RF and Microwave Power Measurement

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• RF power
• RF power traceability
• Diode sensor
• Skin effect
• Connectors
Electrical power is defined as quantity of dissipated energy per unit of time.

The SI (International System of Units) unit of power is the Watt.

In the case of resistive (Ohmic, or linear) load, power that is dissipated at a load can be defined as a product of voltage on the load and current passing through a circuit.

\[ P = VI \]
RF Power

\[ P = \frac{1}{nT} \int_0^{nT} v(t) i(t) dt = \frac{1}{nT} \int_0^{nT} v_p \sin\left(\frac{2\pi}{T} t\right) i_p \sin\left(\frac{2\pi}{T} t + \phi\right) dt \]
Microwave power is measured by sensors.

**Power Sensor Types:**

- Bolometer
  - Barretter
  - Thermistor
- Thermocouple
- Diode

**Properties of Power Sensors:**

- Sensitivity
- Frequency range
- Power range
Microwave power traceability is obtained over power sensors.

http://www.powerbackup.co.za/about-us/
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Microwave power traceability is obtained from effective efficiency measurement of the standard sensor using the microcalorimeter system.
RF Power traceability

Bolometer type sensors

Temperature coefficient of 
barreter

Temperature coefficient of 
thermistor

DC or AF 
source

200Ω

200Ω

Bolometer

EMPIR 15RPT01 workshop, 7. 11. 2016, METAS
Thermistor is a temperature sensitive resistor.

Before the microwave power measurement, thermistor sensor is connected to Wheatstone bridge then DC power applied on it.

\[ P_{DC1} \text{ is related to } V_1 \text{ and } R_1 \]
When the microwave power is applied to thermistor sensor,

\[ \eta = \frac{P_{\text{SUB}}}{P_{\text{RF}}} \]

\( P_{\text{DC2}} \) is related to \( V_2 \) and \( R_1 \)
RF Power traceability

\[ \eta_R = \frac{1}{1 + \frac{V_1^2}{V_1^2 - V_2^2} \frac{e_2 - e_1 L_T}{e_1 L_T}} \]

- \( V_1 \): Wheatstone voltage (V), RF off
- \( V_2 \): Wheatstone voltage (V), RF on
- \( e_1 \): Thermopile output voltage (V), RF off
- \( e_2 \): Thermopile output voltage (V), RF on
- \( L_T \): Thermopile linearity
RF Power traceability

\[ e_1, e_2, L_T \]

\[ A_{dB} \]

\[ \eta = \eta_R (1 + 0.115 A_{dB}) \]

A\textsubscript{dB}: Thin line attenuation (dB)
ρ: Reflection coefficient of the thermistor sensor

\[ CF = \eta \left(1 - \rho^2\right) \]
Type: Twin
Power Range: 1 mW to 10 mW
Connector: Precision N Type
Sensor Type: Thermistor
Operating freq.: 100 kHz to 18 GHz
RF Power traceability

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Characteristic of diode

\[ I = I_0 \left( e^{\frac{V}{V_0}} - 1 \right) \]
Diode sensor

\[ I = I_0 \left( e^{\frac{V}{V_0}} - 1 \right) = I_0 \left[ \frac{V_m}{V_0} \cos \omega t + \frac{1}{2} \left( \frac{V_m}{V_0} \right)^2 \cos^2 \omega t + \frac{1}{8} \left( \frac{V_m}{V_0} \right)^3 \cos^3 \omega t + \ldots \right] \]

In this equation:
- \( I \): Diode current
- \( I_0 \): Leakage current
- \( V_0 \): Thermal voltage

\[ V_0 = \frac{k.T}{e} = \text{Constant} \]

- \( k \): Boltzmann constant
- \( T \): Temperature (K)
- \( e \): Electron charge

example: R&S NRV-Z4 power sensor
Diode sensor

\[ I = 0.25I_0 \left( \frac{V_m}{V_0} \right)^2 + I_0 \left( \frac{V_m}{V_0} \right) \cos \omega t + 0.25I_0 \left( \frac{V_m}{V_0} \right)^2 \cos 2\omega t + \ldots . \]

\[ I = I_{\text{DC}} + I_{\text{AC}} \]

