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Directional Coupler Calibration for Accurate On-line Incident Power Measurements

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Abstract—**This paper proposes a calibration method to properly measure incident power in a directional coupler (DC) when the measurement configuration has low directivity. The proposed method is based on measurements of short-circuits placed at different distances to calibrate the DC response. Results show that the method is clearly robust and provides accurate measurements even for directivities as low as 10 dB.**

Index Terms— **Coupling, Directional coupler, Directivity, Power measurement, Scattering matrix.**

I. INTRODUCTION

THE use of Directional Couplers (DC) for scattering parameter measurements is well known in the microwave engineering field [1]. The main feature of DCs is that they are able to separate the incident wave from the reflected one, and this is the basic principle for the measurement of scattering parameters. This capability comes from the presence of isolated ports, there being a 4-port network that always has two pairs of isolated ports.

Fig. 1 shows the schematic of a typical configuration that uses a DC to measure incident power (wave a_1) through measurements at port 3. The ideal S matrix for the DC is:

$$S = \begin{pmatrix} 0 & S_{12} & S_{13} & 0 \\ S_{21} & 0 & 0 & S_{24} \\ S_{31} & 0 & 0 & S_{34} \\ 0 & S_{42} & S_{43} & 0 \end{pmatrix} \quad (1)$$

Using the ideal scattering matrix (1) while assuming that port 3 is matched ($\Gamma_3 = 0$), makes the power measured at port 3 (P_3) to be:

$$P_3 = \frac{|b_3|^2}{2} = |S_{31}|^2 \, \frac{1}{2}|a_1|^2 = |S_{31}|^2 \, P_{inc} \quad (2)$$

where S_{31} is the coupling (C) of the DC and P_{inc} is the incident power associated with the incident wave a_1.

In this ideal S matrix, ports 1 and 4 are isolated ($S_{41} = S_{14} = 0$) as well as ports 2 and 3 ($S_{32} = S_{23} = 0$).

But, in practice, neither these ports are perfectly isolated nor the diagonal (S_{ii}) is null (the ports are not perfectly matched).

To evaluate the performance of a DC, its directivity (D) is quantified by the ratio between the coupled output power and the power outside the isolation port, and it is calculated as [1]:

$$D = 20log\left(\frac{S_{31}}{S_{41}}\right) = I - C \quad (3)$$

where D is the directivity (dB), C is the coupling (dB), and I is the isolation (dB) between ports 1 and 4.

Under these non-ideal conditions ($S_{ij} \neq 0$, for any $[i, j]$), and assuming $a_3 = a_4 = 0$, the power measured at port 3 is:

$$P_3 = \frac{|b_3|^2}{2} = \frac{1}{2}|a_1|^2 \, |S_{31}|^2 \left|1 + \frac{S_{32}S_{21}}{S_{31}} \frac{\Gamma_L}{1 - S_{22}\Gamma_L}\right|^2 \quad (4)$$

where P_3 is not only the incident power (as ideally in (2)) but also depends on the Γ_L (the reflection coefficient of the load (Z_L) at port 2).

Therefore, the design of DCs, providing accurate measurements of incident power, is not a straightforward task. Since as early as 1968, excellent designs have been obtained [2,3], but depending on the performance or due to the constant evolution of technology, designs are changing [4,5] and being improved, as has been reported very recently [6,7]. It is very important to emphasize that DCs are the best option for high power applications [8], where an accurate calibration and measurement of the incident power becomes a crucial task.

Some research has assessed the quality of the measurements when the DC is not ideal [9,10], but no information was reported about the incident power measurement.

This paper presents a method for correcting power measurements at port 3 (according to (4)) depending on the actual testing load (Z_L) measured and a calibration process based on different short circuits.

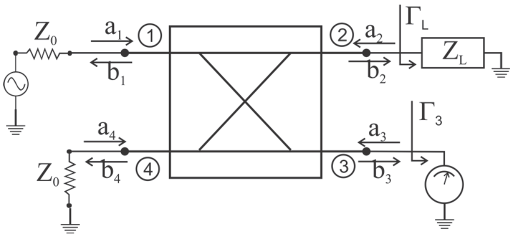

Fig. 1. DC general schematic used for incident power measurement. Port 1 → input; port 2 → through; port 3 → coupled; port 4 → isolation.

