Radio Frequency Electronics

Preliminaries IV

Heinrich Hertz

- Born 22 February 1857, died – 1 January 1894
- Physicist
- Proved conclusively EM waves (theorized by Maxwell), exist.
- “Hz” names in his honor.
- Created the field of contact mechanics (very important in mechanical engineering)

Image from Wikipedia
Resistors

SMT chip resistors

Through-hole, carbon film capacitor
Wire Wound Resistors

Typically > 1 W, and since $P = V^2/R$, this most often implies low resistance. Their physical construction is designed to dissipate the heat. Excellent high-energy pulse handling.

Have 1% tolerance or better, and have good long-term stability.

Given their construction, it is clear the have high inductance and are generally unsuitable for RF work.

They look like this… …or this… …or this… …or even this
Chip Resistors

These are surface-mount (SMT) parts. Small size $\rightarrow$ reduced board size. In quantity they are very inexpensive.

Available in wide range of tolerances and TRCs. For example, parts with tolerances $\pm 0.010\%$ and TRC $\pm 0.2$ ppm/°C, are available, but expensive: $16…$

The generally have lower inductance compared to leaded through-hole resistors.

Two types of technologies, namely, thick film and thin film resistors
Chip Resistors – Thick or Thin Shoot Out

They look the same, but which is better and why?

**Thick Film Chip Resistor**
- Less expensive.
- Can handle higher power surges.
- Worse tolerances, worse TCs.
- More prone to skin effect. Worse frequency response.

**Thin Film Chip Resistor**
- More expensive.
- Easily damaged by power surges.
- Better tolerances, better TCs.
- Less prone to skin effect. Better frequency response.
At first blush it may seem counterintuitive that the skin effect in thin film resistors is less problematic than in thick film resistors.

However, as indicated in the figures below, the change from $R_{low\ freq.}$ to $R_{high\ freq.}$ is more pronounced in thick film than thin film resistors.
Carbon film resistors are the most widely-used through-hole resistors.

The resistive part of the resistor is a carbon film that is then cut away in a spiral to remove carbon.

The more material removed, the higher $R$.

Note that the spiral forms a small inductor. This, along with the lead inductance make them unsuitable in most RF applications.
The resistive part of the resistor is a metal film that is then cut away in a spiral to remove carbon.

Similar appearance as carbon film.

Generally speaking, they are more expensive, higher quality resistors than carbon film resistors.

Still, because of their construction they can have significant inductance.

Images from www.resistorguide.com
Bulk metal film resistors are made with small pieces of metal foil that are cut and then glued to a substrate, and then further processed. They are expensive compared to metal film, metal foil. They are touted as low-inductance, low capacitance resistors.

Manufacturers use special patterns for reduce inductance and capacitance of their metal foil resistors.

SMT metal foil resistor

Though-hole metal foil resistor. 0.01% tolerance, 0.3 W. Cost $14
Resistor Models

Inductance of straight piece of wire

\[ L = \frac{\mu_0}{2\pi} l \left[ \ln \left( \frac{4l}{d} \right) - \frac{3}{4} \right] \] H

\( d = \) diameter of wire in cm

\( l = \) length of wire in cm

50 mm of 22 AWG wire => 50 nH

The parasitic capacitance can have a big impact on the resistor performance at high frequencies
Frequency Dependence of Resistors

The parasitic capacitances can have a big impact on the resistor performance at high frequencies.

Model showing stray and inter-lead capacitances.

Magnitude of 2K thick-film chip resistor as a function of frequency.

From “RF Circuit Design: Theory and Applications”, Ludwig & Bretchko
Resistor Models

Frequency Response of Foil Resistor

Impedance as a percentage of dc resistance

Frequency (MHz)
Manufacturers have developed techniques for making resistors that work well up to several GHz.

Special trimming techniques are used.

