Radio Frequency Electronics

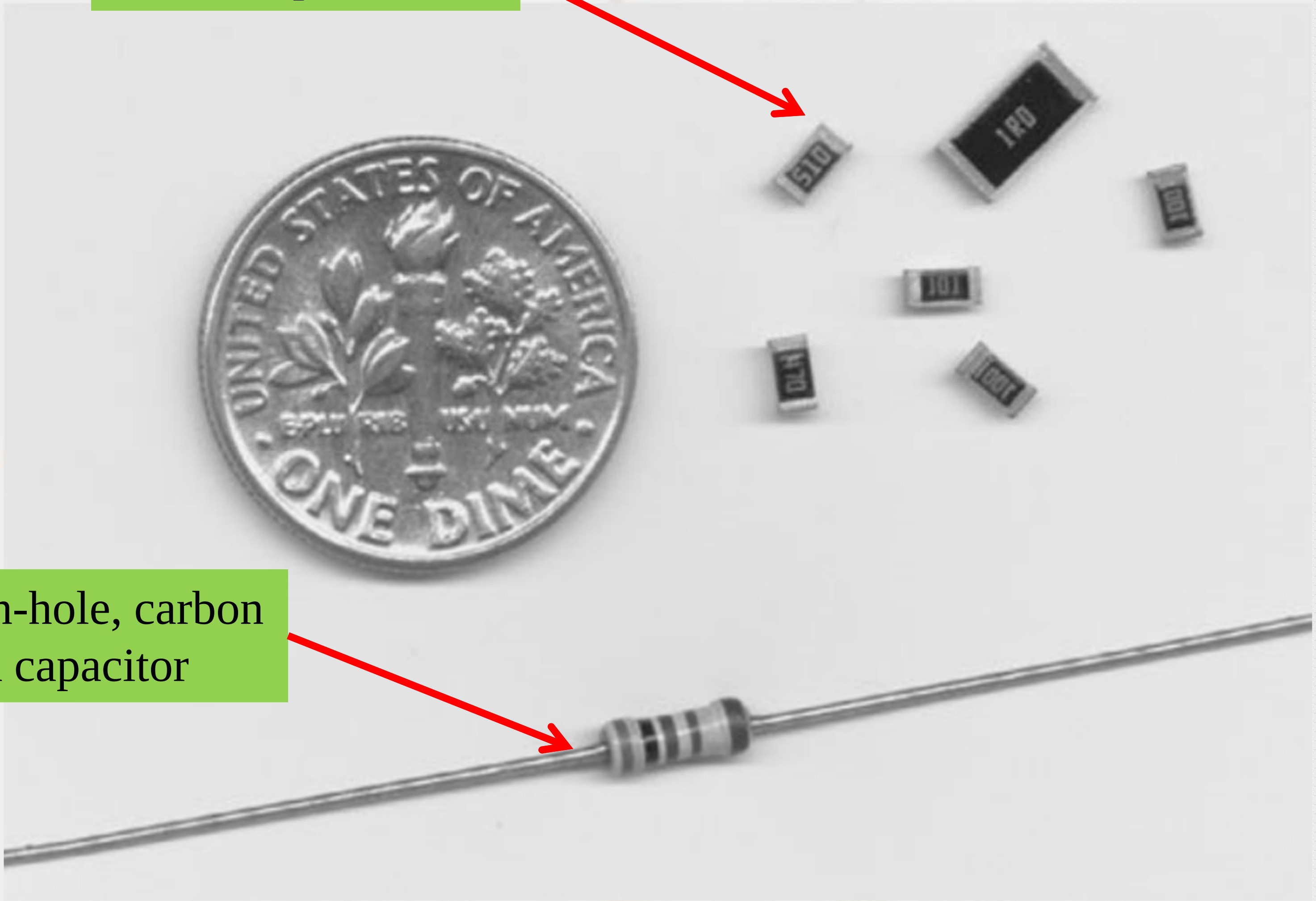
Preliminaries IV

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

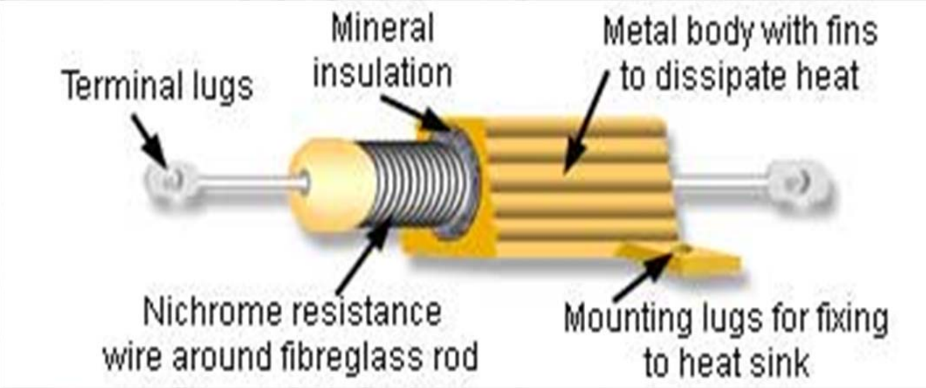
Through-hole, carbon film capacitor

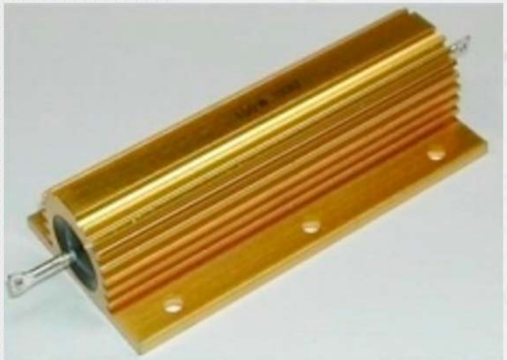
Wire Wound Resistors

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.

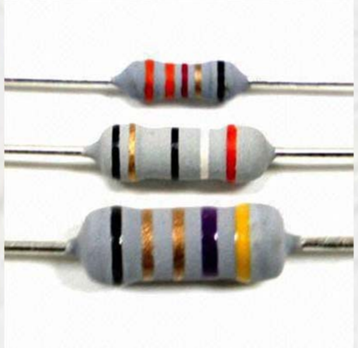
Given their construction, it is clear the have high inductance and are generally unsuitable for RF work.



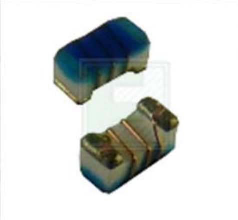


They look like this…

…or this…



…or this…



…or even this

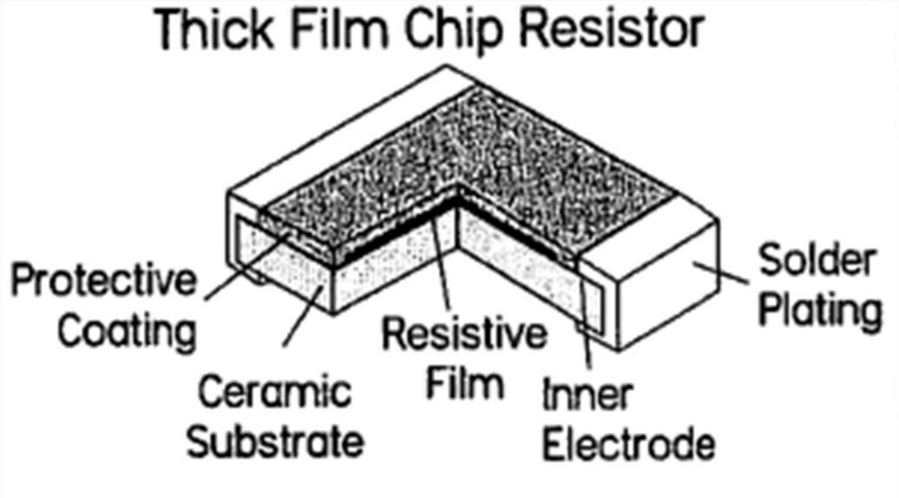
Chip Resistors

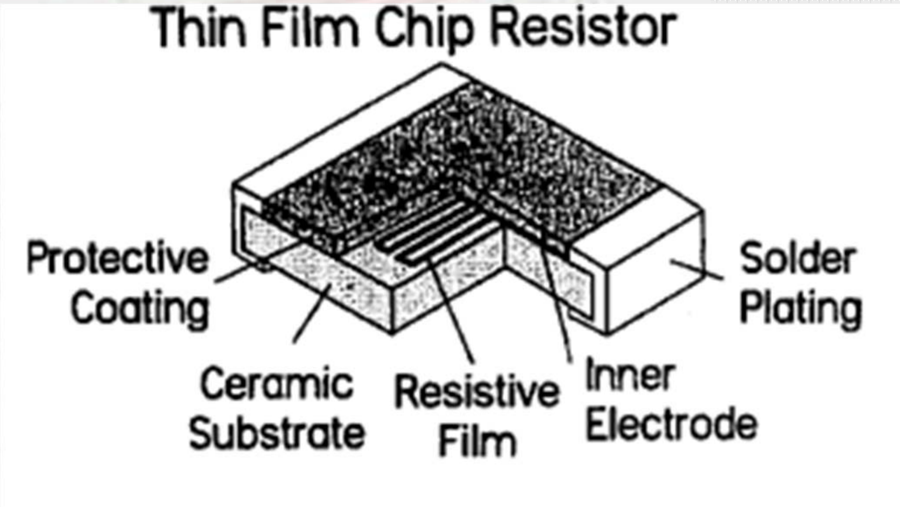
These are surface-mount (SMT) parts. Small size → reduced board size. In quantity they are very inexpensive.

