

# CONTENTS

<b>List of Tables</b>	<b>xvii</b>		
<b>Preface</b>	<b>xix</b>		
<b>ONE: Real-World Passive Components</b>	<b>1</b>		
1x.1 Wire and Connectors	5		
1x.1.1 Wire gauge: resistance, heating, and current-carrying capacity	5		
1x.1.2 Stranding, insulation, and tinning	5		
1x.1.3 Printed circuit wiring	6		
1x.1.4 PCB traces	7		
<i>Resistance and current-carrying capacity; Capacitance and inductance; Transmission-line impedance and attenuation</i>			
Transmission-line impedance and attenuation	7		
1x.1.5 Cable configurations	9		
1x.1.6 Inductance and skin effect	10		
<i>Inductance; Skin effect</i>			
1x.1.7 Capacitive and magnetic coupling	12		
1x.1.8 Mitigation of coupled signals	13		
1x.1.9 Shielded enclosures	13		
1x.1.10 Connectors	15		
1x.1.11 Connectors for RF and high-speed signals	17		
1x.1.12 High-density connectors	18		
1x.1.13 Connector miscellany	19		
1x.2 Resistors	20		
1x.2.1 Temperature coefficient	20		
1x.2.2 Self-capacitance and self-inductance	20		
1x.2.3 Nonlinearity (voltage coefficient)	21		
1x.2.4 Excess noise	22		
1x.2.5 Current-sense resistors and Kelvin connection	23		
1x.2.6 Power-handling capability and transient power	23		
			<i>Do-it-yourself testing; Overload to failure</i>
		1x.2.7 Resistor dividers	26
		1x.2.8 “Digital” Resistors	28
			<i>The digipot zoo; Digipot cautions; Wrapup</i>
		1x.3 Capacitors	34
		1x.3.1 Temperature coefficient	34
		1x.3.2 ESR	35
		1x.3.3 ESL	36
		1x.3.4 Dissipation factor	37
		1x.3.5 Voltage coefficient of capacitance	38
		1x.3.6 AC voltage coefficient	40
		1x.3.7 Aging	40
		1x.3.8 Frequency dependence of capacitance	40
		1x.3.9 Electromechanical self-resonance and microphonics	40
		1x.3.10 Dielectric absorption	42
		1x.3.11 Capacitor choices for typical applications	42
			<i>Bypass and decoupling; Oscillators, filters, and timing; High frequency; Energy storage; AC line filtering; High voltage</i>
		1x.3.12 Capacitor miscellany	44
		1x.4 Inductors	46
		1x.4.1 The basics	46
		1x.4.2 Air-core inductors	46
			<i>Solenoid – approximate; Solenoid – exact; Toroid; Loop</i>
		1x.4.3 Magnetic-core inductors	49
			<i>Ferromagnetic materials; Ferrite-core solenoid; Ferrite-core toroid; Gapped core; Noise and spike suppression</i>

1x.4.4	Inductors and transformers for power converters	58	<b>TWO: Advanced BJT Topics</b>	<b>96</b>	
1x.4.5	Why <i>build</i> it, when you can <i>buy</i> it?	58	2x.1	What's the <i>Actual</i> Leakage Current of BJTs and JFETs?	102
1x.4.6	Inductor examples <i>Radiofrequency “chokes” and bias-T’s</i>	59	2x.2	Current-Source Problems and Fixes	103
1x.5	Poles and Zeros, and the “s-Plane”	65	2x.2.1	Improving current-source performance	103
1x.6	Mechanical Switches and Relays	68	2x.2.2	Current mirrors: multiple outputs and current ratios	105
1x.6.1	Why use <i>mechanical</i> switches or relays?	68	2x.2.3	Widlar logarithmic current mirror	105
1x.6.2	So what's the problem? <i>Relay and switch contact life; Contact protection; Relay coil suppression; Improving relay switching speed</i>	68	2x.2.4	Current source from Widlar mirror	106
