SINGLE-PORT TECHNIQUE FOR ADAPTOR EFFICIENCY EVALUATION*

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Abstract

The 'single-port adaptor efficiency evaluation' (SPAEE) technique uses swept-frequency measurements to evaluate broadband efficiency of low-loss, reciprocal 2-ports, including noninsertable devices such as adaptors. The 2-port is terminated in two reflective terminations, a shielded open and a short. The value of the intrinsic efficiency as a function of frequency is extracted from the automatic network analyzer S_{11} data. The frequency range is limited only by the availability of the two reflective terminations. The major advantages of the SPAEE technique are its simplicity, speed, and accuracy. The expanded uncertainty (k=2) is typically about 1.5%.

1 Introduction

The '*single-port adaptor efficiency evaluation*' (SPAEE) *technique recently developed* at NIST uses swept-frequency measurements to evaluate broadband efficiency of low-loss reciprocal 2-ports, including noninsertable devices such as adaptors. The 2-port device under test (DUT) is terminated in two reflective terminations, a shielded open and a short. The value of the efficiency as a function of frequency is extracted from the automatic network analyzer (ANA) S_{11} data.

The major advantages of the SPAEE technique are its simplicity, speed, and accuracy. The ANA needs a single-port calibration only, instead of the full 2-port calibrations performed twice, as required by the usual 'adaptor-removal' technique needed for noninsertable devices. The frequency range is limited only by the availability of the two reflective terminations.

Connector losses are not negligible compared to the overall loss of a low-loss DUT. The SPAEE technique does not separately evaluate the connector losses, but it does include the loss of one of the connector pairs into the overall measured DUT efficiency. At least in the case of NIST thermal noise calibrations, this approach results in the most useful evaluation of the adaptor's overall efficiency. The connector pair efficiency ***variability*** is attributed in full to the technique uncertainty.

The SPAEE technique relies on the use of a shielded open, a termination not available in waveguide. The efficiency of waveguide-to-waveguide tapers cannot, therefore, be evaluated (at least not routinely; see Sec. 3). The efficiency of coaxial-to-waveguide adaptors can be evaluated so that the loss of the coaxial connector pair is included, while the loss of the flanges is not. The efficiency of coaxial-to-coaxial adaptors can be evaluated with the loss of either connector pair being included.

2 Theory

The theoretical derivation briefly outlined below has two separate starting points. The first is a general expression defining the efficiency of a 2-port *in-situ*, *i.e.*, in normal use. It is forced into a form combining the 2-ports *intrinsic* efficiency and a small correction term. The second is the expression defining the reflection coefficient 'looking' into the DUT while it is terminated in a low-loss reflective termination (*i.e.*, under the conditions prevailing during the efficiency evaluation); it is in turn forced into a form containing the same terms as the first expression. The two configurations are illustrated in Fig. 1.

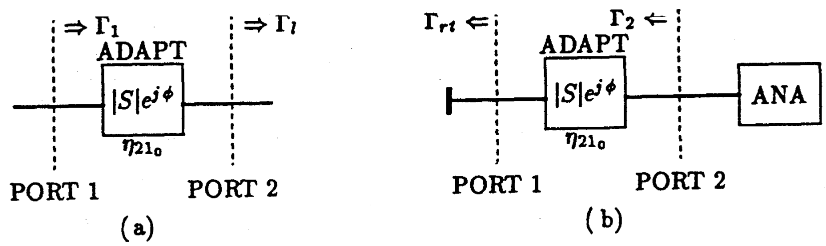

Figure 1: (a) The 2-port during use, (b) the 2-port during evaluation

The theory underlying the SPAEE technique is applicable to low-loss [1], reciprocal 2-ports used in well-matched systems (*i.e.*, systems with negligible third- and higher-order products in reflection coefficients and/or S_{ii}, $i = 1, 2$). The theory also assumes that DUT dissipative losses vary only slowly with frequency.

