DEVELOPMENT OF SELF-CALIBRATION TECHNIQUES FOR ON-WAFER AND FIXTURED MEASUREMENTS: A NOVEL APPROACH

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ABSTRACT

Network Analyzer self-calibration techniques -TRL, LMR, TAR- are developed, implemented and compared in several transmission media. A novel LMR (Line-Match-Reflect) technique based on known LINE and REFLECT Standards, is proposed and compared to conventional LMR (based on known LINE and MATCH Standards) and other techniques (TRL, TAR). They are applied to on-wafer S-parameter measurement as well as to coaxial, waveguide and microstrip media. Experimental results up to 40 GHz are presented.

INTRODUCTION

Due to the inherent redundancy associated to the Network Analyzer self-calibration techniques [1,2,3,4], some calibration standards (shorts, opens, loads) need not be ideal and transmission line standards are not only possible but convenient. Multiple applications can be found in MIC, MMIC and on-wafer measurements [5]. TRL [1] is the most widely used self-calibration technique, giving accurate chip transistor measurements in microstrip up to 40 GHz [6]. Other techniques, like LMR or TAR have been proposed [2,4] and compared to TRL [4,7]. LMR has some advantages over TRL, like inherent broad bandwidth as well as wafer-probe fixed position for on-wafer measurements [8]. However, the suitability of the different techniques to a particular transmission line medium has not been yet fully investigated.

The objectives of this work are the theoretical development, practical implementation and comparative study of self-calibration techniques -TRL, LMR, TAR-. Calibration and measurement programs for the Network Analyzer (HP 8510B from Hewlett-Packard) external controller have been developed to this end. The applications are device measurements using Test-Fixtures as well as wafer-probe stations. A novel LMR technique based on known LINE and REFLECT Standards is here proposed and compared to conventional LMR (based on known LINE and MATCH Standards [4]) and to the other techniques. They are applied to on-wafer calibrations (using a Summit 9000 Cascade-Microtech wafer-probe station), fixtured (microstrip) S-parameter measurements, as well as to coaxial and Ka-band waveguide transmission media. Experimental results are given from 1 to 40 GHz.

THEORETICAL CONSIDERATIONS ON LMR TECHNIQUES

When the LMR (Line-Match-Reflect) technique is applied to microstrip-Test-Fixture based chip transistor measurements, a practical drawback arises. In fact, the MATCH Standard Γ_M should be ideal ($\Gamma_M = 0$) or perfectly known [4,7], a requirement that is difficult to meet in the higher frequency band (20 to 40 GHz) using chip microstrip-mounting loads. To circumvent the difficulty, one option is to assume a non-ideal unknown Match. In this case, the exact value of Γ_M is not relevant for the calibration process (provided it is small and equal at both ports), but an accurate value for the Reflect Standard Γ_R (equal at both ports) has to be provided to the calibration algorithm. The error commited assuming an ideal microstrip short is usually less than the error committed assuming an ideal microstrip load [6]. A similar argument can be used in the waveguide measurement case.

The calibration equations for the case of known-Reflect LMR are not referenced in the literature. Following the same notation as in [4], it can be shown that:

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$$[\overline{U}] = \frac{\overline{V}_{11} + \overline{V}_{22}}{e^{-\gamma l} - \Gamma_R^2 e^{\gamma l}} \begin{bmatrix} -\Gamma_R^2 e^{\gamma l} & \Gamma_R e^{-\gamma l} \\ -\Gamma_R e^{\gamma l} & e^{-\gamma l} \end{bmatrix} \quad (1)$$

where the bar means that the U and V matrices have been appropriately normalized to avoid indetermined elements. γ indicates the LINE propagation constant and l its length. U and V are defined as:

$$[U] = [T_3][T_1]^{-1} \qquad [V] = [M_3][M_1]^{-1}$$

where T_1, T_3 are the transmission matrices of calibration standards 1 and 3 (LINE and MATCH respectively), and M_1, M_3 are their respective measured transmission matrices. Equation (1) has to be used for the known-Reflect LMR calibration process. From (1) it can be seen that this technique has two limitations. The first one is that TMR calibrations (zero-length LINE or THRU) are not allowed because they could lead to indetermined values in (1). The second is that LINE lengthes which are a multiple of a half wavelength are not allowed for the same reason. This may lead to a bandwidth limitation. However, the limitation can be avoided if a very short line is used (a line with a delay ranging from 1 to 10 ps would be suitable up to 40 GHz). Γ_M is unknown but it can easily be computed, as a result of the calibration process, from the following second degree equation:

