Index

abstraction levels, circuit design, 7, 8 accelerometers, 4–5

active current mirrors, 145-58; common-mode properties, 154-58; differential pair with, 148, 150, 151, 154, 190; large-signal analysis of, 149-51; small-signal analysis, 151-54; small-signal behavior in, 145-48 active devices, 611-16; back-end processing, 614-16; basic transistor fabrication, 611-14; fabrication, 611-16 ADC. See analog-to-digital converter amplification mode: noninverting amplifiers, 432-433, 436, 437; unity-gain sampler, 424-25, 429-30 amplifiers: auxiliary, 312; cascade of, 170; continuous-time feedback, 405-7; current, 254-56; differential, 100-34; frequency response of, 166-200; noise in single-stage, 224-33; noninverting, 432-38; nonlinear, 448-63; one-pole feedforward, 348; operational, 291-344; output port, 66-67; single-stage, 47-99, 224-33; switched-capacitor, 423-39; transconductance, 254-56; transimpedance, 254-56; types of, 254-56; variable gain, 126-28; voltage, 254-56, 461 amplitude: distribution, 206-7; limiting, 487-95; output, 512

analog design, 600; introduction to, 1–8; in microprocessors and memories, 5–6; octagon, 48; robust, 7–8 analog layout techniques, 635–60; multifinger transistors, 635–37; passive devices, 644–53; reference distribution, 642–44; symmetry, 637–42 analog-to-digital converter (ADC), 1–2 antenna effect, 634–35 asymmetry, 120–24, 151–52. See also symmetry

auxiliary amplifiers, 312 average power, 202–3

back-end processing, 614–16
bandgap references, 377–404; case study, 397–400; defined, 389; floating, 398–99; general considerations, 377; speed and noise issues, 393–97; temperature-independent references, 384–90. See also reference distribution
bandwidth: large-signal, 295; modification, 252–54; noise, 239; small-signal, 293–95
Barkhausen's Criteria, 346, 483, 487
biasing: constant-G_m, 392–93; supply-independent, 377–81
binary data, 2–3

Bode plots, 346–47, 349, 357, 359, 362, 364, 547, 561 body effect, 23–25; source follower, 71 bonding pads, 657–59 bootstrapping, 566–67 bottom-plate sampling, 423 bounce, 663–65, 668 BSIMs, 591–92, 596–97 bulk, 12; NFETs and PFETs, 36 bulk voltage, 23–25 bypass capacitors, 673

- cancellation, offset, 471-78
- capacitance: fringe, 626; load, 169-70; mutual, 675; parallel, 626-27; parasitic, 171; self-, 675
 - capacitance modeling, MOS device models, 598
 - capacitive coupling, reducing, 654
 - capacitor nonlinearity, 457-58
 - capacitors: accelerometer, 4–5; behavior of MOS devices as, 38–39; bypass, 673; layout in passive devices, 650–52; metal-poly, 620–21; monolithic, 423–24; MOS, 621–24; in passive MOS devices, 619–24; poly-diffusion, 619–20; poly-poly, 620; voltage-dependent, 521–22. See also capacitor
 - nonlinearity; switched-capacitor circuits
 - cascode current mirrors, 139-45
 - cascode current source, 140-45
 - cascode devices, layout, 638
 - cascode differential pair, 126
 - cascode operational amplifiers, 292, 298-99; folded, 301-7; telescopic, 297-99, 303-4, 306

cascode stage, 83-92; frequency response, 185-87; gain boosting in, 310-11; input-output characteristic, 84; model, 186; output impedance, 85-86, 88; shielding property, 89-90; single-stage amplifiers, 232-33; small-signal characteristics, 84-85

cascodes: folded, 90-92; low-voltage, 143-45; self-biased, 398; triple, 307

center frequency in voltage-controlled oscillators (VCOs), 511

CG stage. See common-gate stage

- channel, long versus short, 38
- channel charge injection, 418-20; cancellation, 421-23
- channel-length modulation, 25-27