(1) Under the conditions outlined above, the *in situ* efficiency η_{21} (Fig. 1 a) can be approximated [2] as

$$\eta_{21} \equiv \frac{(1-|\Gamma_l|^2)\,|S_{21}|^2}{(1-|\Gamma_1|^2)\,|1-S_{22}\Gamma_l|^2} \approx \eta_{21_0}\left(1 + 2\,\Re\{\chi\Gamma_l\}\right), \tag{1}$$

where η_{21_0} is the 2-port's intrinsic efficiency, $\eta_{21_0} = |S_{21}|^2/(1-|S_{11}|^2)$, $\Re$ indicates the Real operator, and Γ_l describes the reflection coefficient of the load under the conditions of normal use. Its magnitude is typically small (< 0.1). The term χ is a correction term,

$$\chi \approx |S_{22}|e^{j\phi_{22}}(1-\eta_{21_0}), \tag{2}$$

where ϕ_{22} is the phase angle of the 2-port's S_{22} parameter. The magnitude of χ is close to 0 since $\eta_{21_0} \approx 1$ in low-loss 2-ports, and, moreover, the small value of $1-\eta_{21_0}$ is multiplied by $|S_{22}|$, which is itself small. χ is a quantity intrinsic to the DUT.

(2) During the swept-frequency evaluation the 2-port is terminated (Fig. 1 b) at its port 1 in a high-reflection, low-loss termination characterized by the reflection coefficient $\Gamma_{rt} = |\Gamma_{rt}|e^{j\phi_{rt}}$. The reflection coefficient Γ_2 'looking' into the 2-port/reflective termination combination can be expressed [3] as

$$\Gamma_2 = \frac{|S_{21}|^2|\Gamma_{rt}|e^{j\Psi}}{1-|S_{11}\Gamma_{rt}|^2} + \frac{S_{22}+\sigma S_{11}^*|\Gamma_{rt}|^2}{1-|S_{11}\Gamma_{rt}|^2}, \tag{3}$$

where $\sigma = S_{21}^2 - S_{11}S_{22}$, $\Psi = 2\phi_{21} + \phi' + \phi_{rt}$, and ϕ' is a small phase correction. The expression (3) can be manipulated into a form

$$\frac{|\Gamma_2|}{|\Gamma_{rt}|} \approx k\left|\eta_{21_0} - \frac{|\chi|}{|\Gamma_{rt}|}e^{j(\phi_{11}-\phi'-\phi_{rt})}\right|, \tag{4}$$

where $k \approx 1 - |S_{11}|^2 + |S_{11}\Gamma_{rt}|^2 \approx 1$ for a 2-port of low reflectiveness terminated in a reflective termination of low loss. As previously shown, the magnitude of χ is small. Equation (4) can be therefore approximated as

$$\frac{|\Gamma_2|}{|\Gamma_{rt}|} \approx \eta_{21_0} - \frac{|\chi|}{|\Gamma_{rt}|}\cos(\phi_{11}-\phi'-\phi_{rt}). \tag{5}$$

If ϕ_{11}, ϕ', and ϕ_{rt} are *linearly* dependent on frequency, the right term in (5) averages out over frequency, and the averaged quantity $|\Gamma_2|/|\Gamma_{rt}|$ is equal to the desired quantity η_{21_0}. Although ϕ' is varying with frequency in a nonlinear fashion, it is small in low-reflective devices ($\phi'_{max} \leq 0.2$ rad). The phase angle of the coaxial reflective termination ϕ_{rt} is either constant (in flat terminations), or linearly varying with frequency (in offset terminations). The argument in (5) therefore varies with frequency approximately as the phase of S_{11} does. Most adaptors have leads long enough to suppress higher-mode propagation, so the variation in their S_{11} phase is fast and, to a good approximation, linear with frequency. The right term in (5) can indeed be averaged out over frequency. Therefore,

$$\eta_{21_0} \approx \text{smooth}\left(\frac{|\Gamma_2|}{|\Gamma_{rt}|}\right). \tag{6}$$

3 Implementation and Discussion

In principle, a swept-frequency measurement of a DUT terminated in only one reflective termination should be sufficient. However, it is occasionally possible to confuse fast variations in the reflection coefficient magnitude due to errors in the ANA, with those due to the χ. Because the shielded open and the short are 180° out of phase, the true DUT efficiency must be between the two traces. Once an ANA is calibrated, the effort required for that second sweep is small and, in our experience, well justified.

Figures 2 and 3 are examples of the SPAEE technique: Fig. 2 in a waveguide-to-coaxial adaptor, Fig. 3 in a coaxial-to-coaxial adaptor. In the second case, a Type N-to-3.5 mm adaptor was evaluated both 'as is' and separately, in combination with a 7.5 cm long airline attached to it as shown. The difference in the two efficiencies agreed with the calculated efficiency of the airline within 10^{-3}.

