VNA-Based Material Characterization in THz Domain without Classic Calibration and Time-Gating

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***Abstract*— A method is presented to measure materials and extract the complex permittivity without using classic VNA calibrations and time-gating. It is based on normalization to a "Thru" connection and analyzing error-terms and multiple-reflection phenomena. Measurement results (in free-space) are presented in 75-110 GHz and 500-750 GHz bands. Normalization technique can reduce the overall measurement uncertainties and simplify the material characterization process.**

***Index Terms*— Material characterization, parameter extraction, VNA time-gating, RF metrology, measurement uncertainty.**

I. Introduction

Free-space calibration techniques are complicated in THz domain because of precise-positioning challenges and lack of reliable Short and Line standards. Actually, non-perfect calibration together with time-gating attribute more uncertainties to the final extracted material parameters. Here, we try to use a simple normalization process, analyze/correct the error-terms and then reduce the standing-waves effects. Fig. 1 shows VNA measurement error-terms and the relations between $S_{(measured)}$ and S_{DUT}.

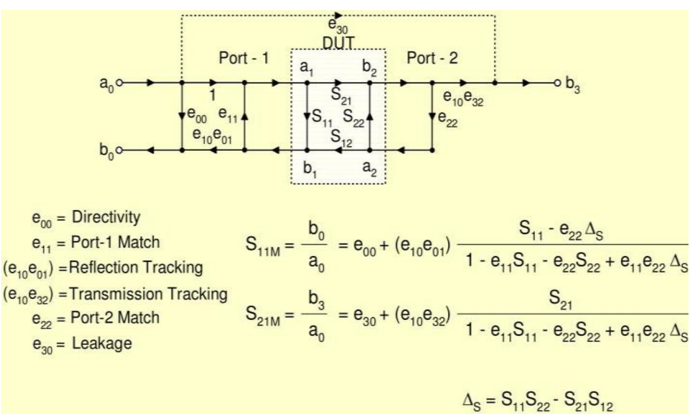

Fig. 1. VNA measured S-parameters ($S_{ij.M}$), error-terms (e_{ij}) and DUT S-parameters (S_{ij}) (courtesy to IEEE-MTT Society).

Ignoring the leakage-term and assuming for DUT ($S_{21.DUT}$, S_{11}=S_{22}) and Thru-connection (S_{21}=S_{12}=1, S_{11}=S_{22}=0), yield:

$$\rightarrow S_{21}(DUT) = \frac{S_{21.M}(DUT)}{S_{21.M}(Thru)} \times \frac{1 - e_{11}e_{22}}{1 + e_{11}e_{22}(S_{11}{}^2 - S_{21}\,S_{21}) - S_{11}(e_{11} + e_{22})} \qquad (1)$$

we can analyze the error-terms of Eq. 1 by looking at the Fabry-Perot effects inside a material-slab (MUT). If the material is not very lossy, $|S_{21}|$max. and $|S_{11}|$min. occur simultaneously [1] at the frequency-points for which $\phi(S_{21}) = n\pi$. Therefore, at $|S_{11}|$min. ($|S_{21}|$max. ≈ 1 & $|S_{11}|$min.≈ 0, for low-loss materials):

$$\rightarrow S_{21}(MUT) = \frac{S_{21.M}(MUT)}{S_{21.M}(Thru)} \; \frac{1 - e_{11}e_{22}}{1 - e_{11}e_{22}\,(S_{21}\,S_{21})} \qquad (2)$$

As deduced from Eq. 2, error-terms and system multiple-reflection on S_{21}(MUT) all approximately vanish for $|S_{21}|$max. & $\phi(S_{21})=n\pi$ points. This is demonstrated for two low-loss materials (Fig. 2: Pyrex and Quartz, 500-750 GHz).

