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M.P. Weidman

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M.P. Weidman

Electromagnetic Fields Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80303-3328

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M. P. Weidman
National Institute of Standards and Technology
Boulder, Colorado 80303

This report describes a basic, but potentially accurate, transfer technique for comparing microwave power sensors. The technique is not new, but the specific applications are. This report is written to supplement the existing literature. The method transfers the effective efficiency of a standard power sensor to an unknown (uncalibrated) power sensor. The power sensors may be bolometric (thermistor mounts), thermoelectric, or diode types, and each type will have inherent limitations. The technique can be implemented with a variety of commercial coaxial and rectangular waveguide components. Measurement uncertainty is discussed in this report so that a potential user can quantify transfer uncertainties.

Key words: direct comparison; effective efficiency; microwave metrology; mismatch uncertainty; power sensor; power meter; power transfer

1. Introduction

This paper shows how to use direct comparison over broad frequency ranges with low uncertainties. In this report, the generic term, power sensor is used to describe several types of microwave sensor in common use. Although the most nearly linear power sensor is the thermistor mount, thermoelectric and diode sensors can also be used (with limitations). All sensors are used with some type of instrumentation or power meter indicator. The indicated power is proportional to the net radio frequency (rf) or microwave power absorbed by the sensor. The purpose of calibration of the sensor is to determine this proportionality.

The direct comparison measurement technique is based on alternate connections of a standard and unknown power meter to a source of rf or microwave power (figure 1). The source can be a signal

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generator, a generator with an isolator or attenuator, or may include a sensor-directional coupler monitor at the generator output. Direct comparison is one of the oldest and most basic of microwave power transfer techniques. References describing this technique as a calibration method date back to 1953 [1]. Other references describe different aspects of this method [2,3]. A good reference for the general topic of power comparison techniques is Part C of [4]. Other calibration techniques, such as the use of the six-port [5] or tuned reflectometers [6], are more complex and are not discussed in detail here.

One of the main sources of uncertainty in any power transfer is caused by the impedance mismatch between the source and the power sensors connected to the source. Figure 1 shows the alternate connection of two sensors to a source. The power sensors in a direct comparison are of the terminating type and usually consist of a standard sensor and one or more unknown sensors. Historically, the direct comparison method was used for single frequency or narrow-band measurements or for measurements where a low uncertainty was not required. The reasons for using the direct comparison instead of other methods are speed and simplicity. There are several options for using the technique depending on the accuracy required. The higher accuracy implementation uses high directivity waveguide
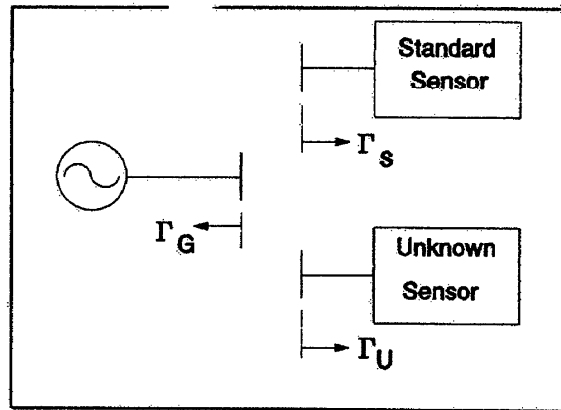
Figure 1. Alternate connection of standard and unknown detectors to a generator.

directional couplers, or in the case of coaxial sensors, VSWR bridges. Full evaluation of the uncertainty in the direct comparison technique requires separate measurements of the complex reflection coefficients Γ_S, Γ_G, and Γ_U. These reflection coefficients apply to the power standard sensor, the equivalent generator, and the device under test (DUT) sensor. The reflection coefficient measurements can be determined using a commercial vector automatic network analyzer (VANA) with appropriate speed and accuracy.

