Appendix A
Useful Formulas and Equations

Ohm's Law

$$V = IR \quad I = \frac{V}{R} \quad R = \frac{V}{I}$$

$$P = IV \quad P = I^2R \quad P = \frac{V^2}{R}$$

n Series Resistances

$$R_{eq} = R_1 + R_2 + \cdots + R_n$$

n Parallel Resistances

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$$

Frequency and Period

$$f = \frac{1}{T} \quad T = \frac{1}{f} \qquad \omega = 2\pi f = \frac{2\pi}{T} \qquad f = \frac{\omega}{2\pi}$$

Inductive and Capacitive Reactance $\left(\mathbf{j} = \sqrt{-1}\right)$

$$X_C = \frac{1}{2\pi fC} \angle -90^\circ \quad X_C = \frac{-j}{2\pi fC} \qquad X_C = \frac{1}{j2\pi fC} \quad |X_C| = \frac{1}{2\pi fC}$$

$$X_L = 2\pi fL \ \angle 90^\circ \qquad X_L = j2\pi fL \quad |X_L| = 2\pi fL$$

D.J. Dailey, *Electronics for Guitarists*, DOI 10.1007/978-1-4419-9536-0,

Bipolar Transistor Relationships

$$I_C = \beta I_B \qquad I_E = I_C + I_B \qquad r_e = \frac{V_T}{I_{CQ}} \qquad I_C \cong I_S\, e^{\frac{V_{BE}}{\eta V_T}}$$

Triode Relationships

$$g_m = \mu\, r_P \qquad \mu = \frac{g_m}{r_P} \qquad r_P = \frac{\mu}{g_m} \qquad I_P = k(V_P + \mu\, V_G)^{\frac{3}{2}}$$

JFET Relationships

$$g_{m0} = \frac{2I_{DSS}}{V_P} \qquad I_D = I_{DSS}\left(1 - \frac{|\,V_{GS}|}{V_P}\right)^2$$

