On-Wafer Calibration Techniques and Applications at V-Band

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***Abstract*—There is considerable interest in HEMT MMIC applications operating at V-band and higher frequencies due to their low noise, high power, and high power efficiency capability. A quantitative investigation of calibration methods have been performed to study the effect of calibration techniques on V-band device measurements and model development. This work compares SOLT, LRM, and multi-line TRL calibrations relative to each other. The analysis is then applied to pseudomorphic InGaAs HEMT devices to provide useful information on the effect of calibration on small signal-intrinsic parameter extraction at V-band.**

I. Introduction

HEMT MMIC Technology is attractive for V-band and higher frequency applications due to their low noise, high power, and high power efficiency capability. InGaAs/InAlAs/InP discrete HEMT's have demonstrated excellent noise figures of 0.7 dB at 60 GHz [1]. Recently, HEMT MMIC's have been demonstrated at V-band and higher frequencies. A V-band 3-stage InP HEMT MMIC LNA has demonstrated 3-dB noise figure and 24-dB associated gain from 56–64 GHz [2]. A 2-stage pseudomorphic (PM) InGaAs HEMT MMIC power amplifier demonstrated 371 mW output power with 11% efficiency [3]. Although these are state-of-the-art results, there is considerable room for improvement.

To enhance the design and performance of these MMIC's, it is essential to improve the accuracy of S-parameter measurements at V-band. The continued development of V-band components requires careful study of the effect of calibration techniques on accurate device model development. Here, we report a systematic investigation of the effect of short-open-load-thru (SOLT), line-reflect-match (LRM), and multi-line thru-reflect-line (TRL) calibration relative to each other. The differences in calibration are especially relevant when operating at higher frequencies [4]. This analysis provides a foundation for the effect of calibration on active device parameter extraction at V-band and other millimeter-wave frequencies.

Manuscript received June 24, 1994. This work was supported in part by research grants from Cascade Microtech, Hewlett-Packard, and TRW.

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IEEE Log Number 9405762.

II. Experimental Technique

Using Cascade Microtech V-band probes [5] and the HP 85109E75 [6] network analyzer (ANA), a quantitative study of calibration conditions and their effect upon active device characterization at millimeter-wave frequencies is presented. For this experiment, we selected a pseudomorphic (PM) HEMT ($In_{0.22}Ga_{0.78}As$ channel, L_g =0.15 μm, W_g =100 μm and biased at V_{ds} =2 V and 100% of I_{dss}) as the DUT. This device typically demonstrated a transconductance of 500 mS/mm and cutoff frequency of 90 GHz.

In our experiment, we used standards from a Cascade Microtech LRM ISS (for SOLT and LRM calibrations) and TRL standards provided by NIST. The LRM and TRL standards are fabricated on a 635-μm alumina substrate and 500-μm GaAs substrate, respectively. As has been previously reported [7], the SOLT calibration technique depends on a precise model of each standard used. These models include open circuit capacitance (open is measured with the probes in air), short circuit inductance (inductance of a shorting bar), inductance of the load, and length of the thru line (coplanar wave transmission line). The LRM calibration does not require precise knowledge of the reflect standards only that they exhibit a high reflection coefficient, e.g., open with probes in air. The LRM assumes all other standards to be ideal. The TRL calibration does not depend on precise knowledge of the reflect standards; in this case an offset short is used, however transmission line standards are assumed to be ideal. The TRL calibration is performed using an algorithm developed by NIST [8]. In all three cases, isolation error terms have been neglected.

After calibrating the network analyzer using the SOLT, LRM, and TRL calibrations (and neglecting the effects of user repeatability errors), the resulting error terms may still be different. These differences can be attributed to assumptions made during calibration.

