/Millimeter-Wave Applications / 12	
1.4 Frequency Bands, Modes, and Waveforms of Operation / 17	
1.5 Analog and Digital Requirements / 18	
1.6 Elementary Definitions / 20	
1.7 Basic RF Transmitters and Receivers / 26	
1.8 Modern CAD for Nonlinear Circuit Analysis / 29	
1.9 Dynamic Load Line / 30	
References / 31	
Bibliography / 32	
Problems / 33	
<b>2 LUMPED AND DISTRIBUTED ELEMENTS</b>	<b>35</b>
2.1 Introduction / 35	
2.2 Transition from RF to Microwave Circuits / 35	
2.3 Parasitic Effects on Lumped Elements / 38	
2.4 Distributed Elements / 45	
2.5 Hybrid Element: Helical Coil / 46	
References / 47	

Bibliography /	49
Problems /	50

### 3 ACTIVE DEVICES

51

3.1	Introduction /	51
3.2	Diodes /	53
3.2.1	Large-Signal Diode Model /	54
3.2.2	Mixer and Detector Diodes /	57
3.2.3	Parameter Trade-Offs /	61
3.2.4	Mixer Diodes /	64
3.2.5	<i>pin</i> Diodes /	65
3.2.6	Tuning Diodes /	77
3.2.7	Abrupt Junction /	78
3.2.8	Linearly Graded Junction /	80
3.2.9	Hyperabrupt Junction /	81
3.2.10	Silicon Versus Gallium Arsenide /	83
3.2.11	$Q$ Factor or Diode Loss /	87
3.2.12	Diode Problems /	91
3.2.13	Diode-Tuned Resonant Circuits /	97
	Tuning Range /	100
3.3	Microwave Transistors /	103
3.3.1	Transistor Classification /	103
3.3.2	Transistor Structure Types /	105
3.3.3	dc Model of BJT /	107
3.4	Heterojunction Bipolar Transistor /	144
3.5	Microwave FET /	150
3.5.1	MOSFETs /	150
3.5.2	Gallium Arsenide MESFETs /	152
3.5.3	HEMT /	176
3.5.4	Foundry Services /	178
	References /	183
	Bibliography /	187
	Problems /	190

### 4 TWO-PORT NETWORKS

192

4.1	Introduction /	192
4.2	Two-Port Parameters /	193
4.3	$S$ Parameters /	197
4.4	$S$ Parameters from SPICE Analysis /	198
4.5	Stability /	199
4.6	Power Gains, Voltage Gain, and Current Gain /	202
4.6.1	Power Gain /	202

4.6.2	Voltage Gain and Current Gain / 207	
4.6.3	Current Gain / 208	
4.7	Three-Ports / 210	
4.8	Derivation of Transducer Power Gain / 213	
4.9	Differential $S$ Parameters / 215	
4.9.1	Measurements / 217	
4.9.2	Example / 218	
4.10	Twisted-Wire Pair Lines / 218	
4.11	Low-Noise and High-Power Amplifier Design / 221	
4.12	Low-Noise Amplifier Design Examples / 224	
	References / 233	
	Bibliography / 234	
	Problems / 234	
<b>5</b>	<b>IMPEDANCE MATCHING</b>	<b>241</b>
5.1	Introduction / 241	
5.2	Smith Charts and Matching / 241	
5.3	Impedance Matching Networks / 249	
5.4	Single-Element Matching / 250	
5.5	Two-Element Matching / 251	
5.6	Matching Networks Using Lumped Elements / 252	
5.7	Matching Networks Using Distributed Elements / 253	
5.7.1	Twisted-Wire Pair Transformers / 253	
5.7.2	Transmission Line Transformers / 254	
5.7.3	Tapered Transmission Lines / 255	
5.8	Bandwidth Constraints for Matching Networks / 257	
	References / 267	
	Bibliography / 268	
	Problems / 268	
<b>6</b>	<b>MICROWAVE FILTERS</b>	<b>273</b>
6.1	Introduction / 273	
6.2	Low-Pass Prototype Filter Design / 274	
6.2.1	Butterworth Response / 274	
6.2.2	Chebyshev Response / 276	
6.3	Transformations / 279	
6.3.1	Low-Pass Filters: Frequency and Impedance Scaling / 279	
6.3.2	High-Pass Filters / 281	
6.3.3	Bandpass Filters / 283	
6.3.4	Narrow-Band Bandpass Filters / 286	
6.3.5	Band-Stop Filters / 289	