Pulsed trim (middle) is less inductive than standard helical trim.
Any conductor generates *thermal* or *Johnson* noise. It is also sometimes called *Nyquist* noise. The cause is the Brownian motion of carriers in the conductor, and this a function of temperature as well as the resistance.

\[ v_{n(rms)} = \sqrt{4kTBR} \]

- \( v_{n(rms)} \) is the rms noise voltage
- \( k \) is Boltzmann’s constant
- \( T \) is the temperature in Kelvin
- \( B \) is the bandwidth over which the noise energy is measured
- \( R \) is the resistance value in \( \Omega \)

Johnson noise is inherent in all resistors

The noise is *white* in that it has a constant power spectral density.
A resistor’s Johnson noise amplified and displayed on an oscilloscope.
One can model Johnson noise with a voltage source in series with a noise-free resistor, or one can model it as a current source in parallel with a noise-free resistor.

$$v_{n(rms)} = \sqrt{4kTB}R$$

$$i_{n(rms)} = \sqrt{4kTB/R}$$

The noise generated by two resistors are uncorrelated. Consequently, the noise voltages don’t add in the as they would if the voltages were correlated:

$$v_n \neq v_{n1} + v_{n2}$$

$$i_n \neq i_{n1} + i_{n2}$$

Rather, the resistors’ noise powers add:

$$v_n^2 = v_{n1}^2 + v_{n2}^2$$

$$i_n^2 = i_{n1}^2 + i_{n2}^2$$
Calculate the Johnson noise generated by a 10K resistor in a 10 kHz bandwidth at room temperature.

In the electronics industry 27°C is widely-used as “room temperature”. This is because it corresponds to 300K, which is easy to work with.

\[
\frac{v_{noise\ (rms)}}{R} = \sqrt{4kTBR}
\]

\[
= \sqrt{4(1.38 \times 10^{-23})(300)(10 \times 10^3)(10 \times 10^3)}
\]

\[
= 1.29 \ \mu V
\]

This may seem small, but could be larger than voltage at cell phone antenna.

Johnson noise places a lower limit on noise performance of a system.

Low noise designs are often low-impedance designs.

In critical applications, relevant parts are cooled down. For example the low noise amplifiers or LNAs in satellite communication links.
Calculate the Johnson noise voltage generated by a 10K resistor in parallel with a 40K resistor at 300 K and in a 10 kHz bandwidth.

**Method 1.** Model resistor with current sources as in (b). Then

\[
i_n^2 = \frac{4kT}{R_1} + \frac{4kT}{R_2}
\]

\[
= 16.6 \times 10^{-21} + 4.1 \times 10^{-21} \text{ } \text{A}^2
\]

\[
= 20.7 \times 10^{-21} \text{ } \text{A}^2
\]

\[
\Rightarrow i_{n(rms)} = \sqrt{20.7 \times 10^{-21}}
\]

\[
= 144 \text{ } \text{pA} \text{ (rms)}
\]

This current flows through \(R_1 || R_2 = 8K\) (see (c)) and will generate an rms voltage of

\[
v_{n(rms)} = (144 \times 10^{-12})(8K)
\]

\[
= 1.15 \mu\text{V} \text{ (rms)}
\]
**Johnson Noise Example**

Calculate the Johnson noise voltage generated by a 10K resistor in parallel with a 40K resistor at 300 K and in a 10 kHz bandwidth.

![Resistors Diagram](a)

**Method 2.** The two resistors are in parallel and for an 8K resistor (see (b)). The rms noise voltage is then

\[
\nu_{\text{noise}(rms)} = \sqrt{4kTBR}
\]

\[
= \sqrt{4(1.38 \times 10^{-23})(300)(10 \times 10^3)(8 \times 10^3)}
\]

\[
= 1.15 \mu V \text{ (rms)}
\]

Which is the same as before
Important Observations

Noise powers add

\[ v_n^2 = v_{n1}^2 + v_{n2}^2 \]
\[ i_n^2 = i_{n1}^2 + i_{n2}^2 \]

\[ v_n = \sqrt{4kTBR} \]

To reduce noise, keep bandwidth \( B \) small, keep \( R \) small.

There are other reason, but one of the reasons RF electronics often have low impedances (50 \( \Omega \)), since it keeps the noise low.

\[ v_n = \sqrt{4kTBR} \]

Because of the square/square root relationship, larger value resistor have a disproportionate impact. Consider \( i \) resistors in series

\[ v_n \approx \sqrt{v_1^2 + v_2^2 + \ldots + v_i^2} \]
Excess Resistor Noise

In addition to Johnson noise resistor exhibit so-called *excess noise*

Excess noise depends heavily on the construction method

Carbon-composition resistors are particularly noisy

<table>
<thead>
<tr>
<th>Type</th>
<th>Noise Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-composition</td>
<td>0.10μV to 3.0μV</td>
</tr>
<tr>
<td>Carbon-film</td>
<td>0.05μV to 0.3μV</td>
</tr>
<tr>
<td>Metal-film</td>
<td>0.02μV to 0.2μV</td>
</tr>
<tr>
<td>Wire-wound</td>
<td>0.01μV to 0.2μV</td>
</tr>
</tbody>
</table>

Typical excess noise, rms/microvolt over one decade of frequency

What is the excess noise of a carbon film resistor between 1 and 5 kHz?