2. Basic Theory

2.1 Efficiency Definitions

The calibration quantity used to characterize terminating power meters is effective efficiency η_E for thermistor sensors and efficiency factor η for the other types of sensors. Efficiency η_E is defined as P_{DC}/P_{RF}, where P_{DC} is the substituted dc power and P_{RF} is the net radio frequency (rf) or microwave power dissipated in the sensor. Substituted dc power is the change in direct current (dc) or low frequency power necessary to maintain the thermistor element or elements at a constant resistance when rf or microwave power is applied to the sensor.

Thermoelectric sensors convert the absorbed rf power to heat, then to dc, and instrumentation amr fies the low level dc and displays the result. Diode sensor-power meters convert rf voltage to dc voltage and display the result. In the square law region, the diode sensor-meter displays a response proportional to rf power (voltage squared). The efficiency factor η of thermoelectric or diode sensors is P_M/P_{RF}, where P_M is the indicated or displayed power meter reading and P_{RF} is the net rf or microwave power dissipated in the sensor.

2.2 Transfer without Directional Coupler

Effective efficiency η_E from a standard thermistor (η for other sensors) to a DUT sensor is transferred using

$$\eta_{EU} = \eta_{ES} \times P_{RATIO} \times MM , \tag{1}$$

where η_{EU} is the effective efficiency of the DUT and η_{ES} is that of the standard. When the power sensors are not thermistors, effective efficiency is replaced by efficiency defined in eq (1). P_{RATIO} is the ratio of two substituted dc or indicated powers,

$$P_{RATIO} = \frac{(P_{DC})'_U}{(P_{DC})_S} , \tag{2}$$

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where $P_{(DC)S}$ is the dc power in the standard and $P_{(DC)U}$ is the dc power in the DUT. For thermoelectric or diode sensors, the P_{DC} are replaced by the indicated powers P_M. The mismatch factor MM is

$$MM = \frac{(1-|\Gamma_s|^2)}{(1-|\Gamma_u|^2)} \times \frac{|1-\Gamma_u\Gamma_g|^2}{|1-\Gamma_s\Gamma_g|^2} ,$$ (3)

where Γ_U, Γ_S, and Γ_G are the respective complex reflection coefficients of the DUT, the standard, and the generator. Application details are described in section 3.

2.3 Transfer with Directional Coupler

A source which includes a generator and directional coupler-sensor on its output has several desirable features. Figure 2 shows the coupler system. The directional coupler samples the incident power from the generator and can be used for power leveling. Recording the side arm and main arm powers simultaneously is the same as leveling. Another feature of the coupler system is that Γ_G at the output of the coupler is a function of only the coupler parameters and not of the generator driving the coupler [2].

A given application may include a waveguide coupler, a voltage standing wave ratio (VSWR) bridge, a power splitter, a quadrature hybrid, or some other type of directional coupling device. In a typical system, a power sensor is permanently attached to the incident-side-arm of the coupler.
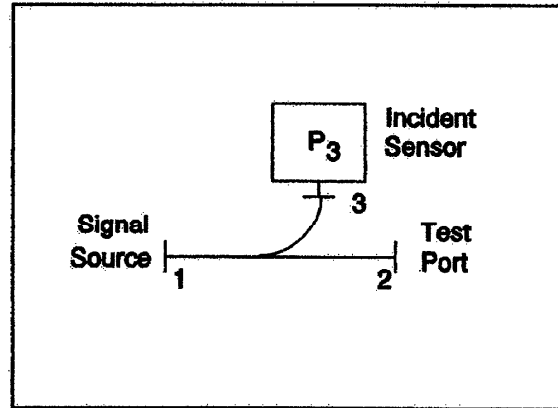
Figure 2. Directional coupler port numbering.