- 6.4 Transmission Line Filters / 291
  - 6.4.1 Semilumped Low-Pass Filters / 294
  - 6.4.2 Richards Transformation / 297
- 6.5 Exact Designs and CAD Tools / 305
- 6.6 Real-Life Filters / 305
  - 6.6.1 Lumped Elements / 306
  - 6.6.2 Transmission Line Elements / 306
  - 6.6.3 Cavity Resonators / 306
  - 6.6.4 Coaxial Dielectric Resonators / 306
  - 6.6.5 Thin-Film Bulk-Wave Acoustic Resonator (FBAR) / 306
- References / 309
- Bibliography / 309
- Problems / 310

## 7 NOISE IN LINEAR TWO-PORTS

311

- 7.1 Introduction / 311
- 7.2 Signal-to-Noise Ratio / 313
- 7.3 Noise Figure Measurements / 315
- 7.4 Noise Parameters and Noise Correlation Matrix / 317
  - 7.4.1 Correlation Matrix / 317
  - 7.4.2 Method of Combining Two-Port Matrix / 318
  - 7.4.3 Noise Transformation Using the  $[ABCD]$  Noise Correlation Matrices / 318
  - 7.4.4 Relation Between the Noise Parameter and  $[C_A]$  / 319
  - 7.4.5 Representation of the  $ABCD$  Correlation Matrix in Terms of Noise Parameters / 321
  - 7.4.6 Noise Correlation Matrix Transformations / 321
  - 7.4.7 Matrix Definitions of Series and Shunt Element / 323
  - 7.4.8 Transferring All Noise Sources to the Input / 323
  - 7.4.9 Transformation of the Noise Sources / 324
  - 7.4.10  $ABCD$  Parameters for CE, CC, and CB Configurations / 324
- 7.5 Noisy Two-Port Description / 326
- 7.6 Noise Figure of Cascaded Networks / 332
- 7.7 Influence of External Parasitic Elements / 334
- 7.8 Noise Circles / 338
- 7.9 Noise Correlation in Linear Two-Ports Using Correlation Matrices / 340

- 7.10 Noise Figure Test Equipment / 343
- 7.11 How to Determine Noise Parameters / 345
- 7.12 Calculation of Noise Properties of Bipolar and FETs / 346
  - 7.12.1 Hybrid- $\Pi$  Configuration / 346
  - 7.12.2 Transformation of Noise Current Source to Input of CE Bipolar Transistor / 348
  - 7.12.3 Noise Factor / 349
  - 7.12.4 Case of Real Source Impedance / 351
  - 7.12.5 Formation of Noise Correlation Matrix of CE Bipolar Transistor / 351
  - 7.12.6 Calculation of Noise Parameter Ignoring Base Resistance / 353
- 7.13 Bipolar Transistor Noise Model in T Configuration / 359
  - 7.13.1 Real Source Impedance / 363
  - 7.13.2 Minimum Noise Factor / 363
  - 7.13.3 Noise Correlation Matrix of Bipolar Transistor in T-Equivalent Configuration / 365
- 7.14 The GaAs FET Noise Model / 367
  - 7.14.1 Model at Room Temperature / 367
  - 7.14.2 Calculation of Noise Parameters / 369
  - 7.14.3 Influence of  $C_{gd}$ ,  $R_{gs}$ , and  $R_s$  on Noise Parameters / 375
  - 7.14.4 Temperature Dependence of Noise Parameters of an FET / 376
  - 7.14.5 Approximation and Discussion / 379
- References / 381
- Bibliography / 383
- Problems / 385

## 8 SMALL- AND LARGE-SIGNAL AMPLIFIER DESIGN

388

- 8.1 Introduction / 388
- 8.2 Single-Stage Amplifier Design / 390
  - 8.2.1 High Gain / 390
  - 8.2.2 Maximum Available Gain and Unilateral Gain / 391
  - 8.2.3 Low-Noise Amplifier / 398
  - 8.2.4 High-Power Amplifier / 400
  - 8.2.5 Broadband Amplifier / 402
  - 8.2.6 Feedback Amplifier / 402
  - 8.2.7 Cascode Amplifier / 405
  - 8.2.8 Multistage Amplifier / 411