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

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

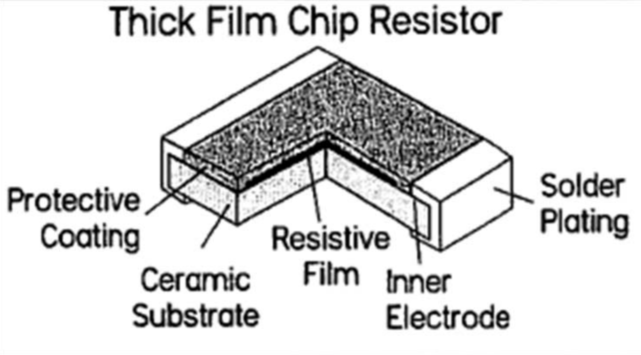
Two types of technologies, namely, thick film and thin film resistors





Chip Resistors – Thick or Thin Shoot Out

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

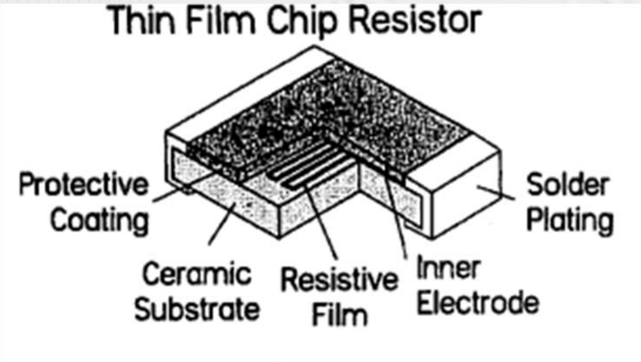


Less expensive.

Can handle higher power surges.

Worse tolerances, worse TCs.

More prone to skin effect. Worse frequency response.



More expensive.

Easily damaged by power surges.

Better tolerances, better TCs.

Less prone to skin effect. Better frequency response.

Counterintuitive?

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 pronounces in thick film than thin film resistors.

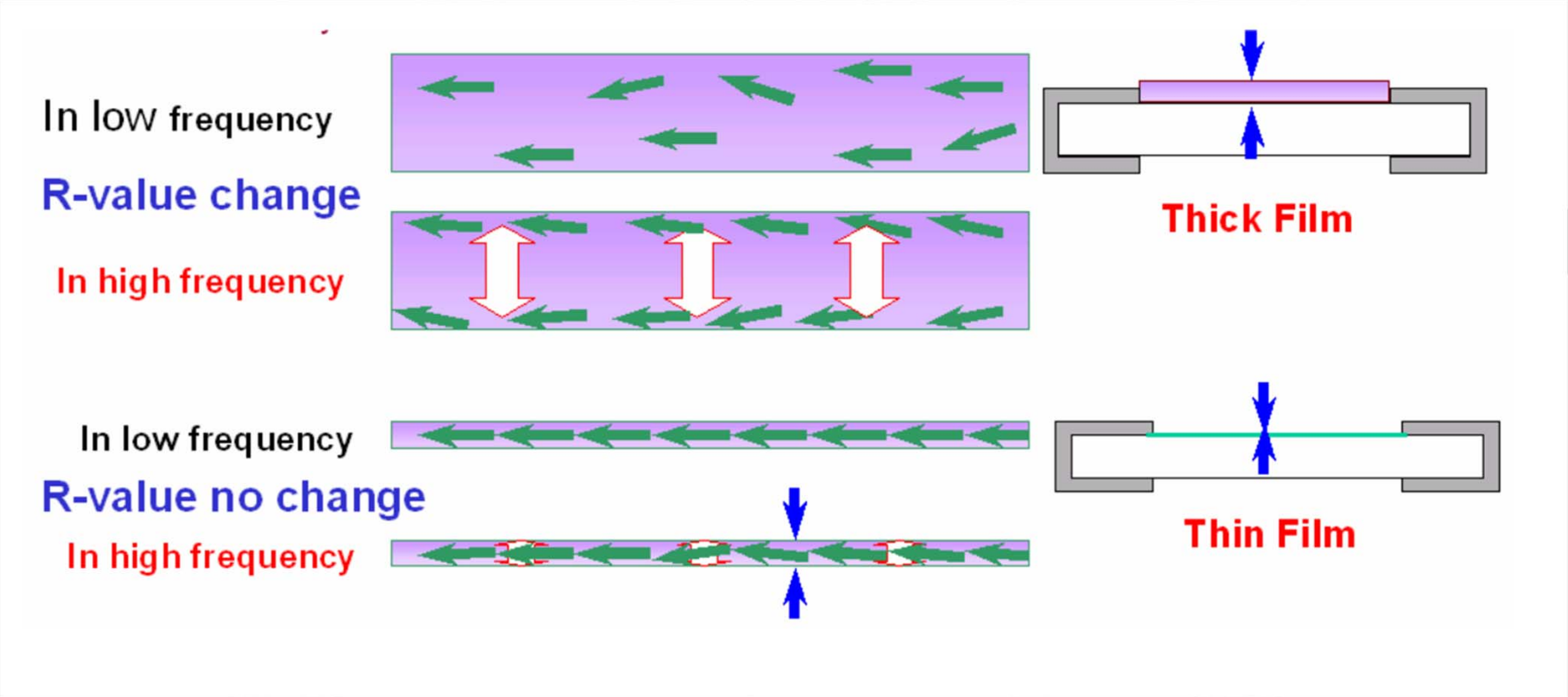


Image from Newark

Carbon 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.

Spiral-cut carbon film

Images from Wikipedia

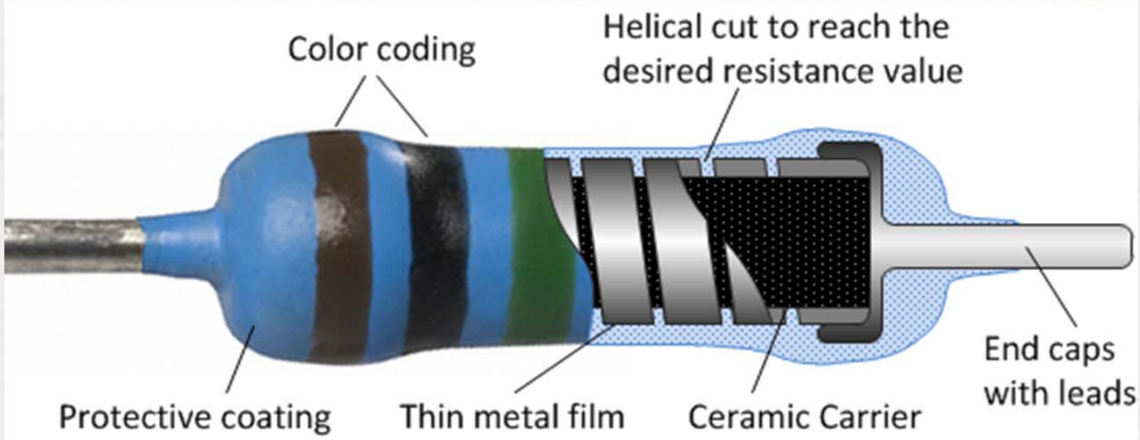
Metal Film Resistors

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**

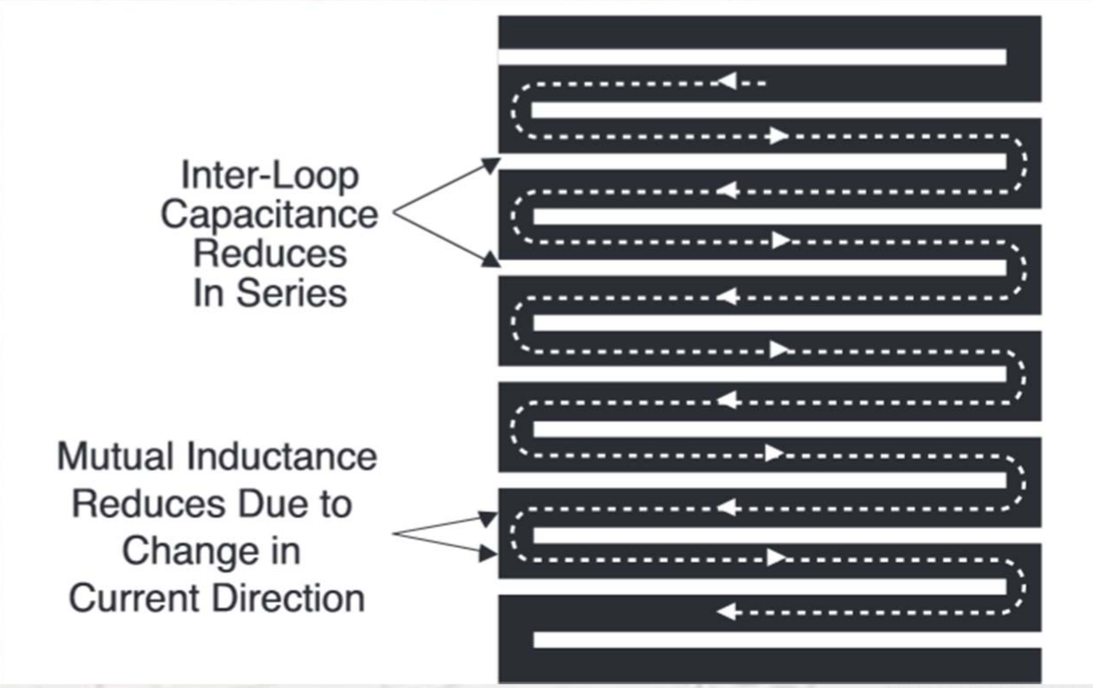
Bulk Metal Foil Resistors

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. The 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.