channel resistance, of MOS capacitors, 622-24

channeling, 609–10

678

Index

charge injection, channel, 418-20, 421-23 charge modeling, MOS device models, 598 charge-pump phase-locked loops (CPPLLs), 549-62; basic, 555-62; charge pumps, 550-55; dynamics, 557-61; linearity, 557; lock acquisition, 549-62; phase/frequency detector, 550-55; stability issues, 561-62; transfer function, 557-61 charge pumps: in charge-pump phase-locked loops (CPPLLs), 550-55; PFD/CP nonidealities, 562-67 charge redistribution in noninverting amplifier, 434 chemical vapor deposition (CVD), 611 circuit design, abstraction levels, 7, 8 circuit symbols, MOS, 12-13 circuits: bandgap reference, 377-404; closed-loop, 250-53; common-gate, 250; differential, 452-54; digital, 12; feedback, 247-54; guard rings for, 663; half, 113-18; noise represented in, 218-24; open-loop, 250, 253-54; precision multiply-by-two, 438-39, 622; RLC, 496-99; sampling, 410-14; switched-capacitor, 405-47 clamp transistors, 332-33 clock: amplification and offset modes controlled by, 472; edges, 427; feedthrough, 420-22 closed-loop circuits, 250-53 closed-loop frequency response, 351-55 closed-loop gain, 248-49, 252; in operational amplifiers, 293; and voltage-voltage feedback, 272-73 closed-loop transfer function, 247 CMFB. See common-mode feedback CMOS (complementary MOS) devices, 6-7; processing technology, 604-30 CMOS inverters, 581; driving load capacitance, 668; ring oscillators using, 490 CMOS oscillators. See oscillators CMOS technology: compatibility with bandgap references, 386; diodes realized in, 523 collector current variation, 385-86 Colpitts oscillators, 502-5 common-centroid layout, 640-41 common-drain stage, 67. See also source follower common-gate circuit, with feedback, 250 common-gate (CG) stage, 76-83; frequency compensation using, 370-71; and frequency response, 183; at high frequencies, 183; input impedance, 80-83; input-output characteristic, 77; input-referred noise, 229-31; output impedance, 80-83; with parasitic capacitance, 171; single-stage amplifiers, 228-31; transfer function, 171 common mode (CM), input-output characteristic, 105 common-mode behavior, differential pair, 105-6 common-mode input, 116-18 common-mode feedback (CMFB): modifying, 323-24; operational amplifiers, 314; switched-capacitor, 442-43; topology, 317 common-mode level, sensing and controlling, 319-22 common-mode noise rejection, 101 common-mode properties, active current mirrors, 154-58 common-mode range, extending, 325-26 common-mode rejection: alternative definition, 478-79; in voltage-controlled oscillators (VCOs), 512 common-mode response, differential amplifiers, 118-24 common-mode signals, response of differential pairs to, 187-93 common-source (CS) stage, 48-67; with current-source load, 58-59; with diode-connected load, 53-58; distortion in, 449; with feedback, 248, 251-52; frequency

response, 172-78; gain stage added to, 219; high-frequency model, 172; input impedance in, 177; and input-referred noise, 219-221; with resistive degeneration, 458-59; single-stage amplifiers, 225-28; with source degeneration, 60-67; and source impedance stimulation, 223-24; transfer function, 172-77; with triode load, 59-60; using n-well resistors, 618; zero calculated in, 176-77 compensation, frequency, 355-61 complementary switches, 422 conduction, subthreshold, 27-28 constant-field scaling, 579 constant-Gm biasing, 392-93 contact spiking, 615-16 contact windows, 615 continuous-time: feedback amplifiers, 405-7; integrator, 439; resistors, 439 control voltage, 126-29 conversion, differential, 120-24 corner frequency, flicker noise, 217-18 correlated sources of noise, 207-9 coupling: capacitive, 654; one-dimensional cross-, 641-42; substrate, 660-65 cross-coupled oscillators, 499-501, 522 CS stage. See common-source stage current: amplifiers, 254-56; copying, 137; drain, 148-49; generating PTAT (proportional to absolute temperature), 390-92; generation versus voltage amplification, 225; meters, 256-58; mismatch, 469-70, 565-67; notation, 8; resistive biasing, 135-36; scaling, 643-44; steering, 515-20; tail, 120-21. See also biasing current-current feedback, 269-70; loading in, 281 current mirrors: active, 135-65, 145-58; basic, 135-39; cascode, 139-45; passive, 135-65 current-source load: common-source stage with, 58-59; differential pair with, 146 current sources: applications, 135-36; cascode, 140-45; NMOS device used by source follower as, 69; noise represented in, 221-22 current-voltage feedback, 263-66; loading in, 275-78 curvature correction, 390 CVD. See chemical vapor deposition Czochralski method, 606 DAC (digital-to-analog converter), 3 dangling bonds, 215 data: binary, 2-3; four-level, 2-3; stored on hard disks, 3; transmission of over long distances, 4 dead zone in phase-locked loops (PLLs), 563-64 deep triode region, MOSFETs operating in, 460-61. See also triode region degeneration, resistive, 458-63 delay-locked loops (DLLs), 570-72 delay variation: by interpolation, 518-20; by positive feedback, 515-18 deposition, 611 design rules, 632-34 designing operational amplifiers, 299-300 device models, choice of, 92-93 devices. See active devices; MOS devices; NMOS devices; passive devices; PMOS devices DIBL. See drain-induced barrier lowering differential amplifiers, 100-34; biased by current mirrors, 138-39; common-mode response, 118-24; Gilbert cell, 126-29