In order to quantify these differences, we study the effect of calibrations on active device measurements. The results presented in this paper are based on the following procedure (see Fig. 1): 1) Generate small-signal models based on S-parameter measurements through V-band. 2) The modeled S-parameters (referred to as ideal S-parameters in Figs. 1 and 3 are un-calibrated and re-calibrated using different permutations of the SOLT, LRM, and TRL error terms, and 3) Perform small signal intrinsic parameter extraction [9]. This procedure allows an accurate prediction to the effect of calibration differences on active

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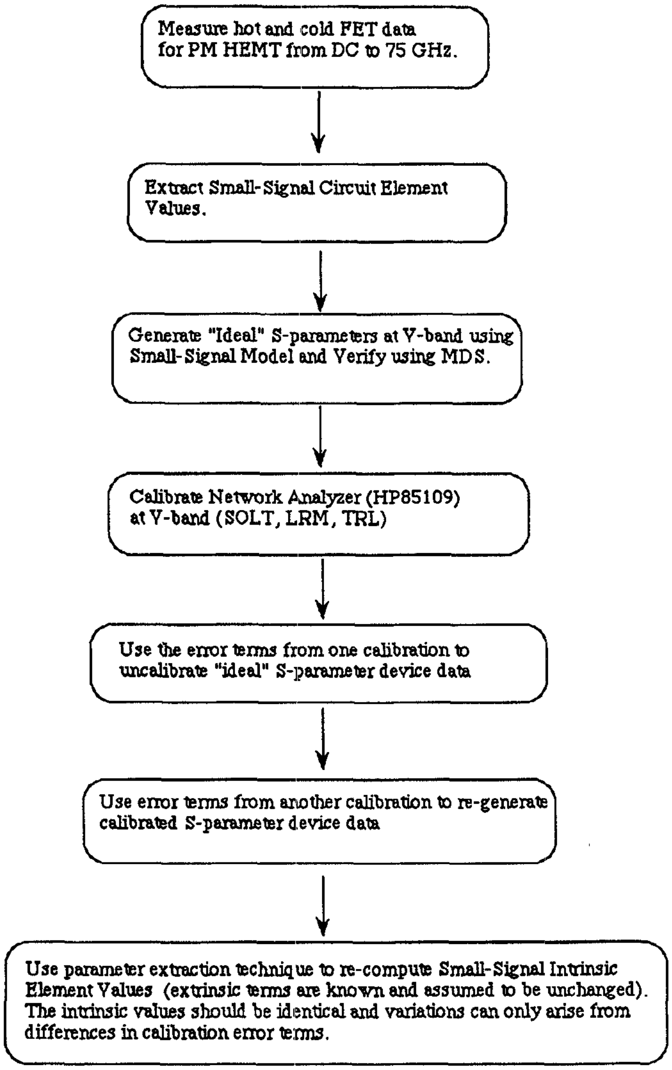
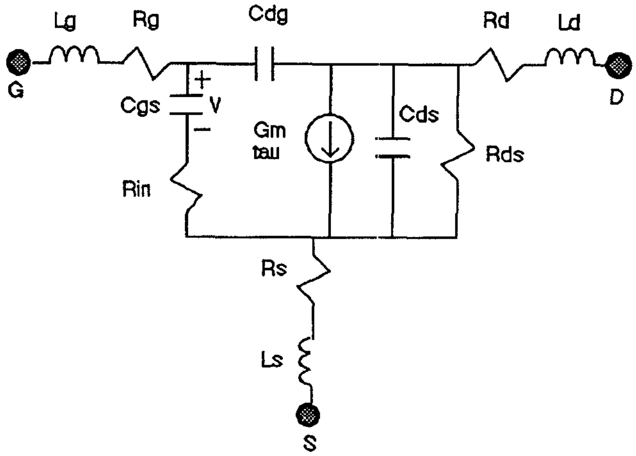


Fig. 1. Flow chart representing steps used for experimental study to determine effect of calibration on intrinsic parameter extraction at V-band.



Cdg	Cgs	Cds	Rds	Rg	Rs	Rd	Rin	Lg	Ld	Ls	Gm
(fF)	(fF)	(fF)	(Ω)	(Ω)	(Ω)	(Ω)	(Ω)	(pH)	(pH)	(pH)	(mS)
8.0	52	10	321	1.0	2.5	3	8.0	15	2.5	2	39

Fig. 2. Hybrid-π model used to fit S-parameters. The element values were extracted using the technique presented in [8]. The extracted values are for PM HEMT with $In_{0.22}Ga_{0.78}As$ channel, L_g =0.15 μm, W_g = 100μm, V_{ds} =2 V, and 100% I_{dss}.