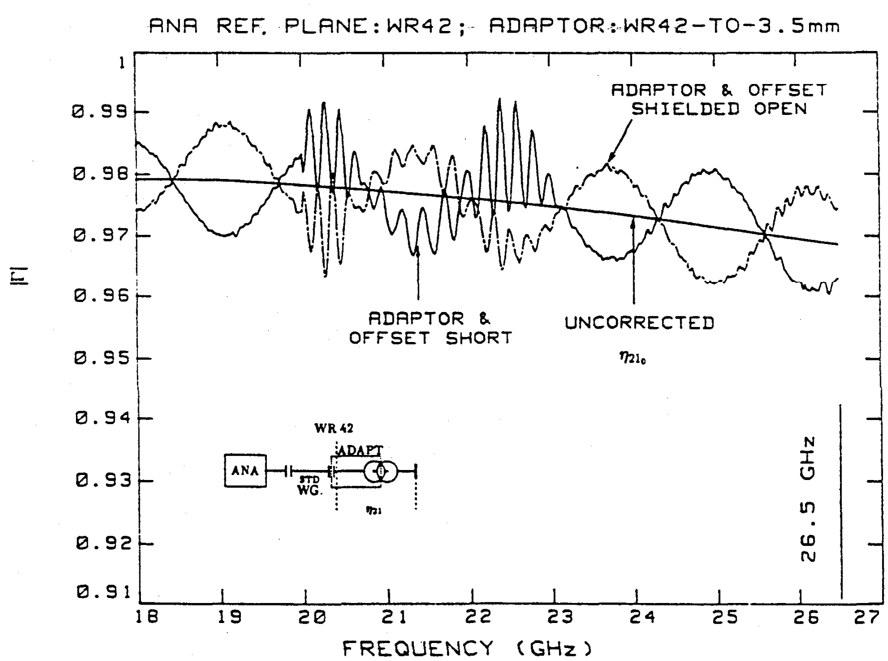

Figure 2: Graphic extraction of the smooth curve in a waveguide-to-coaxial adaptor measurement. 'Uncorrected η_{21_0}' means that the losses of the offset terminations have not yet been accounted for.

Because of the theoretical requirement for small $|S_{ii}|$, $i = 1, 2$, the DUT needs to be prescreened, *i.e.*, terminated in a resistive termination and frequency swept. Until further studies examine the influence of a larger $|S_{ii}|$ on the method accuracy, devices with $|S_{ii}| > 0.1$ or so would have to be rejected.

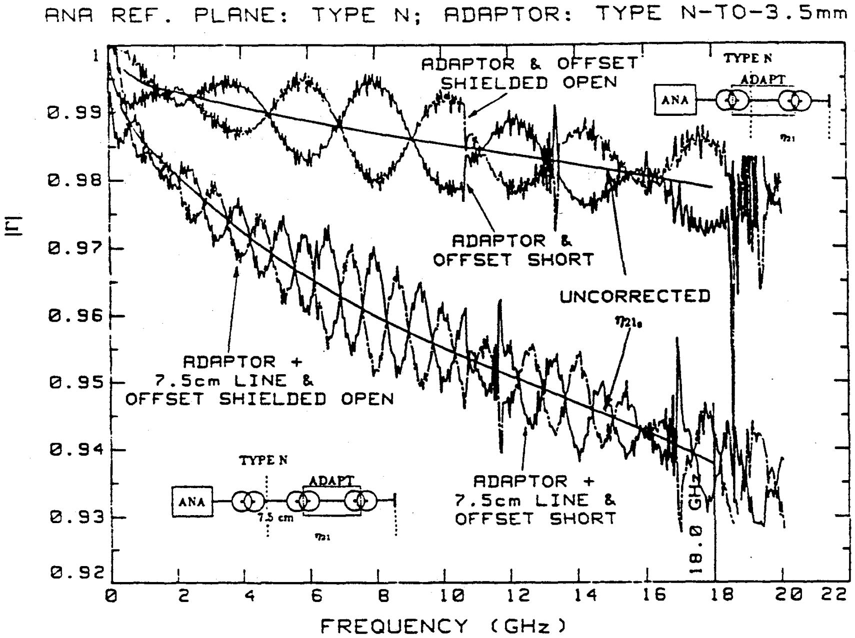

Figure 3: Graphic extraction of the smooth curve in a coaxial-to-coaxial adaptor measurement. The upper curve pertains to the adaptor alone, and the lower curve to the adaptor/airline combination. 'Uncorrected η_{21_0}' means that the losses of the offset terminations have not yet been accounted for.