1x.6.3	Other switch and relay parameters <i>Switches: Function, actuator, bushing, terminals; Relays: Moving-armature, reed, and solid-state</i>	75	2x.3	The Cascode Configuration	108
1x.7	Diodes	77	2x.4	BJT Amplifier Distortion: a SPICE Exploration	110
1x.7.1	Diode characteristics <i>The family tree; Reverse (leakage) current; Forward voltage drop; Dynamic impedance; Peak current; Reverse capacitance; Zener capacitance</i>	77	2x.4.1	Grounded-emitter amplifier	110
1x.7.2	Stored charge and reverse recovery <i>Reverse recovery test circuit; Dependence on reverse and forward currents; Dependence on diode size; Schottky and fast-recovery diodes; Soft-recovery diodes; Step-recovery diodes; A far-out step-recovery application: Larkin's 40-amp kilovolt pulser; What about forward recovery?</i>	83	2x.4.2	Getting the model right	111
1x.7.3	The tunnel diode <i>Current versus voltage: Region of negative resistance; Measuring the tunnel diode characteristic curve; Tunnel diode trigger circuit</i>	89	2x.4.3	Exploring the linearity <i>Input-output transfer function; Gain versus input</i>	112
1x.8	Miscellaneous Circuits with Capacitors and Inductors	94	2x.4.4	Degenerated common-emitter amplifier	114
1x.8.1	Improved leading-edge detector	94	2x.4.5	Differential amplifier <i>Estimating the distortion</i>	114
1x.8.2	Capacitance multipliers	94	2x.4.6	Differential amplifier with emitter degeneration	116
			2x.4.7	Sziklai-connected differential amplifier	116
			2x.4.8	Sziklai-connected differential amplifier with current source	117
			2x.4.9	Sziklai-connected differential amplifier with cascode	118
			2x.4.10	Caprio's quad differential amplifier, with cascode	119
			2x.4.11	Caprio's quad with folded cascode – I	119
			2x.4.12	Caprio's quad with folded cascode – II	120
			2x.4.13	Measured distortion	121
			2x.4.14	Wrapup: amplifier modeling with SPICE	121
			2x.5	Early Effect and Early Voltage	122
			2x.5.1	Measuring Early effect	122
			2x.5.2	Some Early effect formulas	123
			2x.5.3	Consequences of Early effect: Output resistance <i>Maximum single-stage voltage gain; Current-source output impedance</i>	124

2x.6	The Sziklai Configuration	126	2x.14.4	Epilogue: 120 V, 5 A, dc-10 MHz Laboratory Amplifier	152
2x.6.1	Two-transistor “standard” Sziklai	126		<i>Circuit details; Output protec- tion; Transistor choices</i>	
2x.6.2	Three-transistor “enhanced” Sziklai	126			
2x.6.3	Push–pull output stage: a Sziklai application	128			
2x.7	Bipolarity Current Mirrors	129	<b>THREE: Advanced FET Topics</b>		<b>156</b>
2x.7.1	A simple high-speed bipolarity current source	129	3x.1	A Guided Tour of JFETs	161
	<i>Reducing input current; Operat- ing at higher voltages</i>		3x.1.1	Gate current, $I_{GSS}$ and $I_G$	166
2x.7.2	Precision bipolarity current source with folded cascode	131	3x.2	A Closer Look at JFET Transconduc- tance	169
2x.8	The Emitter-Input Differential Amplifier	133	3x.2.1	Dependence of $g_m$ on $I_D$	169
2x.8.1	An application: High-current, high-ratio current mirror	133	3x.2.2	Dependence of $g_m$ on $V_{DS}$	170
2x.8.2	Improving the emitter-input differential amplifier	134	3x.2.3	Performance of the transconductance enhancer	171
2x.9	Transistor Beta versus Collector Current	136	3x.2.4	Transconductance in the JFET source follower	172