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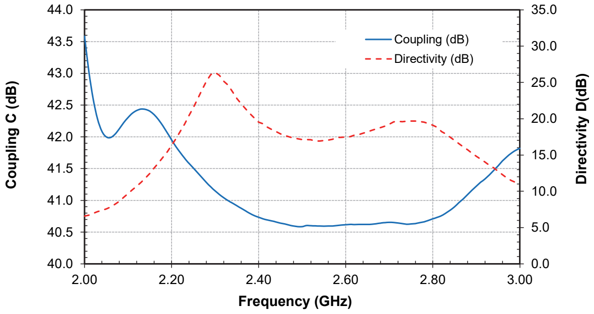


Fig. 2a. Coupling (C) and directivity (D) of a commercial DC.

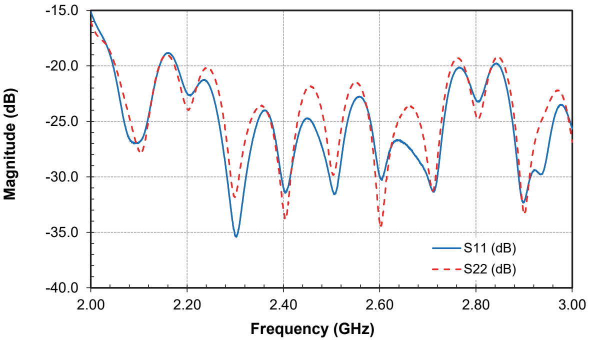


Fig. 2b. S_{ii} (ii=1,2) of a commercial DC.

II. CALIBRATION PROCEDURE

In this section, a calibration method is proposed to evaluate the incident power properly even when the DC is not ideal.

A. *Motivation*

Before presenting the proposed procedure, it is necessary to look at the actual coupling (C) and directivity (D) measurements of a commercial DC (40 dB WR340 cross bidirectional coupler, Sairem) shown in fig. 2a, which will enable us to assess the problem. The scattering parameters of the DC were obtained by means of a ZNB 8 R&S VNA, and the power measurements were performed using a microwave amplifier (83020A, Keysight) fed by a vector signal generator (SMBV100A, R&S) and a USB power sensor (Anritsu MA24218A) placed in the forward port of the bidirectional coupler. It is a 40 dB coupler with around 20 dB of directivity at the operational frequency (2450 MHz ± 25 MHz), which could be considered as a good quality DC.

Parameters S_{11} and S_{22} are shown in fig. 2b, and these reflection values show a good match at ports 1 and 2 (below $-20\ dB$ in almost the whole measured band).

Under these conditions, fig. 3a shows the actual power measured at port 3 for 6 different testing loads placed at port 2, sampling the Smith chart (fig. 3b) widely when the incident power is 1 W. The ideal power, based on the coupling value at each frequency and plotted in red in fig. 3a, is quite different from the actual power measured, with values as far as 3 dB from the real one. By way of example, at 2.454 GHz, there are 2 testing loads [3 and 6] that give the proper value of the incident power, which is 1 W ($P_{in} = -40.64\ dBW$ (P_3 measurement) + 40.64 dB (coupling) = 0 dBW), but the other testing loads give an incident power of 1.29 W ($P_{in} = -39.53\ dBW$ + 40.64 dB = 1.11 dBW), which means an error of 29%.

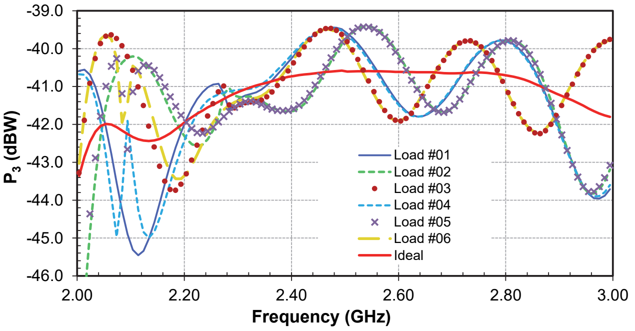


Fig. 3a. Actual incident power measured at different frequencies for each testing load.