differential circuits, 103; nonlinearity of, 452-54 differential conversion, 120-24 differential input, 116-18 differential pairs: with active current mirror, 148, 150, 151, 154, 190; basic, 103-18; cascode, 126; common-mode behavior, 105-6; with common-mode feedback, 314-15; with current-source load, 146; degeneration, 460-62; distortion in, 449; frequency response, 187-93; half circuit, 126; input voltage, 107-10; input-output characteristic, 104; layout, 638-40; lemma, 114; with MOS loads, 124-26; noise in, 233-39; with offset, 465-70; output voltage, 106-7; PMOS, 479; qualitative analysis, 104-7; quantitative analysis, 107-18; small-signal behavior, 110-14; used in tuning ring oscillators, 512-20 differential realization, in noninverting amplifier, 435 differential sampling circuits, 422-23 differential signals: response of differential pairs to, 187-93; versus single-ended, 100-2 digital communications, 2-3 digital signal processor (DSP), 1-2 digital-to-analog converter (DAC), 3 diode-connected device, 137 diode-connected load, CS stage with, 53-58 diodes: layout in passive devices, 652-53; realized in CMOS technology, 523; varactor, 521-25 DIP. See dual-in-line package discrete-time: integrators, 440; resistors, 439 disk drive electronics, 3 dispersion, 657 dissipation, power, 512 distortion: in common-source stage, 449; in differential pair, 449; even-order, 470-71 distribution: amplitude, 206-7; reference, 642-44 drain, 10, 11 drain current, 15-17, 148-49; combining, 149; of common-source device, 62; saturation of, 19 drain-induced barrier lowering (DIBL), 585, 586 drain-source voltage, output impedance variation with, 589-91 DSP (digital signal processor), 1-2 dual-in-line package (DIP), 666 dummy switches, 421-22 dummy transistors, 639-40

electromigration, 626 electrostatic discharge (ESD), 659–60 enclosure, 633–34 ESD. See electrostatic discharge etching, 611 even-order distortion, 470–71 excess phase, in phase-locked loops (PLLs), 542–43 extension, 633–34

fabrication: active devices, 611-16; interconnects, 624-27; of CMOS devices, 611-27; passive devices, 616-24; transistor, 611-14

feedback, 246–90; circuits, 247–54; common-gate circuit with, 250; common-mode, 314–24; common-source stage with, 248, 251–52; current-current, 269–70, 281; current-voltage, 263–66, 275–78; effect of negative on nonlinearity, 454–57; effect on noise, 284–85; error, 246; general considerations, 246–58; increasing output impedance by, 310; networks, 246; oscillatory, 484; polarity, 389; positive, 515–18;

series, 256; shunt, 256; switched-capacitor common-mode, 442-43; system, 246-58; topologies, 258-70; two-pole, 485-86; voltage-current, 266-69, 275-80; voltage-voltage, 258-63, 272-75. See also feedback circuits; negative feedback; positive feedback feedback circuits: bandwidth modification, 252-54; gain desensitization, 247-50; nonlinearity reduction, 254; sense and return mechanisms, 256-58; terminal impedance modification, 250-52 feedback loop, 535; tuned stages, 499 feedforward: amplifiers, one-pole, 348; networks, 246 field oxide, 608 filter, low-pass, 210-211 fingers, transistor, 635-37 five-stage ring oscillators, 491 flicker noise, 215-18; corner frequency, 217-18 flipflops, 551-53 floating: impedance, 166; references, 398-99 folded cascode operational amplifiers, 301-7; noise in, 337-38; slewing in, 331-32 folded cascodes, 90-92 folding, 35; reduction of gate resistance by, 214; white noise, 206; wide transistors, 635-37 folding/folded structures, 31 four-level data, 2-3 four-stage ring oscillators, 491 frequency: center, 511; corner, 217-18; multiplication, 573-74; synthesis, 574-75. See also frequency compensation; frequency response; phase/frequency detectors (PFDs) frequency compensation, 345-48, 355-61; common-gate stage used in, 370-71; Miller compensation, 362-64, 367; other techniques, 369-73; two-stage operational amplifiers, 361-69 frequency response: amplifier, 166-200; cascode stage, 185-87; closed-loop, 351-55; common-gate stage, 183-85; common-source stage, 172-78; differential pair, 187-93; general considerations, 166-71; Miller effect, 166-69, 171, 172, 174, 175, 185; and source followers, 182-85 fringe capacitance, 626

G models, 272 gain: boosting, 309–13; closed-loop, 272–73, 293; common-mode, 154–58; crossover point, 346, 352; desensitization, 247–50; open-loop, 270, 273–75, 292; small-signal, 145–51; stage, added to common-source stage, 219; voltage, 151–54 gate: resistance, 214–15; shadowing, 639; voltage, 144 gates, 10, 11; OR, 532–33 Gilbert cell, 126–29 gradient, 640 ground bounce, 663–65 guard rings, 663

half-circuit concept, 151–52, 187–89 half circuits, 113–18; differential pair, 126; folded cascode operational amplifiers, 303 high frequencies, common-gate stage at, 183 high-frequency model: cascode stage, 185; common-source stage, 172 hot carrier effects, 589 hybrid models, 270–72, 281