2x.10	Parasitic Oscillations in the Emitter Fol- lower	138	3x.3	Measuring JFET Transconductance	174
2x.11	BJT Bandwidth and $f_T$	140	3x.4	A Closer Look at JFET Output Imp- edance	175
2x.11.1	Transistor amplifiers at high frequencies: first look	140	3x.4.1	A JFET’s $g_{os}$ -limited gain, $G_{max}$	175
	<i>Reducing the effect of load ca- pacitance</i>		3x.4.2	Source degeneration: another way to mitigate the $g_{os}$ effect	176
2x.11.2	High-frequency amplifiers: the ac model	140	3x.4.3	Dependence of $g_{os}$ on drain current density	177
	<i>ac model; Effects of collector voltage and current on transis- tor capacitances; Low- and high- current regions; SPICE param- eters; Comparing SPICE models with measured <math>f_T</math>; Wideband mi- cropower BJTs; Collector–base time constant and maximum os- cillation frequency</i>		3x.4.4	Dependence of $g_{os}$ and $G_{max}$ on $V_{DS}$	178
2x.11.3	A high-frequency calculation example	145	3x.4.5	A parting shot: $g_{os}$ – sometimes it matters, sometimes it doesn’t	178
2x.12	Two-terminal Negative Resistance Cir- cuit	146	3x.4.6	Example: A low-noise open-loop differential amplifier	178
2x.13	If It Quacks Like an Inductor . . .	148	3x.5	MOSFETs as Linear Transistors	180
2x.14	“Designs by the Masters”: $\pm 20$ V, 5 ns, 50 $\Omega$ Amplifier	150	3x.5.1	Output characteristics and transfer function	180
2x.14.1	Output stage block diagram	150		<i>Datasheet curves; Measured data</i>	
2x.14.2	Output stage: the full enchilada	150	3x.5.2	Linear operation: hotspot SOA limitation	182
2x.14.3	Output stage: some fine points	152	3x.5.3	Exploring the subthreshold region	182
				<i>MOSFETs at low drain voltage; MOSFETs at high drain voltage</i>	
			3x.5.4	Exploring a high-voltage MOSFET	185
				<i>IOTP1N120 transfer character- istics; IOTP1N120 transconduc- tance</i>	
			3x.5.5	SPICE models for power MOSFETs in the subthreshold region	187

3x.5.6	Typical SPICE model for a power MOSFET	189	3x.11.2	The next 15 years	222
	<i>Equivalent circuit; Model capacitances; Other models</i>			<i>Logic-level gates; Packages; P-channel MOSFETs; High-voltage parts; Capacitances</i>	
3x.5.7	An unusual low-voltage MOSFET	191	3x.11.3	Four kinds of power MOSFETs	228
3x.6	Floating High-Voltage Current Sources	193		<i>Comparison of capacitances; Energy: what does all this capacitance stuff mean? Conclusion</i>	
3x.6.1	Raising output impedance with a cascode	193	3x.12	Measuring MOSFET Gate Charge	233
3x.6.2	Reducing power dissipation	195	3x.12.1	The gate charge curve depends on load current	233
3x.6.3	Small-signal output impedance	195	3x.12.2	Gate charge curves at constant load current	233
3x.6.4	Low-cost predictable current source	196	3x.12.3	The gate charge curve depends also on drain voltage	234
3x.6.5	Current sources for higher voltages	197	3x.12.4	Gate charge test circuit	234
	<i>A simple scheme; Distributed series string; Some applications: HV amplifier; HV probe; High-voltage current sources: 250 <math>\mu</math>A; High-voltage current sources: 2 mA; Current sources in high-voltage amplifiers; High-voltage current sources: 5 mA and more; Perfect high-voltage current source</i>		3x.12.5	The Miller plateau	235
