Microwave Thin Film Resistors - CH Series

By Didier Darrouzes and Aimen Oueslati

ABSTRACT

High frequency circuits are strongly anchored in the evolution of wireless technologies, offering a powerful way to send and receive data faster. The need for speed concerns communications in almost all markets - military, aerospace, automotive, and, obviously, mobile 5G. Passive components must comply with the physical specificities linked to these frequencies, and resistors are no exception. The "microwave" frequency range is 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 a few basics on microwave properties and to describe the behavior of Vishay Sfernice CH resistors in the frequencies between 100 MHz and 50 GHz.

A BRIEF HISTORY (2)

James Clerk Maxwell (born in Edinburgh, 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. In 1888, Heinrich Hertz (born in Hamburg, Germany) was the first to produce an electromagnetic wave at about the 1 GHz frequency. His work had a great impact on the development of radio engineering. In the 1930s, Guglielmo Marconi (born in Bologna, Italy) demonstrated that it was possible to connect two points on the earth by electromagnetic waves in the air, marking the beginning of radio communication. In following years, numerous other discoveries were made and contributed to applications in medicine, industrial heating, radio astronomy, particle accelerators, electronics, and more.

MICROWAVE FREQUENCY BANDS

According to the International Telecommunication Union (1), the microwave frequency range covers three bands: UHF, SHF, and EHF.

SYMBOLS	F RANGE (3) (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, radar, cable and satellite television broadcasting
EHF (Extremely High Frequency)	30 to 300	Radio astronomy, microwave remote sensing, amateur radio, satellite radio

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

Notes

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

(2) 'Micro-ondes' Paul F Combes Dunod (1996)

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

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

BASIC KNOWLEDGE

In order to illustrate the microwave effect we can take the simple usage of a resistor load (R = 50 Ω) connected to a signal generator (R_g = 50 Ω) through a transmission line (RF cable, connectors and PCB line) of length = l.

In low frequencies $\lambda >> l$ (Fig. 1a) there is no propagation delay due to the wavelength and the voltage potential is the same along the transmission line, there is also no signal reflection from the load to the generator since $Z_g = R = 50\ \Omega$ and the maximum power is transmitted to the load $P_{max.} = (V_g / 2)^2 / R$.

Resistor load exhibits "pure" resistance behavior, showing negligible parasitic inductance and capacitance values.

In very high frequencies $\lambda << l$ (Fig. 1b) additional phenomena appear. All the parasitic elements which are either due to the resistors by construction or generated by the resistor to PCB line interface change the load resistor value from its initial "pure" resistance to a complex load impedance $Z \neq 50\ \Omega$.

The drawback of this phenomenon is impedance mismatch and therefore:

- Less power transmitted to the load
- Reflection effect with coefficient factor $\Gamma = (Z - Z_c) / (Z + Z_c)$ where Z_c is the characteristic impedance of the transmission line
- Propagation delay is involved and the voltage potential is different in two points of the transmission line $V(0) \neq V(l)$

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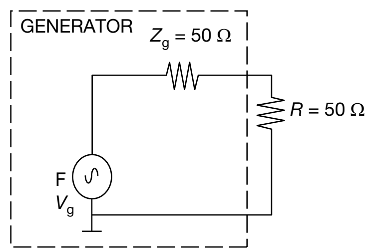

Fig. 1a

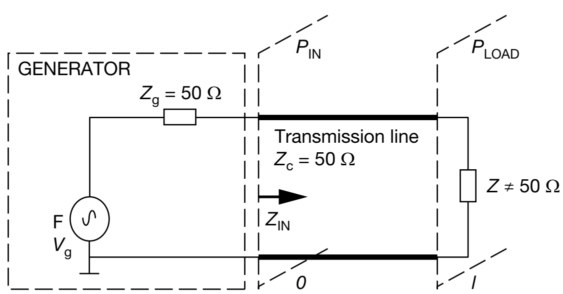

Fig. 1b

(Fig. 1a) 50 Ω resistor load in low frequency is matched to a 50 Ω resistor of the generator. This same resistor becomes a complex impedance in high frequency (Fig. 1b), leading to a mismatch.

