Ask The Applications Engineer—24

by Steve Guinta

RESISTANCE

Q. I'd like to understand the differences between available resistor types and how to select the right one for a particular application.

A. Sure, let's talk first about the familiar "discrete" or axial-lead type resistors we're used to working with in the lab; then we'll compare cost and performance tradeoffs of the discretes and thin- or thick-film networks.

Axial Lead Types: The three most common types of axial-lead resistors we'll talk about are *carbon composition*, or carbon film, *metal film* and *wirewound*:

- *carbon composition* or carbon film-type resistors are used in general-purpose circuits where initial accuracy and stability with variations of temperature aren't deemed critical. Typical applications include their use as a collector or emitter load, in transistor/FET biasing networks, as a discharge path for charged capacitors, and as pull-up and/or pull-down elements in digital logic circuits.

  Carbon-type resistors are assigned a series of standard values (Table 1) in a quasi-logarithmic sequence, from 1 ohm to 22 megohms, with tolerances from 2% (carbon film) to 5% up to 20% (carbon composition). Power dissipation ratings range from 1/8 watt up to 2 watts. The 1/4-watt and 1/2-watt, 5% and 10% types tend to be the most popular.

  Carbon-type resistors have a poor temperature coefficient (typically 5,000 ppm/°C); so they are not well suited for precision applications requiring little resistance change over temperature, but they are inexpensive—as little as 3 cents [USD 0.03] each in 1,000 quantities.

  Table 1 lists a decade (10:1 range) of standard resistance values for 2% and 5% tolerances, spaced 10% apart. The smaller subset in lightface denote the only values available with 10% or 20% tolerances; they are spaced 20% apart.

Table 1. Standard resistor values: 2%, 5% and 10%

10	**16**	27	**43**	68
11	18	**30**	47	**75**
12	**20**	33	**51**	82
13	22	**36**	56	**91**
15	**24**	39	**62**	100

Carbon-type resistors use color-coded bands to identify the resistor's ohmic value and tolerance:

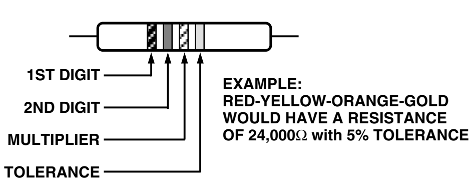


Table 2. Color code for carbon-type resistors

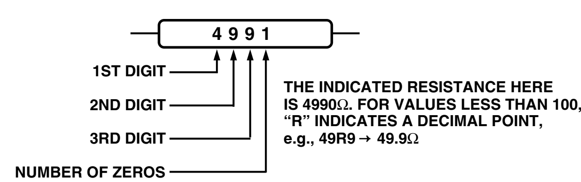
digit	color	multiple	# of zeros	tolerance
–	silver	0.01	–2	10%
–	gold	0.10	–1	5%
0	black	1	0	–
1	brown	10	1	–
2	red	100	2	2%
3	orange	1 k	3	–
4	yellow	10 k	4	–
5	green	100 k	5	–
6	blue	1 M	6	–
7	violet	10 M	7	–
8	gray	–	–	–
9	white	–	–	–
–	none	–	–	20%

- *Metal film* resistors are chosen for precision applications where initial accuracy, low temperature coefficient, and lower noise are required. Metal film resistors are generally composed of Nichrome, tin oxide or tantalum nitride, and are available in either a hermetically sealed or molded phenolic body. Typical applications include bridge circuits, RC oscillators and active filters. Initial accuracies range from 0.1 to 1.0 %, with temperature coefficients ranging between 10 and 100 ppm/°C. Standard values range from 10.0 Ω to 301 kΩ in discrete increments of 2% (for 0.5% and 1% rated tolerances).

Table 3. Standard values for film-type resistors

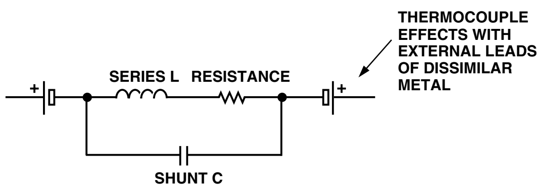
1.00	1.29	1.68	2.17	2.81	3.64	4.70	6.08	7.87
1.02	1.32	1.71	2.22	2.87	3.71	4.80	6.21	8.03
1.04	1.35	1.74	2.26	2.92	3.78	4.89	6.33	8.19
1.06	1.37	1.78	2.31	2.98	3.86	4.99	6.46	8.35
1.08	1.40	1.82	2.35	3.04	3.94	5.09	6.59	8.52
1.10	1.43	1.85	2.40	3.10	4.01	5.19	6.72	8.69
1.13	1.46	1.89	2.45	3.17	4.09	5.30	6.85	8.86
1.15	1.49	1.93	2.50	3.23	4.18	5.40	6.99	9.04
1.17	1.52	1.96	2.55	3.29	4.26	5.51	7.13	9.22
1.20	1.55	2.00	2.60	3.36	4.34	5.62	7.27	9.41
1.22	1.58	2.04	2.65	3.43	4.43	5.73	7.42	9.59
1.24	1.61	2.09	2.70	3.49	4.52	5.85	7.56	9.79
1.27	1.64	2.13	2.76	3.56	4.61	5.96	7.72	9.98

Metal film resistors use a 4 digit numbering sequence to identify the resistor value instead of the color band scheme used for carbon types:



- *Wirewound* precision resistors are extremely accurate and stable (0.05%, <10 ppm/°C); they are used in demanding applications, such as tuning networks and precision attenuator circuits. Typical resistance values run from 0.1 Ω to 1.2 MΩ.