The smoothing is done either graphically (by hand) or numerically, by fitting a regression curve to data. It is important to censor data points above or below the applicable frequency limits. Until more experience is accumulated, the graphs must be visually inspected even if smoothing is performed numerically, in order to verify the expected frequency behavior of the curves.

If the value of $|\Gamma_{rt}|$ in (6) is known, it is easy to correct for it; however, at least at frequencies up to 26 GHz, omitting this step results in a negligible error for calibration-quality reflective terminations.

Certain calibration kits contain only offset shorts and offset shielded opens. The additional loss A (in dB) of the offset segment is either directly given, or is calculable from the specifications. The intrinsic efficiency of the DUT can be extracted from the measured efficiency η_{casc} of the DUT/offset cascade, according to

$$\eta_{21_0} = \frac{\eta_{casc}}{10^{-A/10}}. \tag{7}$$

In our experience, the losses in the offset segments of the offset short and the offset shielded open have been so similar that a common correction is sufficient. Figure 4 shows the mean value curve 'offset-loss corrected' into the true intrinsic efficiency of the DUT.

Figure 5 illustrates the need for two different reflection terminations. A waveguide-to-coaxial adaptor has been terminated with two coaxial reflective terminations. If either one were used singly, the efficiency would have possibly been confused with the upper or the lower curve.

If the DUT is so short that smoothing becomes too uncertain, an extra length of a line should be attached to the port 1 (Fig. 1 b) during the evaluation. Sometimes the line can be left permanently attached to the adaptor (with the added advantage of assuring good higher-order mode suppression). However, if the combination is judged to be too lossy or mechanically unsuitable, the intrinsic efficiency of the line can be calculated and the adaptor's intrinsic efficiency corrected according to (7) (Fig. 3).

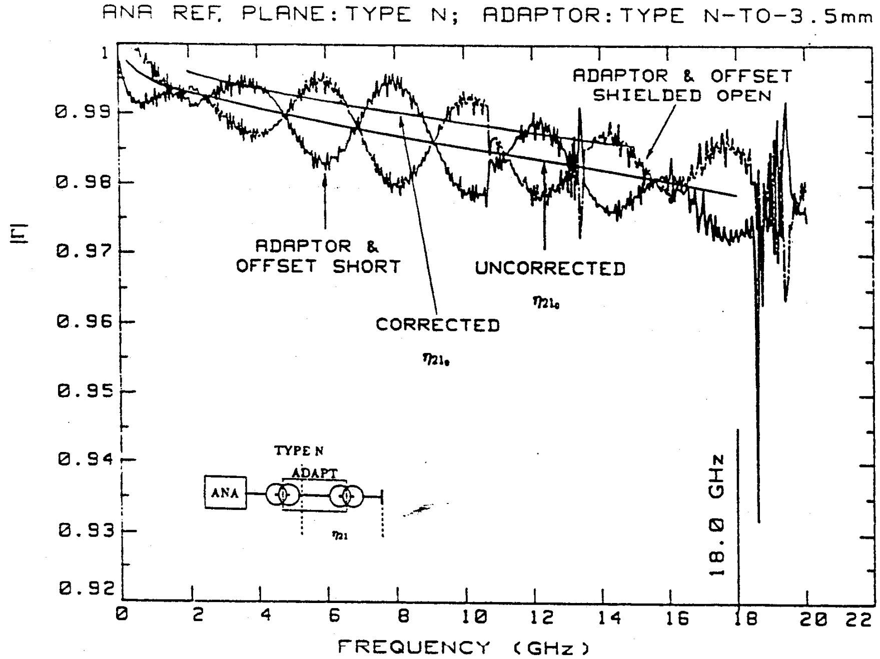

Figure 4: Efficiency of an adaptor corrected for the losses of the offset terminations

The SPAEE technique includes the losses of one of the connector pairs into the overall measured DUT efficiency. The connector pair whose efficiency is included is the one formed between the DUT and the reflective terminations used in the evaluation. The user must determine, depending on the application, which connector pair losses need to be included into the overall DUT loss, and orient the DUT accordingly during the evaluation. The arbitrary orientation is permissible because for low-loss devices, intrinsic efficiencies η_{21_0} and η_{12_0} are approximately equal. In the case of NIST noise calibrations, the connector pair whose loss needs to be included in the overall adaptor efficiency is the pair formed between the DUT (customer's noise source) and the adaptor (at Port 1, Fig. 1a). The other connector pair, the pair formed between the adaptor and the radiometer, is included in the common loss (in the radiometer front end), so its loss does not matter. During the evaluation the adaptor is therefore oriented so the Port 1 is terminated in the reflective terminations (Fig. 1b).