I/V characteristics, derivation, 15-23 impedance: floating, 166; input, 177, 179, 261-63, 265-66, 266-68; modification, 250-52; output, 173, 259-60, 264-65, 266-68, 310, 386-89, 393-97, 589-91; source, 223-24. See also input impedance; output impedance inductance: mutual, 673-75; self-, 668-73 inductors, monolithic, 495, 521, 524 injection, channel charge, 418-20, 421-23 input: common-mode, 116-18; differential, 116-18 input characteristics: of nonlinear systems, 448; of phase/frequency detectors (PFDs), 553-55; of sampling circuits, 419. See also input/output characteristic; output characteristics input differential voltage, 107-10 input impedance: in a common-source stage, 177; and current-voltage feedback, 265-66; source follower, 73, 179; and voltage-current feedback, 266-68; and voltage-voltage feedback, 261-63 input nodes: in cascode stage, 185-87; in common-gate stage, 183-85; in common-source stage, 172-77; and differential pairs, 187-93; and source followers, 178-82. See also nodes; output nodes input-output characteristic, 47-48, 49, 54; cascode stage, 84; common-gate stage, 77; common mode, 105; common-source stage with diode-connected load, 56; differential pair, 104; large-signal, 150; source follower, 68. See also input characteristics; output characteristics input-output transfer function, 169 input poles: in cascode stage, 185-87; in common-gate stage, 183-85; in common-source stage, 172-77; and differential pairs, 187-93; and source followers, 178-82. See also poles; output poles input range limitations, 325-26 input-referred noise, 219-24; of a differential pair, 233-39 input-referred thermal noise: common-gate stage, 229-31; voltage, 225-28 input voltage: notation, 8; versus voltage gain of source follower, 69 integrated circuits, 6; layout and packaging, 631-75; notations, 8 integrators: discrete-time, 440; parasitic-insensitive, 441; switched-capacitor, 439-42 interconnects: fabrication, 624-27; layout in passive devices, 653-57; parallel capacitance, 626-27; series resistance, 624-25 interface, dangling bonds at, 215 interpolation, delay variation by, 518-20 inverters. See CMOS inverters ion implantation, 608-10 jitter: in phase-locked loops (PLLs), 563-64, 567-70;

Just: In plase-locked loops (PLLs), 505–64, 507–70; reducing in phase-locked loops (PLLs), 576–77; in voltage-controlled oscillators (VCOs), 568–70 junction capacitances, scaling, 580–82

kT/C noise, 421

large-signal analysis, of active current mirrors, 149–51 large-signal bandwidth, operational amplifiers, 295 large-signal behavior: cascode current source, 140–45; folded-cascode stage, 91–92 large-signal input-output characteristic, 150 latch-up, 627–28 layout, 631–60; analog, 635–60; antenna effect, 634–35;

cascode devices, 638; common-centroid, 640-41;

design rules, 632-34; differential pairs, 638-40; general considerations, 631-32; minimum enclosure, 633-34; minimum extension, 633-34; minimum spacing, 633-34; minimum width, 632-33; multifinger transistors, 635-37; PMOS device, 631-32; symmetry, 637-42 LC oscillators, 495-509; Colpitts, 502-5; cross-coupled, 499-501; one-port, 505-9; tuning in, 521-25 LC tanks, 496-98 lemma: differential pair, 114; noise calculation, 224; voltage gain, 66-68 length, 11 level shifters, source followers as, 178-82 linear settling, 327, 333-34 linearity: in charge-pump phase-locked loops (CPPLLs), 557; operational amplifiers, 296; tuning, 511-12. See also nonlinearity linearization, 61; techniques, 458-63 lithography sequence, 607 load capacitance, 169-70 loading, effect of, 270-84; in current-current feedback, 281; in current-voltage feedback, 275-78; summarizing effects of, 283-84; two-port network models, 270-72; in voltage-current feedback, 278-80; in voltage-voltage feedback, 272-75 loads, MOS, differential pair with, 124-26 lock acquisition, in charge-pump phase-locked loops (CPPLLs), 549-62 locking, 533-42 long-channel devices, versus short-channel devices, 38 loop gain, 248; Bode plots, 346, 349, 357, 359, 362, 547, 561; in charge-pump phase-locked loops (CPPLLs), 559-62; computation, 249; and current-voltage feedback, 264, 275-78; in feedback loop, 500; in two- and three-pole systems, 486-87. See also closed-loop gain; open-loop gain loops, phase-locked, 532-78 low-pass filter, 210, 211

low-voltage cascode, 143-45

mathematical model, voltage-controlled oscillators, 525-30 memories, 5-6 metal 1, 614-15 metal-oxide-silicon field-effect transistors. See MOSFETs metal-poly capacitors, 620-21 meters, current and voltage, 256-58 microprocessors, 5-6 Miller compensation, 362-64, 367 Miller effect, 166-69, 171, 172, 174, 175, 185 Miller's theorem, 166-69, 193-95 mismatch, 120-24, 463-79; and common-mode gain, 157; current, 469-70, 565-67; DC offsets, 465-79; MOSFET, 463-79; threshold voltage, 471 mobility degradation with vertical field, 585-87 models: cascode stage, 186; choice of, 92-93; G, 272-73; high-frequency, 172; high-frequency, of cascode stage, 185; hybrid, 270-72, 281; mathematical, of voltage-controlled oscillators, 525-30; MOS device. 28-38, 591-99; MOS device BSIM series, 596-97; MOS device Level 1, 592; MOS device Level 2, 593-95; MOS device Level 3, 595-96; MOS small-signal, 33-36; MOS SPICE, 36-37; small-signal, 61, 65-66; small-signal of CS stage, 52; two-port network, 270; Y, 270-72, 278; Z, 270-72, 276

