Microwave Thin Film Resistors

By Benjamin Nicolle and Tony Qi

ABSTRACT

High frequency field is strongly anchored in the evolution of wireless technologies and shows a powerful way to exchange data faster and faster answering to a human need continuously more demanding. That concerns almost all the communication markets, as for instance: military, aerospace, automotive and obviously mobile 5G communication. Technologies of passive components must comply with the physical specificities linked to these frequencies. Resistors are not an exception. The "microwave" frequency range is given from 300 MHz to 300 GHz [1], but lumped resistors while entering into this range are more limited.

The aim of this application note is to present few basis about the microwave properties and to describe the behavior of the Sfernice CH / CHA resistors in the frequencies between 100 MHz and 70 GHz and the AEC-Q200 certification for harsh environments.

A FEW WORDS ABOUT HISTORY [2]

James Clerck MAXWELL (Scotland) was the founder of the microwave theory expressing his famous formulas in the 1860s. His "Treatise on electricity and magnetism" was published in 1873. Heinrich HERTZ (German Confederation) was the first to produce an electromagnetic wave about 1 GHz frequency in 1888. His work had a great impact on the development of the radio engineering. In the 1930s, Guglielmo MARCONI (Italy) demonstrated that it was possible to connect 2 points on the earth by electromagnetic waves in the air. It was the beginning of the radio communication. The following years, numerous other applications were found and developed in many applications: medicine, industrial heating, radio astronomy, particle accelerator, electronics, …

MICROWAVE FREQUENCY BANDS

It might be useful to remind the frequency ranges covered by the microwaves. According to the International Telecommunication Union [1], the microwave frequency range covers 3 bands: UHF, SHF and EHF.

SYMBOLS	F RANGE (1) (GHz)	SOME APPLICATIONS
UHF (Ultra High Frequency)	0.3 to 3	Television broadcast, microwave oven, radio astronomy, mobile phone, bluetooth, …
SHF (Super High Frequency)	3 to 30	Radio astronomy, communication, radars, cable and satellite television broadcasting…
EHF Extremely High Frequency)	30 to 300	Radio astronomy, microwave remote sensing, amateur radio, satellite radio

Note

(1) The lower limits are exclusive; the upper limits are inclusive

Between 1 GHz and 110 GHz, the Institute of Electrical and Electronics Engineers (IEEE) Association defines sub-bands as shown in the table below.

BANDS	F RANGE	WAVELENGTH
L	1 GHz to 2 GHz	30 cm to 15 cm
S	2 GHz to 4 GHz	15 cm to 7.5 cm
C	4 GHz to 8 GHz	7.5 cm to 3.75 cm
X	8 GHz to 12 GHz	3.75 cm to 2.5 cm
Ku	12 GHz to 18 GHz	2.5 cm to 1.67 cm
K	18 GHz to 26.5 GHz	1.67 cm to 1.13 cm
Ka	26.5 GHz to 40 GHz	1.13 cm to 0.75 cm
Q	33 GHz to 50 GHz	9 mm to 6 mm
V	50 GHz to 75 GHz	6 mm to 4 mm
W	75 GHz to 110 GHz	4 mm to 2.73 mm

BASIC KNOWLEDGE

In low frequencies, resistors behave like "pure" resistance values showing negligible parasitic inductance and capacitance values. These parasitic elements are inherent to resistors by construction but also generated by the interface resistor-circuit. They become more troublesome as the frequency increases deviating progressively the resistor soldered on the circuit from its initial "pure" resistance value to complex impedance. The drawback of this phenomenon is a possible impedance mismatching with the circuit.

Microwave Thin Film Resistors

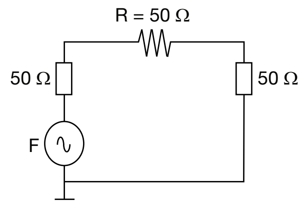


Fig. 1

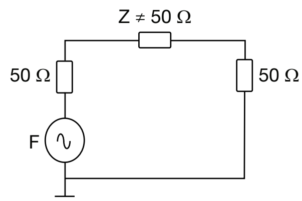
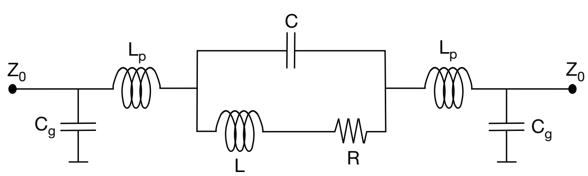


Fig. 2

Fig. 1 shows a 50 Ω resistor in low frequency matched to a 50 Ω surge impedance circuit whereas this same resistor become a complex impedance in high frequency (Fig. 2) leading to a mismatching.