Appendix B
Selected Tube Characteristic Curves

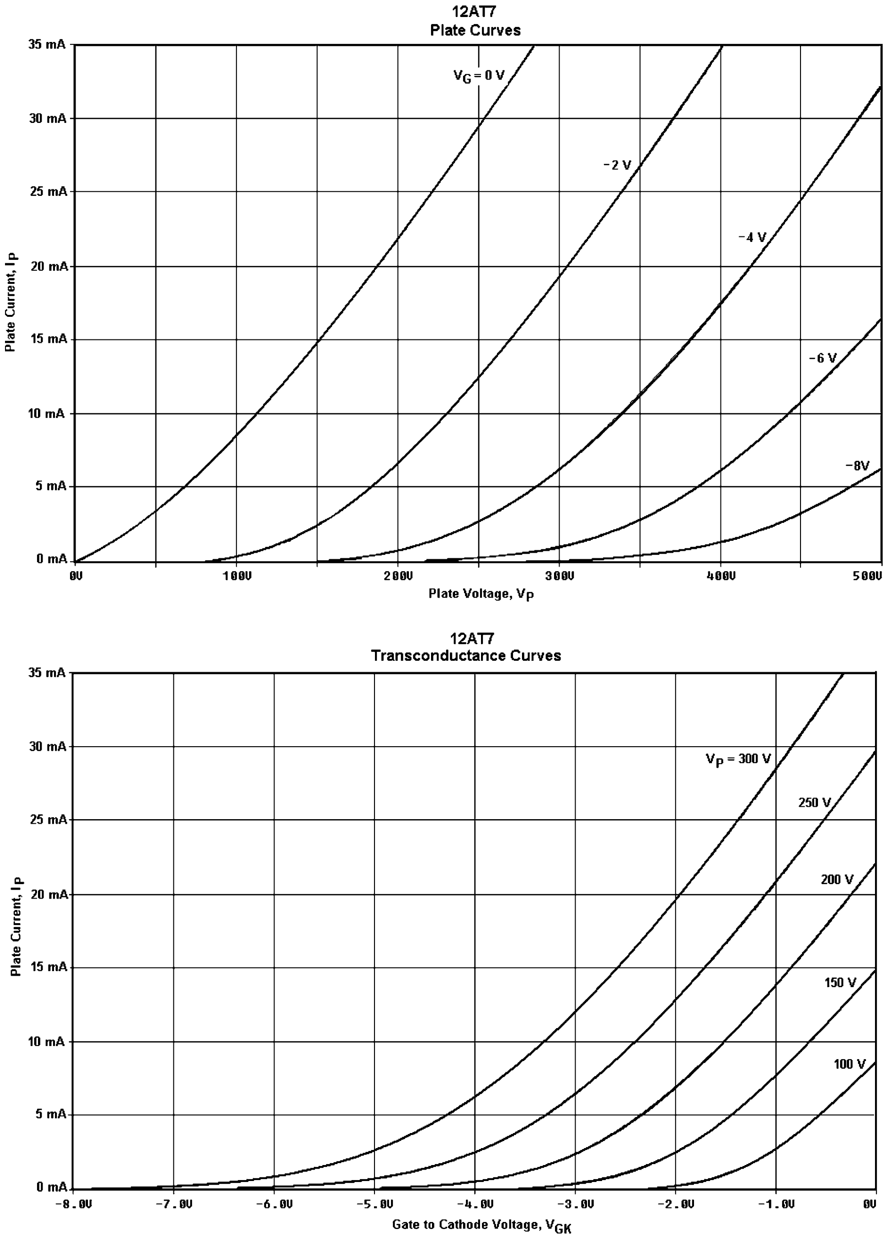


Fig. B.1 12AT7 plate and transconductance curves

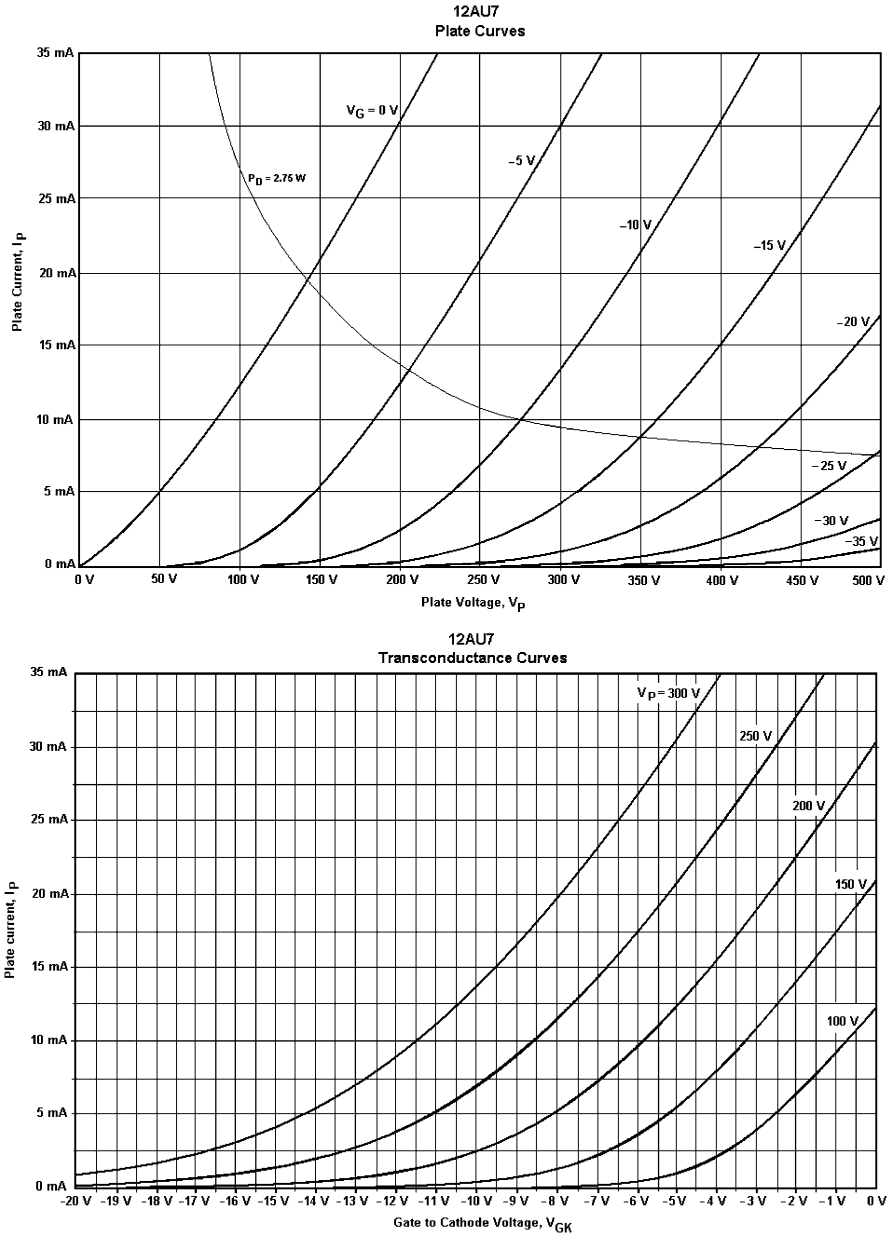


Fig. B.2 12AU7 plate and transconductance curves

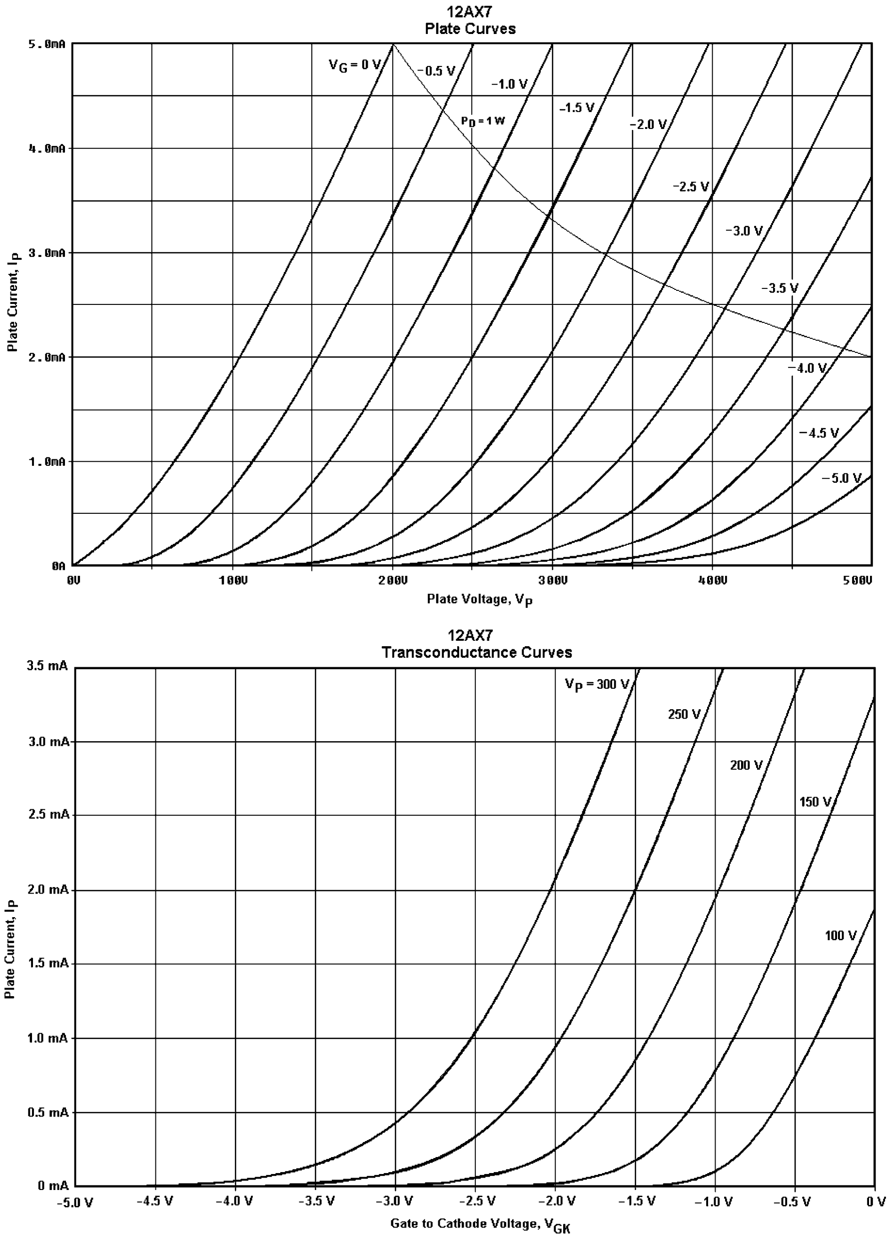
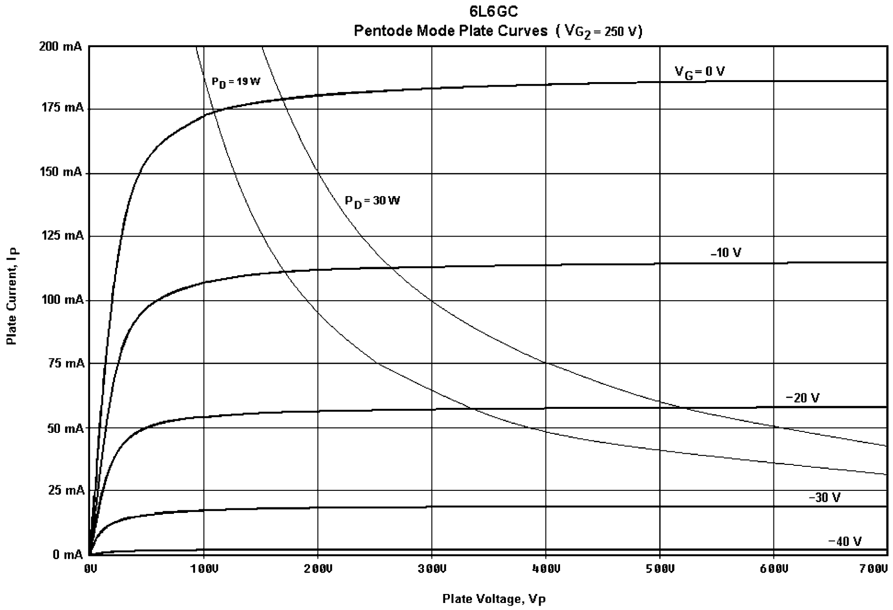
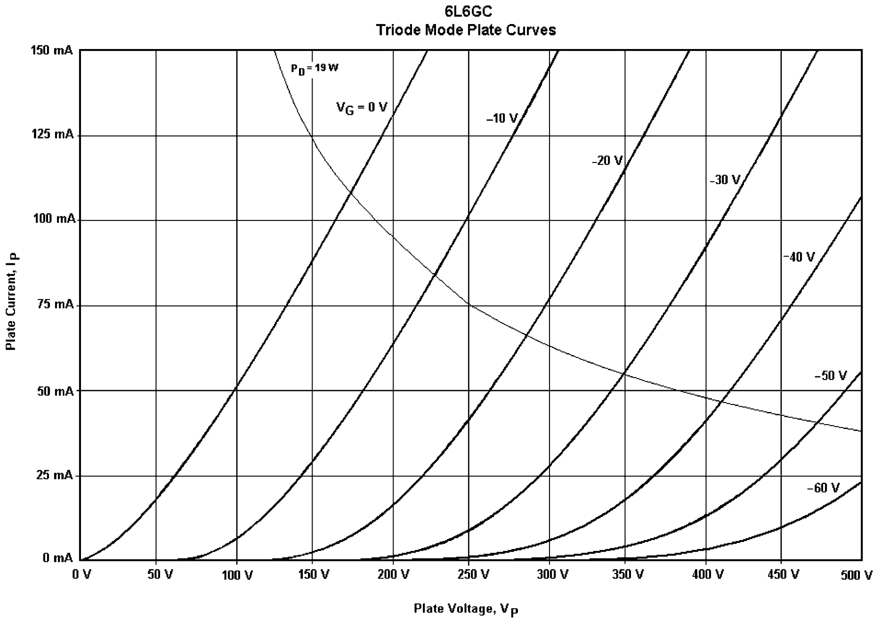