monolithic: capacitors, 423-24; inductors, 495, 521, 524

output-referred, 219; predicting properties of, 201-2; MOS: circuit symbols, 12-13; I/V characteristics, 13-23 MOS capacitors, 621-24; channel resistance of, 622-24 MOS device models, 591-99; BSIM series, 591-92, 596-97; charge and capacitance modeling, 598; Level 1, 592; Level 2, 593-95; Level 3, 595-96; temperature dependence, 599 MOS devices: active, 611-16; behavior as a capacitor, 38-39; noisy lines, 101 capacitances, 29-33; fabricating, 611-27; layout, 28-29; models, 28-38, 591-99; passive, 616-24; processing technology, 604-30; small-signal model, 33-36; subthreshold characteristics, 27-28; as switches, 413-23; transconductance, 22, 28. See also NMOS devices; PMOS devices MOS loads, differential pair with, 124-26 MOS SPICE models, 36-37 Norton equivalent, 66-67 MOS technology. See MOSFETs MOSFETs (metal-oxide-silicon field-effect transistors), 6; notations, 8 common-mode sensing using, 319; as controlled linear resistor, 18-19; layout, 28-29; mismatches in, 463-79; ohmic sections, 213-14; operating in deep triode region, 460-61; parameter variations, 599-600; physics, 9-38; reducing effect of mismatched, 397-400; relationship between drain current and terminal voltage, 15-17; saturated, one-pole systems, 252-54 19-21; scaling, 579-83; small-signal model, 33-36; one-port oscillators, 505-9 structure, 10-12; as switches, 10, 410-14; thermal noise, 212-15; transconductance, 392 multifinger transistors, 635-37 multiply-by-two circuits, 438-39; with MOS capacitor, 622 multipole systems, 349-51 mutual capacitance, 675 mutual inductance, 673-75 n-type MOS devices. See NMOS devices natural signals, processing of, 1-2 negative feedback: effect of on nonlinearity, 454-57; system, 345-46. See also feedback; feedback circuits; positive feedback negative resistance, 505-9 negative-TC (temperature coefficient) voltage, 381-82 NFETs: bulk, 36; threshold voltage, 14. See also NMOS NMOS (n-type MOS) devices, 6; bulk voltage, 23-25; in cross-coupled oscillators, 524-25; in gain-boosting amplifiers, 311; latch-up in, 627-28; in operational 361-69, 368-69 amplifiers, 301-5; parameters of Level 1 SPICE optical receivers, 4 models, 37; versus PMOS devices, 37; process OR gates, 532-33 corners based on speed of, 600; processing technology, 604-30; structure, 10-12; as switches, 410-14, 416; used by source follower as current nodes: association with poles, 169-71; in cascode stage, 185-87; in common-gate stage, 183-85; and (VCOs), 512 differential pairs, 187-93; input, 172-77; interaction between, 170, output, 172-77; and source followers, 178-82. See also input nodes; noise, 201-45; amplitude distribution, 206-7; average power, 202-3; bandwidth, 239; calculation lemma, 224; cascode stage, 232-33; common-gate stage, 228-31; common-mode, 101; common-source stage, 225-28; corner frequency, 217-18; correlated and uncorrelated sources, 207-9; in differential pairs, 233-39; effect of feedback on, 184-85; flicker, 215-18; input-referred, 219-24; kT/C, 421; in operational amplifiers, 296, 336-40;

devices

source, 69

output nodes

reduced by offset cancellation, 476-78; reference generator, 393-97; representation in circuits, 218-24; in self-inductance, 668-69; in source followers, 231-32; sources, 218-19; spectrum, 203-6; statistical characteristics, 201-9; thermal, 209-15; types of, 209-18; white, 204-5 noninverting amplifiers, 432-38: precision considerations, 435-36; speed considerations, 436-38 nonlinear systems, input-output characteristic, 47-48 nonlinearity, 448-63; capacitor, 457-58; definition of, 450; of differential circuits, 452-54; effect of negative

feedback on, 454-57; general considerations, 448-52; reduction, 254. See also linearity

offset: DC, 465-70; operational amplifier, 296, 386-89 offset cancellation, 471-76; noise reduced by, 476-78 ohmic sections, MOSFET, 213-14 one-dimensional cross-coupling, 641-42 one-pole feedforward amplifiers, 348 one-stage operational amplifiers, 296-307 op amps. See operational amplifiers open-loop circuits, 250, 253-54 open-loop gain, 248-49, 270; in operational amplifiers, 292; and voltage-voltage feedback, 273-75 open-loop transfer function, 247 operational amplifiers, 291-344; cascode, 292, 298-99; closed-loop gain, 293; common-mode feedback, 314; designing, 299-300; folded cascode, 301-7, 331-32, 337-38; gain, 291-92; gain boosting, 309-13; input range limitations, 325-26; large-signal bandwidth, 295; linearity, 296; noise and offset, 296; noise in, 336-40; offset and output impedance, 386-89; one-stage, 296-307; open-loop gain, 292; output swing, 295, 298; performance parameters, 291-96; power supply rejection, 334-36; slew rate, 326-34; small-signal bandwidth, 293; supply rejection, 296; telescopic, 331, 336-37, 356-61; telescopic cascode, 297-99, 303-4, 306; topology comparison, 313-14; triple cascode, 307; two-stage, 307-9, 338-40,