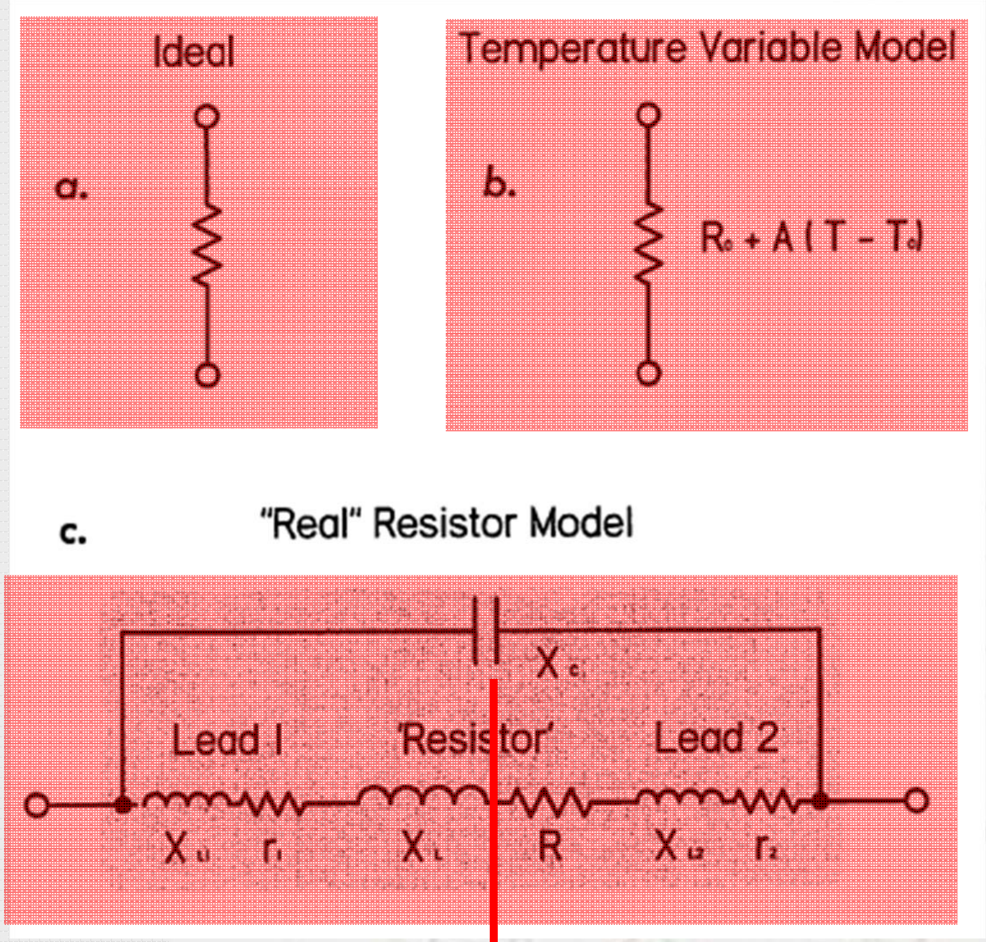
SMT metal foil resistor

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



Images from **www.resistorguide.com**

Resistor Models



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

Inductance of straight piece of wire

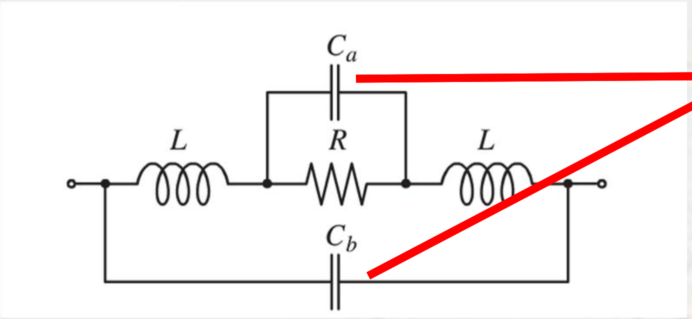
$$L = \frac{\mu_0}{2\pi} l \left[\ln\left(\frac{4l}{d}\right) - \frac{3}{4} \right] \text{ H}$$