Fig. B.3 12AX7 plate and transconductance curves



6L6GC
Pentode Mode Plate Curves (V_{G2} = 250 V)



6L6GC
Triode Mode Plate Curves

Fig. B.4 6L6GC pentode and triode mode plate curves

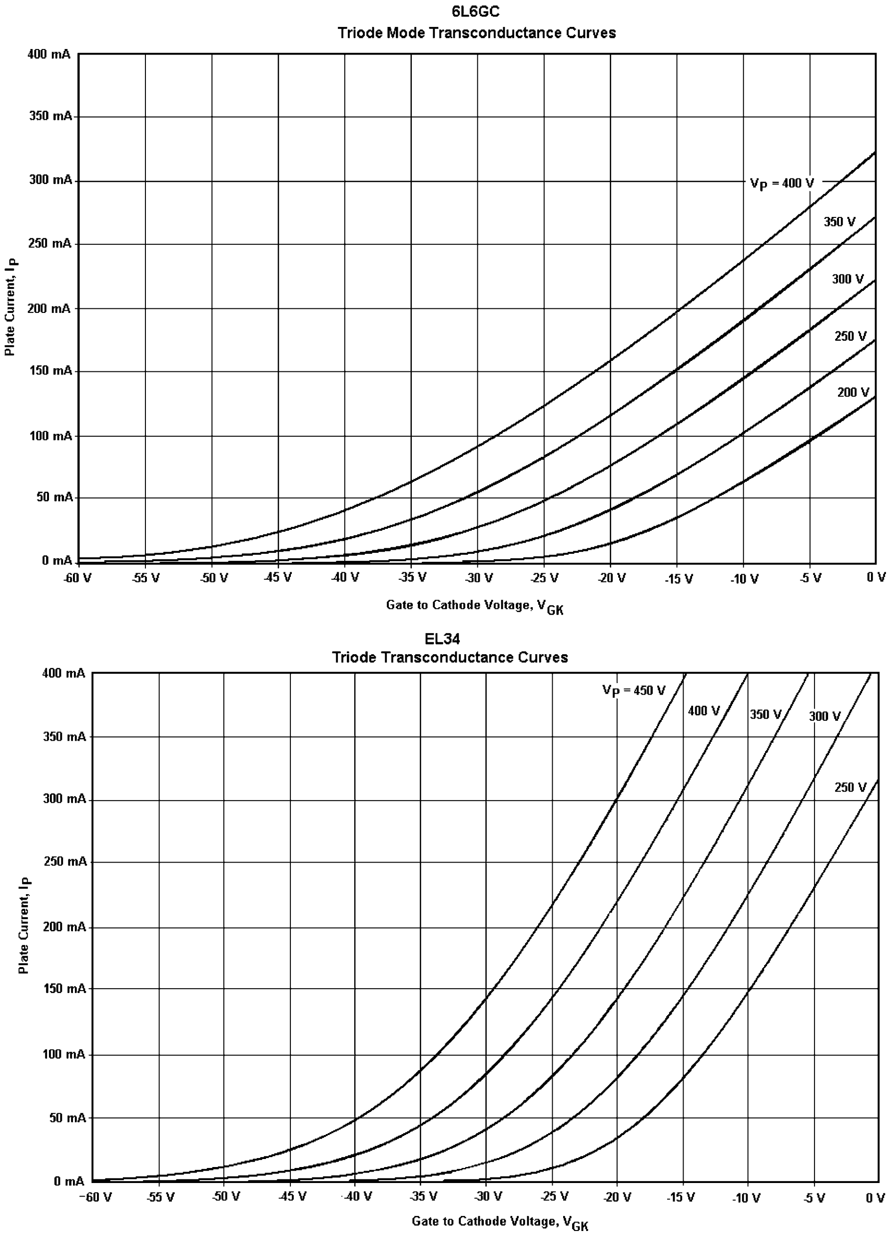


Fig. B.5 6L6GC and EL34 triode mode transconductance curves

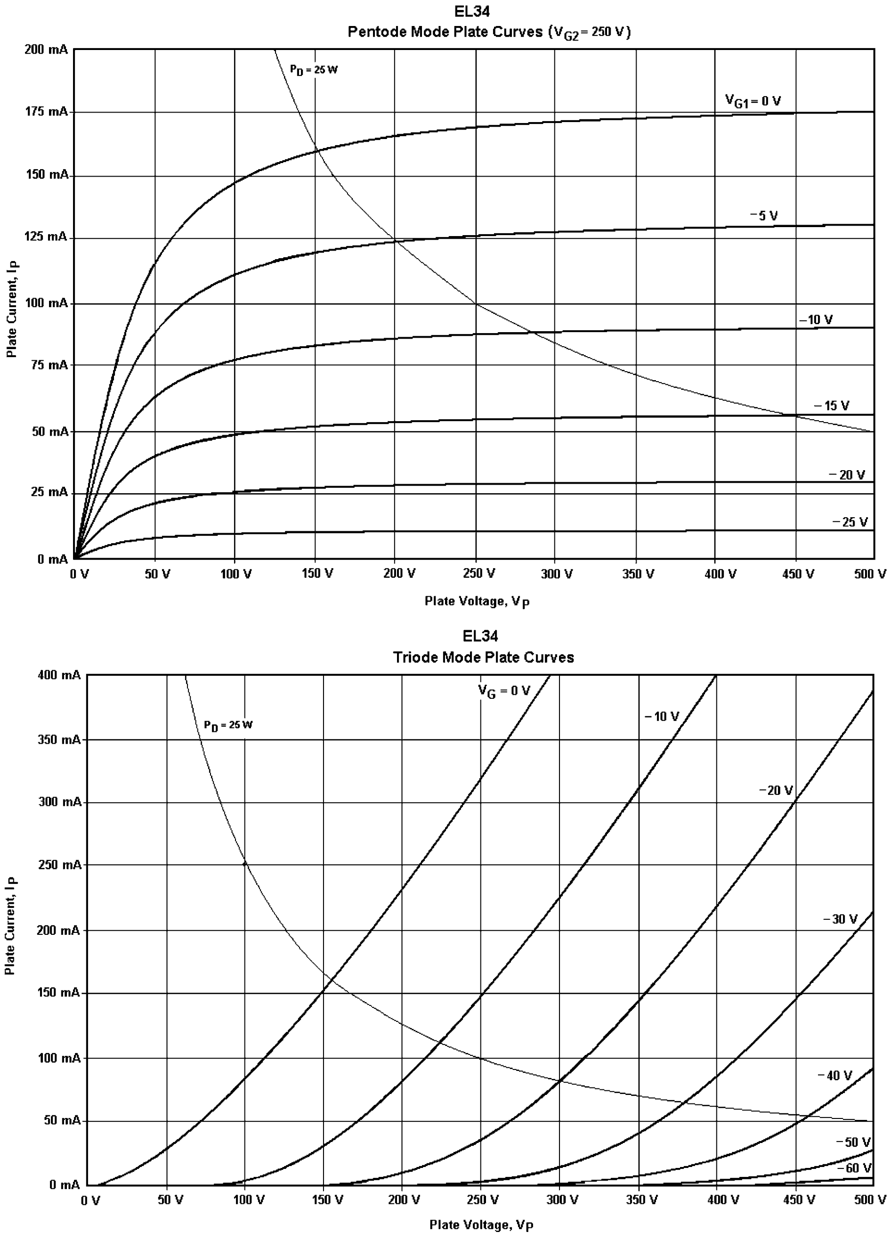


Fig. B.6 EL34 pentode and triode mode plate curves

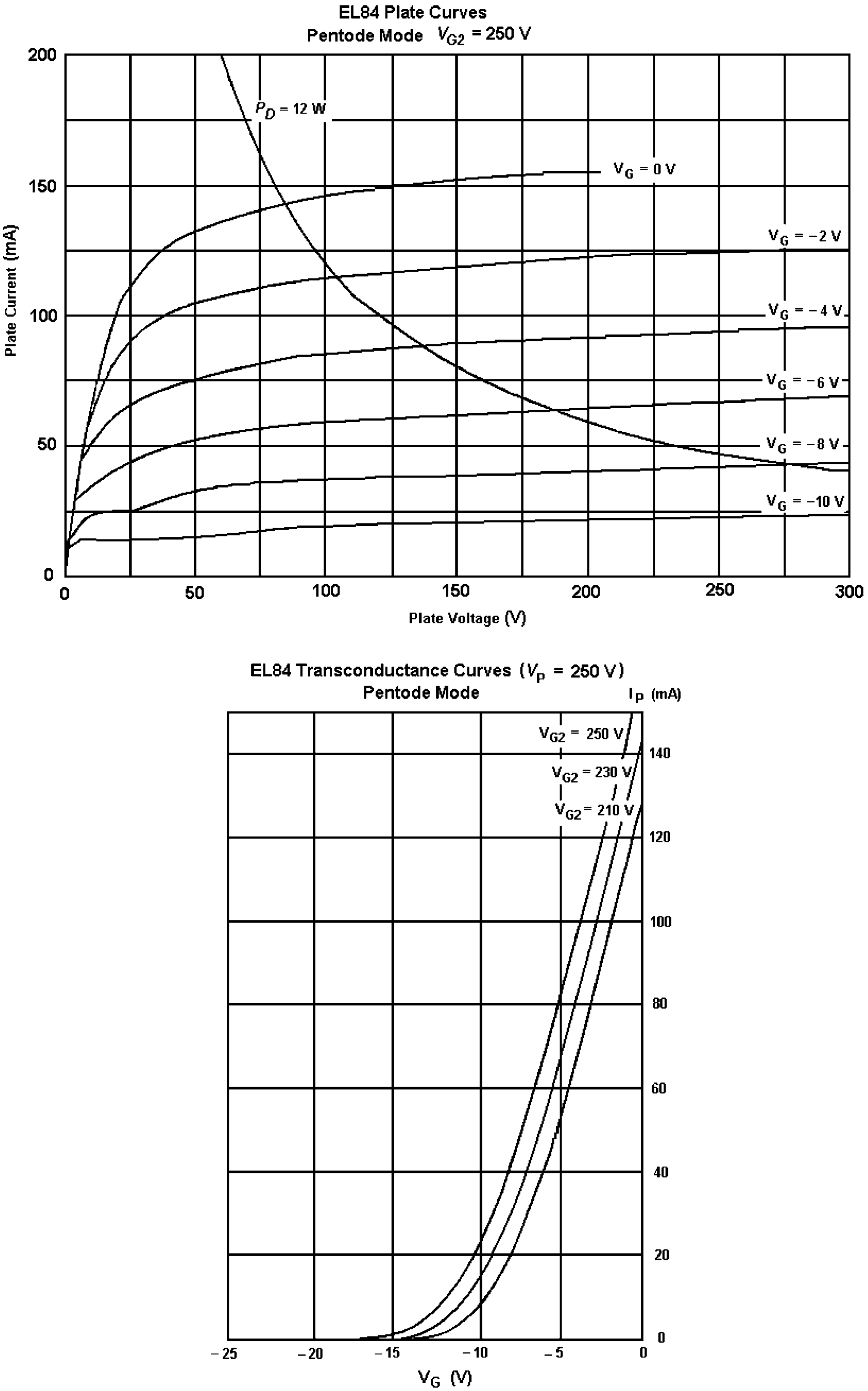


Fig. B.7 EL84 pentode mode plate and transconductance curves

Appendix C
Basic Vacuum Tube Operating Principles

Diodes

The diode is the simplest vacuum tube. Recall that the vacuum tube diode operates by thermionic emission of electrons from a heated cathode within the evacuated glass envelope of the tube, as shown in Fig. C.1.

Reverse Bias

When the anode is at a negative potential with respect to the cathode $V_{AK} \leq 0$ V, the diode is said to be reverse biased, and the current flow through the tube is approximately zero. This occurs because the free electrons around the cathode are repelled by the negative potential at the anode, as shown in Fig. C.1a.

Forward Bias

If the anode terminal is made positive with respect to the cathode $V_{AK} > 0$ V, electrons that are attracted from the cathode are free to travel through the vacuum to the anode, as shown in Fig. C.1b. This is condition is referred to as forward bias.

The current that flows in a forward biased vacuum tube diode is not a linear function of the applied voltage, but rather obeys what is called the Child–Langmuir law, which is

$$I_A = k\,V_P^{\frac{3}{2}} \tag{C.1}$$