Effective efficiency η_E from a standard thermistor to a DUT with a directional coupler is transferred with eq (1). When the power sensors are not thermistors, effective efficiency is replaced by the efficiency factor η. Let R be the ratio of substituted dc powers, P_{SIDE}/P_{MAIN}, where P_{SIDE} is the dc power in the sensor on the side arm of the coupler, and P_{MAIN} is the dc power in the power sensor on the main arm. In addition, let R_S be that ratio with

the standard connected and R_U be the ratio with the DUT connected. Then a new P_{RATIO} is

$$P_{RATIO} = \frac{R_S}{R_U},$$ (4)

which involves four dc powers. It is not necessary to control the power level of the source if P_{MAIN} and P_{SIDE} are measured simultaneously. If any of the sensors are not thermistors, the dc powers are replaced by the power meter indicated powers. Mismatch factor MM is the same as shown in eq (3), where Γ_U and Γ_S are the same, and Γ_G is the complex reflection coefficient of the coupler equivalent generator. The definition of Γ_G for a directional coupler comes from ref. [2] and is

$$\Gamma_G = S_{22} - \frac{S_{12}S_{23}}{S_{13}},$$ (5)

where the S_{ij} are the scattering parameters (S-parameters) of the directional coupler used in the power transfer. Figure 2 shows the port numbering for the S-parameters of the coupler.

3. Applications

The value of η_{ES} of a standard thermistor or η of a standard thermoelectric (or diode) sensor must be known for a power transfer. Efficiency η_{ES} may come from a national laboratory, a calibration laboratory, or a manufacturer.

The other information necessary for an accurate power transfer is MM. The complex values of Γ_G, Γ_S, and Γ_U are required for best accuracy. If it is possible to measure only the magnitude of the reflection coefficients, then there is an uncertainty in percent in MM of

$$\Delta(MM) = 200(|\Gamma_G||\Gamma_S| + |\Gamma_G||\Gamma_U|).$$ (6)

For typical values of Γ_G, Γ_S, and Γ_U, the uncertainty in MM can range from 1 percent to 15 percent if only magnitudes of Γ are measured. Equation (6) comes from a first-order approximation to the derivative of eq (3).

3.1 Measurement of Γ_G without a Directional Coupler

Γ_G for an active source is difficult to measure, although a technique has been suggested if the source can tolerate high reflected power [7,8]. A better way to use a source without the directional coupler is to put an isolator or attenuator on its output. If low power is a problem, then the isolator would be preferable, but isolators are limited in frequency range.

An approximation to Γ_G with an attenuator or isolator on the output of the generator is Γ looking back into the output of the attenuator or isolator. This Γ can be measured without the generator turned on. The uncertainty of this measurement depends on the Γ looking back into the active generator and the amount of attenuation or isolation. Every 10 dB of attenua. or 20 dB of isolation will reduce the effect of the active source Γ by an order of magnitude. The proximation to Γ_G is due to the fact that the measurement looking back into the attenuator (or is .ator), toward the generator, is performed with the generator off and is typically negligible.

As an example, for an active generator with $\Gamma = 0.3 \pm 0.3$ and 20 dB of attenuation or 40 dB of isolation, the uncertainty in Γ_G would be 0.003. The estimate of uncertainty for the generator Γ_G (± 0.3) applies to most known signal generators. The approximation uncertainty in Γ_G must be propagated through MM. The propagation of uncertainty in MM due to uncertainties in reflection coefficient is analyzed in Appendix A.

3.2 Measurement of Γ_G of a Directional Coupler

The definition of Γ_G is given in eq (5). Γ_G is a function of the S-parameters of the coupler only and is not affected by the generator. Reference [2] describes one way to measure Γ_G, but this method requires a tuning adjustment at each measurement frequency.

An approximate measurement method, which can be done over a broad frequency range with a vector network analyzer, is to measure only the S_{22} term for the coupler. The second term in eq (5) involves the directivity $20*log(|S_{23}|/|S_{13}|)$ and the main line loss $20*log(|S_{12}|)$. S-parameters are defined as voltage ratios, so that decibel (dB) values are $20*log(S)$. The second term on the right side of eq (5) can be ignored if the directivity is high. The magnitude of the directivity term is shown in the examples.

S_{22} is the Γ looking into port 2 (fig. 2) with the other ports terminated in nonreflecting loads. There are three elements to the uncertainty in Γ_G when approximating it by S_{22}:

(1)   The finite directivity of the coupler or bridge.