d = diameter of wire in cm

l = length of wire in cm

50 mm of 22 AWG wire => 50 nH

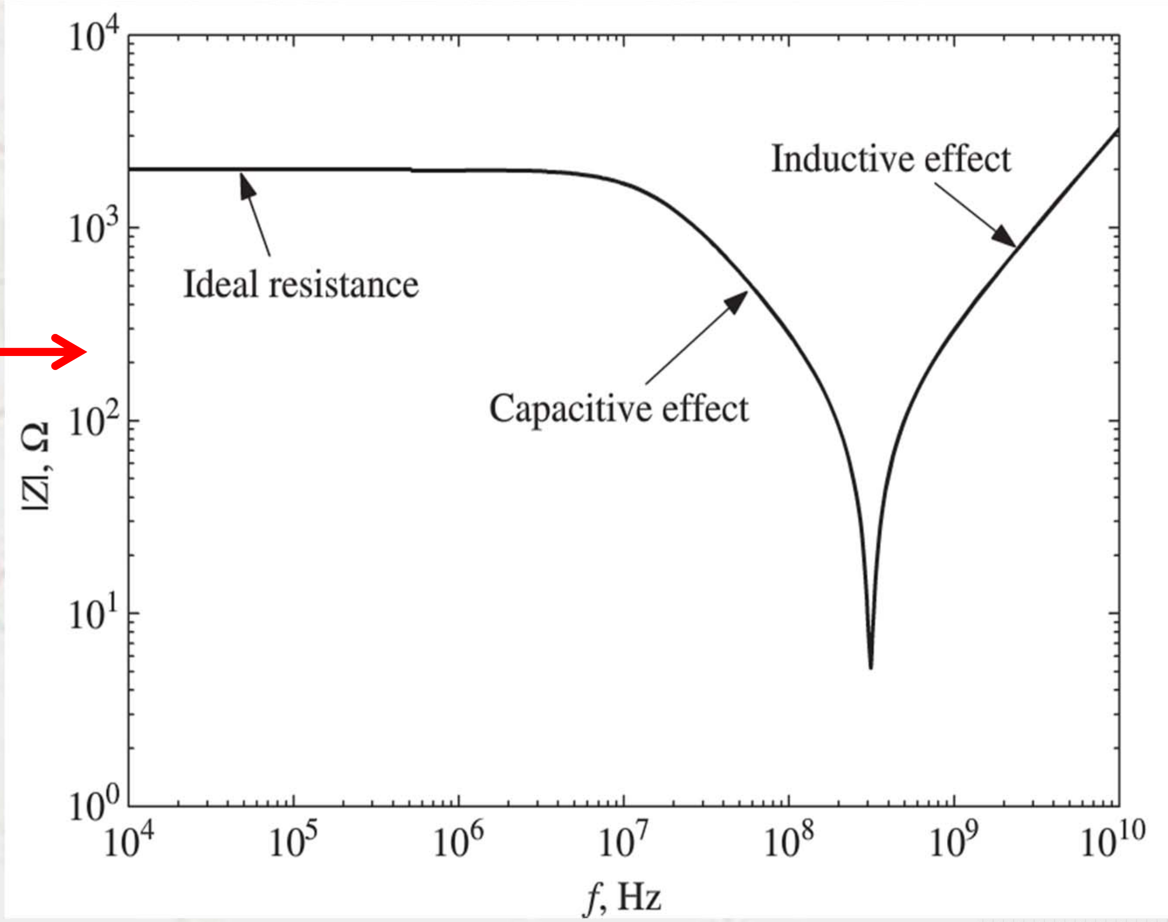
Frequency Dependence of Resistors



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

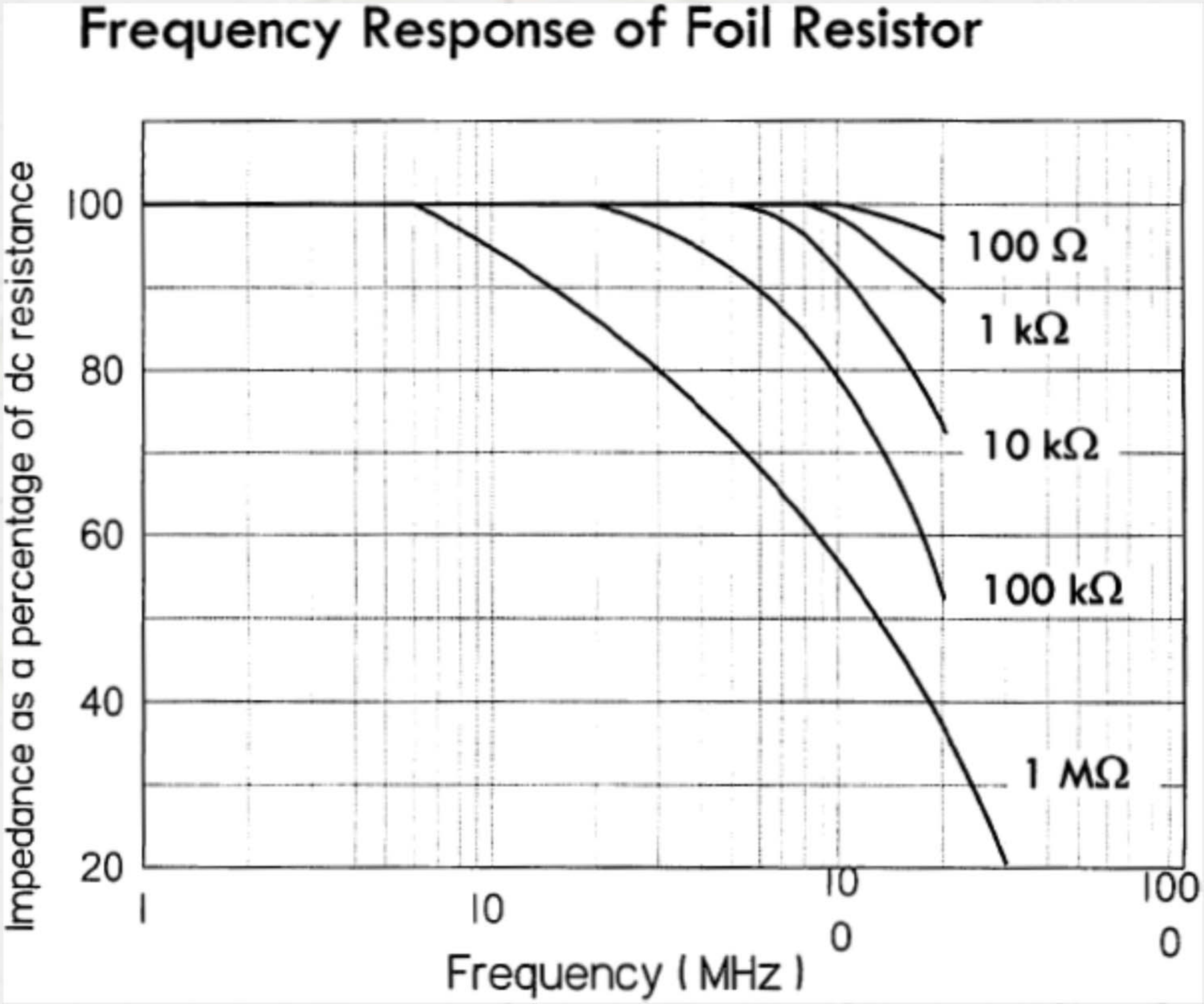
Model showing stray and inter-lead capacitances.