$$\Gamma_M^2[C_{VQ}e^{\gamma l} - (\overline{Q}_{11} + \overline{Q}_{22})\overline{U}_{22}e^{\gamma l}] + \Gamma_M[(\overline{Q}_{11} + \overline{Q}_{22})(\overline{U}_{12}e^{\gamma l} - \overline{U}_{21}e^{-\gamma l})]$$

$$+ e^{-\gamma l}[(\overline{Q}_{11} + \overline{Q}_{22})\overline{U}_{11} - C_{VQ}] = 0$$

$$C_{VQ} = \overline{V}_{11}\overline{Q}_{22} - \overline{V}_{12}\overline{Q}_{21} + \overline{V}_{22}\overline{Q}_{11} - \overline{V}_{21}\overline{Q}_{12}$$

where the bar again indicates normalization to avoid indetermined elements. Q is defined as:

$$[Q] = [M_2][M_1]^{-1}$$

where M_2 is the measured transmission matrix of calibration standard 2 (REFLECT).

EXPERIMENTAL RESULTS

Calibration algorithms based on the 8-term error model [2], were written in an HP 217 Computer to calibrate an HP 8510 B Network Analyzer. TRL, TAR and both LMRs were implemented. The feasibility of known-Reflect LMR is demonstrated in figure 1, where the measurement of a shifted Ka-waveguide short is compared to the measurement using TRL. The measured phases using both methods are in a very good agreement and they also agree with the theoretical value. The measured magnitude using known-Reflect LMR shows the smallest ripple, but it does not show the waveguide losses as for the TRL case. The reason is that the LINE was assumed to be ideal (no losses) for the former.

The analogous behaviour of known-Reflect LMR compared to TRL can also be seen in conventional (known-Match) LMR. This is shown in figure 2, where a coaxial shielded-open is measured using TRL, known-Match LMR and TAR calibrations, and compared to its theoretical value (straight line). The measurement frequency range is 5-35 GHz due to the bandwidth limitation associated to TRL. The best results are obtained with TRL and LMR calibrations. TAR shows a ripple (2°) due to the mismatch of the ATTENUATOR Standard.

Chip transistor S-parameter measurements were performed in a microstrip Test-Fixture [6] using known-Reflect LMR and TRL. A chip microstrip-mounting load was used to implement the MATCH Standard. The frequency range was restricted to the 5-16 GHz margin to guarantee MATCH return losses better than -10 dB. Figure 3 compares the measured S_{11} parameter of the Toshiba GaAs MESFET JS-8830-AS using both techniques. They show a very close agreement.

The autocalibration techniques were evaluated and compared using a Summit-9000 (Cascade-Microtech) wafer-probe Station and coplanar calibration substrates (ISS and LRM) up to 40 GHz. The THRU (TRL, TAR) and LINE (LMRs) Standards are 1 ps lines. Two TRL LINE Standards are used to cover the 1-40 GHz band (10 ps for higher frequencies and 40 ps for lower frequencies). The Reflect Standard is an open circuit. Figure 4 shows the measurements of an open, a short, a 40 ps line and a 20 dB attenuator, using the above calibrations. A very good agreement is always obtained using both LMRs. TRL agrees with LMRs only for the open an short measurements. The Attenuator and 40 ps-line TRL-measurements show differences compared to LRMs and TAR, probably because TRL is a LINE-based technique. In fact, the LINE has different manufacturing characteristics compared to the MATCH and ATENUATTOR Standards, and it also has losses and dispersion. The open and short $|S_{11}|$ TAR-measurements show dispersion probably because of a probe overlap associated to the ATTENUATOR Standard. This is in accord with [8]. The Attenuator and 40 ps-line TAR-measurements show very good agreement with LRMs.

CONCLUSIONS

The known-Reflect LMR calibration has been theoreticaly investigated and implemented. It shows some advantages in transmission media in which the MATCH Standard deviates from ideality (microstrip, waveguide). Comparative coaxial, waveguide and microstrip measurements have been presented showing good agreement between both known-Reflect LMR and TRL. TAR offers worse results due to the poor ATTENUATOR return losses. On-wafer measurements show similar results using both LMRs. TRL and TAR may have dispersion effects due to the LINE and ATTENUATOR Standards. Selection of a calibration technique depends on the DUT to be measured and the Standard available characteristics.

REFERENCES

[1] G.F. Engen, C.A. Hoer
"Thru-Reflect-Line: an improved technique for calibrating the dual six-port automatic network analyzer". IEEE Trans. on Microwave Theory and Techniques, vol MTT-27, no. 12, pp. 987-993, december 1979.

