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Comparison between time- and frequency-domain high-frequency device characterizations

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***Abstract* — We characterize a high-frequency device consisting of coplanar and coaxial elements using time- and frequency domain methods. As frequency-domain technique we employ conventional vector network analysis, while as time-domain technique a recently developed laser-based vector network analyzer is used. This allows us to compare both methods in the frequency range from 10 GHz to 110 GHz for the first time. We obtain good agreement in almost the entire frequency range.**

***Index Terms* — high-frequency devices, vector network analyzer, electro-optic sampling.**

I. Introduction

High-frequency devices are usually characterized in the frequency domain using electronic vector network analyzers (VNA) [1]. Yet, the advent of femtosecond laser technology also enabled the characterization of such devices in the time domain. Corresponding methods have already been employed for the characterization of oscilloscopes [2,3] or photodiodes [4]. Although laser-based optoelectronic techniques have an incredibly large bandwidth and are assumed to provide traceability to the SI, corresponding verification does not exist. With regard to frequency-domain VNA measurements, traceability for planar circuits is currently being developed within the new European project PlanarCal [5].

Recently, we have demonstrated a one-port laser-based optoelectronic VNA [6], where femtosecond laser pulses are used to measure voltage signals in the time-domain on a planar waveguide. The separation between forward and backward propagating signals, being the key task of VNAs, is realized by measuring voltage signals at different positions on the planar waveguide. With this improvement laser-based techniques can now be used to perform vector network analysis considering every type of mismatch [6].

Here we characterize a device under test using both, laser-based and conventional VNAs. We measure the DUT's scattering parameter $\mathbf{S}_{12}$ with both methods and obtain good agreement in the frequency range from 10 GHz to 110 GHz. Our study constitutes a successful first step for independent validation of time-domain and frequency-domain methods for which very different physical properties (electric fields and power waves, respectively) are measured.

II. Device under test

Our device unter test (DUT) consists of several different elements and is pictured in Fig. 1. A 20-cm long semirigid cable is connected to a coaxial-coplanar microwave probe both having 1.0-mm coaxial connectors. The microwave probe is attached to a 2-mm long coplanar waveguide (CPW). While the end of the CPW constitutes port 1 with a characteristic impedance $\mathbf{Z}_{\mathrm{CPW}}$ being complex at low frequencies [6], the end of the coaxial semi-rigid cable constitutes port 2 with a characteristic impedance taken as 50 Ω. Our comparison will focus on the $\mathbf{S}_{12}$ scattering parameter, see also Fig. 1, with the characteristic port impedances as noted above, i.e., no impedance transformation is performed.

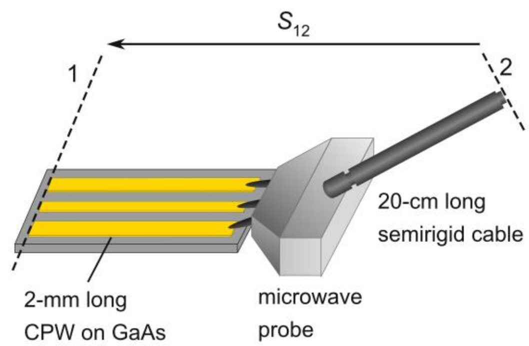

Fig. 1: Device under test and definition of scattering parameters.

III. Frequency-Domain Technique: Conventional VNA

For the frequency-domain measurement of $\mathbf{S}_{12}$ of our DUT we split up the DUT of Fig. 1 in two parts: the planar-coaxial part consisting of the 2-mm CPW length and the microwave probe, and the 20-cm semirigid cable part with coaxial 1.0-mm ports. For characterizing the semirigid cable we first performed a two-port 1.0-mm calibration as recommended by the manufacturer of the broadband VNA system (Anritsu VectorStar). This calibration consists of a low-band and high-band part employing different calibration standards suitable for the respective band, which are merged afterwards to provide the bandwidth from 1 to 110 GHz used in this experiment. For characterizing the planar-coaxial part, we utilized the two-port second-tier procedure described in [7]. To this end, two microwave probes from the same manufacturer with the same GSG footprint were employed. We used the same two-port 1.0-mm calibration as in the semirigid cable characterization part to establish the coaxial reference plane at the coaxial ports. Then, we contacted CPW artifacts of different lengths together with a reflect standard on the low-loss GaAs substrate. Using these measurements, we performed a second-tier Multiline-TRL calibration [8], moving the on-wafer reference plane into the middle of a 4-mm long CPW. Even though possible, we did not normalize the reference impedance at the on-wafer port to 50 Ω. The characteristics of the planar-coaxial part of the DUT were obtained as error boxes from the second-tier calibration.