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

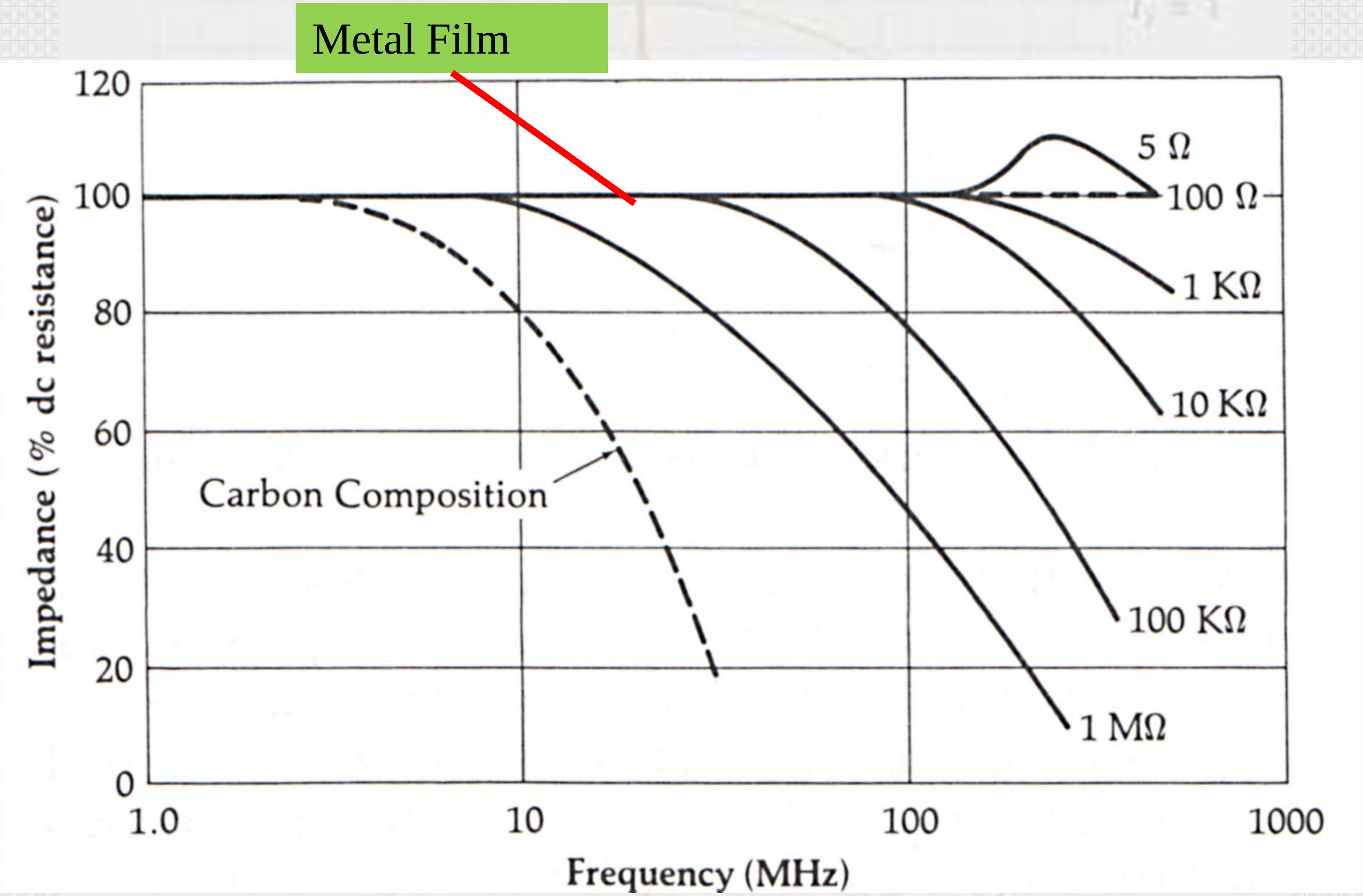


From “RF Circuit Design: Theory and Applications”, Ludwig & Bretchko

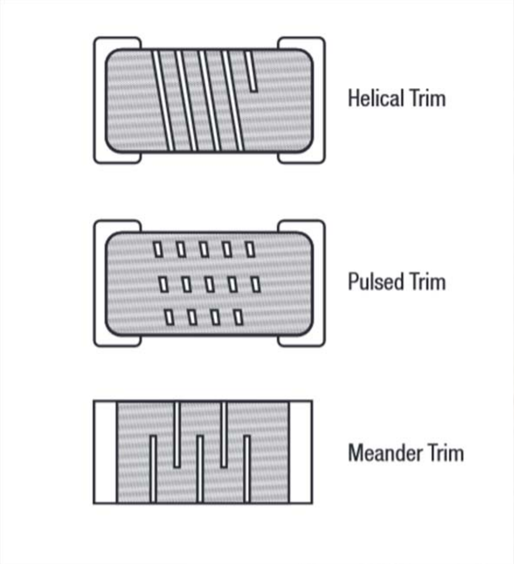
Resistor Models



Resistor Models



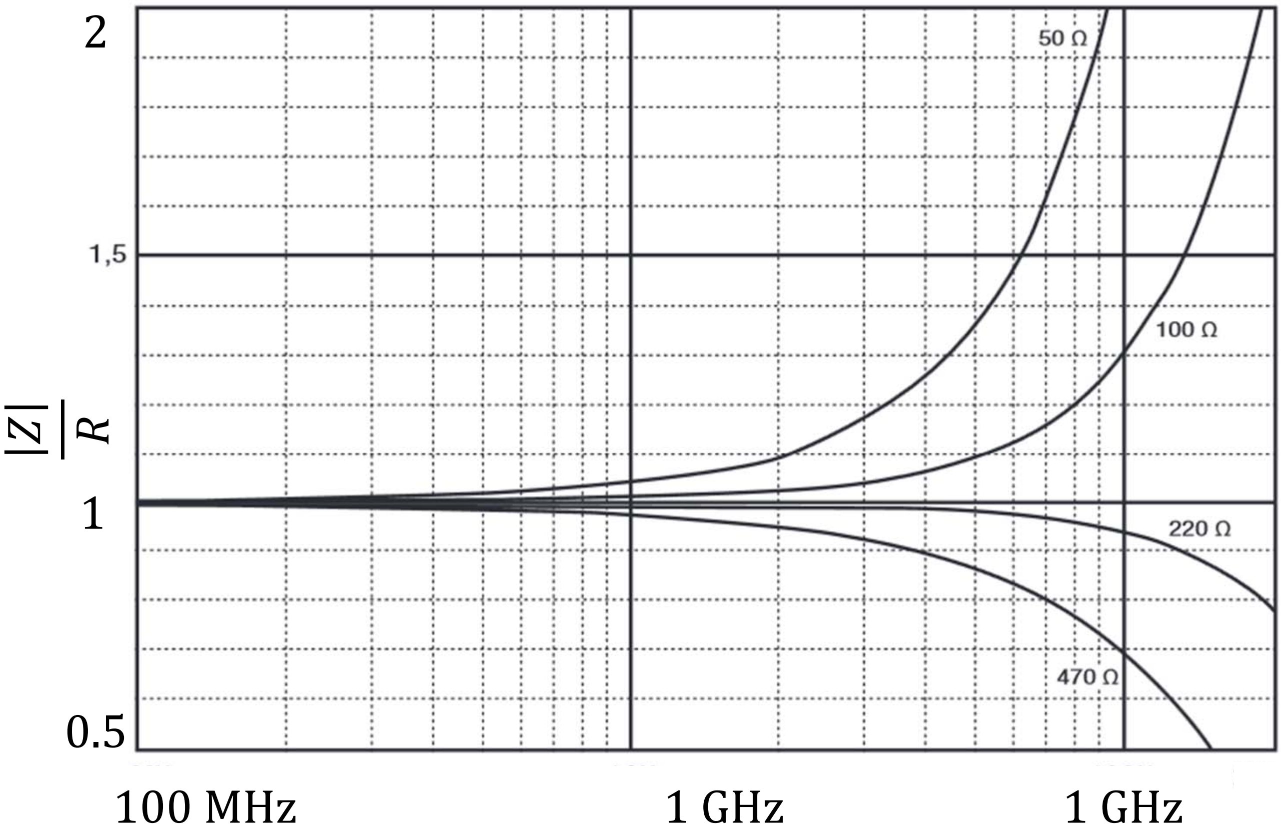
Microwave Resistors



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.

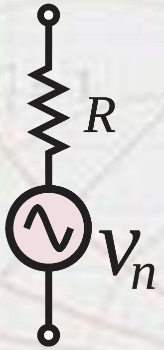


Change in Resistance for 0805 Microwave Resistors

Thermal or Johnson Noise

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

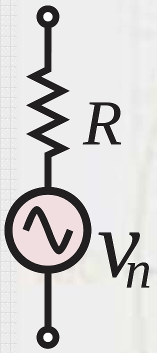
B is the bandwidth over which the noise energy is measured

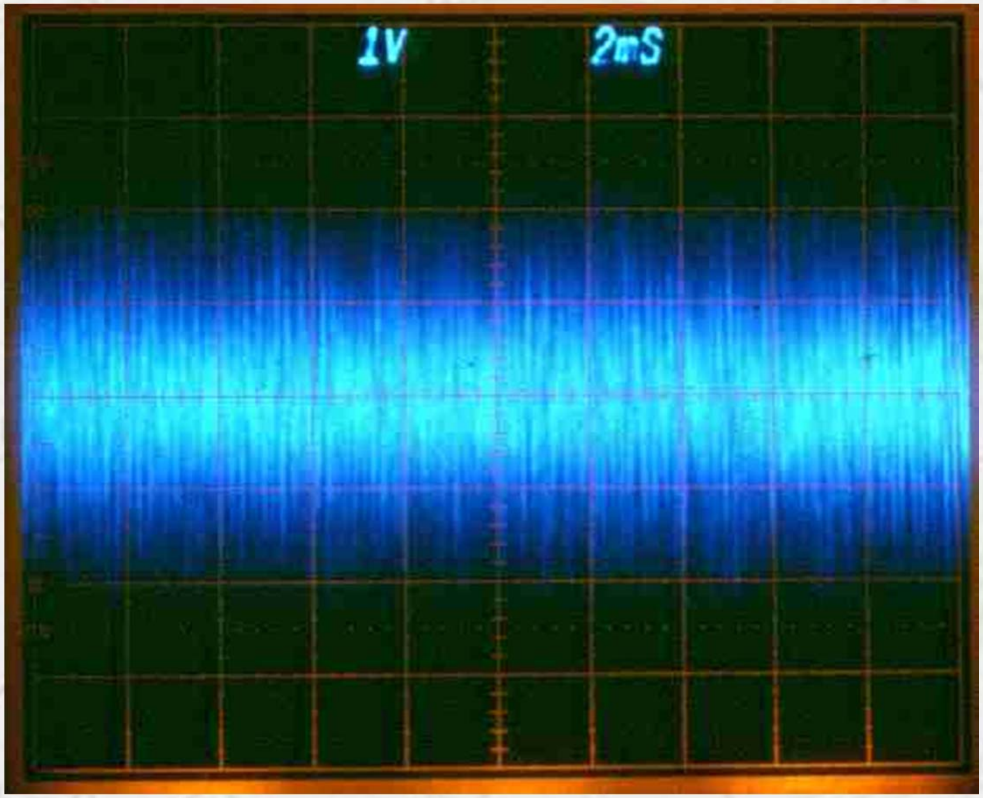
R is the resistance value in Ω

Johnson noise is inherent in all resistors

The noise is *white* in that it has a constant power spectral density

Johnson Noise

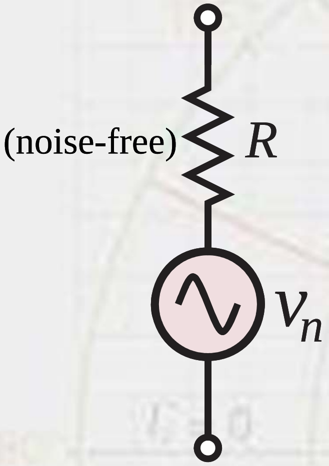


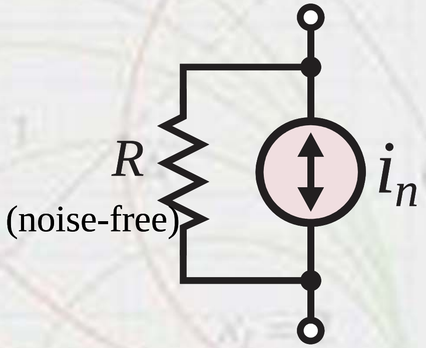


A resistor’s Johnson noise amplified and displayed on an oscilloscope.

Noise Models

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.





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

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

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:

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

$$i_n^2 = i_{n1}^2 + i_{n2}^2$$

Johnson Noise Example

Calculate the Johnson noise generated by a 10K resistor in a 10 kHz bandwidth at room temperature.

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

$$v_{noise(rms)} = \sqrt{4kTBR}$$

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

$$= 1.29\ \mu\mathrm{V}$$

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

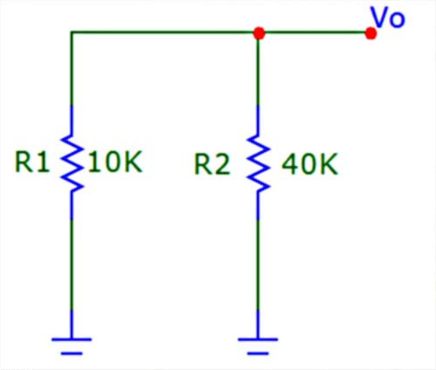
Johnson noise places a lower limit on noise performance of a system.

Low noise designs are often low-impedance designs.

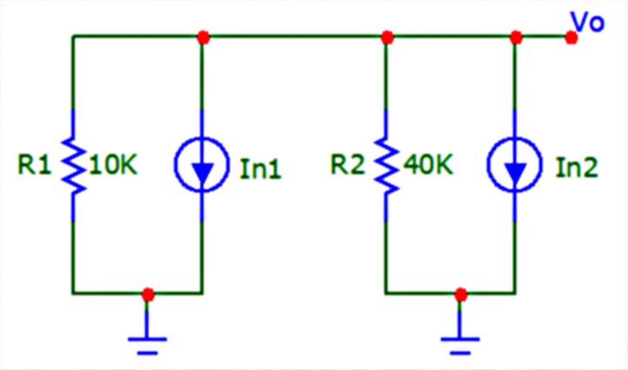
In critical applications, relevant parts are cooled down. For example the low noise amplifiers or LNAs in satellite communication links.