DC current:

\[ I_{\text{DC}} = \left( \frac{0.25I_0}{V_0^2} \right)V_m^2 \]

diode sensor – rather a voltage detector than a power detector

very sensitive to impedance mismatch
The DC component of current is proportional with the square of the applied voltage magnitude

\[ I_{DC} \propto V_m^2 \]

Since microwave power, \( P_m \), is proportional with the square of voltage, it is also proportional with the DC current.

\[ P_m \propto V_m^2 \quad \text{and} \quad I_{DC} \propto V_m^2 \quad \Rightarrow \quad P_m \propto I_{DC} \]
Characteristic output of diode sensor
Diode sensor

The generated voltage is rectified by the diode and while the AC component flows to ground, the DC component is resulted on ampermeter.
typical power measurement method: the power is measured through amplified low-frequency AC or DC voltage

source: [http://www.keysight.com/find/backtobasics](http://www.keysight.com/find/backtobasics)
Diode sensor

Measurement errors due to harmonics

- dependent on the crest factor (peak / average ratio), major errors can occur outside the square-law region
- improvement by use a full-wave rectifier instead of a half-way rectifier (elimination of even harmonics, i.e. 2\textsuperscript{nd}, 4\textsuperscript{th}, ...)
- phase between the harmonics is important

Waveform distortion due to the 2\textsuperscript{nd} order harmonic

Voltage and Power Measurements, R&S application note, 1999
Diode sensor

measurement errors due to harmonics

Voltage and Power Measurements, R&S application note, 1999

2\textsuperscript{nd} harmonic

3\textsuperscript{rd} harmonic
Diode sensor

increase of dynamic range
(90 dB, three different power paths)

e.g. R&S NRP-Z23 three-path diode power sensors

automatic path switching in power transition regions
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Skin effect

Effect of skin depth

\[ \delta = \frac{1}{\sqrt{\pi \cdot \sigma \cdot \mu \cdot f}} \]

\( \sigma \): Conductivity of the metal

\( \mu \): Permeability of the metal

\( f \): Frequency
Skin effect

\[ \delta = \frac{1}{\sqrt{\pi \cdot \sigma \cdot \mu \cdot f}} \]

- \( \sigma \): Conductivity of the metal
- \( \mu \): Permeability of the metal
- \( f \): Frequency
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Transmission lines and connectors according to the frequency range

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Transmission Line</th>
<th>Connector Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-2 (?) GHz</td>
<td>Coaxial, Microstrip lines</td>
<td>BNC</td>
</tr>
<tr>
<td>DC-18GHz</td>
<td>Coaxial, Waveguide, Microstrip lines</td>
<td>7 mm, Type N</td>
</tr>
<tr>
<td>DC-26.5 GHz</td>
<td>Coaxial, Waveguide, Microstrip lines</td>
<td>SMA, 3.5 mm</td>
</tr>
<tr>
<td>DC-40 GHz</td>
<td>Coaxial, Waveguide, Microstrip lines</td>
<td>2.92 mm</td>
</tr>
<tr>
<td>DC-50 GHz</td>
<td>Coaxial, Waveguide, Microstrip lines</td>
<td>2.4 mm</td>
</tr>
</tbody>
</table>
Connectors
Connectors

• Coaxial transmission lines, consist of the nested two conductors.

• In order to keep constant the distance between conductors, an insulating material is used with certain intervals or continuously.

• The inner conductor is usually a single wire, the outer conductor is woven.

• Coaxial transmission lines, carry the signal as the electromagnetic wave. There is no radiation loss at the coaxial lines.

• But there are copper losses in both coaxial and two wire lines. The copper losses are related to the square of the current which is flowing in the conductor and the resistance of the conductor( $I^2 R$ ) and are expressed in Watt unit.

• Even if the conductor is produced with any metal different from copper, the loss is called copper loss.
2. IEEE 287 standard.
3. Guidance on Selecting and Handling Coaxial RF Connectors used with Rohde & Schwarz Test Equipment, Rohde & Schwarz, 2012
EMPIR project “15RPT01 Development of RF and microwave metrology capability”
http://rfmw.cmi.cz/

Thank you for attention