The constant k is the *perveance* of the diode. A high value of perveance results in a diode that drops less voltage at a given forward current. For typical vacuum tube diodes, k ranges from approximately 0.003 to 0.00035. The forward bias current vs. voltage relationships for three common vacuum tube diodes, the 5AR4, 5U4-GB,

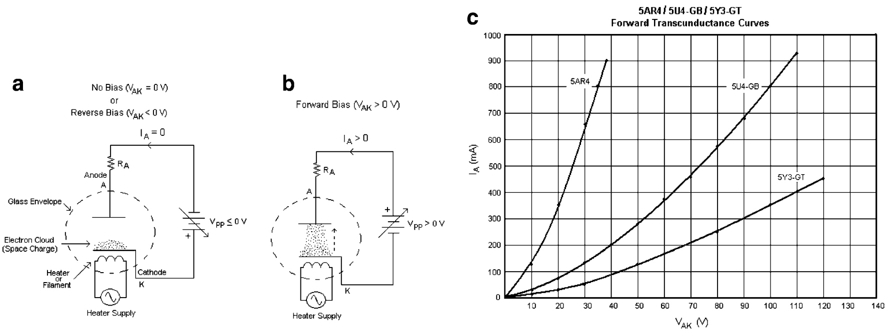


Fig. C.1 Vacuum tube diode operation

and the 5Y3-GT, are shown in Fig. C.1c. All three diodes closely follow the Child–Langmuir law, with the value of *k* varying from 0.003 for the 5AR4, to 0.00035 for the 5Y3-GT.

Triodes

If we take a vacuum tube diode and place a fine wire *grid*, often called the *control grid*, in between the cathode and the anode (which we will now refer to as the *plate*), a triode may be represented as shown in Fig. C.2. The function of the grid is to allow control of the flow of electrons from the cathode to the plate.

Examine Fig. C.2a. In this case, there is no bias applied to the grid of the triode. That is, the grid and cathode are at the same potential, which in this case is ground, and $V_{GK} = 0$ V. Physically, the grid has very little cross-sectional area. This, plus the fact that the grid is at the same potential as the cathode means that nearly all of the electrons that leave the cathode make it across to the plate. The grid leakage current is quite small, on the order of 1 nA or less, and so may be ignored in this discussion. With no bias, the plate current I_P will increase with plate voltage V_P just as it would for a normal vacuum tube diode.