(2)   The assumption of a matched load on port 1 when measuring Γ at port 2. Attenuation between port 1 and port 2 reduces the effect of not having a matched load on port 1 by $|S_{12}|*|S_{21}|$. This is the same order of magnitude reduction for each 10 dB of attenuation as described in section 2.1.

(3)   An imperfect load on port 3.

Some examples should clarify the measurement of Γ_G. If the directivity of the coupler is 40 dB, the uncertainty in $|\Gamma_G|$ from element (1) is 0.01. With an isolator of 20 dB, or a 10 dB attenuator on port 2, (along with 40 dB directivity) the uncertainty in $|\Gamma_G|$ due to element (1) would ≈ 0.001, which is negligible for most purposes.

For a 3 dB coupler (without an attenuator or isolator) with a 0.02 load on port 1, element (2) would result in an uncertainty of 0.01. A better condition would be to add a 10 dB pad or 20 dB isolator on port 2, then element (2) would result in an uncertainty of 0.002.

Element (3), which is a function of the load on port 3 involves the two-way loss from port 2 to port 3 and for a 40 dB coupler directivity and 3 dB forward coupling, the effect of the Γ on port 3 is reduced by 0.00005. Even a short circuit on port 3 has little effect on S_{22}.

All of the uncertainties in Γ_G must be propagated through MM to get the uncertainty in the power transfer, which is described in Appendix A. The previous examples should help explain how to calculate an uncertainty in MM for different combinations of hardware.

3.3. Other Types of Directional Couplers

Figure 2 and the general description so far correspond to waveguide directional couplers. Other types of couplers are useful for the direct comparison power transfer method.

3.3.1 VSWR Bridge

Figure 3 shows the rf hardware for one possible coaxial power calibration system. The VSWR bridge

is the same as the directional coupler. The VSWR bridge was originally designed for measuring VSWR with the generator on arm 2, the test port on arm 1 and a sensor on arm 3. The application of this device to a power transfer is a new innovation. The 3 dB attenuator on arm 2 of the bridge provides 6 dB of return loss isolation for the S_{22} measurement. S_{22} is defined with matched loads on all other ports. In the example of figure 3, a nonideal lo^d with $\Gamma=0.02$ connected to port 1, when measuring S_{22}, ^;!
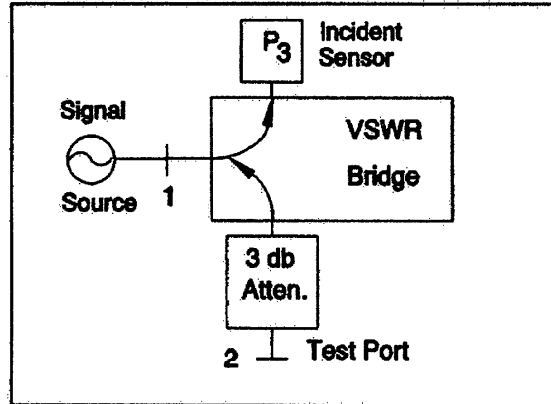

Figure 3. VSWR bridge used as directional coupler for power transfer.

create an uncertainty in S_{22} of 0.02 times 0.1: '9 or 0.0025. The 0.1259 term comes from the two-way loss through the sum of the 3 dB attenuator a^ the 6 dB coupling inherent to the VSWR bridge (9 dB corresponds to a voltage ratio of 0.1259). The uncertainty due to finite directivity is $|S_{23}*S_{12}|/|S_{13}|$ or 0.00355. The uncertainty due to finite directivity, for this example, is based on a directivity ($|S_{23}/S_{13}|$) of 40 dB plus the 9 dB loss from port 1 to port 2 (6 dB coupling + 3 dB attenuator).