PARASITIC EFFECT

For thin film technology, the impedance *Z* of the SMD resistor mounted on PCB can be modelled according to the drawing below. This model is valid from DC to 50 GHz frequency.

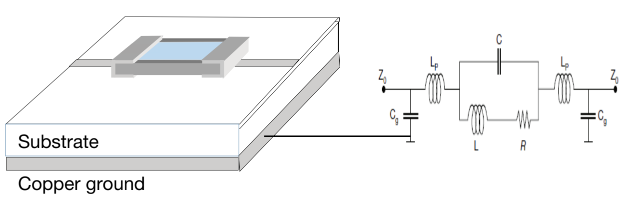

Fig. 2

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 for showing the evolution of a "real" resistor impedance vs. frequency compared to a perfect 50 Ω resistor

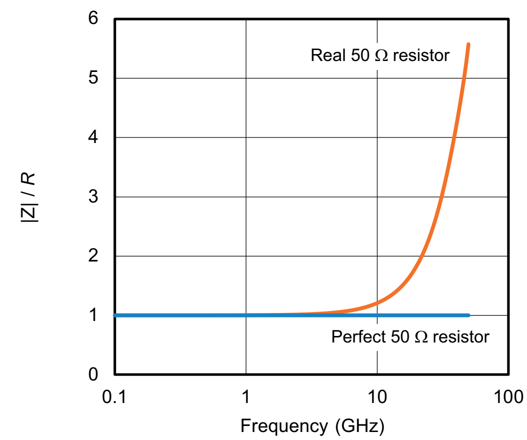

Fig. 3 - As the frequency increases, the impedance deviates from 50 Ω

TEST AND MEASUREMENT

The impedance *Z* is certainly useful, but it can't be measured directly, as all parasitic effects of the generator, connector and PCB line mismatch should be taken into account. This is why measuring the reflected and transmitted waves is a much better method for determining the impedance. In this approach, the scattering parameters (S parameters) are used. After a proper calibration we can extract the S parameters of the Device Under Test (DUT) and understand how it can modify a signal in both forward and reverse directions.

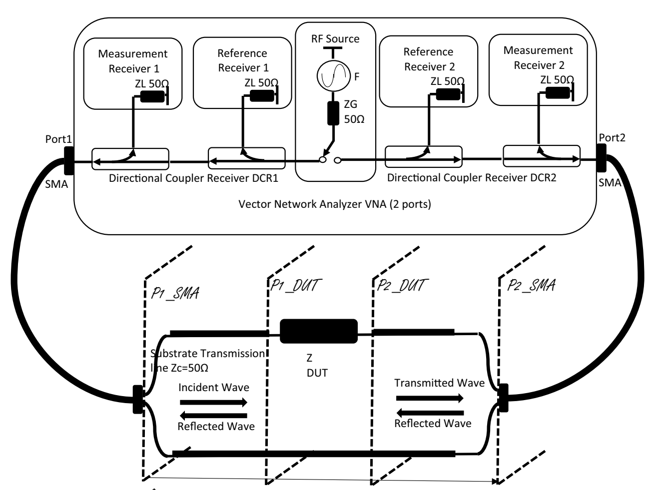

Fig. 4a - Test setup for S parameter measurement with 2 port VNA. Port1 is connected to the RF source.

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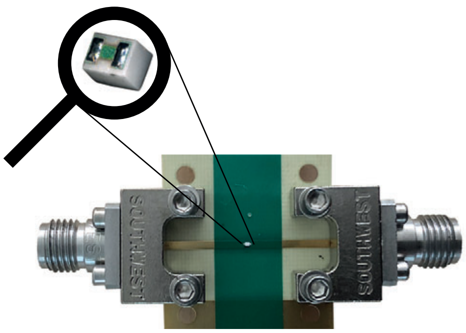
Fig. 4b - Test measurement PCB with SMD resistor and SMA connectors mounted

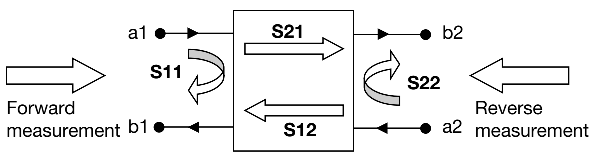

Fig. 5

- 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

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

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 determined as follows:

- 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 complex values, so their magnitude can be calculated in the same manner as all complex values.