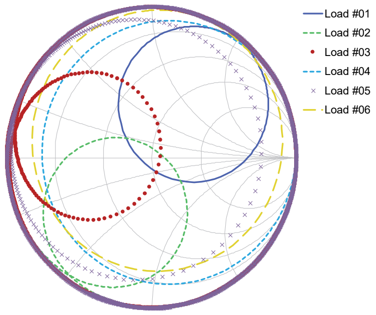


Fig. 3b. The 6 testing loads applied at port 2 sampling widely the Smith Chart

In the next subsection, we describe our DC calibration method to obtain accurate measurements of the incident power.

B. *Calibration method*

It can be generally assumed that S_{22} is low in most commercial DCs. In this case, S_{22} is below $-20\ dB$ (fig. 2b) within the range [2.2, 2.7] GHz, which is close to zero. This allows us to approximate $1/(1-S_{22}\Gamma_L)$, found in (4), to $(1+S_{22}\Gamma_L)$ which is the 1st order of the Maclaurin series. Thus:

$$P_3 = \frac{|b_3|^2}{2} \approx \frac{1}{2}|a_1|^2|S_{31}|^2|1+\alpha\Gamma_2(1+\beta\Gamma_2)|^2 \tag{5}$$

where $\beta = S_{22}$ and $\alpha = \frac{S_{32}S_{21}}{S_{31}}$.

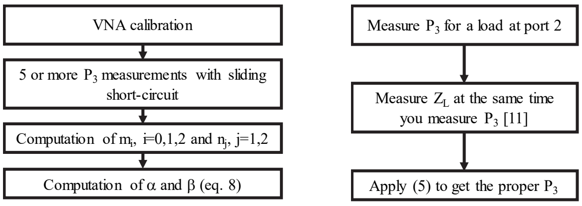
The proposed calibration method consists of measuring the system's response when loaded with a short circuit at different distances from the measurement port (port 2). This means that:

$$\Gamma_2 = -e^{-2\gamma L_i} = e^{j\theta_i} \tag{6}$$

where L_i is the physical length, $\gamma = j\sqrt{\omega^2\mu\varepsilon - k_c^2}$ is the propagation constant, and k_c is the cut-off wavenumber of the transmission line used to move the short circuit away from the port; for example, for a TEM mode $k_c = 0$ and for a TE$_{10}$ mode in a rectangular waveguide, WR340 in our case, $k_c = \pi/a$, where a is the rectangular waveguide width. The angle θ_i is the phase shift related to the time delay due to the back and forth wave propagation introduced by the port extension length.

Expanding (5) and converting it into cartesian coordinates using Euler's formula, for each short-circuit, we have:

$$P_3 = \frac{1}{2}|a_1|^2|S_{31}|^2 \begin{Bmatrix} m_0 + m_1\cos(\theta_i) + m_2\cos(2\theta_i) + \\ +n_1\sin(\theta_i) + n_2\sin(2\theta_i) \end{Bmatrix} \tag{7}$$



(a) (b)

Fig. 4. Flow charts explaining the calibration (a) and measurement method (b)