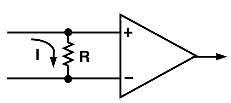
High Frequency Effects: Unlike its "ideal" counterpart, a "real" resistor, like a real capacitor (*Analog Dialogue* 30-2), suffers from parasitics. (Actually, any two-terminal element may look like a resistor, capacitor, inductor, or damped resonant circuit, depending on the frequency it's tested at.)



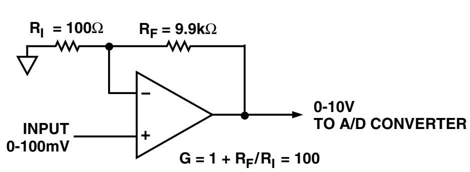
Factors such as resistor base material and the ratio of length to cross-sectional area determine the extent to which the parasitic L and C affect the constancy of a resistor's effective dc resistance at high frequencies. Film type resistors generally have excellent high-frequency response; the best maintain their accuracy to about 100 MHz. Carbon types are useful to about 1 MHz. Wirewound resistors have the highest inductance, and hence the poorest frequency response. Even if they are non-inductively wound, they tend to have high capacitance and are likely to be unsuitable for use above 50 kHz.

Q. *What about temperature effects? Should I always use resistors with the lowest temperature coefficients (TCRs)?*

A. Not necessarily. A lot depends on the application. For the single resistor shown here, measuring current in a loop, the current produces a voltage across the resistor equal to I × R. In this application, the absolute accuracy of resistance at any temperature would be critical to the accuracy of the current measurement, so a resistor with a very low TC would be used.



A different example is the behavior of gain-setting resistors in a gain-of-100 op amp circuit, shown below. In this type of application, where gain accuracy depends on the ratio of resistances (a ratiometric configuration), resistance matching, and the tracking of the resistance temperature coefficients (TCRs), is more critical than absolute accuracy.



Here are a couple of examples that make the point.

1. Assume both resistors have an actual TC of 100 ppm/°C (i.e., 0.01%/°C). The resistance following a temperature change, ΔT, is

$$R = R_0(1 + TC\,\Delta T)$$

For a 10°C temperature rise, both R_f and R_i increase by 0.01%/°C × 10°C = 0.1%. Op amp gains are [to a very good approximation] $1 + R_F/R_I$. Since both resistance values, though quite different (99:1), have increased by the same *percentage*, their ratio—hence the gain—is unchanged. Note that the gain accuracy depends just on the resistance *ratio*, independently of the absolute values.

2. Assume that R_I has a TC of 100 ppm/°C, but R_F's TC is only 75 ppm/°C. For a 10°C change, R_I increases by 0.1% to 1.001 times its initial value, and R_F increases by 0.075% to 1.00075 times its initial value. The new value of gain is

$$(1.00075\,R_F)/(1.001\,R_I) = 0.99975\,R_F/R_I$$

For an ambient temperature change of 10°C, the amplifier circuit's gain has decreased by 0.025% (equivalent to 1 LSB in a 12-bit system).

Another parameter that's not often understood is the self-heating effect in a resistor.

Q. *What's that?*

A. Self-heating causes a change in resistance because of the increase in temperature when the dissipated power increases. Most manufacturers' data sheets will include a specification called "thermal resistance" or "thermal derating", expressed in degrees C per watt (°C/W). For a 1/4-watt resistor of typical size, the thermal resistance is about 125°C/W. Let's apply this to the example of the above op amp circuit for full-scale input:

Power dissipated by R_I is

E^2/R = (100 mV)^2/100 Ω = 100 μW, leading to a temperature change of 100 μW × 125°C/W = 0.0125°C, and a negligible 1-ppm resistance change (0.00012%).

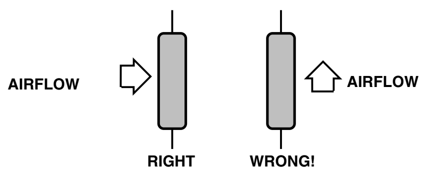
Power dissipated by R_F is

$^2/R$ = (9.9 V)^2/9900 Ω = 9.9 mW, leading to a temperature change of 0.0099 W × 125°C/W = 1.24°C, and a resistance change of 0.0124%, which translates directly into a 0.012% gain change.