In Fig. C.2b, the grid is biased to a more negative potential than the cathode. Now, the positive potential of the plate exerts less attractive force on the electrons surrounding the cathode, and the plate current will be reduced relative to that which would flow with no bias on the grid. If we step the grid bias voltage from zero to some maximum value, a family of plate characteristic curves is generated. Figure C.3 shows the plate characteristic curves for the 12AU7 triode. The equation that describes these curves is

$$i_P = k(V_P + \mu v_G)^{\frac{3}{2}} \tag{C.2}$$

When there is no bias applied to the triode, the term μv_G is zero, and (C.2) reduces to the standard Child–Langmuir equation for a diode, (C.1).

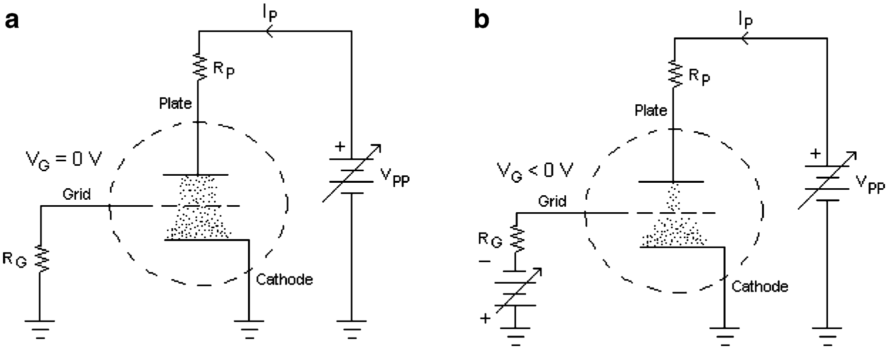


Fig. C.2 The addition of the grid creates a triode

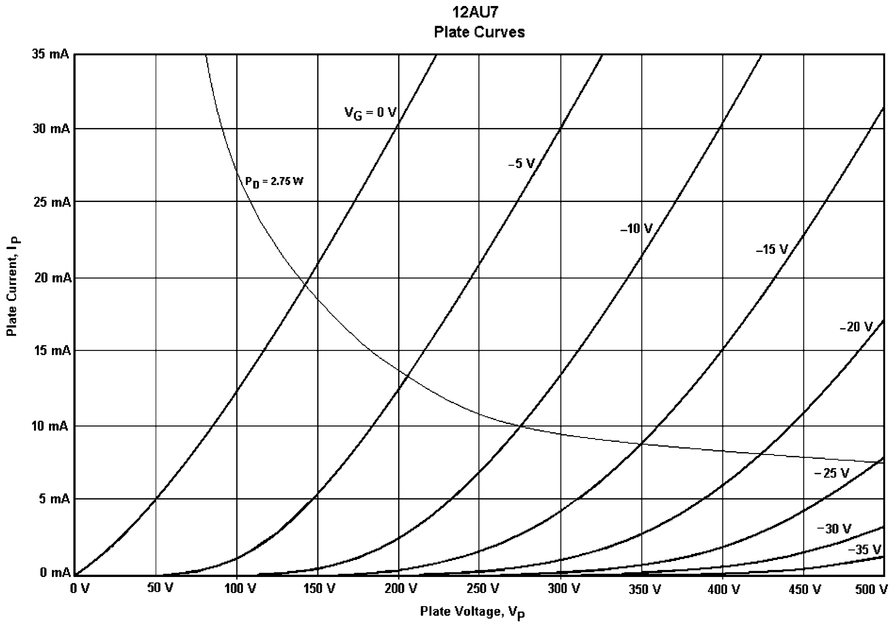


Fig. C.3 Plate characteristic curves for the 12AU7

Amplification Factor

The parameter μ (Greek mu) is called the amplification factor. The value of μ depends on the construction of the tube. For example the 6AS7-G is a low-mu triode with $\mu = 2$, while the 12AX7 is a high-mu triode with $\mu = 100$. The actual value of μ varies somewhat from one tube to another of the same type, but it is generally close enough to the published value that in many cases we can consider it to be the same for

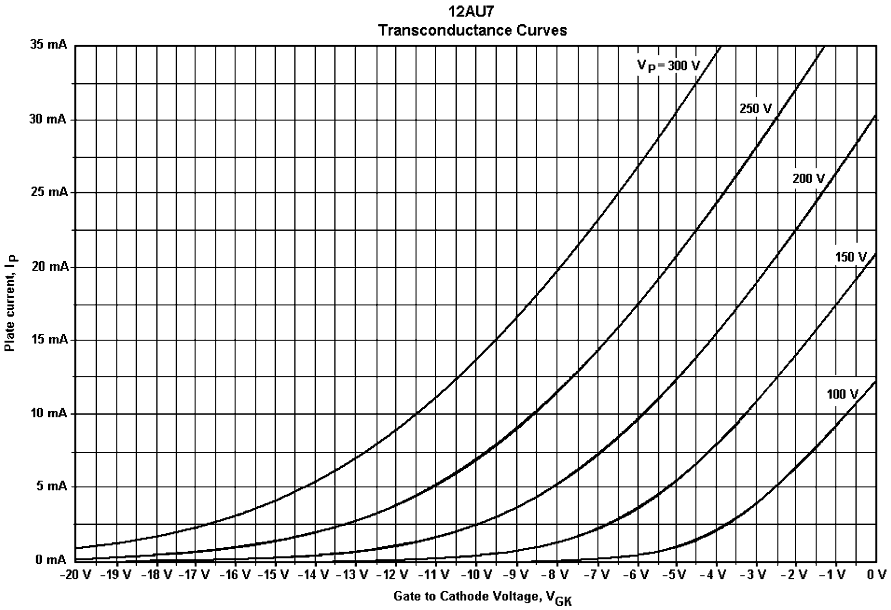


Fig. C.4 Transconductance curves for the 12AU7

every tube of the same type. This is in sharp contrast to bipolar transistors where, for example, beta may vary wildly from one device to another with the same part number.

Transconductance

The parameter that relates plate current I_P to gate bias voltage V_{GK} is called *transconductance*, which is designated as g_m. We can plot plate current as a function of grid voltage at various plate voltage levels. This produces a family of transconductance curves, such as those shown for the 12AU7 in Fig. C.4.

Transconductance allows us to view the triode as a voltage-controlled current-source. Looking at the triode from an AC signal standpoint, we have

$$i_P = g_m v_G \tag{C.3}$$

Where the AC plate current i_P is controlled by the AC grid voltage v_G. We are taking some liberties here, assuming that $v_G = v_{GK}$, which is true when there is no cathode resistance in the AC equivalent circuit.

Plate Resistance

The effective internal resistance of the plate r_P is another basic tube parameter that is very important. For example, maximum power transfer from the tube to a load that is driven by the plate occurs when $r_P = R_L$. Although it is generally not necessary to have a precise match between r_P and R_L, triodes with low plate resistance are better suited for driving low resistance loads than triodes with high plate resistance.

Plate resistance, amplification factor, and transconductance are related by the following equation.

$$\mu = g_m r_P \tag{C.4}$$

Tetrodes

A tetrode is a four-terminal tube that is created with the addition of a *screen grid* between the plate and the control grid. The function of the screen grid is to shield the control grid from the plate, which reduces the effective input capacitance of the tube. The screen grid is typically held at a slightly less positive voltage than the plate, and is often bypassed to ground to enhance the shielding effect and reduce input capacitance to a minimum. The schematic symbol for a tetrode is shown in Fig. C.5.