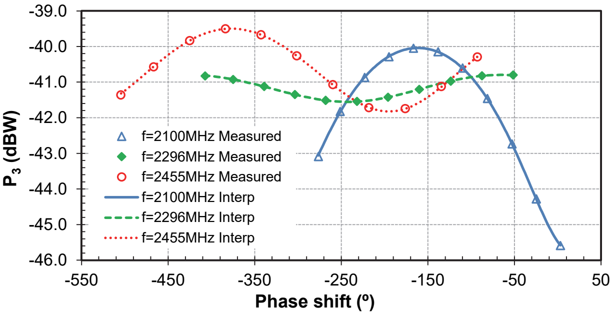


Fig. 5. Measured power at port 3 at 3 different frequencies

where

$$\begin{aligned} m_0 &= 1+\alpha_R^2+\alpha_I^2+\delta_R^2+\delta_I^2 \\ m_1 &= 2(\alpha_R+\alpha_R\delta_R+\alpha_I\delta_I) \\ m_2 &= 2\delta_R \\ n_1 &= -2(\alpha_I-\alpha_I\delta_R+\alpha_R\delta_I) \\ n_2 &= -2\delta_I \\ \alpha = \alpha_R+j\alpha_I \;\; ; \;\; \beta &= \beta_R+j\beta_I; \;\; \delta=\alpha\beta=\delta_R+j\delta_I \end{aligned} \tag{8}$$

According to (7), the power measured at port 3, when port 2 is loaded with a short circuit, describes a 2nd order trigonometric polynomial due to the load mismatch.

And once values m_0, m_1, m_2, n_1 and n_2 are known, then values α and β are also known [note that α_R, α_I and δ_R, δ_I are only intermediate variables to obtain α and β from (8)] and (5) can be used for any load (Z_L) at port 2, because α and β are already computed. Loads at port 2 can be measured at the same time that the power is computed if the whole system has been properly calibrated to measure the load [11].

Values m_0, m_1, m_2, n_1 and n_2 can be found by a trigonometric interpolation [12], and this must be done once per frequency. To sum up, the flow charts in fig. 4 shows how to apply this calibration method. Fig. 4a shows the 1st step, which consists in the calibration, and Fig. 4b shows the measurement procedure for any load.

This method was applied to the commercial DC. Fig. 5 shows the measurements taken at port 3 for a set of 11 different positions (dots) of a short circuit at 3 different frequencies and using a trigonometric interpolation following (5) (solid line).

Fig. 5 proves that (7) models the power at port 3 properly. Then (5) can be applied, once parameters m_0, m_1, m_2, n_1 and n_2 are known for each frequency, to correct the incident power properly for any load at port 2.

For example, fig. 6 shows the corrected power at 3 different frequencies for 6 different testing loads. The 3 frequencies were selected using the following criteria: (i) f=2.454 GHz is in the working band of the DC, as described in the specification sheet; (ii) f=2.294 GHz is out of the band, but the scattering matrix says that the behavior should be even better (better directivity), and (iii) f=2.104 GHz is a frequency which is far from the center, but with a directivity that could be considered good enough in other applications (D≈10 dB).

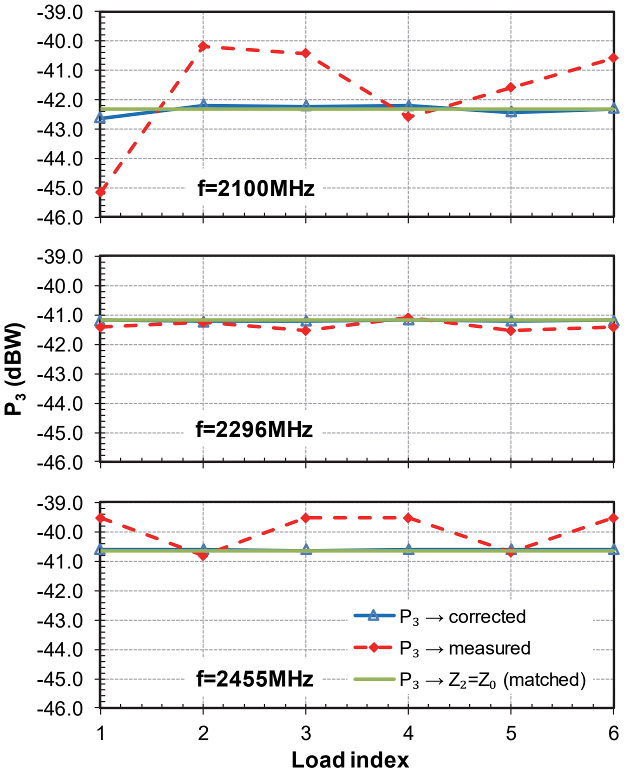


Fig. 6. Power measured at port 3 at 3 different frequencies for 6 different testing loads.