Ex:

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

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

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

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

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

TECHNICAL SOLUTION

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

The Vishay Sfernice CH microwave family features a nichrome resistive layer on a pure alumina substrate (99.5 %). The termination materials are either SnAg or gold over nickel barrier.

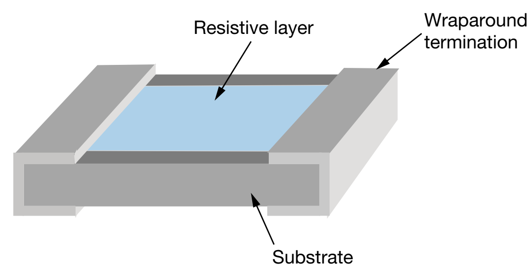

Fig. 6 - Wraparound design

The advantage of this wraparound resistor above is that it is soldered on a circuit in the same way as other SMDs. The resistive layer is a straight and large path, which has the effect of easing the signal passage and thus reducing the parasitic elements. Even if this design demonstrates high performances in many cases, it is not the best one. The signal has to cross the entire resistor length, which can be considered as a parasitic inductance. The shorter the current path, the less the parasitic inductance. It is possible to reduce this current path length either by reducing the size of the component or by drawing the terminations closer to each other, as shown below.

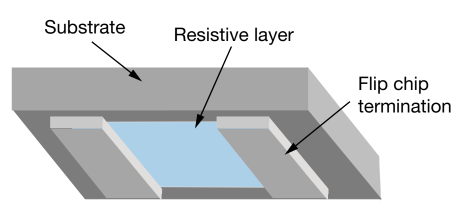

Fig. 7 - Flip chip design

With this flip chip design, the resistive layer is facing the circuit, which is not the case for the wraparound design. This reduces the signal path length, the effects of which are visible on the S parameters curves as well as on the |Z|/R curve. Its impedance is more stable along the frequency axis.

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For example at 50 GHz, on a substrate with $\varepsilon_r = 3.6$, we have a typical wavelength of $\lambda = 3$ mm.

With a CH flip-chip 02016 size we can achieve a resistor line length of l = 300 μm which is $\leq \lambda / 10$. So there is no issue to use a lumped element.

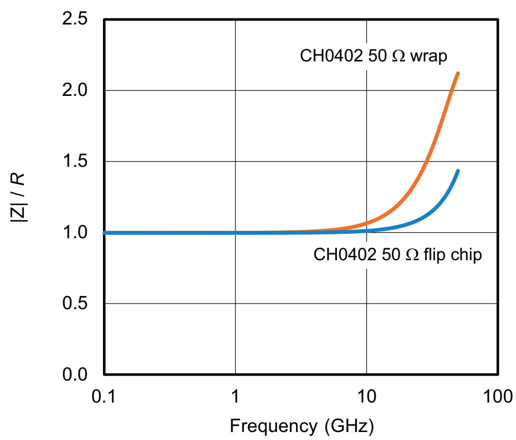


Fig. 8 - Comparison of flip chip and wraparound designs

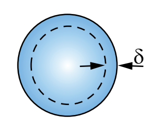
The above curves give the |Z|/*R* for CH resistors in the 0402 case size with flip chip and wraparound designs. After 10 GHz, the performances become significantly different, with the flip chip design showing less impact from parasitic elements.

PHYSICAL CONSIDERATIONS

Lateral Skin Effect

The skin effect refers to the 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. Up to 90 % of the current is flowing into this skin depth between the surface of the conductor and δ. It depends on the frequency of the current and the electrical and magnetic properties of the conductor. As a reminder, in a wire circular cross-section, an approximation of the skin effect relationship is:

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



Where:

- δ is the skin thickness in meters [m]
- ω is the angular frequency (2 μ*f*) [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
- 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 is the case with thin film technology, this phenomenon is more complex [(1)]. The thin film is measured in nanometers, so the skin effect is not significant at the thickness axis, even at 50 GHz. This is not true for the width, where the current distribution looks like as shown below.