The presence of the screen grid has some negative effects on tube characteristics as well. For example, since the screen grid is held at a relatively high positive potential, it will accelerate electrons as they move from the cathode toward the plate. The increased energy of the electrons striking the plate causes secondary electrons to be emitted from the plate back toward the screen grid. Many of these secondary electrons are captured by the screen grid, resulting in significant screen grid current which is undesirable. The creation of secondary emission current can also cause undesirable nonlinear behavior of the tetrode, even causing negative resistance under some conditions.

Pentodes

The undesirable characteristics of the tetrode are improved by the addition of a fifth element, called a *suppressor grid*. This forms a *pentode*. The schematic symbol for a pentode is shown in Fig. C.6. The suppressor grid is located between the screen

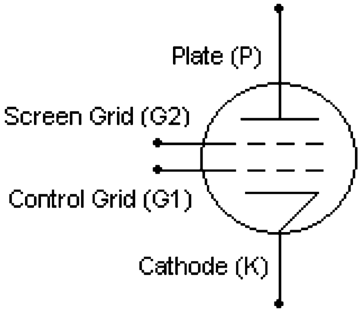
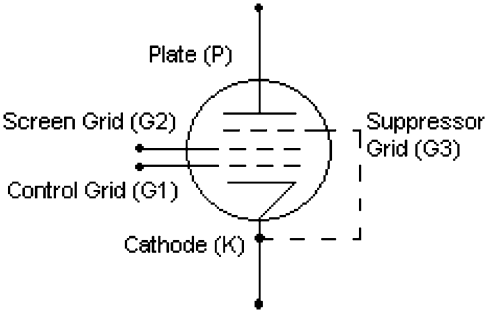


Fig. C.5 Schematic symbol for a tetrode

Fig. C.6 Schematic symbol for the pentode



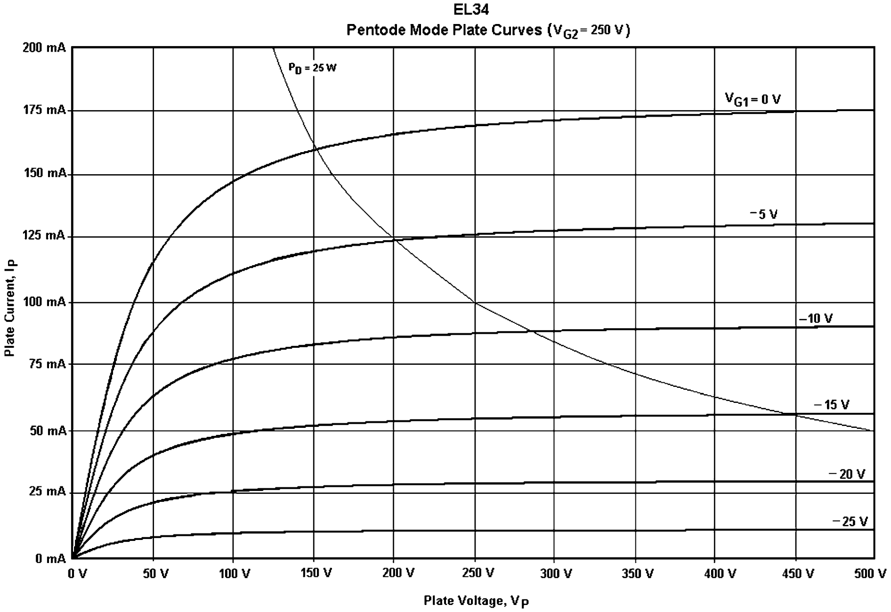


Fig. C.7 Plate characteristic curves for the EL34 pentode

grid and the plate inside the tube. Most often the suppressor grid is tied directly to the cathode, which holds it at a very negative potential relative to the plate. The function of the suppressor grid is to repel secondary emission electrons back to the plate, preventing them from causing excessive current flow and power dissipation in the screen grid.

Pentodes generally have much higher effective plate resistance r_P, and amplification factor μ, than triodes. The plate characteristic curves for pentodes are very similar to those of bipolar transistors and field effect transistors. The plate curves for the EL34 pentode are shown in Fig. C.7.

The pentode can also be configured to operate as a triode simply by connecting the screen grid directly to the plate. Operation as a triode significantly reduces r_P, μ, and maximum power output, but is often used to obtain particularly desirable overdrive and distortion characteristics.

Index

A

Absolute value function, 136
AC equivalent circuit, 66, 78, 80, 282
AC load line, 60, 205–208, 226–228, 231, 235, 240–242, 249–251, 263, 266
Active region, 57, 58, 65, 66, 70, 81
Aliasing, 158
All-pass filter, 149–150, 153–156, 185, 190
Amplitude modulation, 169, 175, 176
Anode (plate), 18, 141, 280
Anti-aliasing filter, 159
Antiphase, 211
Asymptotic response, 8, 32, 55
Audio frequency range, 56
Audio taper, 38–40, 47, 180, 183

B

Balanced modulator, 176–180
Bandpass (BP) filter, 149, 180–188, 192
Bandstop filter, 180, 181, 186
Bandwidth, 53, 55–57, 75, 77, 90–92, 105, 109, 182
Barrier potential, 4, 9, 16, 58, 59, 65, 98, 112, 120, 135, 136, 145, 146, 161, 162
Baxandall tone control, 47–49
BBD. *See* Bucket-brigade device (BBD)
β (Beta), 61, 62, 64, 89, 106, 116, 120, 264, 282
Beta independence, 67–68
Bias, 4, 18, 19, 58, 65, 80–82, 93, 94, 96–98, 100, 102, 106, 112, 125, 126, 146, 161, 162, 165, 167, 169, 174, 175, 197, 201, 205, 206, 212–213, 218, 219, 225, 231, 239, 245, 248, 249, 260, 279, 280, 282
Bias current, 93, 94, 98, 100, 102, 146, 167, 218, 225, 245, 279
Biasing, 57–59, 61, 65, 68, 80, 81, 87, 93, 104, 106, 111, 112, 116, 125, 126, 158, 173, 197, 201–202, 246, 249, 259–260
Bipolar, 1, 14–17, 51, 57, 63, 80, 84, 87–89, 93, 94, 114–115, 120, 125, 127, 141, 153, 214, 247, 270, 282, 284
BJT, 63, 64, 80, 84, 85, 87, 88, 107, 125, 126, 136, 141, 190, 202, 209, 211, 215
Bleeder, 245
Bode plot, 8
BP filter. *See* Bandpass (BP) filter149, 181, 182, 184–186, 188
Bridge, 15, 16, 33, 42, 43, 136
Bridge rectifier, 3, 4, 22
Bucket-brigade device (BBD), 156–160, 190
Bypass capacitor, 66, 76, 78, 81, 84, 142, 201, 208, 221, 244

C

Cadmium sulfide (CdS), 150, 151
Capacitive coupling, 85, 201, 205, 216, 262
Cathode, 17–19, 197, 200–211, 219, 221, 230, 236, 239, 244–247, 249, 252, 256, 259, 260, 265, 267, 279, 280, 282–284
Cathode feedback, 201–202
Cathode follower, 211–215, 247
Cathode resistor, 205, 213, 223, 224, 232, 239, 252, 256, 259, 260, 267
Cathode stripping, 236
Cathodyne, 211, 214, 215, 247, 265
CD, 166
CdS. *See* Cadmium sulfide (CdS)
Child–Langmuir law, 23, 141, 190, 280