- oscillators, 482-531; Colpitts, 502-5; cross-coupled 499-501, 522; general considerations, 482-84; LC, 495-509, 521-25; one-port, 505-9; ring, 484-95; voltage controlled (VCOs), 482-531, 510-30
- output amplitude, in voltage-controlled oscillators

output characteristics: nonlinear systems, 448; of phase/frequency detectors (PFDs), 553-55; sampling circuit, 419. See also input characteristics; input/output characteristic

output impedance, 173; boosting, 310-11; cascode stage, 85-86, 88; and current-voltage feedback, 264-65; operational amplifier, 386-89; reference generator, 393-97; source follower, 70, 73, 180-82; variation with drain-source voltage, 589-91; and voltage-current feedback, 266-68; and voltage-voltage feedback, 259-60

output nodes: in cascode stage, 185-87; in common-gate

stage, 183-85; in common-source stage, 172-77; and differential pairs, 187-93; and source followers, 178 - 82output phase, in phased-locked loops (PLLs), 533-36 output poles: in cascode stage, 185-87; in common-gate stage, 183-85; in common-source stage, 172-77; and differential pairs, 187-93; and source followers, 178-82. See also input poles; poles output port, 66-67 output-referred noise, 219 output signal purity, in voltage-controlled oscillators (VCOs), 512 output spectrum theorem, 205-6 output swing, 106-7, 295, 298 output voltage, 66-67, 149-50; notation, 8; swing, 106-7, 295, 298 oxidation, 608 oxide spacers, 614 p-type MOS devices. See PMOS devices packaging, 666-75; dual-in-line package, 666; mutual inductance, 673-75; parasitics, 667-68; self- and mutual capacitance, 675; self-inductance, 668-73 pads, bonding, 657-59 parallel capacitance, of interconnects, 626-27 parameter variations, in MOSFETs, 599-600 parasitic: capacitance, 171; -insensitive integrators, 441; packaging, 667-68 passive current mirrors, 135-65 passive devices: analog layout techniques, 644-53; capacitor layout, 650-52; diode layout, 652-53; fabrication, 616-24; interconnect layout, 653-57; MOS, 616-24; pads and electrostatic discharge (ESD) protection, 657-660; resistor layout, 645-50 passive MOS devices, 616-24; capacitors in, 619-24; resistors, 616-18 PDs. See phase detectors PFDs. See phase/frequency detectors PFETs, bulk, 36. See also PMOS devices phase crossover point, 346, 352 phase detectors (PDs), 532-33 phase/frequency detectors (PFDs): in charge-pump phase-locked loops (CPPLLs), 550-55; PFD/CP nonidealities, 562-67 phase-locked loops (PLLs), 532-78; applications, 572-77; dynamics, 542-49; excess phase, 542-43; frequency multiplication, 573-74; frequency synthesis, 574-75; jitter, 563-64, 567-70; jitter reduction, 576-77; nonideal effects, 562-70; phase detectors (PD), 532-33: response to small transients in locked condition, 539-42; settling speed, 545-46; simple, 532-49; skew reduction, 575-76; transfer function, 542-49; waveforms in locked condition, 536-39 phase margin, 351-55 photolithography, 606-8 photoresists, 607 pinch-off behavior, 20, 25; effect of scaling on, 582 plates: bottom, 423-24; top, 423 PLLs. See phase-locked loops PMOS (p-type MOS) devices, 6; in cross-coupled oscillators, 524-25; differential pairs, 479; diode-connected, 56; in gain-boosting amplifiers, 311-12; latch-up in,

In gam-boosting ampriners, 511-12, factor-op in, 627-28; layout, 631-32; versus NMOS devices, 37; in operational amplifiers, 301-6; parameters of Level I SPICE models, 37; process corners based on speed of, 600; processing technology, 604-30; in ring

oscillators, 494-95; source follower, 74; structure, 10-12; as switches, 414, 415, 416, 419; threshold phenomenon, 15 poles: association with nodes, 169-71; in cascode stage, 185-87; in common-gate stage, 183-85; and differential pairs, 187-93; dominant, 358-61; input, 172-77; multipole systems, 349-51; nondominant, 361; output, 172-77; plotting location of, 347-48; and source followers, 178-82; two-pole feedback systems, 485--86. See also input poles; output poles poly-diffusion capacitors, 619-20 poly-poly capacitors, 620 positive feedback, tuning, 515-18. See also feedback; feedback circuits; negative feedback positive-TC (temperature coefficient) voltage, 382-84 power dissipation, in voltage-controlled oscillators (VCOs), 512 power spectral density (PSD), 204-5 power supply rejection, operational amplifiers, 334-36 precision: in noninverting amplifiers, 435-36; in sampling circuits, 417-21; in unity-gain sampler/buffers, 428-29 precision multiply-by-two circuits, 438-39, 622 process corners, 599-600 processing: back-end, 614-16; CMOS devices, 604-30; deposition and etching, 611; ion implantation, 608-10; latch-up, 627-28; oxidation, 608; photolithography, 606--8; wafers, 605--6 PTAT (proportional to absolute temperature) current generation, 390-92 qualitative analysis, differential pairs, 104-7 quantitative analysis, differential pairs, 107-18 receivers: optical, 4; wireless, 3-4 reduction, nonlinearity, 254 reference distribution, 642-44. See also bandgap references reference generator, output impedance, 393-97 rejection: common-mode, 512; common-mode noise, 101; power supply, 334-36; supply, 296 resistance, 35; calculating, 63-66; gate, 214-15; negative, 505-9; output, 70; series, 624; sheet, 605 resistive biasing, 135-36 resistive degeneration, 458-63 resistive load, common-source stage with, 48-67 resistors: continuous-time, 439; discrete-time, 439; layout in passive devices, 645-50; mismatched, 120-24; in passive MOS devices, 616-18; thermal noise, 209-12 ring oscillators, 484-95; amplitude limiting, 487-95; four- and five-stage, 491; three-stage, 486-89; tuning in, 512-21 ringing, 182 ripple, 536; in charge-pump phase-locked loops (CPPLLs), 562 RLC circuits, 496-99 samplers: and offset cancellation, 476-78; unity-gain, 424-32 sampling, bottom-plate, 423 sampling circuits: differential, 422-23; precision considerations, 417-21; speed considerations, 414-17 sampling mode: noninverting amplifiers, 432-433;