Note

[(1)] The lateral skin effect in a flat conductor-V. Belevitch Philips tech. Rev 32, 221-231 1971

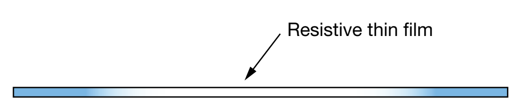


Fig. 9 - A non-linear current distribution in the layer. Current is more concentrated in the lateral sides (dark areas)

For example with CH series NiCr thin film we have a skin effect σ = 0.36 μm at 50 GHz.

The CH series thickness is 0.1 μm so it will not be impacted by the skin effect.

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TYPICAL CH PERFORMANCE CURVES

S parameters

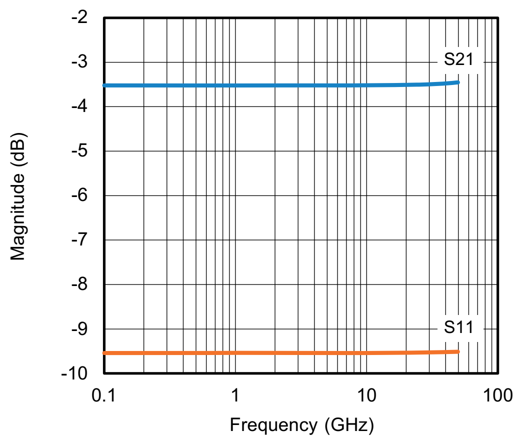

Fig. 10 - CH02016 flip chip ($Z_0 = Z_g = R = 50\ \Omega$)

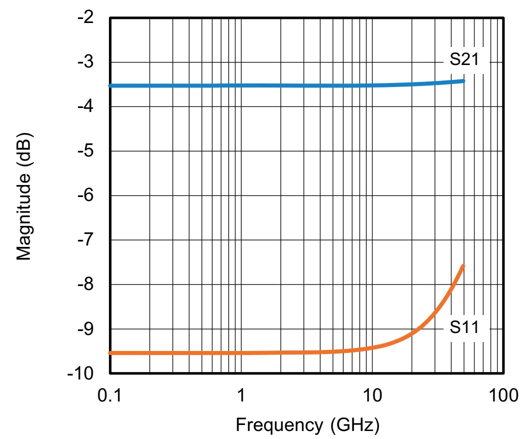

Fig. 11 - CH02016 flip chip ($Z_0 = Z_g = R = 100\ \Omega$)

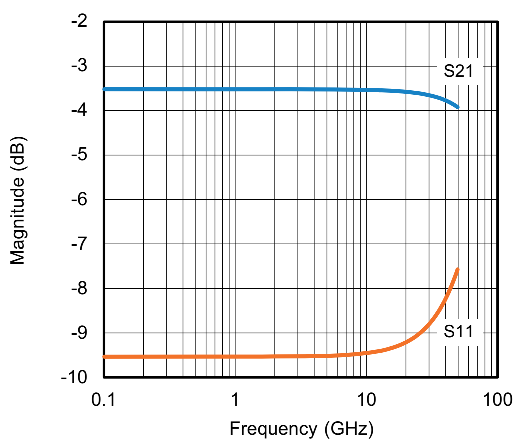

Fig. 12 - CH0402 flip chip ($Z_0 = Z_g = R = 50\ \Omega$)

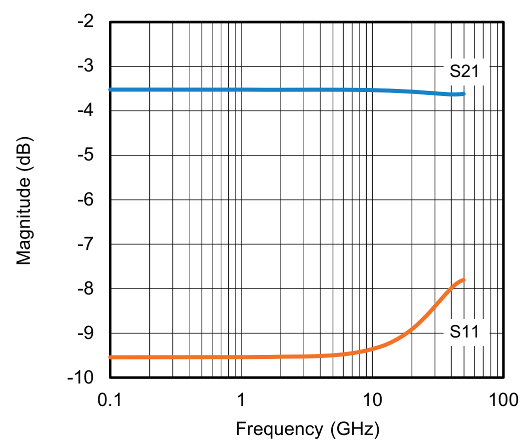

Fig. 13 - CH0402 flip chip ($Z_0 = Z_g = R = 100\ \Omega$)

For more details, please consult our CH series datasheet: www.vishay.com/doc?53014