IV. TIME-DOMAIN TECHNIQUE: LASER-BASED VNA

The laser-based setup is described in detail in [6]. Ultrashort voltage pulses are generated by focusing a laser beam (~350 fs pulse width, ~800 nm center wavelength) onto a biased photoconductive gap, which is integrated into a 4-mm long CPW. The CPW is evaporated onto low-temperature-grown GaAs with a carrier life time ~1 ps enabling the generation of very short voltage pulses. A second laser beam (~100 fs pulse width, ~1600 nm center wavelength), which is synchronized to the first laser beam is used to measure the electric field of the voltage pulses by employing the electro-optic effect of the GaAs substrate and a typical electro-optic detection set-up. By changing the time delay between the two laser pulses the shape of the voltage pulse is obtained.

Measurement of two voltage pulses $\mathbf{V}_1$ and $\mathbf{V}_2$ at different positions on the CPW allows for the separation of forward and backward propagating voltage signals [6]. This in turn enables us to calculate the complex reflection coefficient at the CPW measurement plane, which we place 2 mm away from the end of the CPW. Attaching the microwave probe with the semi-rigid cable to the CPW, we obtain our DUT. If the coaxial end of the DUT is terminated with a short the reflection coefficient at the CPW measurement plane will be equal to:

$$\mathbf{\Gamma}_{\mathrm{CPW}} = \mathbf{S}_{11} + \frac{\mathbf{S}_{12}\mathbf{S}_{21}\mathbf{R}_S}{1-\mathbf{R}_S\mathbf{S}_{22}}\,. \tag{1}$$

Here $\mathbf{\Gamma}_{\mathrm{CPW}}$ and $\mathbf{S}_{11}$ are functions of the two measured voltage pulses with $\mathbf{\Gamma}_{\mathrm{CPW}} = f_1(\mathbf{V}_1, \mathbf{V}_2)$ and $\mathbf{S}_{11} = f_2(\mathbf{V}_1, \mathbf{V}_2)$. While it is not possible with our one-port laser-based VNA to measure $\mathbf{S}_{22}$ precisely, its magnitude and phase which enters (1) can be estimated from a part of the time-domain reflection coefficient $\mathbf{\Gamma}_{\mathrm{CPW}}$. The magnitude and phase of the reflection coefficient of the short $\mathbf{R}_s$ is obtained from numerical calculations [2]. After additionally considering the reciprocity relation $\mathbf{S}_{21}/\mathbf{S}_{12} \equiv f_3(\mathbf{Z}_{\mathrm{CPW}}, 50\,\Omega)$ as defined in [9], it is possible to solve (1) for $\mathbf{S}_{12}$.

The uncertainty analysis for the time-domain measurements is performed with Monte-Carlo simulations. In this analysis, the probability density functions of the input variables have either been obtained from repeated measurements or from other information.

V. DISCUSSION AND CONCLUSIONS

The amplitude of our DUT's $\mathbf{S}_{12}$ parameter obtained from both the time- and frequency domain methods are shown in Fig. 2. With the conventional VNA we obtain data up to 110 GHz limited by the calibration-kit definitions provided by the manufacturer. The effective bandwidth of the time-domain VNA is mainly limited by the width of the ultrashort voltage pulses. We typically obtain spectral components >500 GHz [6]. Below 10 GHz the uncertainty of the time-domain result is very large. This is mainly due to the measurement over limited time windows and the subsequent data analysis. Therefore we only compare the range from 10 GHz to 110 GHz. We obtain a good agreement between both techniques, although the 95% confidence intervals do not overlap at every frequency point. In this regard we emphasize two things: (i) The model from which the time-domain results were extracted is not perfect and might contain some small systematic errors. (ii) The uncertainty analysis for the frequency-domain measurements is still under development [5]. We believe that this might explain the differences at certain frequencies between the time- and frequency-domain results. In any case we take our results as a first encouraging step towards mutual verification of time- and frequency-domain high-frequency device characterization.

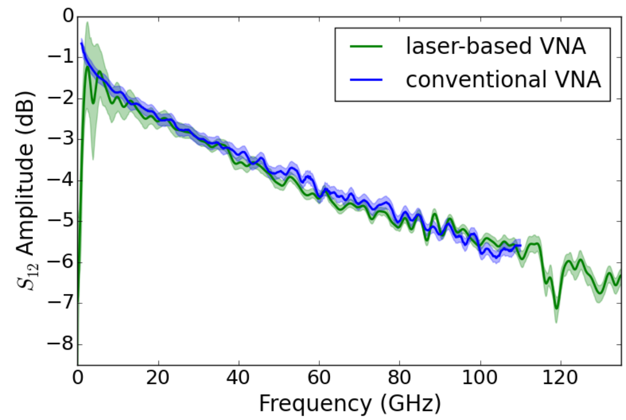

Fig. 2: Amplitude of $\mathbf{S}_{12}$ of the DUT obtained from the time- and frequency-domain techniques (thick lines). The 95% confidence intervals are marked by the light semi-transparent colors.

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