The green line is the ideal value, assuming infinite directivity; the red line is the incident power measured in each different testing load, and the blue line is the corrected incident power when applying the method described in this paper. The results confirm the validity of the proposed method which substantially increases the measurement accuracy.

III. CONCLUSION

A calibration method of a DC is proposed, based on several measurements of a short-circuit, to accurately measure the incident power for any load, regardless of the directivity of the DC. The method has been validated with real measurements and a set of 6 different testing loads that are sampling the Smith chart widely. The method is able to provide accurate values of the incident power, correcting ripples of up to 5 dB in the uncorrected measured power, even for frequencies with a directivity of 10 dB.

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REFERENCES

[1] Robert E. Collin, “Foundations for Microwave Engineering”, IEEE Press, second ed. 2001. ISBN: 0.7803-6031-1.

[2] Ralph Levy, "Analysis and Synthesis of Waveguide Multiaperture Directional Couplers". IEEE Trans. Micro. Theory and Techniques, Vol. MTT-16, No. 12, pp. 995-1006, December 1968, DOI: 10.1109/GMTT.1968.1123407.

[3] K.Yamamoto, H. Kurusu, S. Suzuki and M. Miyashita, "High-Directivity Enhancement With Passive and Active Bypass Circuit Techniques for GaAs MMIC Microstrip Directional Couplers". IEEE Trans. Micro. Theory and Techniques, Vol. MTT-59, No. 12, pp. 3095-3107, December 2011, DOI: 10.1109/TMTT.2011.2169982.

[4] J. Huang, Qing Hao, Jingzhao She and Zhenghe Feng, "A six-port coupler with high directivity for VSWR measurement". 2005 Asia-Pacific Microwave Conference Proceedings, 4-7 Dec. 2005. DOI: 10.1109/APMC.2005.1606811.

[5] Abdullah Eroglu and Sathwik Madishetti, "Six-Port Coupler Design for High-Power Radio Frequency Applications". IEEE Trans. Instrumentation and Measurement, Vol. 63, No. 6, pp. 1600-1612, June 2014, DOI: 10.1109/TIM.2013.2289702

[6] Zheng-Bin Wang , Xin Wei, Han-Ping Fang, Hua-Mei Zhang and Ye-Rong Zhang, "A Compact and Broadband Directional Coupler for High-Power Radio Frequency Applications". IEEE Micro. and Wir. Comp. Let., Vol. 30, No. 2, Feb. 2020, DOI: 10.1109/LMWC.2020.2964672

[7] Mohamed A. Nasr and Ahmed A. Kishk, "Analysis and Design of Broadband Ridge-Gap-Waveguide Tight and Loose Hybrid Couplers". IEEE Trans. Micro. Theory and Techniques, Vol. MTT-68, No. 8, pp. 3368-3378, August 2020, DOI: 10.1109/TMTT.2020.3002167

[8] MECA Electronics, "Why Directional Couplers Are Better for High Power Measurements vs. Attenuators". http://www.e-meca.com/app_notes/Why%20Directional%20Couplers%20Are%20Better%20for%20High%20Power%20Measurements%20(full).pdf

[9] T. Mukaihata, M. F. Bottjer and H. J. Tondreau, "Rapid Broad-Band Directional Coupler Directivity Measurements". IRE Trans. Instrumentation, Vol. I-9, No. 2, pp. 196-202, Sept. 1960, DOI: 10.1109/IRE-I.1960.5006916.

[10] X. Wang, J. She and Z. Fend, "Real Time Measurement of VSWR with Directional Couplers". 4th Int. Conf. on Microwave and Millimeter Wave Technologies Proc., 18-21 Aug. 2004, DOI: 10.1109/ICMMT.2004.1411630

[11] M. Hiebel, “Vector network analyzer (vna) calibration: The basics,” Rohde & Schwarz, Tech. Rep., 2008.

[12] Curve Fitting Toolbox 3.5.11 MathWorks, Inc (https://es.mathworks.com/help/curvefit/fourier.html)