switched-capacitor circuits, 408–9, 410–23; unity-gain sampler, 424–25, 429 sampling switches, 410–23

682

saturation, 49; region, 19-21, 22-23, 49; velocity, 587-89 scaling: constant-field, 579; current, 643-44; theory, 579-83 second-order effects, 23-28 self-capacitance, 675 self-inductance, 668-73 sense and return mechanisms, 256-58 sensors, 4-5 series feedback, 256 series resistance, of interconnects, 624-25 settling speed, in phase-locked loops (PLLs), 545-46 shadowing, 639 sheet resistance, 605 shielding, 655-56; cascode stage, 89-90 short-channel devices, versus long-channel devices, 38 short-channel effects, 583-91; drain-induced barrier lowering (DIBL), 585, 586; hot carrier effects, 589; mobility degradation with vertical field, 585-87; output impedance variation with drain-source voltage, 589; threshold voltage variation, 583-85; velocity saturation, 587-89 shunt feedback, 256 signals: differential, 100-2; output, 512; single-ended, 100-2 silicide, 614, 616-17 · single-ended signals, versus differential signals, 100-2 single-pole system, 252-54 single-stage amplifiers, 47-99, 224-33; basic concepts, 47-48; cascode stage, 83-92, 232-33; choice of device models, 92-93; common-gate stage, 76-83, 228-31; common-source stage, 48-67, 225-28; source followers, 67-76, 231-32 sinusoid waveform, 525-26 skew, 565-66; eliminating in voltage-controlled oscillators, 533-36; reducing in phase-locked loops (PLLs), 575--76 slew rate, operational amplifiers, 326-34 slewing: negative, 372; positive, 372; in two-stage operation amplifiers, 368-69; in unity-gain sampler/buffer, 431-32 small-signal analysis, of active current mirrors, 151-54 small-signal bandwidth, operational amplifiers, 293-95 small-signal behavior: in active current mirrors, 145-48; differential pair, 110-14 small-signal characteristics, cascode stage, 84-85 small-signal gain, 145-51; calculating, 68-69; in nonlinear amplifiers, 450, 452-54 small-signal models, 61; of common-source stage, 52 small-signal output resistance, calculating, 70-72 source, 10, 11 source degeneration, common stage with, 60-67 source/drain junction capacitance, scaling, 580-82 source followers, 67-76; common-mode feedback using, 318; drawbacks of, 73-76; input impedance, 73, 179; input-output characteristic, 68; intrinsic, 72; as level shifters, 145, 178-82; output impedance, 70, 73, 180-82; single-stage amplifiers, 231-32; small-signal equivalent circuit, 68-69 source impedance, 223-24 spacers, oxide, 614 spacing, layout, 633-34 spectral shaping, 205-6 speed: in noninverting amplifiers, 436-38; reference generator, 393-97; in sampling circuits, 414-17; settling, 545-46; in unity-gain sampler/buffers, 429-32 SPICE models, 36-37 spiking, contact, 615-16