3x.7	Bandwidth of the Cascode; BJT versus FET	206	3x.13	Pulse Energy in Power MOSFETs	238
3x.7.1	The common-gate/common-base amplifier	206	3x.13.1	Limited only by maximum junction temperature	238
3x.7.2	Cascode as common-gate/common-base amplifier	206		<i>Controlled Conduction; Avalanche Mode</i>	
3x.7.3	Estimating cascode bandwidth	207	3x.13.2	Alternative graphs	240
3x.7.4	What about MOSFETs?	208	3x.14	MOSFET Gate Drivers	242
3x.7.5	Bandwidth of the source follower	208	3x.15	High-Voltage Pulsers	244
3x.8	Bandwidth of the Source Follower with a Capacitive Load	209	3x.15.1	Two-switch +600 V pulser	244
3x.8.1	Follower with resistive signal source	209	3x.15.2	Two-switch +500 V 20 A fast pulser	246
3x.8.2	Follower driven with a current signal	210	3x.15.3	Two-switch reversible kilovolt pulser	247
3x.9	High-Voltage Probe with High Input Impedance	213	3x.15.4	Output monitor	247
3x.9.1	Compensated-offset MOSFET follower	213	3x.15.5	Three-switch bipolarity kilovolt pulser	249
3x.9.2	Bootstrapped op-amp follower	213	3x.16	MOSFET ON-Resistance versus Temperature	251
3x.10	CMOS Linear Amplifiers	217	3x.17	Thyristors, IGBTs, and Wide-bandgap MOSFETs	252
3x.11	MOSFETs Through the Ages	219	3x.17.1	Insulated-gate bipolar transistor (IGBT)	252
3x.11.1	A MOSFET Saga: the First 30 Years	219	3x.17.2	Thyristors	252
			3x.17.3	Silicon carbide and gallium nitride MOSFETs	253
			3x.18	Power Transistors for Linear Amplifiers	254
			3x.19	Generating Fast High-Current LED Pulses	258
			3x.19.1	10 ns pulser	258
			3x.19.2	High-power pulser	258
				<i>Wiring; Gate voltage; Power dissipation</i>	
			3x.19.3	Integrated LED Drivers	261

3x.20 Precision 1.5 kV 1 $\mu$ s Ramp	262	4x.4.1 Stability of the composite amplifier	299
3x.21 Fast Shutoff of High-Energy Magnetic Field	264	4x.4.2 Some more applications	300
3x.21.1 Helmholtz coils, rapid field shutoff	264	4x.4.3 Some cautions	302
3x.21.2 High voltage, high current switches	264	4x.5 High-Speed Op-amps I: Voltage Feedback	304
3x.22 Precision Charge-dispensing Piezo Positioner	266	4x.5.1 Voltage feedback and current feedback	304
3x.22.1 Fast MOSFET pulsed charge dispenser	266	<i>Some confusing terms</i>	
3x.22.2 Analog charge dispenser	268	4x.5.2 Overview of the table	305
3x.22.3 Small-step pulsed charge dispenser	269	4x.5.3 Scatterplots: Seeking trends	308
<b>FOUR: Advanced Topics in Operational Amplifiers</b>	<b>271</b>	4x.6 High-speed Op-amps II: Current Feedback	316
4x.1 From Philbrick to SMT	276	4x.6.1 Properties of CFBs	316
4x.2 Feedback Stability and Phase Margins	278	<i>Closed-loop bandwidth; Slew rate and output current; The feedback network and stability; Input current and precision</i>	
4x.2.1 Sliding $f_2$ : phase margin and circuit performance	279	4x.6.2 Care and feeding of CFBs	318
4x.2.2 What about amplifiers with $G_{CL} > 1$ ?	280	4x.6.3 “Hybrid” VFB+CFB op-amps	319
4x.2.3 Applying Bode plots to amplifier design	280	4x.6.4 When to use CFBs	320
4x.2.4 Afterword: High-speed op-amps <i>SPICEing the 3-pole op-amp</i>	281	4x.6.5 Mathematical postscript: bandwidth and gain in CFBs	320