[2] H.-J. Eul, B. Schiek
"Thru-Match-Reflect: one result of a rigorous theory for de-embedding and network analyzer calibration"
18th European Microwave Conference, pp. 909-914. Stockholm, september 1988.

[3] R.A. Soares, P. Gouzien, P. Legaud, G. Follot
"A unified mathematical approach to two-port calibration techniques and some applications". IEEE Trans. on Microwave Theory and Techniques, vol MTT-37, no. 11, pp. 1669-1674, november 1989.

[4] H.-J. Eul, B. Schiek
"A generalized theory and new calibration procedures for network analyzer self-calibration". IEEE Trans. on Microwave Theory and Techniques, vol MTT-39, no. 4, pp. 724-731, april, 1991.

[5] J.T. Barr, T. Burcham, A.C. Davidson, E.W. Strid
"Advancements in on-wafer probing calibration techniques
Hewlett-Packard RF & Microwave measurement symposium and exhibition, 1990.

[6] L. Pradell, C. Sabater, E. Artal, A. Comerón, J. Bará, I. Corbella, J. Fortuny
"TRL calibration applied to the measurement of chip transistor S-parameter up to 40 GHz". 20th European Microwave Conference, pp. 214-219. Budapest, september 1988.

[7] H.-J. Eul
"Generalized calibration procedures for network analyzer calibration and verification"
Workshop of MIOP-91. Stuttgart, april 1990.

[8] S. Lautzenhiser, A. Davidson, K. Jones
"Improve accuracy of on-wafer tests via LRM calibration"
Microwaves & RF, vol. 29, no. 1, january 1990.

For all figures:

(1) : Known-Reflect LMR
(2) : Known-Match LMR
(3) : TRL
(4) : TAR

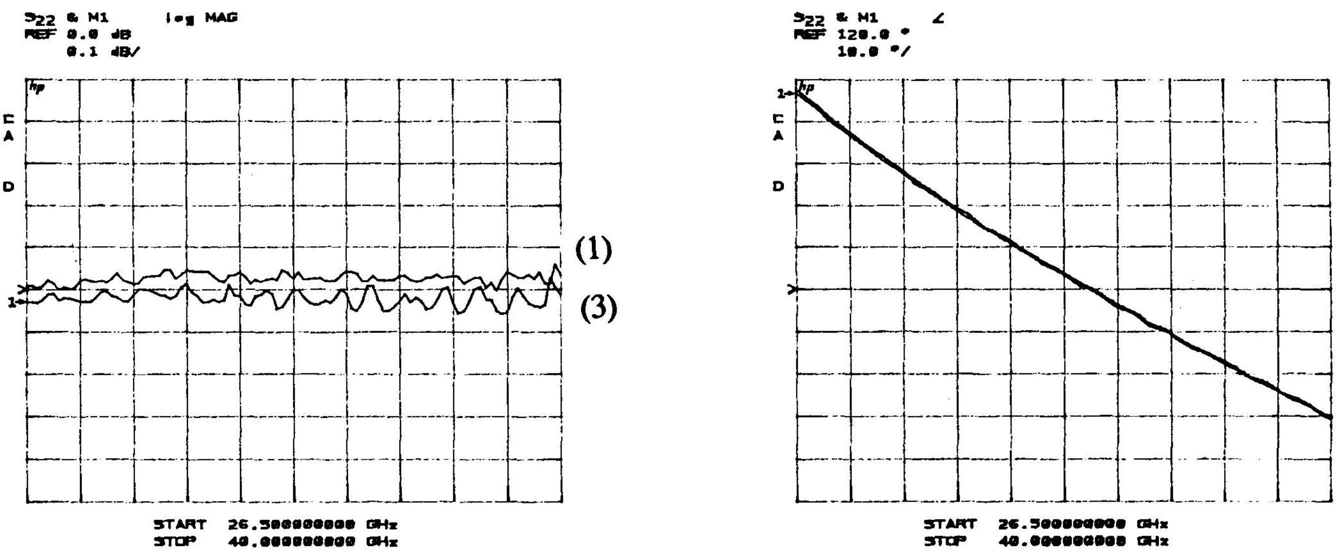

Figure 1 Ka-band waveguide shifted-short mesurement

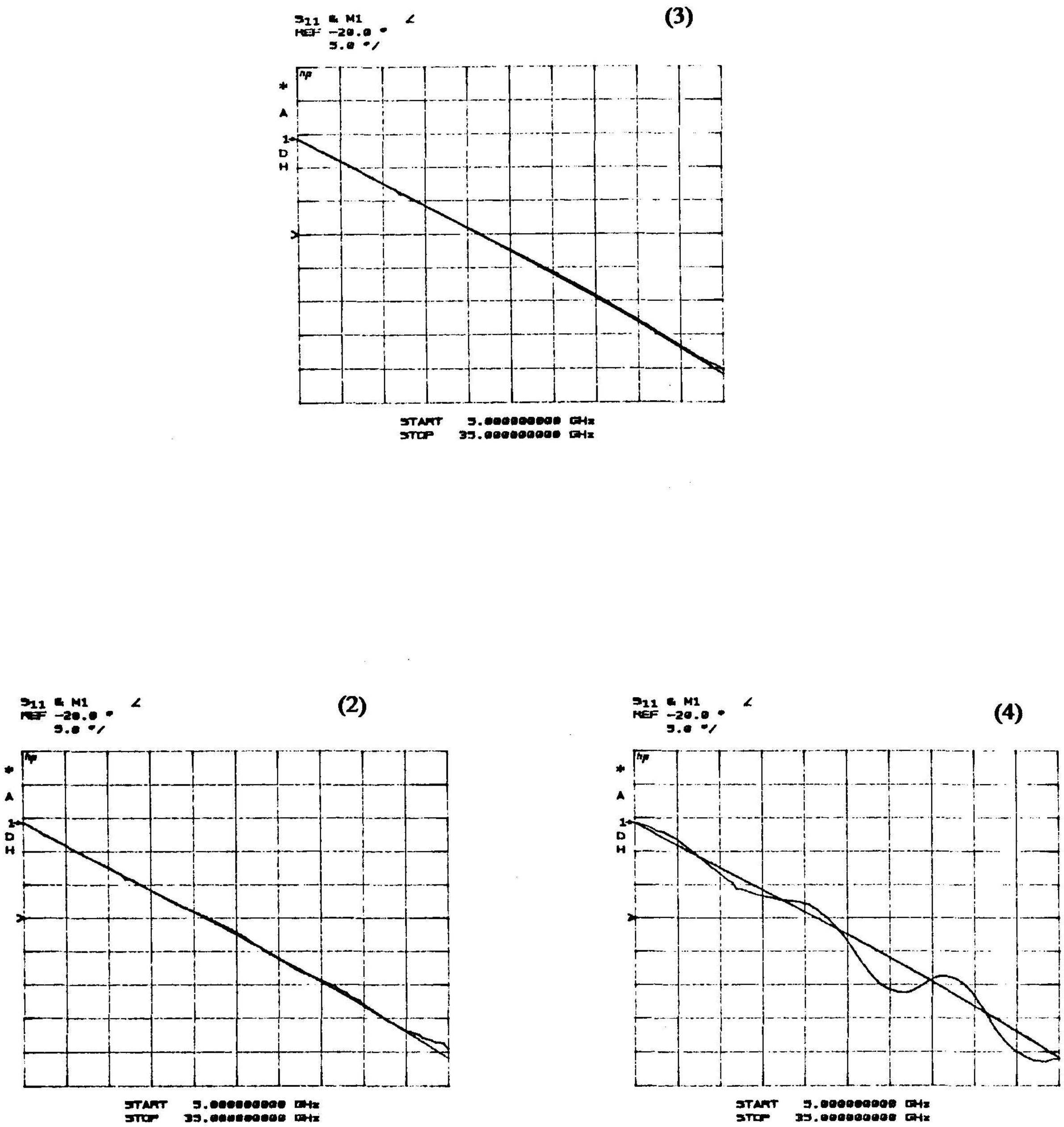

Figure 2 Coaxial open circuit measurements compared to the theoretical characteristics

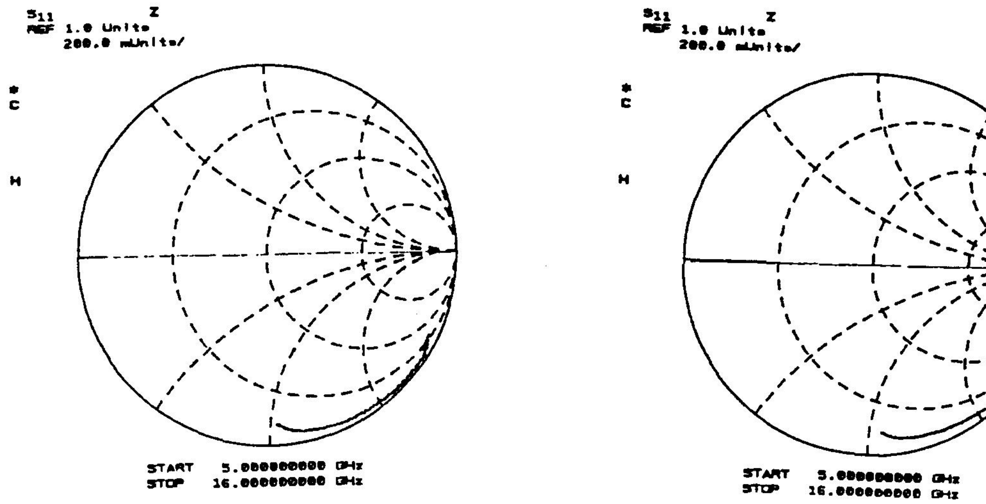

Figure 3 JS-8830-AS measured S_{11} parameter using TRL and LMR (known REFLECT) and a Microstrip Test-Fixture.