For the thin film technology, the impedance Z of the resistor can be modeled according to the drawing hereunder. This model is valid at least for the frequencies between 0.1 GHz and 70 GHz.



Where:

- R is the nominal resistance value
- L is the inductance relevant to the resistor
- C is the capacitance relevant to the resistor
- L_p is the parasitic inductance due to the mounting of the resistor on the circuit
- C_g is the parasitic capacitance due to the mounting of the resistor on the circuit
- Z_0 is the characteristic impedance of the line

Since the impedance is a function of the frequency, the |Z|/R curve is especially convenient to show the evolution of a "real" resistor impedance vs frequency compared to a perfect 50 Ω resistor.

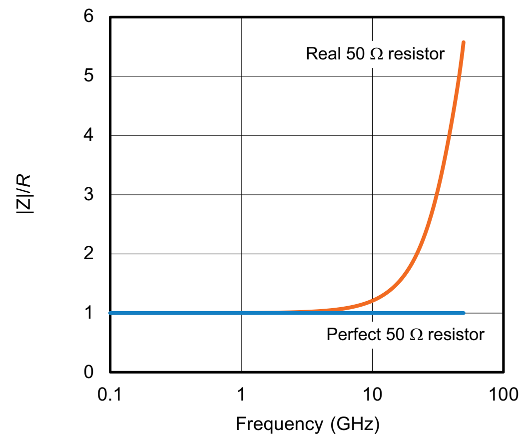
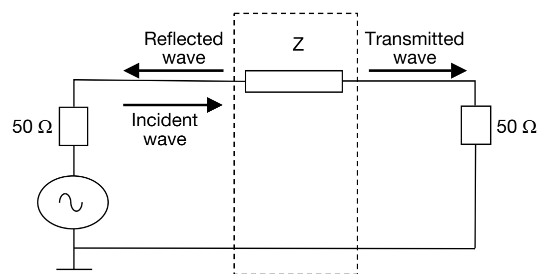
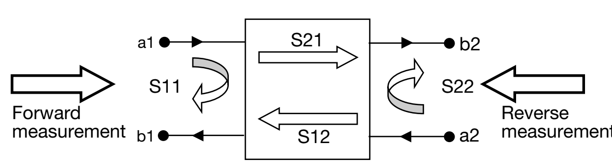


Fig. 3 - As the frequency increases, the impedance deviates from 50 Ω and shows the beginning of a resonant frequency

The impedance Z is certainly useful but not possible to measure directly. Indeed, as the signal wavelength can be very small compared to the length of the circuit, the voltage and current values are not constant along the line. This is why measuring the reflected and transmitted waves is a much better way to determine the impedance. In this approach, the scattering parameters (S parameters) are used. They describe how the "device under test" (DUT) modifies a signal in both forward and reverse direction.



A wave is sent to the impedance Z through a 50Ω surge impedance line the reflected and the transmitted waves are then measured. This above diagram is equivalent to the following "4-poles" system (four S parameters).



- S11 is the reflection at the forward measurement
- S21 is the transmission at the forward measurement
- S12 is the transmission at the reverse measurement
- S22 is the reflection at the reverse measurement

Microwave Thin Film Resistors

a1, b1, a2, and b2 are waves defined as being the square root of the power.

- $|a1|^2$ represents the incident power at the forward measurement
- $|b1|^2$ represents the reflected power at the forward measurement
- $|b2|^2$ represents the reflected power at the reverse measurement
- $|a2|^2$ represents the incident power at the reverse measurement

The scattering matrix links the incident waves a1, a2, and the outgoing waves b1, b2 by the linear equation:

$$\begin{bmatrix} b1 \\ b2 \end{bmatrix} = \begin{bmatrix} S11 & S12 \\ S21 & S22 \end{bmatrix} \begin{bmatrix} a1 \\ a2 \end{bmatrix}$$

Therefore, the S parameters can be determinate as the following:

- S11 = b1/a1 with a2 = 0
- S21 = b2/a1 with a2 = 0
- S12 = b1/a2 with a1 = 0
- S22 = b2/a2 with a1 = 0

S parameters are vector values. So their magnitude can be calculated in the same manner than all vector values.