Johnson Noise Example

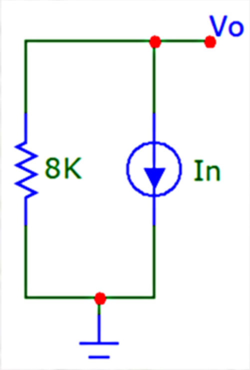
Calculate the Johnson noise voltage generated by a 10K resistor in parallel with a 40K resistor at 300 K and in a 10 kHz bandwidth.



(a)



(b)



(c)

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

$$i_n^2 = i_{n1}^2 + i_{n2}^2$$

$$i_n^2 = 4kTB/R_1 + 4kTB/R_2$$

$$= 16.610^{-21} + 4.1 \times 10^{-21} \;\; \mathrm{A}^2$$

$$= 20.7 \times 10^{-21} \;\; \mathrm{A}^2$$

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

$$= 144 \text{ pA} \;\; (\mathrm{rms})$$

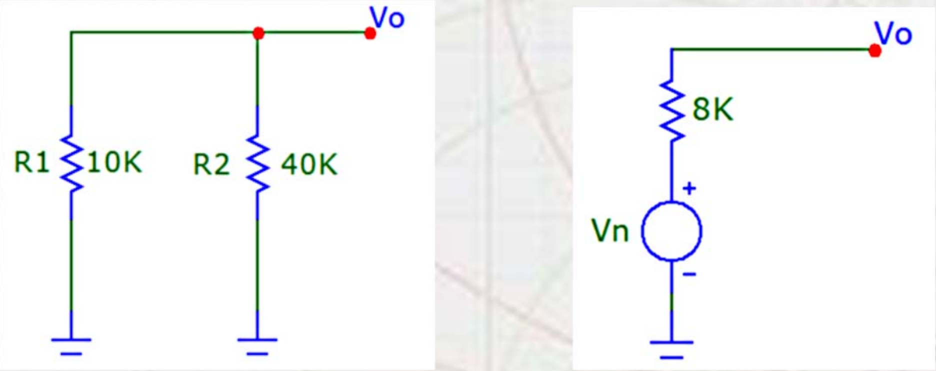
This current flows through $R_1||R_2 = 8\text{K}$ (see (c)) and will generate an rms voltage of

$$v_{n(\mathrm{rms})} = (144 \times 10^{-12})(8\text{K})$$

$$= 1.15 \; \mu\text{V} \;\; (\mathrm{rms})$$

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.



(a) (b)

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

$$v_{noise(rms)} = \sqrt{4kTBR}$$

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

$$= 1.15\ \mu\text{V}\ \ \text{(rms)}$$

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 Ω), 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

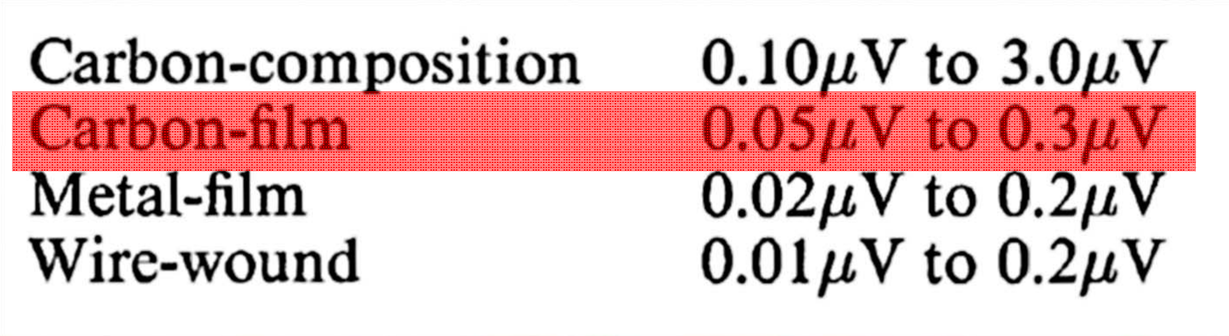
$$v_n \approx \sqrt{v_1^2 + v_2^2 + \cdots v_i^2}$$

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



Carbon-composition	$0.10\mu V$ to $3.0\mu V$
Carbon-film	$0.05\mu V$ to $0.3\mu V$
Metal-film	$0.02\mu V$ to $0.2\mu V$
Wire-wound	$0.01\mu V$ to $0.2\mu V$

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

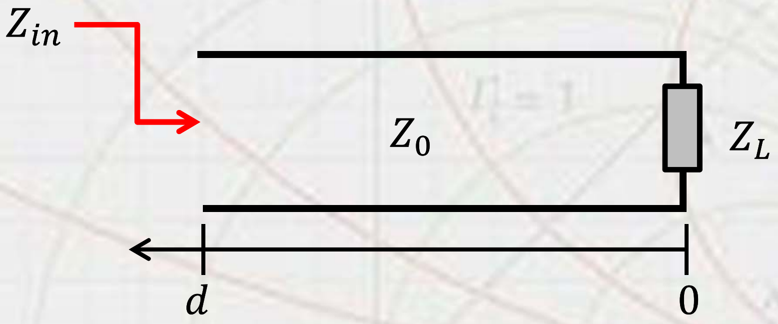
What is the excess noise of a carbon film resistor between 1 and 5 kHz ?

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

$$\Rightarrow \text{Excess noise between } (0.7)(0.05) = 0.035 \text{ and } (0.7)(0.3) = 0.21\ \mu V$$

Transmission Lines

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 β (wavenumber) is

$$\beta = \frac{\omega}{v_p}$$

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

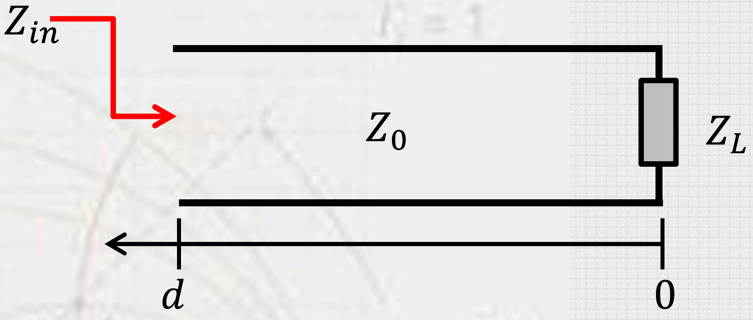
$$v_p = \frac{1}{\sqrt{LC}}$$

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.

Transmission Lines

Problem Consider a lossless transmission line with $L = 209.4$ H/m and $C = 119.5$ pF/m. Assume the line is terminated in a short circuit. Calculate the input impedance of the line at a distance $l = 100$ mm at 2.4 GHz.



Solution

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

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

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

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

$$Z_{in}(0.1) = j(48.86) \tan(7.54)$$ $$Z_{in}(0.1) = j(48.86) \tan(7.54) = -j150.5\ \Omega$$

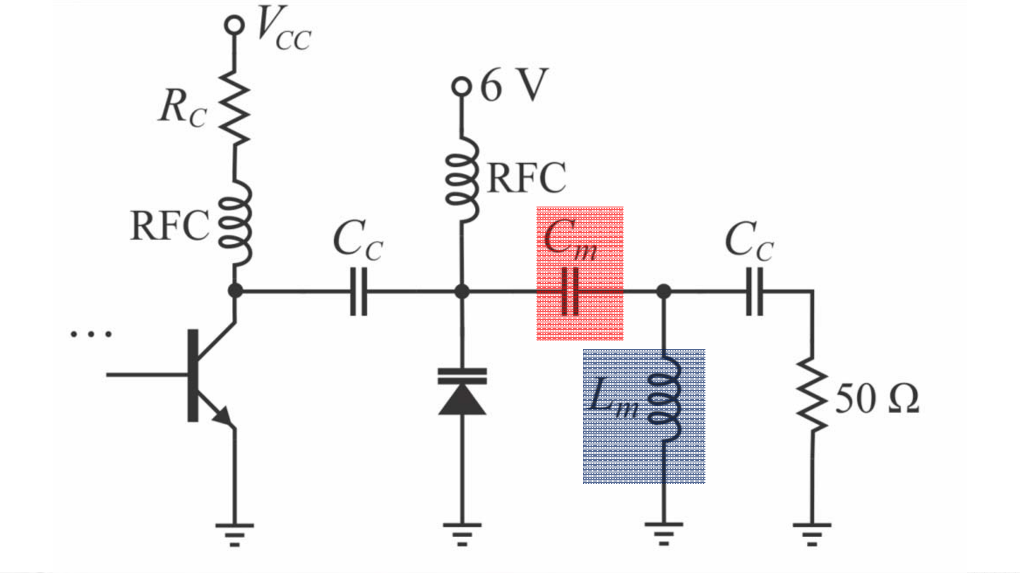
Microstrip Transmission Lines

Microwave amplifier that drives a 50 Ω 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.