3.3.2 Resistive Power Splitter

Another type of coaxial directional coupler is the resistive power splitter shown schematically in figure 4. This device has a nominal coupling of 6 dB between ports 1 and 2 and ports 1 and 3. If this device is perfectly symmetrical with no parasitic reactances, $S_{22} = 0.25$, $S_{23} = 0.25$, and

$S_{13} = S_{12}$, so Γ_G from eq (5) is zero. S_{22} for a power splitter is not a good approximation to Γ_G, so even though Γ_G may be small, a measurement of its value is difficult but necessary for a thorough uncertainty analysis. One way to measure Γ_G is to use a VANA to measure all the complex S-parameters in eq (5) and calculate Γ_G. A slight modification to this takes advantage of the approximation, $S_{21} = S_{31}$, so that from eq (5) $\Gamma_G = S_{22}-S_{23}$, but this method still requires
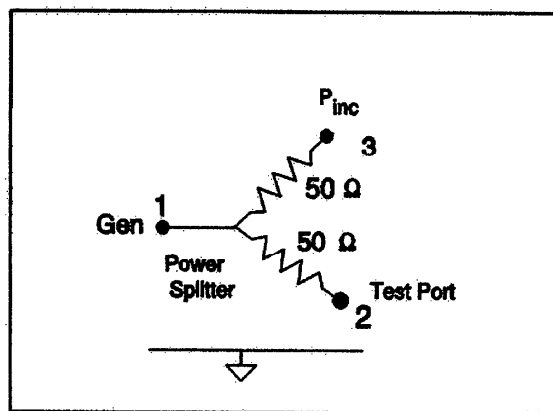

Figure 4. Schematic representation of coaxial-resistive power splitter.

measurement of complex S-parameters. A third way is to use a sliding short coupled to a slotted line [7,8], but since this is a single frequency method, it would be just as easy to use the method described in ref. [2]. A comparison of the second and third methods for measuring Γ_G on power splitters show a range of uncertainties of 0.01 to 0.03 in Γ_G [9]. As in the preceding sections, any uncertainty in Γ_G must be propagated through MM (eq (3)) to determine the uncertainty in the power transfer.

5. Uncertainty Analysis

This section is intended as a general guide in determining the uncertainty for a power transfer using the techniques described in the previous sections. The method of combining uncertainties, root sum of squares (RSS), for example, or probability considerations (coverage factors) are left t .⁻⁺ user.

The uncertainty in measuring η_{ES} for an unknown device (DUT) is a combin⁻ on of the uncertainties in the elements in eqs (1) to (3). The following list of uncertainties can be used as a guideline.

Power Standard η_{ES} Uncertainty:
The first element on the right side of eq (1) is the effective efficiency η_{ES} of the standard thermistor mount. The value of this uncertainty normally comes from the standards or calibration laboratory which provides the efficiency for the working standard.

P_{ratio} Uncertainty:
Sources of uncertainty include, but are not limited to, power and frequency instability and connector repeatability. Instrumentation uncertainties such as resolution or offsets also occur here. These uncertainties are determined experimentally, using the actual hardware, by repeating the process and calculating the variability (standard deviation).

Mismatch Factor Uncertainty:
Mismatch factor MM in eq (3) has an uncertainty based on the VANA measurement of the reflection coefficients Γ and the approximations described in the basic theory above. The VANA uncertainty is dependent on the calibration technique, for example, sliding load or TRL. Equation (3) shows that the effect of the Γ measurement on the power measurement is of second order. The differential of eq (3), expressed as partial derivatives, can be used to determine the uncertainty in the power transfer. Appendix A gives the equations.

6. Conclusions

Several relatively simple calibration procedures which yield a power sensor transfer with an uncertainty which can be fully characterized have been described. The transfer system can be constructed from commercially available hardware.

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Appendix A. Uncertainty in Mismatch Factor

This appendix shows the derivation of the equations necessary to calculate the uncertainty in MM defined in the Basic Theory section 2.