Example:

$$|S11| = \sqrt{Re(S11)^2 + Im(S11)^2}$$

Generally, the S parameters are expressed in decibel (dB). Since they are ratio between 2 voltages, the formula to apply is:

$$|S11|_{dB} = 20 \times \log(|S11|)$$

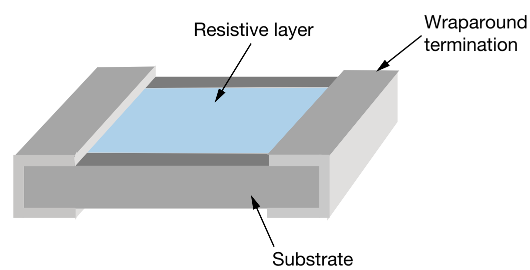
The four scattering parameters give everything of the behavior of the DUT, they are enough to fully characterize a system. Based on them, calculations are needed to go further and for instance to find the constitutive elements of the DUT. So example, the magnitude of the impedance Z can be easily determined by this simple relationship:

$$|Z| = \frac{2 \times Z_0 \times |S11|}{1 - |S11|}$$

TECHNICAL SOLUTION

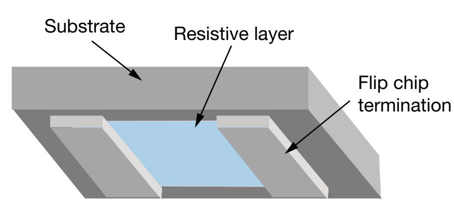
The thin film technology applied to resistors is appropriated to reduce the parasitic inductance and capacitance. Basically, the resistor is made by a substrate on which a thin metallic resistive layer is vacuum deposited and etched by photolithography.

Vishay Sfernice proposes the CH / CHA microwave family where the resistive layer material is Nichrome on a pure alumina substrate (99.5%). The termination materials are either SnAg or gold over nickel barrier.



Wraparound design

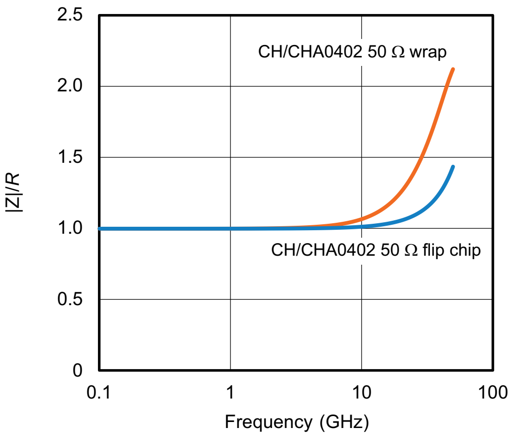
The advantage of this above wraparound resistor is the soldering on a circuit which is classically the one used for the other SMD's. The resistive layer is a straight and large path which has for effect to ease the passage of the signal and consequently to reduce the parasitic elements. Even if this design demonstrates honorable performances in many cases, it is not the best one. Indeed, the signal has to cross all the resistor length which can be modeled as a parasitic inductance: the less the current path length is, the less the parasitic inductance is. It is possible to reduce this current path length (inductance) either by reducing the size of the component or by drawing the terminations closer each other for such a frozen size. This is what the following design shows.



Flip chip design

With this flip chip design, the resistive layer is facing the circuit, whereas it is not the case for the wraparound design. So there is also here a gain in the reduction of the signal path length. The influence of this flip chip design is visible on the S parameters curves as well as on the |Z|/R curve. Its impedance is more stable along the frequency axis.

Microwave Thin Film Resistors

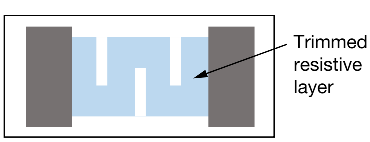


Comparison of flip chip and wraparound designs

The above curves give the evolution of |Z| for 0402 size CH / CHA resistors in flip chip and wraparound designs. After 10 GHz, the performances become significantly different, the flip chip design being less impacted by parasitic elements.