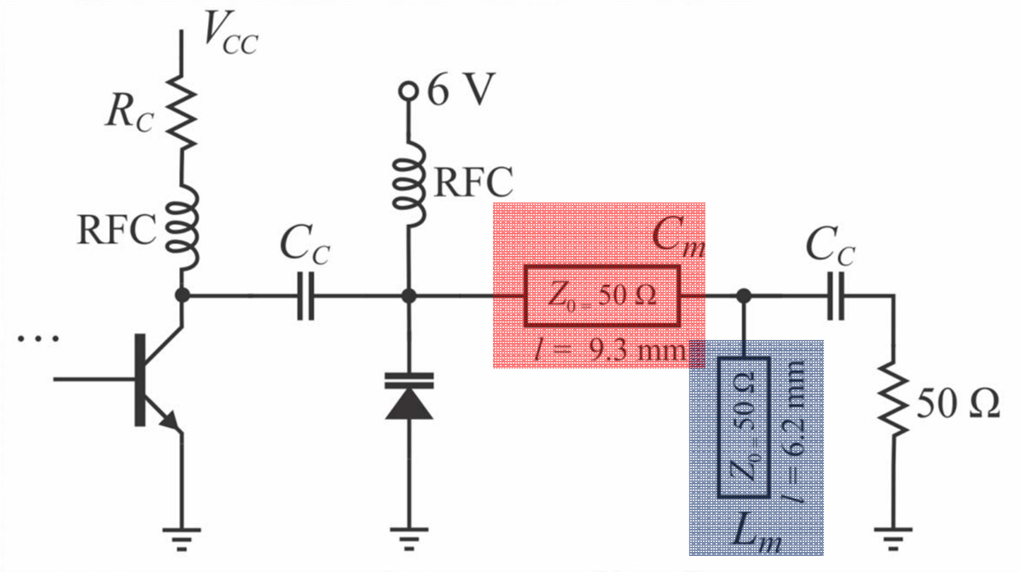
At the operating frequency, lumped C_m and L_m are not feasible.



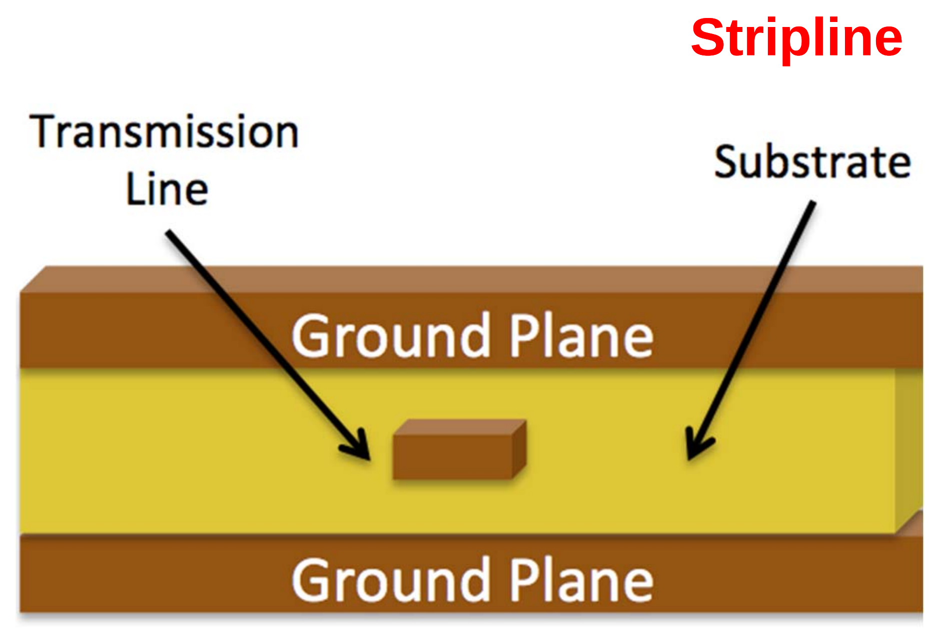
Implement C_m and L_m as microstrip transmission lines.

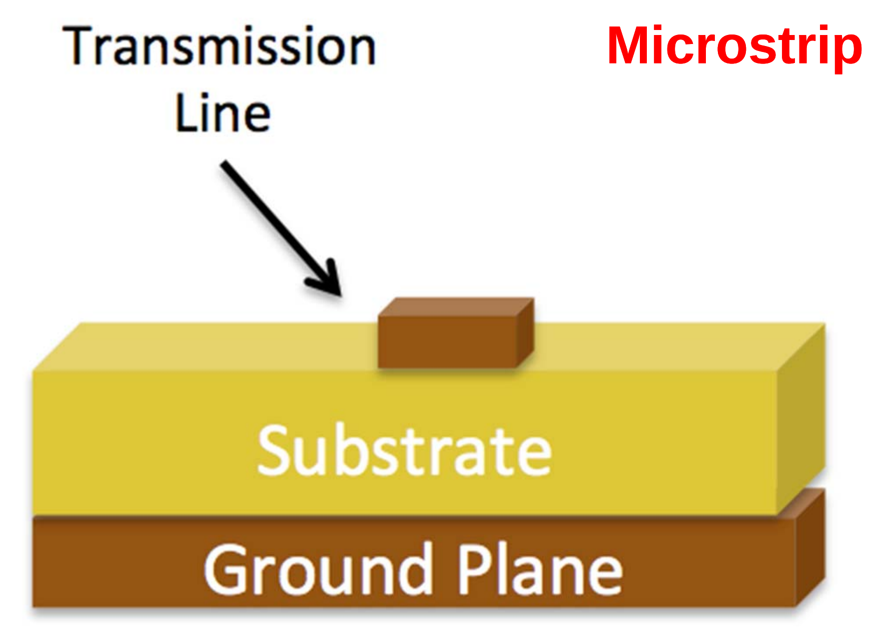
Line width and height, and substrate ε_r determine characteristic impedance, which is chosen to be 50 Ω.

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

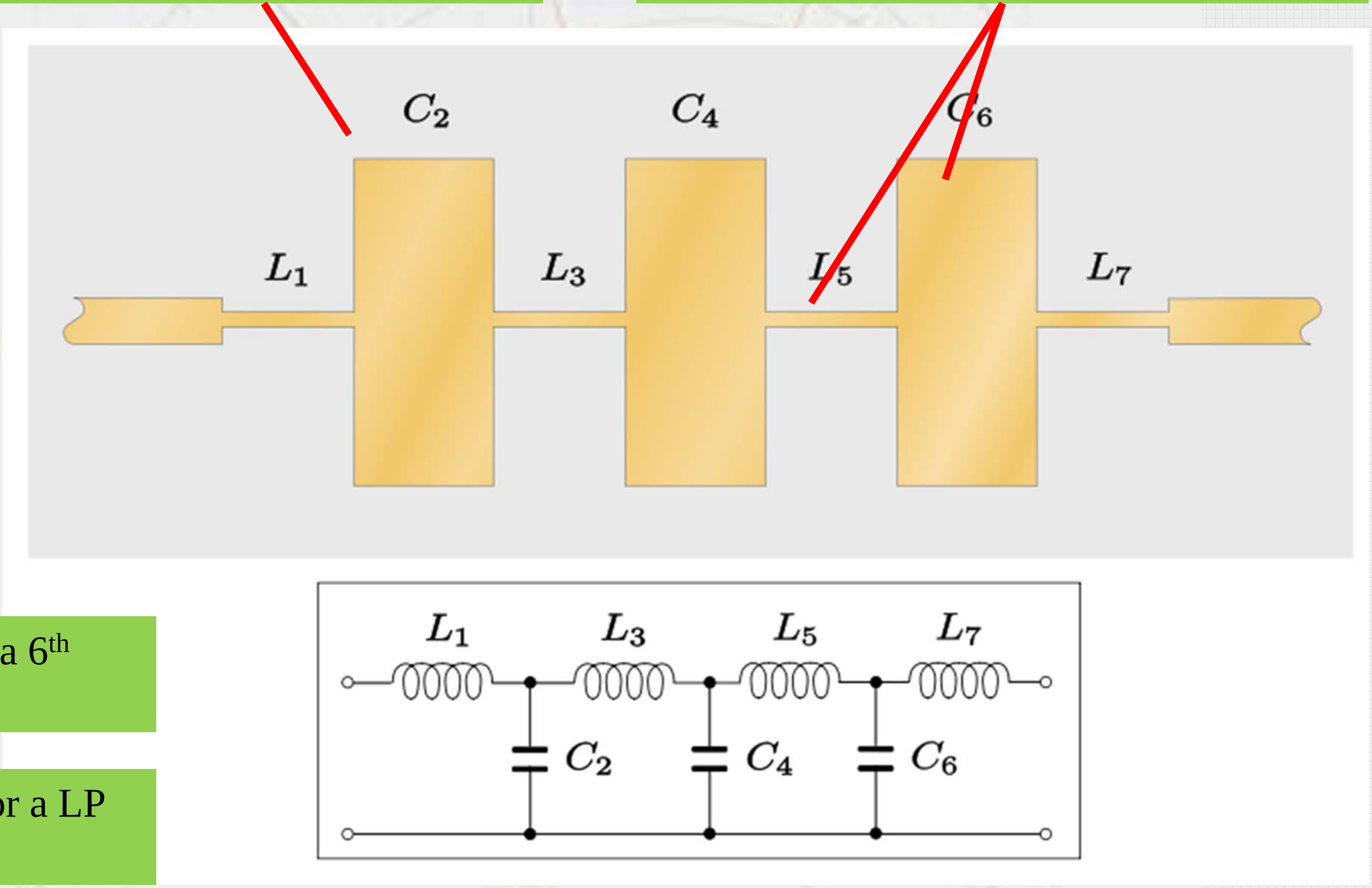
- Dielectric losses are less (when using identical materials)
- Cheaper and easier to manufacture
- Location of traces on top and bottom layers leads to easier debugging

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 aground plane.