- 8.2.9 Distributed Amplifier and Matrix Amplifier / 412
- 8.2.10 Millimeter-Wave Amplifiers / 416
- 8.3 Frequency Multipliers / 416
  - 8.3.1 Introduction / 416
  - 8.3.2 Passive Frequency Multiplication / 417
  - 8.3.3 Active Frequency Multiplication / 418
- 8.4 Design Example of 1.9-GHz PCS and 2.1-GHz W-CDMA Amplifiers / 420
- 8.5 Stability Analysis and Limitations / 422
  - References / 426
  - Bibliography / 429
  - Problems / 431

**9 POWER AMPLIFIER DESIGN**

**433**

- 9.1 Introduction / 433
- 9.2 Device Modeling and Characterization / 434
- 9.3 Optimum Loading / 464
- 9.4 Single-Stage Power Amplifier Design / 466
- 9.5 Multistage Design / 472
- 9.6 Power-Distributed Amplifiers / 480
- 9.7 Class of Operation / 500
- 9.8 Power Amplifier Stability / 509
- 9.9 Amplifier Linearization Methods / 512
  - References / 514
  - Bibliography / 518
  - Problems / 519

**10 OSCILLATOR DESIGN**

**520**

- 10.1 Introduction / 520
- 10.2 Compressed Smith Chart / 525
- 10.3 Series or Parallel Resonance / 526
- 10.4 Resonators / 528
  - 10.4.1 Dielectric Resonators / 529
  - 10.4.2 YIG Resonators / 532
  - 10.4.3 Varactor Resonators / 533
  - 10.4.4 Ceramic Resonators / 537
  - 10.4.5 Resonator Measurements / 540
- 10.5 Two-Port Oscillator Design / 544
- 10.6 Negative Resistance from Transistor Model / 550
- 10.7 Oscillator  $Q$  and Output Power / 559

- 10.8 Noise in Oscillators: Linear Approach / 563
  - 10.8.1 Using a Spectrum Analyzer / 563
  - 10.8.2 Two-Oscillator Method / 565
  - 10.8.3 Leeson's Oscillator Model / 573
  - 10.8.4 Low-Noise Design / 579
- 10.9 Analytic Approach to Optimum Oscillator Design Using  $S$  Parameters / 591
- 10.10 Nonlinear Active Models for Oscillators / 605
  - 10.10.1 Diodes with Hyperabrupt Junction / 605
  - 10.10.2 Silicon Versus Gallium Arsenide / 606
  - 10.10.3 Expressions for  $g_m$  and  $G_d$  / 609
  - 10.10.4 Nonlinear Expressions for  $C_{gs}$ ,  $G_{gf}$ , and  $R_i$  / 611
  - 10.10.5 Analytic Simulation of  $I-V$  Characteristics / 612
  - 10.10.6 Equivalent-Circuit Derivation / 612
  - 10.10.7 Determination of Oscillation Conditions / 615
  - 10.10.8 Nonlinear Analysis / 616
  - 10.10.9 Conclusion / 616
- 10.11 Oscillator Design Using Nonlinear Cad Tools / 617
  - 10.11.1 Parameter Extraction Method / 621
  - 10.11.2 Example of Nonlinear Design Methodology: 4-GHz Oscillator-Amplifier / 625
  - 10.11.3 Conclusion / 629
- 10.12 Microwave Oscillators Performance / 631
- 10.13 Design of an Oscillator Using Large-Signal  $Y$  Parameters / 634
- 10.14 Example for Large-Signal Design Based on Bessel Functions / 637
- 10.15 Design Example for Best Phase Noise and Good Output Power / 641
- 10.16 CAD Solution for Calculating Phase Noise in Oscillators / 650
  - 10.16.1 General Analysis of Noise Due to Modulation and Conversion in Oscillators / 651
  - 10.16.2 Modulation by a Sinusoidal Signal / 651
  - 10.16.3 Modulation by a Noise Signal / 653
  - 10.16.4 Oscillator Noise Models / 654
  - 10.16.5 Modulation and Conversion Noise / 656
  - 10.16.6 Nonlinear Approach for Computation of Noise Analysis of Oscillator Circuits / 656
  - 10.16.7 Noise Generation in Oscillators / 658
  - 10.16.8 Frequency Conversion Approach / 659