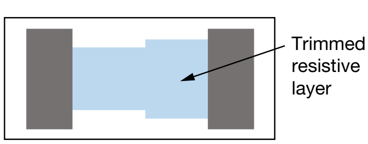
High Frequency Trimming

Adjusting the resistance value of the thin film resistors requires a trimming adapted to the microwaves. Here again the goal is to reduce as much as possible the parasitic elements. Several cuts exist, hereunder 2 of them are shown.



Serpentine Cut - flip chip design

The "Serpentine Cut" design allows to adjust a large range of resistance values but does not give the best result in terms of performances.



Edge Cut - flip chip design

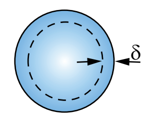
The "Edge Cut" design represents the best solution for high frequency performances. It is taken for HF Thin Film resistors.

PHYSICAL CONSIDERATIONS

Lateral Skin Effect

The skin effect is a tendency for alternating current to be distributed at the edge of a conductor in such a way that the current density decreases from the edge ("skin") to the center of the conductor. As a result, the resistance value grows, influenced by the restricted surface of the current distribution. The skin depth, δ, is defined as the depth where the current density is just 1/e (about 37 %) of the value at the surface. It depends on the frequency of the current, and the electrical and magnetic properties of the conductor. As a reminder, in a wire of circular cross-section, an approximation of the skin effect relationship is:

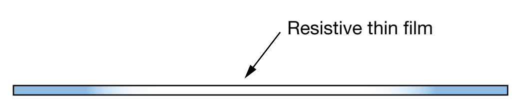
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{1}{\sqrt{\sigma\mu\pi f}}$$



Where:

- δ is the skin thickness in meters [m]
- ω is the angular frequency (2 µf) [rad/s]
- f is the frequency in Hertz [Hz]
- $\mu = \mu_r \mu_o$ [H/m]
- μ_r is the relative magnetic permeability of the conductor [H/m]
- μ_o is the absolute magnetic permeability of free space [H/m]
- σ is the conductivity of the conductor [S/m]

However, in a flat conductor as it is case in the thin film technology, this phenomenon is much complex [3]. The thin film is about some nanometers, so the skin effect is not significant in the thickness axis even at 70 GHz. This is not true for the width where the current distribution looks like here-after.



A non-linear current distribution in the layer,
current more concentrated in the lateral sides (dark areas)

AEC-Q200 CERTIFICATION

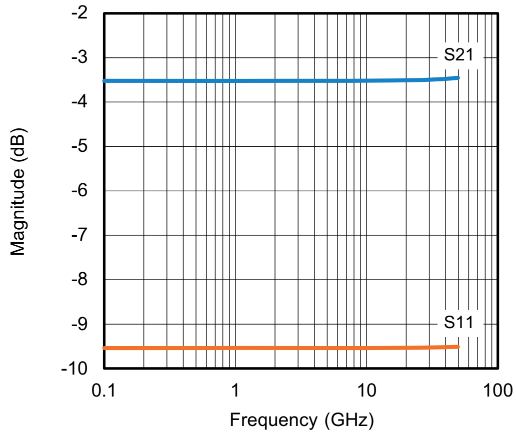
Automotive applications require electronic components that must operate reliably even when the environment is harsh. The Automotive Electronics Council (AEC) established the AEC-Q200 standards for passive components. The CHA 02016/0402 are qualified to these standards and demonstrates exceptional performance.

For more details, please consult our CH / CHA series datasheets.