Choke, 21, 237, 253, 262
Chorus, 159–160
Class A, 7, 58–60, 62, 63, 69, 79–81, 93, 96, 107, 111, 127, 136, 137, 142, 196, 197, 200–211, 215, 216, 218, 220–232, 234, 237–247, 253, 254, 266
Class AB, 7, 59, 112–113, 116, 117, 141, 246
Class B, 7, 58, 59, 62, 111, 112, 135, 216, 246
Clipper, 144–146
Clipping, 58–60, 74, 79, 84, 94, 107, 133, 134, 136, 137, 141, 144–146, 158, 202, 228, 244
CMRR. *See* Common mode rejection ratio (CMRR)
Comb-filter, 147, 150, 154, 155
Common base, 62–63
Common cathode, 200–212, 214, 244, 247, 265
Common emitter (CE), 61–63, 65–77, 80, 84, 96, 107, 111
Common gate, 63
Common mode rejection, 28, 97
Common mode rejection ratio (CMRR), 88, 97
Common source, 28, 63, 79–81, 84, 201, 207
Complementary symmetry, 111
Complex plane, 155
Compliance, 71, 74, 75, 114, 121, 153, 228, 233
Compression, 165–169
Compressor, 129, 165, 166
Conduction angle, 58
Cord capacitance, 36
Core saturation, 218
Corner frequency, 8, 22, 35, 36, 40, 45, 46, 49, 50, 76, 83, 84, 107, 108, 159, 161, 222
Coupling capacitor, 66, 79, 80, 83, 85, 96, 111, 114, 139, 173, 174
Critical frequency, 150
Crossover distortion, 112–113, 125, 135, 246
Current difference amplifier (CDA), 100–103, 110
Current gain, 52, 61, 62
Current mirror, 98, 102
Cutoff, 57–60, 111–113, 165, 202, 208

D
Darlington pair (Darlington transistor), 116
DC equivalent circuit, 66, 201
DC load line, 205–208, 265
Decade, 8, 32, 49, 56
Decibel, 8, 52–53, 105, 165
Decoupling capacitor, 13, 116, 123
Derating, 119, 128
Differential amplifier, 87, 97, 110, 174, 214, 215, 253
Differential pair, 95–97, 214
Diode, 1, 3, 4, 8, 9, 16–21, 58, 113, 116, 125, 126, 136, 141, 146, 150, 161, 167, 195, 198, 236, 245, 279–280
Diode clipper, 144–146
Double-pole, single-throw (DPST), 1, 14, 95
DPDT, 188, 236
DPST. *See* Double-pole, single-throw (DPST)
Dropout voltage, 12
Dynamic emitter resistance (r_e), 70, 78, 106
Dynamic range, 165, 166, 191
Dynamic resistance, 67, 106, 146

E
Efficiency, 18, 58, 111, 117, 141, 200, 215, 216, 219, 246
Emitter bypass, 66, 76, 78, 84, 107, 142
Emitter follower, 61–63, 96, 111–113, 116, 127, 211
Envelope, 18, 100, 160–161, 163–167, 169, 171, 175, 179, 180, 188, 191, 237, 279
Envelope controlled filter, 188
Envelope follower, 22, 160–166, 169, 179, 180
Even function, 131, 132, 134, 137
Exponential transfer characteristic, 141

F
Feedback, 76–81, 89, 90, 93, 94, 102, 104, 124, 133, 141, 146, 153, 162, 181, 201–202, 257, 260
Field effect transistor (FET), 51, 63, 167, 284
Filter response, 8, 52, 155, 182, 186
First-order filter, 7, 35, 76
Fixed bias, 197, 260
Flanger, 158–159
Flanging, 154–159
Frampton, Peter, 178

Frequency domain, 5, 7–8, 129, 132, 133, 140, 175
Full scale voltage, 166
Full-wave rectifier, 3, 16, 19–22, 136, 161–163
Fundamental frequency, 4, 5, 27, 92

G
Gain-bandwidth product (GBW), 88, 90, 91, 101, 102, 109, 167
Gamma network, 222
Geometric mean, 183
Germanium diode, 144, 145
Germanium transistor, 64, 65
Global feedback, 79
g_m, 81, 82, 84, 98, 99, 108, 110, 167, 191, 198, 202, 209, 214, 222, 230, 239, 256, 265, 270, 282
g_{m0}, 80–82, 108, 270
Grid biasing, 259–260
Grid resistor, 207, 210, 221
Ground loop, 122, 123, 262
Gyrator, 185–187, 192, 193

H
Half-wave rectifier, 161–163, 190
Hard clipping, 141
Harmonic, 5, 21, 28, 29, 33, 43, 73, 74, 92, 131–138, 141, 142, 144, 145, 158, 165, 176, 177, 183, 247
Harmonic distortion, 134, 138, 142, 158
Headroom, 12, 74, 153, 233
Heat sink, 11, 13, 111, 117–119
High pass (HP) filter, 32, 35, 45, 46, 49, 76, 83, 84, 107, 114, 149
HP filter. *See* High pass (HP) filter
Humbucker, 28–33, 40, 42–44
Hyperbola, 202, 227

I
I_{DSS}, 79–82, 108, 270
IGMF bandpass filter, 181–184, 192
Impulse, 133
Inductance, 31, 42, 49, 123, 181, 185, 186, 192, 219
Inductive reactance, 131, 187
Intermodulation distortion, 137, 139–140
Inverting op amp, 90, 95, 109

J
Junction FETs (JFET), 63, 79–83, 85–88, 98, 108, 201, 207, 211, 270

L
Lamp, incandescent, 10–11, 245
Large signal bandwidth, 92
LDR, 153, 159, 169, 170, 185
Least significant bit (LSB), 166
LED. *See* Light emitting diode (LED)
Lenz's law, 25, 49
LFO. *See* Low-frequency oscillator (LFO)
Light emitting diode (LED), 8–11, 22, 23, 125, 145, 146, 150, 151, 153, 169
Linear taper, 37, 38, 46, 233
Loading, 2, 6, 10, 11, 15, 40, 45, 54, 55, 75, 79, 82, 105, 124, 142, 147, 163, 177, 188, 189, 256
Load line, 58–60, 93, 204–210, 226–228, 231, 235, 240–242, 249–251, 263, 265, 266
Local feedback, 79
Logarithmic amplifier, 146–147, 166
Long-tailed pair, 95
Low dropout (LDO), 12
Low-frequency oscillator (LFO), 153, 154, 156, 158–160, 175
Low pass (LP) filter, 7, 8, 32, 35, 39, 44–46, 49, 64, 104, 149, 158–161, 163–165, 177, 222
LP filter. *See* Low pass (LP) filter
LSB. *See* Least significant bit (LSB)

M
Magnetic saturation, 218
Metal oxide semiconductor FETs (MOSFET), 63, 125–126, 156, 157, 219, 264
Microphonics, 36, 235
Midband, 55
Model, pickup, 32
Modulation, 100, 160, 169, 174–178
MOSFET. *See* Metal oxide semiconductor FETs (MOSFET)
Motorboating, 123
μ (mu). *See* Voltage gain μ (mu)
Multiple stage amplifier, 79, 84–86

N
National Electrical Manufacturers Association (NEMA), 1
NE–2, 8

Negative feedback, 76–79, 89, 90, 94, 102, 124, 133, 141, 260
NEMA. *See* National Electrical Manufacturers Association (NEMA)
New, old-stock (NOS), 196, 208, 211
Noninverting op amp, 93, 109, 187
NOS. *See* New, old-stock (NOS)
Notch filter, 180–182, 186
Noval base, 239
Nyquist sampling theorem, 158, 190

O
Octave, 8, 140, 178, 183
Odd function, 131, 132, 134, 135
Operational amplifier (Op amp), 7, 14, 51, 87–98, 100, 102–104, 109, 116, 117, 133, 134, 141–147, 161–163, 165, 167, 173, 174, 177, 182, 185–187, 192, 195, 196, 256
Operational transconductance amplifier (OTA), 97–101, 110, 167, 169, 191
Optocoupler (photocoupler), 150–151, 153, 169
Orthogonal wiring, 263
Oscillator, 62, 103–104, 121, 153, 156, 159, 160, 169, 175–178, 196
OTA. *See* Operational transconductance amplifier (OTA)
Output transformer, 124, 216–219, 222, 225–226, 231, 232, 240–242, 245, 249–250, 252, 263
Overdrive, 68, 75, 129, 141–144, 221, 230, 235, 244, 284