- 10.16.9 Conversion Noise Analysis / 659
- 10.16.10 Noise Performance Index Due to Frequency Conversion / 660
- 10.16.11 Modulation Noise Analysis / 661
- 10.16.12 Noise Performance Index Due to Contribution of Modulation Noise / 664
- 10.16.13 PM–AM Correlation Coefficient / 665
- 10.17 Validation Circuits / 666
  - 10.17.1 1000-MHz Ceramic Resonator Oscillator (CRO) / 666
  - 10.17.2 4100-MHz Oscillator with Transmission Line Resonators / 668
  - 10.17.3 2000-MHz GaAs FET-Based Oscillator / 671
- 10.18 Analytical Approach for Designing Efficient Microwave FET and Bipolar Oscillators (Optimum Power) / 674
  - 10.18.1 Series Feedback (MESFET) / 676
  - 10.18.2 Parallel Feedback (MESFET) / 682
  - 10.18.3 Series Feedback (Bipolar) / 684
  - 10.18.4 Parallel Feedback (Bipolar) / 687
  - 10.18.5 An FET Example / 688
  - 10.18.6 Simulated Results / 697
  - 10.18.7 Synthesizers / 701
  - 10.18.8 Self-Oscillating Mixer / 703
- References / 703
- Bibliography / 707
- Problems / 718

**11 MICROWAVE MIXER DESIGN**

**724**

- 11.1 Introduction / 724
- 11.2 Diode Mixer Theory / 728
- 11.3 Single-Diode Mixers / 743
- 11.4 Single-Balanced Mixers / 753
- 11.5 Double-Balanced Mixers / 769
- 11.6 FET Mixer Theory / 794
- 11.7 Balanced FET Mixers / 818
- 11.8 Special Mixer Circuits / 832
- 11.9 Using Modern CAD Tools / 843
- 11.10 Mixer Noise / 850
  - References / 863
  - Bibliography / 866
  - Problems / 867

<b>12</b>	<b>RF SWITCHES AND ATTENUATORS</b>	<b>869</b>
12.1	<i>pin</i> Diodes / 869	
12.2	<i>pin</i> Diode Switches / 872	
12.3	<i>pin</i> Diode Attenuators / 881	
12.4	FET Switches / 886	
	References / 889	
	Bibliography / 890	
<b>13</b>	<b>MICROWAVE COMPUTER-AIDED WORKSTATIONS FOR MMIC REQUIREMENTS</b>	<b>891</b>
13.1	Introduction / 891	
	13.1.1 Integrated Microwave Workstation Approach / 891	
	13.1.2 Nonlinear Tools / 893	
13.2	Gallium Arsenide MMIC Foundries: Role of CAD / 897	
13.3	Yield-Driven Design / 901	
	13.3.1 No Simple Task / 901	
	13.3.2 Rethinking Design / 902	
	13.3.3 Hitting the Mark / 903	
13.4	Designing Nonlinear Circuits Using the Harmonic Balance Method / 905	
	13.4.1 Splitting the Linear and Nonlinear Portion / 906	
	13.4.2 How Does the Program Work? / 906	
	13.4.3 Examples / 913	
13.5	Programmable Microwave Tuning System / 914	
	13.5.1 The PMT System / 915	
	13.5.2 Tuning Techniques / 916	
	13.5.3 The PMTS Approach / 918	
13.6	Introduction to MMIC Considering Layout Effects / 920	
	13.6.1 Component and Interconnection Modules / 923	
13.7	GaAs MMIC Layout Software / 927	
	13.7.1 Capabilities / 927	
	13.7.2 Example / 928	
13.8	Practical Design Example / 930	
	13.8.1 The Design / 930	
	13.8.2 The Elements / 932	
	13.8.3 The Input Filter / 932	
	13.8.4 The Dielectric Resonator / 932	
	13.8.5 The Branch Line Coupler / 934	
	13.8.6 Other Circuit Elements / 934	
13.9	CAD Applications / 935	
	Bibliography / 956	

<b>Appendix A</b>	<b>BIP: GUMMEL-POON BIPOLAR TRANSISTOR MODEL</b>	<b>959</b>
<b>Appendix B</b>	<b>LEVEL 3 MOSFET</b>	<b>966</b>
<b>Appendix C</b>	<b>NOISE PARAMETERS OF GaAs MESFETs</b>	<b>969</b>
<b>Appendix D</b>	<b>DERIVATIONS FOR UNILATERAL GAIN SECTION</b>	<b>982</b>
<b>Appendix E</b>	<b>VECTOR REPRESENTATION OF TWO-TONE INTERMODULATION PRODUCTS</b>	<b>985</b>
<b>Appendix F</b>	<b>PASSIVE MICROWAVE ELEMENTS</b>	<b>1005</b>
<b>INDEX</b>		<b>1027</b>