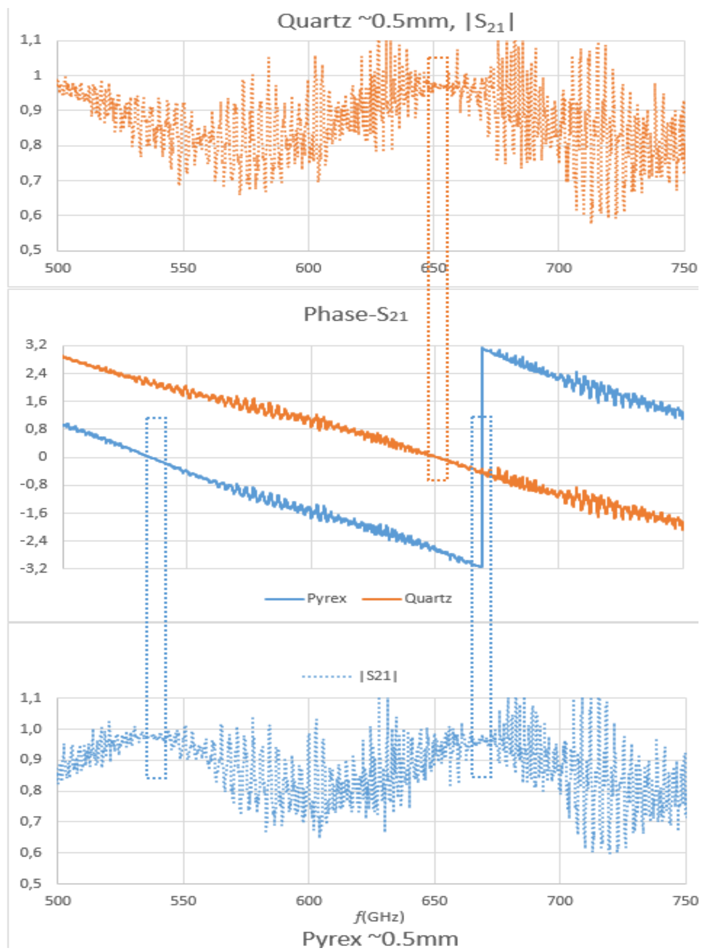

Fig. 2. Normalized S_{21}(MUT): Pyrex and Quartz, 500-750GHz.

Actually, reliable results of S_{21} even for a limited number of points in a given frequency-range are of interest. "Normal" homogeneous materials have nearly constant permittivity (slight rising of imaginary-part with the frequency) in mm-wave/THz domain. Permittivity can be extracted at "best" points of S_{21} (phase and amplitude) using relevant extraction methods [2]. Fig. 3 show the results for a low-loss material (Quartz) and a thicker slab of Plexiglass. The free-space mode-convertor here is Swissto12-MCK@ set of two corrugated horn antennas. The device is supposed to convert waveguide propagation modes to TEM on its aperture where the MUT is installed.