P
Parasitic oscillation, 116, 121
Passband, 8, 35, 182
Pentode, 195, 197–199, 215, 219–222, 225, 226, 230, 232, 233, 237, 239, 240, 243, 247, 253, 256, 258, 264, 274, 276, 277, 283–284
Periodic signal, 130
Permeability, 31
Perveance, 18, 19, 279
Phase, 28, 42–44, 51, 53, 61, 70, 72, 77, 80, 86, 92, 130, 131, 133, 137, 155, 178, 190, 191, 257
Phaser, 153–155
Phase response, 149, 155
Phase shifter, 49, 147–154, 156, 160, 185
Phase shift oscillator, 103, 121, 153
Phase-splitter, 211–215, 245–247, 252, 253, 265, 267
Photoresistor, 150, 151, 153
Pickup, 25–51, 63, 75, 79, 81–84, 142, 166, 177, 256
Pickup phasing, 42–44
Piecewise-continuous, 135, 162
Piezoelectric pickup, 33–36, 63, 79, 81–84
Pi filter, 20, 21
Pitch, 27, 130–131, 139, 140, 169
Pitch shifting, 174–178
Plate, 18, 141, 195–197, 201–205, 207–210, 212, 219, 221–231, 235, 239–242, 245, 246, 248–252, 256–258, 260, 266, 267, 280–284
Plate curves, 204–206, 210, 220, 227, 248, 271–274, 276, 284
Plate resistor, 205, 212, 235
Pole piece, 26, 28, 29, 31
Potentiometer, 37–41, 44, 46, 83, 86, 133, 142, 145, 153, 160, 177, 178, 180, 183, 185, 188, 233, 262
Power bandwidth, 92, 109
Power gain, 52, 53, 61, 62, 105
Power supply
  bipolar, 14–17, 84, 87, 114–115, 153
  vacuum tube diode, 17–21
Power transformer, 21, 196, 200, 216, 218, 231, 237, 245, 253, 260
Preamplifier (preamp), 36, 63, 68, 75, 79, 81–84, 93, 141, 142, 235
Precision rectifier, 160–164, 169, 179
Push-pull, 111–117, 125–127, 135, 141, 211, 216–218, 237, 245–255, 260, 267

Q
Q-point, 58–60, 66–70, 72, 81, 83–86, 106, 108, 201, 202, 204–206, 208–210, 212, 223, 224, 226–228, 231–232, 239–242, 247–251, 260, 266, 267
Quadratic, 139, 140
Quiescent, 58, 65, 202, 223, 235, 239, 245, 248

R
Radian, 131
RC filter, 22, 45, 46, 76
Reflected load resistance, 217, 222, 225, 228, 230, 239, 240, 249
Regulator, 6, 11–14, 16, 17, 23, 52, 123
Relaxation oscillator, 153

Resistance-coupled, 200–211, 215, 219, 223, 252, 253
Resistance coupling, 201, 215
Resonance, 34, 186, 187
Resonant frequency, 181, 191
Reverb, 129, 169–174, 189, 236, 237, 255–259
Reverb spring (tank), 171–173, 256–258
Rheostat, 39, 40
Ring modulator, 176–178, 191
Ripple, 6, 7, 10, 11, 14, 17, 21, 22, 52, 117
Rolloff rate, 32, 49
Root-mean-squared (RMS), 4, 22, 114, 117, 119, 198, 217, 229, 243, 251

S
SAD. *See* Sampled analog delay (SAD)
Safe operating area (SOA), 202, 204, 209, 226, 227, 231
Sampled analog delay (SAD), 156, 157, 159
Saturation, 57, 59, 60, 84, 165, 218, 245
Schmitt trigger, 153
Self bias, 80, 108, 201, 207
Shelving response, 45
Signal envelope, 160–161, 165, 166, 179
Single ended, 216–221, 223, 225, 226, 230, 234, 236, 244, 245, 247, 248, 252
Single-pole, single-throw (SPST), 1, 156
Single-pot tone control, 45–47
Sinusoidal waveform, 4, 22, 130
Slew rate, 53, 56–57, 75, 92, 99, 102, 105
Snubber, 222
SOA. *See* Safe operating area (SOA)
Soft clipping, 141
Source feedback bias, 80, 81
Source follower, 63, 125, 211
Space charge region, 18
SPDT, 156, 188
Spectrum, 5, 74, 129, 132, 133, 135, 136, 140, 145, 175, 176
Spectrum analyzer, 74, 129
SPST. *See* Single-pole, single-throw (SPST)
Standby, 226, 232, 236
Star ground, 122, 262
Step function, 56
Stop band, 8, 32, 36, 180, 181, 186
Sustain, 165–169
Swamping, 79
Swamping resistor, 120
Symmetry, 111, 131–137, 161, 246, 247
Sziklai pair, 116

T
T_{60}, 171, 173
Talk box, 178, 179
Tetrode, 198, 219, 283
Thermal resistance, 118, 119
Thermal runaway, 120, 125
Three-halves power law, 18
Time constant, 163, 171
Time domain, 129, 131, 135, 140
TO–3, 64, 118, 119
Tone control, 22, 25–50, 121, 137, 244, 253, 256–258
Transconductance (gm), 18, 81–83, 97–100, 108, 167, 202, 209, 219, 222, 230, 239, 247, 264, 282, 283
Transconductance curves, 19, 145, 195–196, 203, 206, 210, 223, 224, 231, 239, 248, 266, 271–273, 275, 277, 282
Transducer, 25, 33, 84
Transfer function, 38–39, 50, 52, 133–137, 144, 145, 247
Transformer coupled phase-splitter, 215
Transformer coupling, 58, 215–219, 256, 258, 266
Transformer, filament, 2, 10
Transistor, 13, 21, 51, 57–68, 71, 72, 74, 80, 84, 85, 87, 89, 92, 93, 95–98, 104, 106, 111–113, 116–121, 123, 125–128, 135, 137, 141, 142, 145, 165, 195–197, 201, 211, 214–216, 219, 247, 256, 257, 264, 270, 282, 284
Tremolo, 169, 170, 175
Trigonometric identity, 139, 191
Triode, 141, 190, 195, 197–199, 202, 215, 219–223, 225, 226, 230, 232, 233, 237, 239, 243, 244, 247–250, 253, 254, 256, 258, 259, 266, 270, 274–276, 280–284
True bypass, 188
Turns-ratio, 228, 229, 242, 250

U
Underdamped, 32, 40
Unilateral, 257, 258
Unilateral network, 258, 259

V
V_{BE} multiplier, 126, 128
VCA. *See* Voltage controlled amplifier (VCA)

Vibrato, 169
Virtual short circuit, 94
Vocoder, 129, 178–180
Voltage amplifier, 53, 200
Voltage controlled amplifier (VCA), 100, 166–169, 175, 176
Voltage divider, 37, 39, 40, 50, 55, 93, 103, 169, 170, 187
Voltage divider bias, 65–76, 106
Voltage gain μ (mu), 51, 53, 55, 61–63, 70–72, 74, 77, 78, 81, 83–87, 91, 95, 97, 99, 103, 107–109, 112, 113, 115, 124, 133, 134, 137, 146, 186, 202, 207–209, 211, 213–215, 221, 229, 233, 243, 244, 251–253, 256, 263, 266
Voltage regulator, 6, 11–14, 52, 123
Volume control, 25, 38–40, 82, 86

W
Wah-Wah, 49, 129, 180–188, 192, 193
Wiper, 37, 39, 45, 46, 258

Z
Zener diode, 125
Zobel network, 123–124