square wave amplification, 253

stability, 345-76; in charge-pump phase-locked loops (CPPLLs), 561-62; general considerations, 345-48 stages: delay, 518-20; in ring oscillators, 486-92; tuned, 498-99, 502 start-up, 389-90 statistical characteristics of noise, 201-9 step response, 326-27 structure, MOSFET, 10-12 substrate, 10-12; bounce, 663-65; coupling, 660-65 subthreshold conduction, 27-28 supply: dependence, 389-90; rejection, 296; in voltage-controlled oscillators (VCOs), 512 supply-independent biasing, 377-81 switched-capacitor amplifiers, 423-39 switched-capacitor circuits, 405-47; in amplification mode, 408-9; general considerations, 405-9; in sampling mode, 408-9, 410-23 switched-capacitor common-mode feedback, 442-43 switched-capacitor integrator, 439-42 switches: complementary, 422; dummy, 421-22; MOSFETs as, 10, 410-14; sampling, 410-23; zero-offset, 414 symbols, MOS, 12-13 symmetry, 113-14, 117-20, 149-50; in layouts, 637-42. See also asymmetry tail current, 120-21 . - **- -** tanks, LC, 496-98 telephone bandwidth, and spectral shaping, 205-6 telescopic cascode operational amplifiers, 297-99, 303-4, 306. See also telescopic operational amplifiers telescopic operational amplifiers: frequency compensation, 356-61; noise in, 336-37; slewing in, 331. See also telescopic cascode operational amplifiers temperature, proportional to absolute (PTAT), 377, 390-92 temperature dependence: forms, 377; in MOS device models, 599 temperature-independent references, 381; bandgap references, 384-90; negative-TC (temperature coefficient) voltage, 381-82; positive-TC (temperature coefficient) voltage, 382-84 temperature-independent voltage, 384-85 terminal impedance modification, 250-52 terminals, 10-11 thermal noise, 209-15; MOSFETs, 212-15; resistors, 209-12; voltage, 225-28 Thevenin equivalent, 72, 79, 112, 153, 191, 437 three-pole systems, 350-51 three-stage ring oscillators, 486-89 threshold voltage, 10, 13-15, 27-28, 149-50; mismatches, 471; variation, 583-85 time-domain response, 347-48 topologies: comparison of operational amplifier, 313-14; common-mode feedback, 317; current-folding, 518; feedback, 258-70; folded cascode operational amplifiers, 302; operational amplifiers, 296-98; phase-locked loops (PLLs), 533-42 transconductance, 22, 28, 48; amplifiers, 254-56; MOSFET, 392; of common-source devices, 62, 66 transfer function: in charge-pump phase-locked loops (CPPLLs), 557-61; closed-loop, 247; common-gate stage, 171; common-source stage, 172-77; input-output, 169; open-loop, 247; in phase-locked loops (PLLs), 542-49; and spectral shaping, 205-6 transients in locked condition, response of phase-locked loops (PLLs) to, 539-42 transimpedance amplifiers, 254-56

684

transistors: dummy, 639-40; fabrication of, 611-14; multifinger, 635-37. See also CMOS devices; MOSFETs triode load, CS stage with, 59-60 triode region, 17-18, 22-23, 49, 149; common-mode sensing using MOSFETs in, 319; deep, 460-61 triple cascode operational amplifiers, 307 tuned stages, 498-99, 502 tuning: delay variation by interpolation, 518-20; delay variation by positive feedback, 515-18; in LC oscillators, 521-25; linearity, in voltage-controlled oscillators, 511-12; range, in voltage-controlled oscillators, 511; in ring oscillators, 512-21; wide-range, 520-21 turn-on phenomenon, 14-15 two-pole systems, 349-50 two-port network models, 270-72 two-stage operational amplifiers, 307-9; frequency compensation, 361-69; noise in, 338-40; slewing in, 368-69

uncorrelated sources of noise, 207-9 unity-gain buffer, 325, 355. See also unity-gain sampler/buffer unity-gain sampler/buffer, 424-32; precision considerations, 428-29; slewing behavior, 431-32; speed considerations, 429-32. See also unity-gain buffer

varactors, 521-25

variable-gain amplifiers (VGAs), 126–28 velocity saturation, 587–89 vertical field, mobility degradation with, 585–87 VGAs. *See* variable-gain amplifiers vias, 615

voltage: amplification, versus current generation, 225; amplifiers, 461; bulk, 23–25; control, 126–29; drain-source, 589–91; floating reference, 398–99; gate, 144; input, 69, 107–10; input-referred thermal noise, 225–28; limitations, 28; meters, 256–58; negative-TC (temperature coefficient), 381–82; notation, 8; output, 66–67, 106–7, 149–50; positive-TC (temperature coefficient), 382–84; sources, noise represented in, 221–22; temperature-independent, 384–85; threshold, 13–15, 27–28, 149–50, 583–85

voltage-controlled oscillators (VCOs), 510–30; center frequency, 511; common-mode rejection, 512; definition, 510; eliminating skew in, 533–36; jitter in, 568–70; mathematical models, 525–30; output amplitude, 512; output signal purity, 512; power dissipation, 512; supply, 512; tuning linearity, 511–12; tuning range, 511. See also oscillators

voltage-current feedback, 266–69; and input impedance, 266–68; loading in, 275–80; and output impedance, 266–68

voltage-dependent capacitors, 521-22

voltage gain, 86-87, 151-54; lemma, 66-68; small-signal, 452-54

voltage-voltage feedback, 258-63; and closed loop gain, 272-73; loading in, 272-75; and open loop gain, 273-75

wafers: in device fabrication, 611-16; introducing dopants into, 608-10⁻ processing, 605-6 waveforms, 525-30 ittery, 568; in locked condition, 536-39;

ring oscille ~ 347, 490; sinusoid, 525–26; with a skew, 534 white noise, 204–5; folded, 206

wide-range tuning, 520-21 width, layout, 632-33

wireless receivers, 3-4

Y models, 270-72, 278

Z models, 270-72, 276

zero: calculation in common-source stage, 176-77; in right half plane, 364-65, 369 zero-offset switches, 414

Index