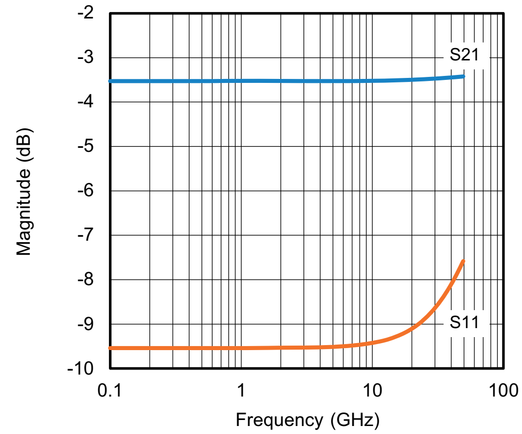
Microwave Thin Film Resistors

EXAMPLES OF CH/CHA PERFORMANCE CURVES

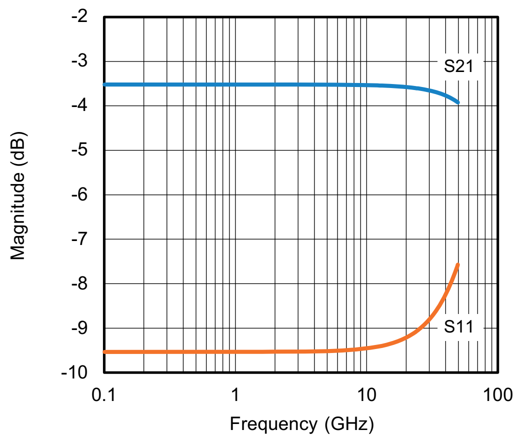
S parameters



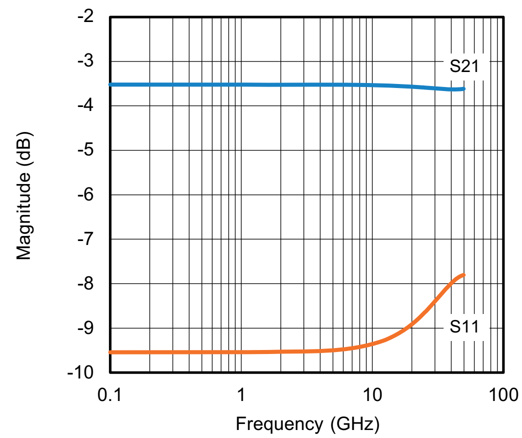
CH/CHA02016 flip chip (Z_0 = R = 50 Ω)



CH/CHA02016 flip chip (Z_0 = R = 100 Ω)



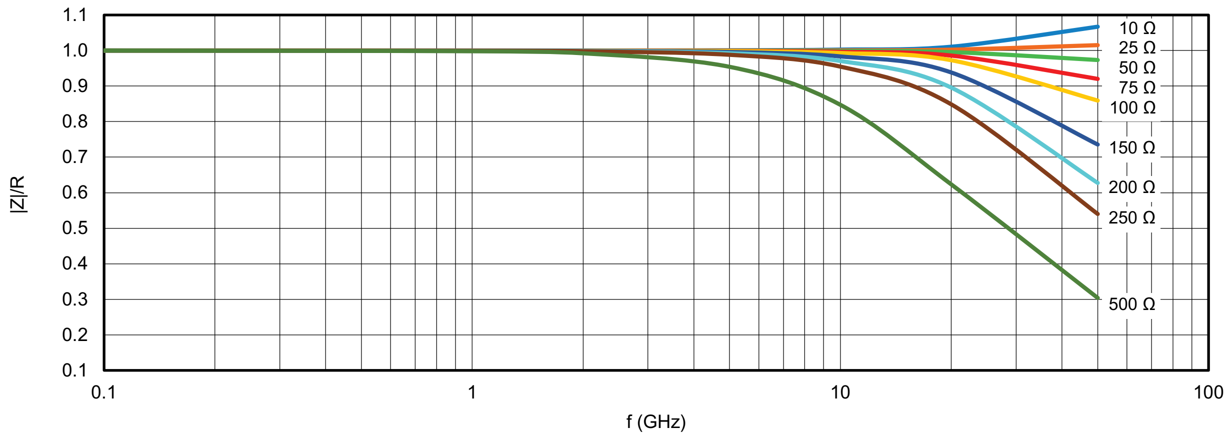
CH/CHA0402 flip chip (Z_0 = R = 50 Ω)