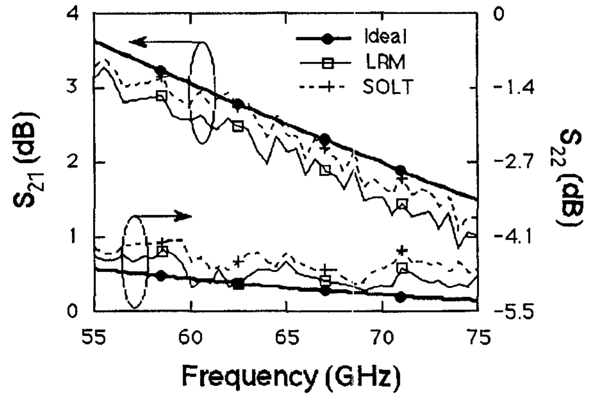


Fig. 3. Effect of un-calibrating modeled (or "ideal") S-parameters with TRL calibration and re-calibration with LRM and SOLT calibration for PM HEMT at V-band. The PM HEMT has L_g =0.15 μm with 22% Indium channel composition.

device intrinsic parameter extraction, with known extrinsic parameters.

III. Results and Discussion

The hybrid-π (see Fig. 2) small signal parameters values are obtained from measurements in our laboratory and validated based on the Hot/Cold FET extraction technique. Additional details can be found in [9], [10]. Calibration sets generated by performing SOLT, LRM, and TRL calibrations are compared relative to each other. In Fig. 3, we show the effect of un-calibrating the model (or ideal) S-parameters of a PM HEMT with a TRL calibration and re-calibrating with the SOLT and the LRM calibration.

The re-calibrated S-parameter data is used to uniquely calculate the small-signal intrinsic element values of the PM HEMT using the algorithm outlined in [9]. To compare the effect of calibration on parameter extraction, we assume the device extrinsic parameters remain unchanged after re-calibration. A valid comparison for the effect of calibration on parameter extraction is achieved by calculating the intrinsic small-signal element values based upon re-calibrated S-parameters (un-calibrated and re-calibrated using two different calibration sets). The results are shown in Fig. 4.

The variation of Rds for the SOLT calibration relative to either of the other calibrations is due to the modeling of the open and short standards. A first-order frequency-dependent model for the probes in air is used, which may not be accurate at V-band. The variation observed in intrinsic capacitance elements and device transconductance is small and primarily due to the different substrate materials. In addition, differences in the calibrations can arise from the transition between probe tip and standards [4]. Additional differences in calibration arise from probe placement and the effect of isolation error terms.

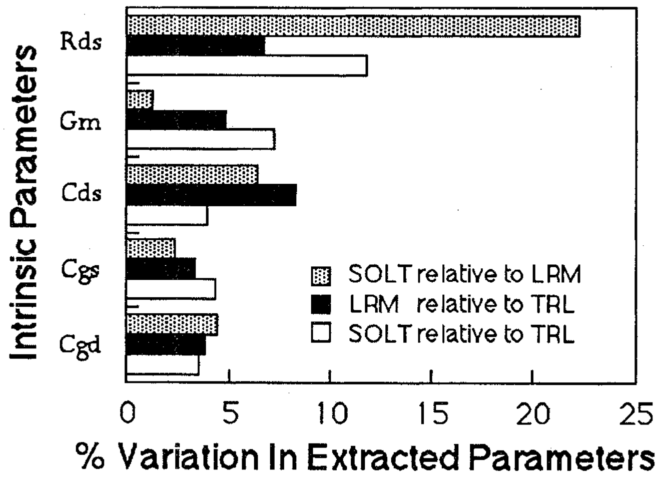


Fig. 4. Variation of extracted small-signal parameters due to different calibration techniques at V-band.

In conclusion, an experimental procedure is presented to quantify the effect of device measurements and parameter extraction at millimeter-wave frequencies. We demonstrate that the choice of calibration can significantly affect parameter extraction at V-band. Future investigations need to be performed to study these differences and improve calibration assumptions.

ACKNOWLEDGMENT

The authors would like to acknowledge the helpful comments of Ed Godshalk from Cascade Microtech and Dylan Williams of NIST.

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