4x.3 Transresistance Amplifiers	283	4x.6.6 Remarks on the table	321
4x.3.1 Stability problem	283	4x.7 Power Supply Rejection Ratio	324
4x.3.2 Stability solution	283	4x.8 Capacitive-Feedback Transimpedance Amplifiers	326
4x.3.3 An example: PIN diode amplifier	285	4x.8.1 Capacitive-feedback TIA for gigabit optical receivers	326
<i>Gaining speed; “Pedal to the metal”; Sub-picofarad capacitors</i>		4x.9 Slew Rate: A Detailed Look	328
4x.3.4 A complete photodiode amplifier design	288	4x.9.1 Increasing slew rate	328
4x.3.5 Gain-switching	289	4x.9.2 Case study: high-voltage pulse generator	330
4x.3.6 Some loose ends	290	4x.10 Bias-Current Cancellation	332
4x.3.7 Designs by the masters: A wide-range linear transimpedance amplifier	291	4x.10.1 The best of both worlds?	332
4x.3.8 A “starlight-to-sunlight” linear photometer	293	4x.10.2 Bias cancellation: the circuits	332
4x.3.9 Autoranging wideband transimpedance amplifier	296	<i>Simplest: Mirroring the base current of a cascode twin; Better: Bootstrapping the cascode bias; Another way: replicating the emitter current</i>	
4x.3.10 Multiple-range cascode-bootstrap wideband TIA	297	4x.10.3 Bias cancellation: how well does it work?	334
4x.4 Unity-Gain Buffers	299	4x.11 Rail-to-Rail Op-amps	336
		4x.11.1 Rail-to-rail inputs	336
		4x.11.2 Rail-to-rail outputs	336
		4x.11.3 Output near ground: when “RRO” isn’t	336
		4x.11.4 Offsetting the negative supply terminal	338

4x.11.5 Designs by the masters: the Monticelli output stage	339	4x.23.9 Faster HV amplifier: 1MHz and 1200V	376
4x.12 Slewing and Settling	342	<i>Transistor choices; Circuit changes</i>	
4x.12.1 Dependence on $f_T$	342	4x.24 High-Voltage Bipolarity Current Source	380
<i>Slew-rate enhanced op-amps</i>		4x.24.1 Performance issues	381
4x.12.2 A caution: 'scope overdrive artifacts	343	4x.25 Ripple Reduction in PWM	383
4x.13 Resistorless Op-amp Gain Stage	346	4x.26 Nodal Loop Analysis: MOSFET Current Source	386
4x.14 Silicon Photomultipliers	348	4x.26.1 Example: MOSFET current source	386
4x.14.1 SiPM characteristics	348	<i>Nodal model; KCL equations; Node equations; Results</i>	
4x.14.2 SiPM construction	348	4x.26.2 Example: fast 2.5 A pulsed current	389
4x.14.3 SiPM characteristics, electronics, and waveforms	349		
4x.15 External Current Limiting	351		
4x.16 Designs by the Masters: Bulletproof Input Protection	353		
4x.17 Canceling Base-Current Error in the Current Source	356	<b>NINE: Advanced Topics in Power Control</b>	<b>391</b>
4x.18 Analog “Function” Circuits	357	9x.1 Reverse Polarity Protection	396
4x.18.1 The Lorenz attractor	357	9x.2 Lithium-Ion Single-Cell Power Subsystem	397
4x.18.2 Summing amplifiers	357	9x.2.1 Charger features	397
<i>Non-inverting Adder; Adder-subtractor</i>		9x.2.2 Monitor and Protect	397
4x.19 Normalizing Transimpedance Amplifier	360	9x.2.3 Output voltage regulator	398
4x.20 Logarithmic Amplifier	362	9x.2.4 Multiple cells: a “battery”	399
4x.20.1 Temperature compensation of gain	362	9x.3 Low-Voltage Boost Converters	400
4x.21 A Circuit Cure for Diode Leakage	364	9x.4 Foldback Current Limiting	402
4x.22 Capacitive Loads: Another View	365	9x.5 PWM for DC Motors	403