Thermocouple Effects: Wirewound precision resistors have another problem. The junction of the resistance wire and the resistor lead forms a thermocouple which has a thermoelectric EMF of 42 μV/°C for the standard "Alloy 180"/Nichrome junction of an ordinary wirewound resistor. If a resistor is chosen with the [more expensive] copper/nichrome junction, the value is 2.5 μV/°C. ("Alloy 180" is the standard component lead alloy of 77% copper and 23% nickel.)

Such thermocouple effects are unimportant in ac applications, and they cancel out when both ends of the resistor are at the same temperature; however if one end is warmer than the other, either because of the power being dissipated in the resistor, or its location with respect to heat sources, the net thermoelectric EMF will introduce an erroneous dc voltage into the circuit. With an ordinary wirewound resistor, a temperature differential of only 4°C will introduce a dc error of 168 µV—which is greater than 1 LSB in a 10-V/16-bit system!

This problem can be fixed by mounting wirewound resistors so as to insure that temperature differentials are minimized. This may be done by keeping both leads of equal length, to equalize thermal conduction through them, by insuring that any airflow (whether forced or natural convection) is normal to the resistor body, and by taking care that both ends of the resistor are at the same thermal distance (i.e., receive equal heat flow) from any heat source on the PC board.



Q. *What are the differences between "thin-film" and "thick-film" networks, and what are the advantages/disadvantages of using a resistor network over discrete parts?*

A. Besides the obvious advantage of taking up considerably less real estate, resistor networks—whether as a separate entity, or part of a monolithic IC—offer the advantages of high accuracy via laser trimming, tight TC matching, and good temperature tracking. Typical applications for discrete networks are in precision attenuators and gain setting stages. Thin film networks are also used in the design of monolithic (IC) and hybrid instrumentation amplifiers, and in CMOS D/A and A/D converters that employ an R-2R Ladder network topology.

Thick film resistors are the lowest-cost type—they have fair matching (<0.1%), but poor TC performance (>100 ppm/°C) and tracking (>10 ppm/°C). They are produced by screening or electroplating the resistive element onto a substrate material, such as glass or ceramic.

Thin film networks are moderately priced and offer good matching (0.01%), plus good TC (<100 ppm/°C) and tracking (<10 ppm/°C). All are laser trimmable. Thin film networks are manufactured using vapor deposition.

Tables 4 compares the advantages/disadvantages of a thick film and several types of thin-film resistor networks. Table 5 compares substrate materials.

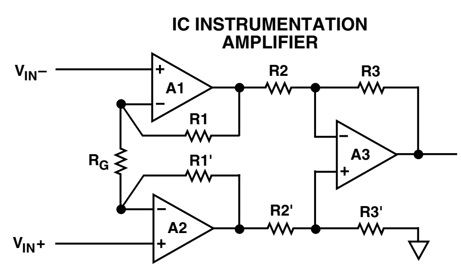
Table 4. Resistor Networks

Type	Advantages	Disadvantages
Thick film	Low cost High power Laser-trimmable Readily available	Fair matching (0.1%) Poor TC (>100 ppm/°C) Poor tracking TC (10 ppm/°C)
Thin film on glass	Good matching (<0.01%) Good TC (<100 ppm/°C) Good tracking TC (2 ppm/°C) Moderate cost Laser-trimmable Low capacitance	Delicate Often large geometry Low power
Thin film on ceramic	Good matching (<0.01%) Good TC (<100 ppm/°C) Good tracking TC (2 ppm/°C) Moderate cost Laser-trimmable Low capacitance Suitable for hybrid IC substrate	Often large geometry
Thin film on silicon	Good matching (<0.01%) Good TC (<100 ppm/°C) Good tracking TC (2 ppm/°C) Moderate cost Laser-trimmable Low capacitance Suitable for hybrid IC substrate	

Table 5. Substrate Materials

Substrate	Advantages	Disadvantages
Glass	Low capacitance	Delicate Low power Large geometry
Ceramic	Low capacitance Suitable for hybrid IC substrate	Large geometry
Silicon	Suitable for monolithic construction	Low power Capacitance to substrate
Sapphire	Low capacitance	Low power Higher cost

In the example of the IC instrumentation amplifier shown below, tight matching between resistors R1-R1', R2-R2', R3-R3' insures high common-mode rejection (as much as 120 dB, dc to 60 Hz). While it is possible to achieve higher common-mode rejection using discrete op amps and resistors, the arduous task of matching the resistor elements is undesirable in a production environment.



Matching, rather than absolute accuracy, is also important in R-2R ladder networks (including the feedback resistor) of the type used in CMOS D/A converters. To achieve *n*-bit performance, the resistors have to be matched to within 1/2*n*, which is easily achieved through laser trimming. Absolute accuracy error, however, can be as much as ±20%. Shown here is a typical R-2R ladder network used in a CMOS digital-analog converter.