Losses of the connector pairs formed during the evaluation and during use are slightly different, due to connector variability. This variability is included into the SPAEE technique combined uncertainty.

For waveguide adaptor evaluation we routinely extend the ANA port by attaching a standard section of a waveguide, and define the reference plane at its end. Further work is needed to understand the mechanism accounting for the resulting 'better behavior' of the adaptors.

Other mechanisms operating during an ANA swept-frequency measurement can result in periodic oscillations in the measured reflection. They are, however, beyond the scope of this paper.

4 Verification

Several methods were used to verify the SPAEE technique. The efficiency of a WR42-to-3.5 mm adaptor was compared to measurements previously done on the NIST waveguide 6-port calibration system, using the same adaptor. Measurements of two 'identical' adaptors connected back-to-back were performed using the NIST coaxial 6-port calibration system. Measurement of both the S_{11} and S_{21} parameters were done

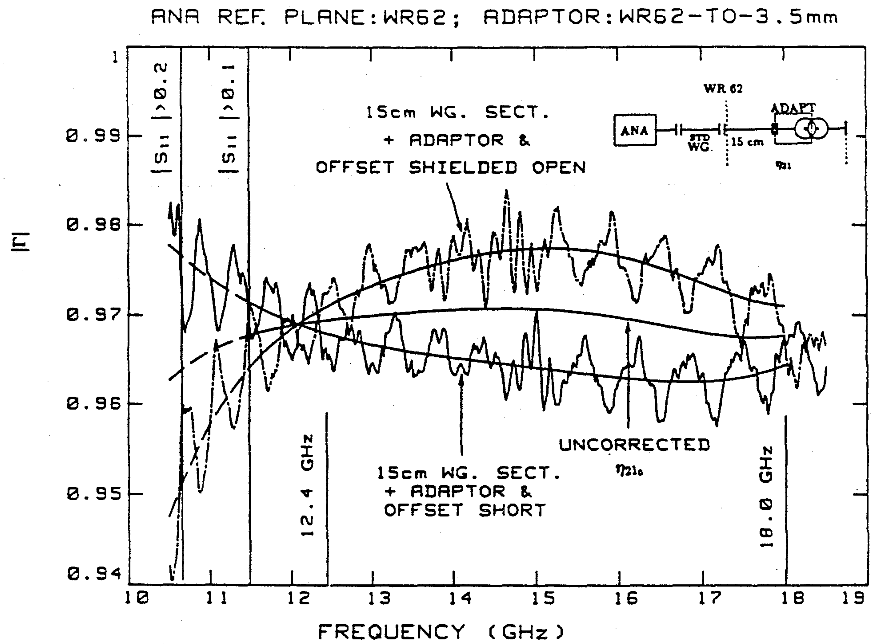

Figure 5: Efficiency of an adaptor: the need for 2 different reflection terminations. 'Uncorrected η_{21_0}' means that the losses of the offset terminations have not yet been accounted for.

by the 'adaptor-removal' technique using a commercial ANA. Thermal noise measurements were performed with an adaptor evaluated with several lengths of airline. Additional noise measurements were done with and without an adaptor; a waveguide source was measured directly in its band at the edge frequency, and through an adaptor in another band at the same frequency. In all cases, results agreed well within the claimed expanded [4] (k=2) uncertainty of about 1.5%.

5 Conclusion

The new SPAEE technique has been used by the NIST Noise Calibration Service for about two years. It has enabled us to measure noise sources in connectors for which we do not possess primary standards or radiometers. More work is needed to explain occasional anomalies, determine allowable upper limits of the DUT loss and reflectiveness, and reduce the typical 1.5% expanded uncertainty.

References

[1] D. M. Kerns and R. W. Beatty, Basic Theory of Waveguide Junctions and Introductory Microwave Network Analysis, Pergamon Press, 1967.

[2] W.C. Daywitt and G. Counas, "Measuring adapter efficiency using a sliding short circuit," IEEE Trans. MTT, Vol. 38, No.3, pp.231-237, 1990.

[3] W.C. Daywitt, "Determining adapter efficiency by envelope averaging swept-frequency reflection data," IEEE Trans. MTT, Vol. 38, No.11, pp. 1748-1752, 1990.

[4] Guide to the Expression of Uncertainty in Measurement, ISO 1993.