# decades = \[ \log \left( \frac{5}{1} \right) \approx 0.7 \]

⇒ Excess noise between \((0.7)(0.05) = 0.035\) and \((0.7)(0.3) = 0.21\ μV\)
Consider a lossless transmission line with characteristic impedance $Z_0$. Assume the line is terminated in an impedance $Z_L$.

At a distance $d$ from the termination, the impedance of the line looking back is given by:

$$Z_{in}(d) = Z_0 \frac{Z_L + jZ_0 \tan(\beta d)}{Z_0 + jZ_L \tan(\beta d)}$$

and $\beta$ (wavenumber) is

$$\beta = \frac{\omega}{v_p} = \frac{2\pi}{\lambda} = \omega \sqrt{LC}$$

and the phase velocity (propagation speed) is $v_p$

Because this is true, we can simulate inductors and capacitors with sections of transmission lines. This is widely-used in matching networks for antennas and microstrip matching networks for transistor amplifiers.
**Problem** Consider a lossless transmission line with \( L = 209.4 \text{ H/m} \) and \( C = 119.5 \text{ pF/m} \). Assume the line is terminated in a short circuit. Calculate the input impedance of the line at a distance \( l = 100 \text{ mm} \) at 2.4 GHz.

**Solution**

\[
Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{209.4 \times 10^{-9}}{119.5 \times 10^{-12}}} = 48.86 \Omega
\]

\[
v_p = \frac{1}{\sqrt{LC}} = 2 \times 10^8 \text{ m/s}
\]

\[
\beta = \frac{\omega}{v_p} = \frac{(2\pi)(2.4 \times 10^9)}{2 \times 10^8} = 75.4 \text{ m}^{-1} \quad \Rightarrow \beta d = 7.54
\]

\[
Z_{in}(d) = Z_0 \frac{Z_L + jZ_0 \tan(\beta d)}{Z_0 + jZ_L \tan(\beta d)}
\]

\[
Z_{in}(0.1) = j(48.86) \tan(7.54)
\]

\[
Z_{in}(d) = jZ_0 \tan(\beta d)
\]

\[
Z_{in}(0.1) = j(48.86) \tan(7.54) = -j150.5 \Omega
\]
Microwave amplifier that drives a 50 $\Omega$ load.

A simple \( LC \) matching network transforms the load so that it appears as the complex conjugate of the amplifier output impedance.

This allows for maximum power transfer.

At the operating frequency, lumped \( C_m \) and \( L_m \) are not feasible.

Implement \( C_m \) and \( L_m \) as microstrip transmission lines.

Line width and height, and substrate \( \varepsilon_r \) determine characteristic impedance, which is chosen to be 50 $\Omega$.

The length of the microstrip lines determine whether they appear as an inductance or capacitance.
Microstrip and Stripline Transmission Lines

- Greater isolation of transmission lines
- Supports more densely populated designs (traces are smaller, large number of internal layers possible)
- Requires stricter manufacturing tolerances

- Dielectric losses are less (when using identical materials)
- Cheaper and easier to manufacture
- Location of traces on top and bottom layers leads to easier debugging

From www.bitweenie.com
Microstrip and Stripline Transmission Lines

This is a PCB seen from above with sections of copper traces at the top. On the bottom is solid copper called a ground plane.

The various sections form transmission lines that function as inductors and capacitors.

The result is a 6th order filter.

Is this a HP or a LP filter?
Microstrip and Stripline Transmission Lines

(a) Teflon epoxy ($\varepsilon_r = 2.55$)

(b) Alumina ($\varepsilon_r = 10.0$)

(a) Sandwich structure

(b) Cross-sectional field distribution

From “RF Circuit Design: Theory and Applications”, Ludwig & Bretchko
One can create PCB transmission lines with different characteristic impedance by manipulating the microstrip geometry.
That's All Folks