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

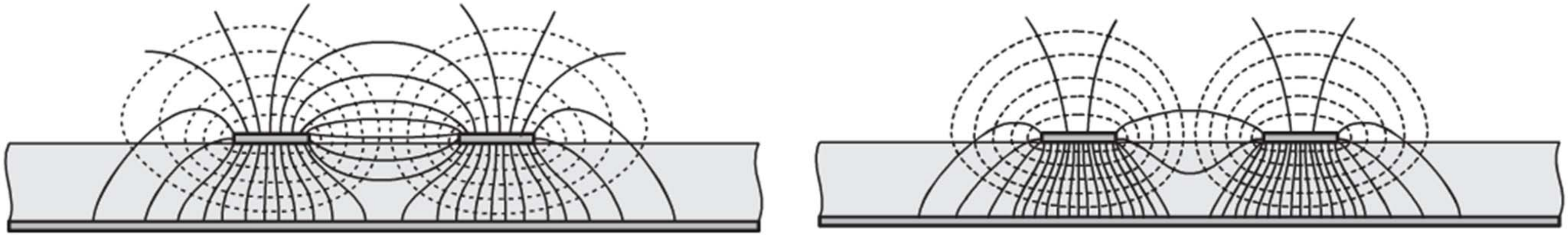


The result is a 6th order filter.

Is this a HP or a LP filter?

Microstrip and Stripline Transmission Lines

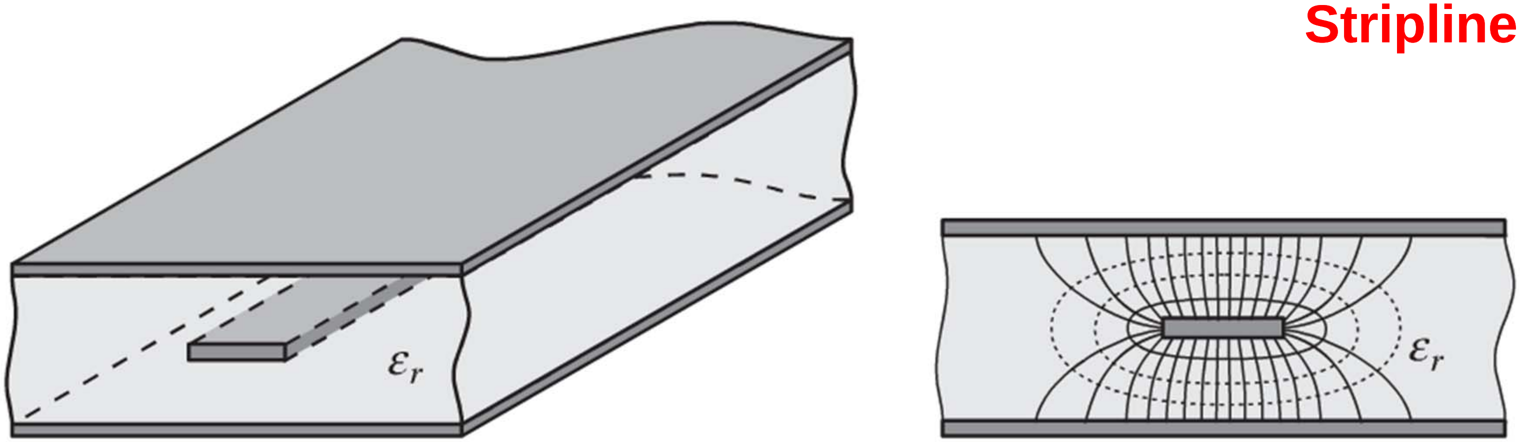
Microstrip



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

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

Stripline

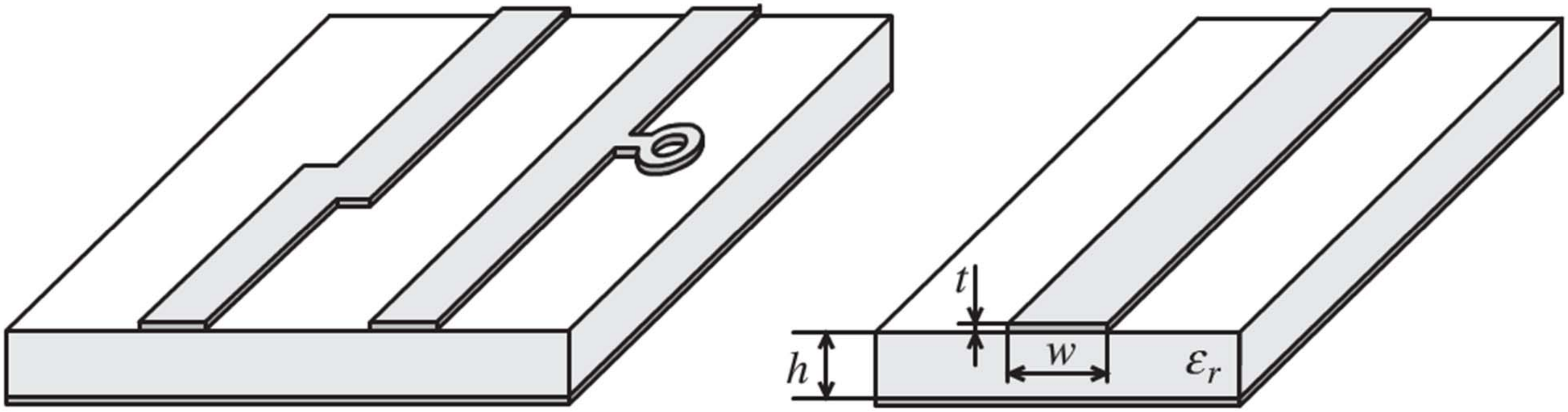


(a) Sandwich structure

(b) Cross-sectional field distribution

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

Microstrip Transmission Lines

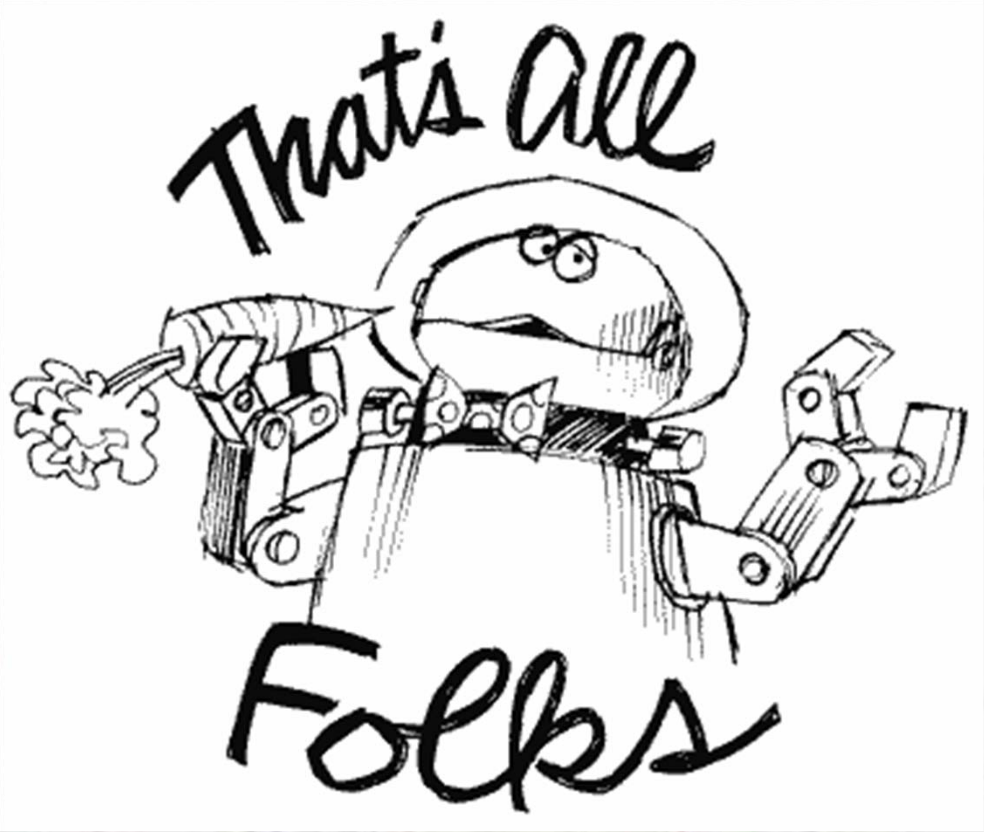


(a) Printed circuit board section

(b) Microstrip line

One can create PCB transmission lines with different characteristic impedance by manipulating the microstrip geometry.

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


That's All
Folks