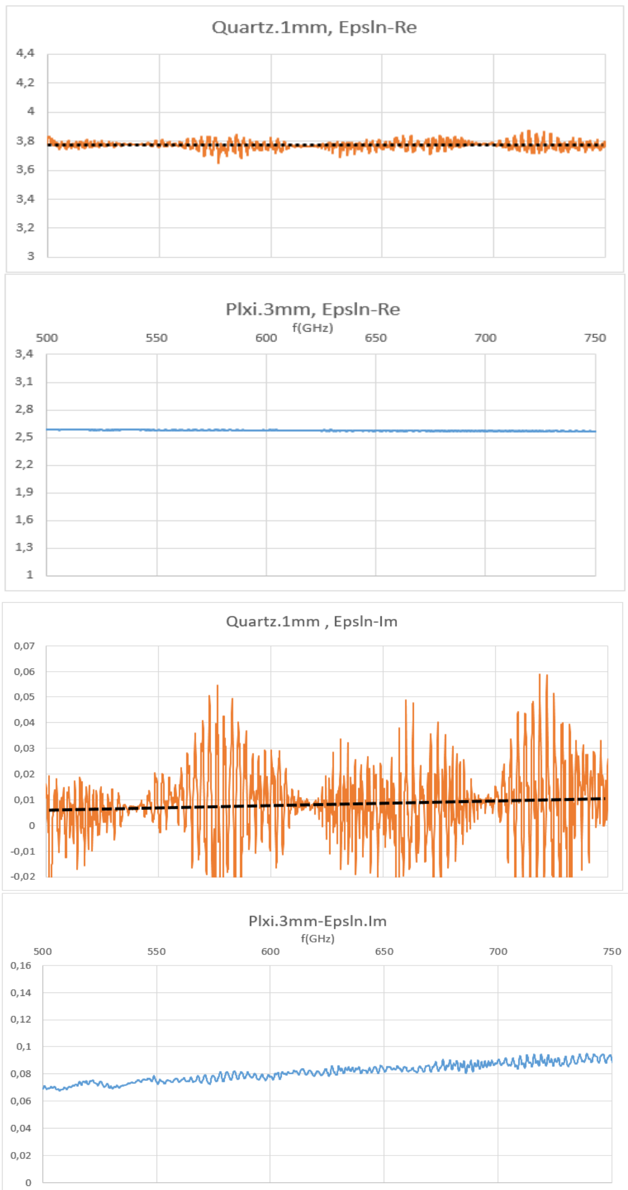

Fig. 3. Permittivity (Epsilon real & imaginary parts) of Plexiglass-3mm and Quartz-1 mm, 500-750 GHz.

As shown in Fig. 3, for a thicker material which is not very low-loss (Plexiglass, for example) multiple-reflection effects are less apparent because of energy damping in the MUT.

II. Reducing Multiple-Reflection Effects

From the VNA error-terms (Eq. 1-2), we can see S_{11}(DUT) and "$e_{11} + e_{22}$" have the most important roles. S_{11}(DUT) can be reduced over the whole frequency-range (from the VNA point-of-view) by tilting the MUT slab. Meanwhile, inserting low-reflection absorbers will decrease "e_{11} & e_{22}".

Besides, we are working on some new techniques based on "standard-known" material instead of classic "Line" that can help to calculate "$e_{11} + e_{22}$", directly.

A thin slab of low-loss materials (HR-Si, Quartz, Alumina …) can be characterized as the "standard-known" load (the "best points" of S_{21} are enough in this case), and used as "Line" to calculate the error-terms.

The above-mentioned methods have been successfully tested for the 75-110 GHz band (Fig. 4), and are in progress for the 500-750 GHz frequency-range.

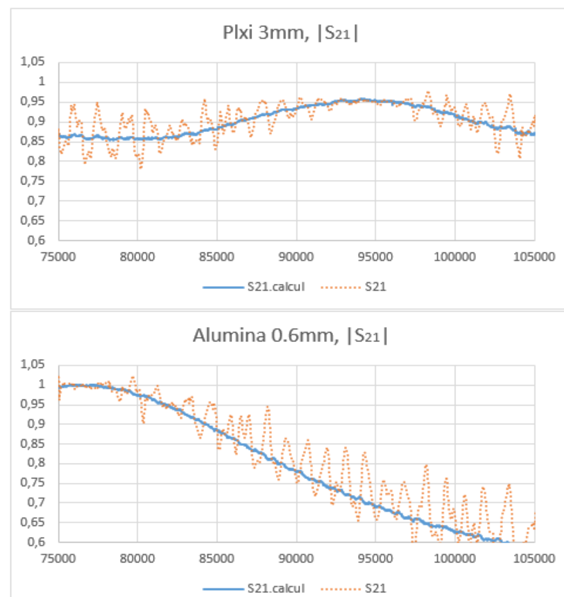

Fig. 4. Methods to reduce the multiple reflections, $S21|_{normalized}$ raw and corrected: 75-110 GHz, Alumina-0.6mm and Plexiglass-3mm.

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