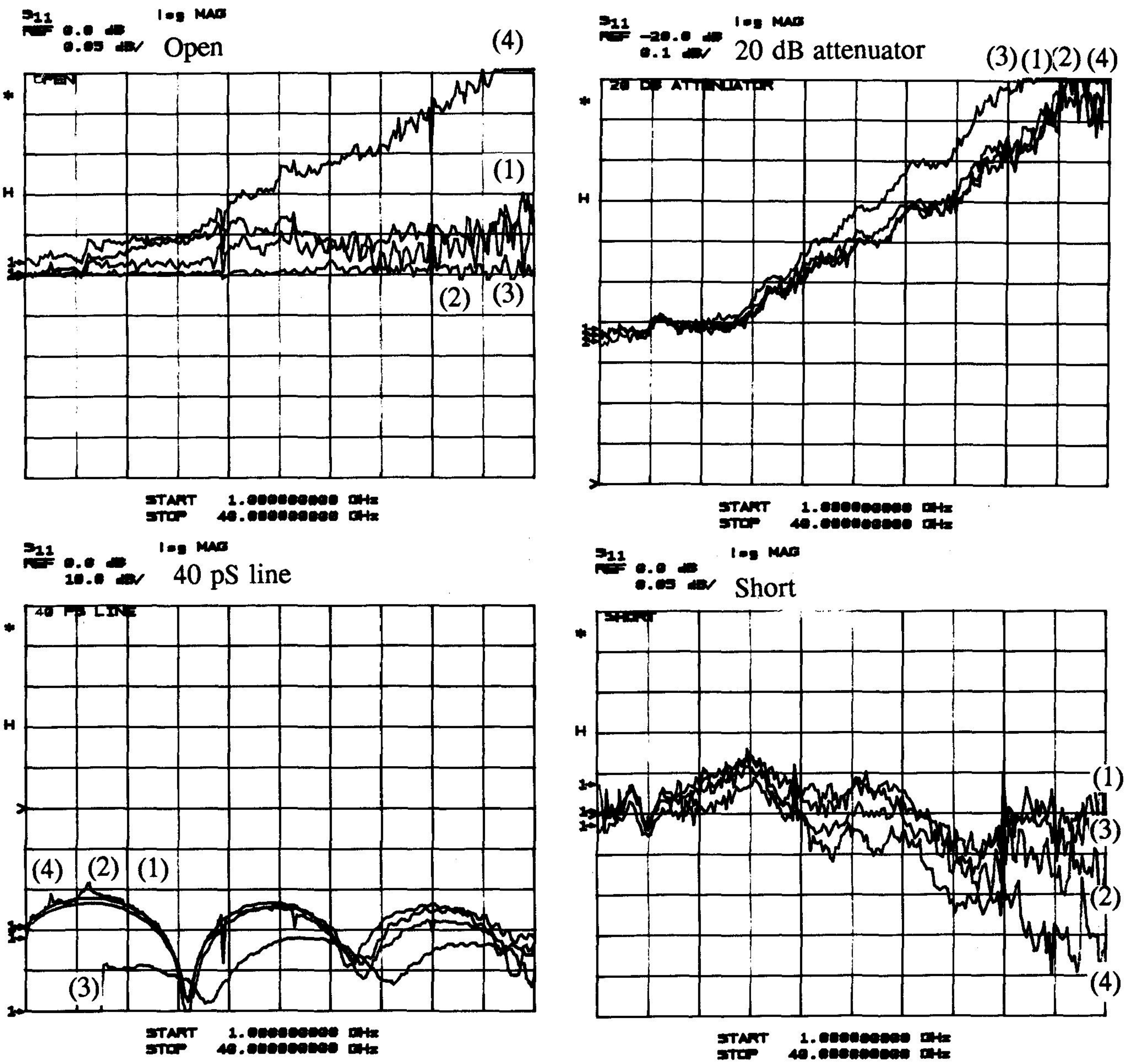

Figure 4 On-wafer measurements. 1-40 GHz.