Equation (3) is repeated here as eq (A1),

$$MM = \frac{(1-|\Gamma_S|^2)|1-\Gamma_G\Gamma_U|^2}{(1-|\Gamma_U|^2)|1-\Gamma_G\Gamma_S|^2} ,$$

(A1)

where the mismatch factor MM. The differential of MM is

$$d(MM) = \frac{\partial(MM)}{\partial|\Gamma_G|} \cdot d|\Gamma_G| + \frac{\partial(MM)}{\partial|\Gamma_S|} d|\Gamma_S| + \frac{\partial(MM)}{\partial|\Gamma_U|} d|\Gamma_U| + \frac{\partial(MM)}{\partial\phi_{GS}} d\phi_{GS} + \frac{\partial(MM)}{\partial\phi_{GU}} d\phi_{GU} ,$$

(A2)

where the partials are with respect to the magnitudes of the three Γs, and Φ_{GS}, and Φ_{GU} are defined by

$$\phi_{GS} = \phi_G + \phi_S ,$$

(A3)

$$\phi_{GU} = \phi_G + \phi_U ,$$

(A4)

where Φ_G, Φ_S, and Φ_U are the phase angles of Γ_G, Γ_S, and Γ_U.

In order to simplify the algebra, the second ratio in MM in eq (A1) was changed to

$$\frac{|1-\Gamma_G\Gamma_U|^2}{|1-\Gamma_G\Gamma_S|^2} = \frac{1-2|\Gamma_G\Gamma_U|COS(\Phi_G + \Phi_U) + |\Gamma_G\Gamma_U|^2}{1-2|\Gamma_G\Gamma_S|COS(\Phi_G + \Phi_S) + |\Gamma_G\Gamma_S|^2}$$

(A5)

This simplification gets rid of the complex terms in eq (A1) and leads to the use of Φ_{GS} and Φ_{GU} in

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eq (A2).

Equations (A6) through (A10) follow from eqs (A2) through (A5).

$$\frac{\partial(MM)}{\partial|\Gamma_G|} = 2\left[\frac{(MMd)B(1-C^2)(AB-D)-(MMn)C(1-B^2)(AC-E)}{(MMd)^2}\right], \qquad (A6)$$

$$\frac{\partial(MM)}{\partial|\Gamma_U|} = 2\left[\frac{A(1-C^2)(AB-D)+(MMn)B/(1-B^2)}{(MMd)}\right], \qquad (A7)$$

$$\frac{\partial(MM)}{\partial|\Gamma_S|} = -2(MMn)\left[\frac{A(1-B^2)(AC-E)}{(M\ d)^2}\ \frac{(MMd)C/(1-C^2)}{}\right], \qquad (A8)$$

$$\frac{\partial(MM)}{\partial(D)} = \frac{-2AB(1-C^2)}{(MMd)}, \qquad (A9)$$

$$\frac{\partial(MM)}{\partial(E)} = \frac{2(MMn)AC(1-B^2)}{(MMd)^2}. \qquad (A10)$$

Definitions for the shorthand terms in eqs (A6) through (A10) are

$$MMn = \text{numerator of MM ratio}, \qquad (A11)$$

$$MMd = \text{denominator of MM ratio}, \qquad (A12)$$

$$A=|\Gamma_G|, \ B=|\Gamma_U|, \ \text{and} \ C=|\Gamma_S|, \qquad (A13)$$

$$D=COS(\phi_G+\phi_U), \ \text{and} \ E=COS(\phi_G+\phi_S). \qquad (A14)$$

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The phase angle uncertainties which are needed along with eqs (A9) and (A10) are defined in eq (A15). The partial derivative of *MM* with respect to *D* and *E* are multiplied by *d(D)* and *d(E)* and then replace the last two terms in eq (A2):

$$d(D) = -SIN(\phi_{GU})d(\phi_{GU}) \quad and \quad d(E) = -SIN(\phi_{GS})d(\phi_{GS}), \tag{A15}$$

where *d(Φ)* is the uncertainty in Φ_{GS} and Φ_{GU} in radians. In reflection coefficient measurements, the uncertainty in the phase of Γ is inversely proportional to the magnitude of Γ. As the magnitude of Γ approaches zero, the uncertainty in the phase of Γ approaches $\pm\pi$ rad, but the product *AB* in the numerator of eq (A9) or *AC* in the numerator of (A10) approaches zero at the same time, so the partial derivatives of *MM* times the differentials, *d(Φ)*, approach zero.

Equations (A6) through (A15) are used in the calculation of the uncertainty in the power transfer caused by uncertainties in the reflection coefficient measurements.

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