4x.22.1 Frequency of oscillation	365	9x.5.1 The myth: PWM as secret sauce	403
4x.22.2 So, how about a few equations?	366	<i>An experiment; Toy trains and sewing machines; Another experiment</i>	
4x.23 Precision High-Voltage Amplifier	368	9x.5.2 Wrapup: PWM versus dc for motor drive	405
4x.23.1 Overview	368	9x.5.3 Afterword: DC motor model	407
4x.23.2 High-voltage output stage	368	<i>Series resistance: Op-amp analogy</i>	
4x.23.3 Front-end amplifier stage	370	9x.6 Transformer + Rectifier + Capacitor = Giant Spikes!	410
4x.23.4 Feedback stability	371	9x.6.1 The effect	410
4x.23.5 Circuit capacitances and capacitive loads	372	9x.6.2 Calculations and cures	410
<i>No load, no feedback capacitance; Add feedback capacitance; Add load capacitance; Output series resistor; SPICE analysis</i>		9x.7 Low-Voltage Clamp/Crowbar	412
4x.23.6 Output slew rate	374	9x.7.1 New clamp/crowbar	412
4x.23.7 Measured performance	374	<i>Circuit operation; Additional details; Performance</i>	
4x.23.8 Variations: unipolarity, higher voltages, greater speed	375	9x.8 High-Efficiency (“Green”) Switching Power Supplies	415
<i>MOSFET transistor choices</i>		9x.9 Power Factor Correction (PFC)	418
		9x.10 High-Side High-Voltage Switching	421
		9x.11 High-Side Current Sensing	423

9x.11.1 Pulse generator overcurrent limit	423	9x.25.3 TVS devices	475
9x.11.2 Current monitor for high-voltage amplifier	424	<i>Gas surge arrestors; Metal oxide varistors; Zener TVSs</i>	
<i>Current monitor for HV bipolarity amplifier</i>		9x.25.4 MOV versus zener TVS	477
9x.12 High-Voltage Discharge Circuit	427	9x.25.5 “Series-mode” transient protection	478
9x.13 Beware Counterfeits (or, Don’t Bite into That Apple)	428	9x.25.6 TVS circuit example	479
9x.14 Low-Noise Isolated Power	432	<i>Fast-switching magnet</i>	
9x.15 Low-Current Non-isolated DC Supplies	437	9x.25.7 Transient test circuit	480
9x.15.1 Simplest circuit:		<i>Standard test pulses</i>	
reactance-limited zener bias	437	9x.25.8 Transient thermal response	482
9x.15.2 Improved circuit: full-wave rectifier	437	Parts Index	484
9x.15.3 Why hasn’t Silicon Valley responded?	438	Subject Index	494
9x.15.4 Case study: ceiling fan	438		
9x.15.5 Inverse Marx generator	439		
9x.16 Bus Converter: the “DC Transformer”	442		
9x.16.1 Differences from classic switch-mode converter	442		
9x.16.2 Bus converter applications	442		
9x.16.3 Bus converter example	442		
9x.16.4 A few comments	443		
9x.17 Negative-Input Switching Converters	446		
9x.17.1 Negative buck from positive boost	446		
9x.17.2 Negative boost from positive buck	446		
9x.18 Precision Negative Bias Supply for Silicon Photomultipliers	448		
9x.19 High-Voltage Negative Regulator	450		
9x.20 The Capacitance Multiplier, Revisited	451		
9x.21 Precision Low-Noise Laboratory Power Supply	453		
9x.21.1 Overview	453		
9x.21.2 Circuit details	455		
9x.21.3 Performance	456		
9x.22 Lumens to Watts (Optical)	459		
9x.23 Sending Power on a Beam of Light	461		
9x.24 “It’s Too Hot” Redux	465		
9x.24.1 The finger test	465		
9x.24.2 Better thermometry	465		
9x.25 Transient Voltage Protection and Transient Thermal Response	474		
9x.25.1 The problem	474		
9x.25.2 The solution	474		