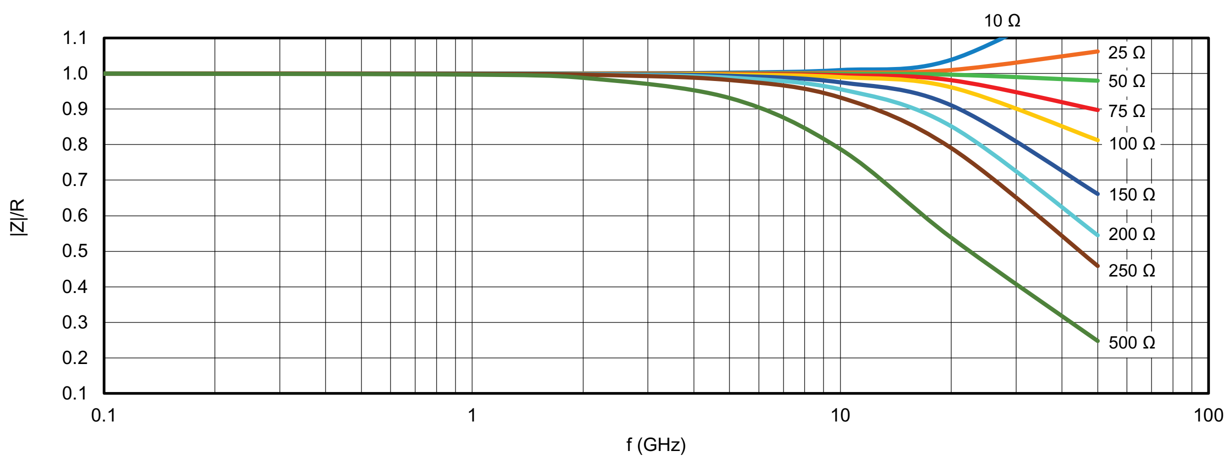
CH/CHA0402 flip chip (Z_0 = R = 100 Ω)

Microwave Thin Film Resistors

INTERNAL IMPEDANCE CURVES



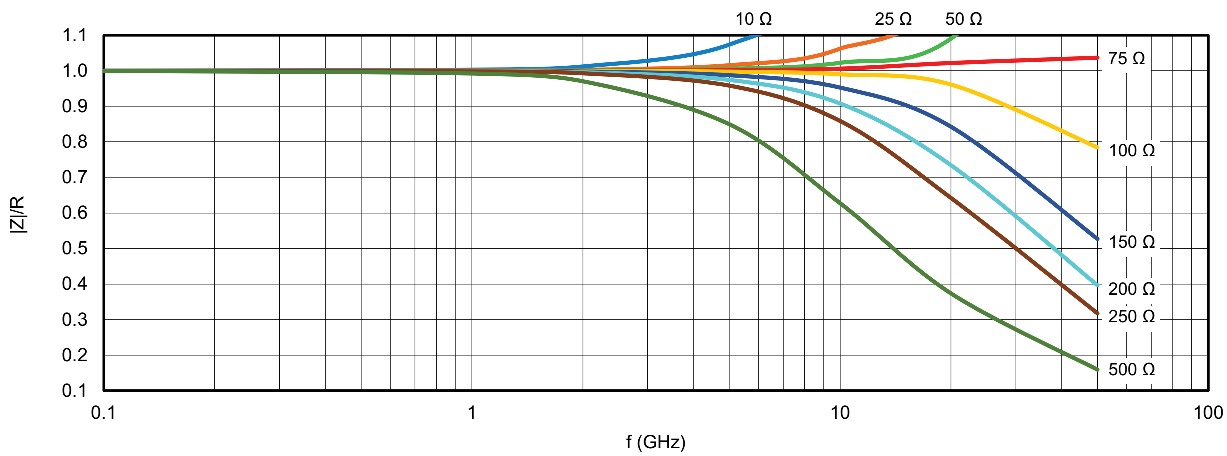
Internal impedance curve for 02016 size (F and P terminations)



Internal impedance curve for 0402 size (F termination)

For technical questions, contact: sferthinfilm@vishay.com

Microwave Thin Film Resistors



Internal impedance curve for 0402 size (N termination)

REFERENCES

[1] International Telecommunication Union Radiocommunication Sector (ITU-R) – Recommendation ITU-R V.431-8 (08/2015)

[2] "Micro-ondes" Paul F Combes Dunod (1996).

[3] Keller B. Reto, (2023), Design for Electromagnetic Compatibility In a Nutshell, Theory & Practice, Springer Ed., August 2022