A NOVEL MILLIMETER-WAVE HEMT NOISE MODELING PROCEDURE

M. D. DuFault, Johnny Z. Lin and Arvind K. Sharma

TRW Electronic Systems and Technology Division
One Space Park, Redondo Beach, CA 90278

Abstract

Significant improvements in the accuracy of noise models of millimeter-wave HEMT devices are obtained using on-wafer noise prematched structures and through enhanced accuracy of calibration. This procedure enables scaling of device noise models obtained at microwave frequencies to millimeter wave frequencies. Good correlation between noise parameters of scaled devices with experimental data at millimeter wave frequencies is obtained.

Introduction

Modern millimeter wave receivers demand excellent noise figure performance. This requires the low noise amplifier to be as near to optimum as possible. The successful design of these low noise amplifiers depends heavily on the existence of an accurate device noise model.

At present, millimeter wave low noise amplifiers are designed utilizing scaled and extrapolated HEMT noise models of relatively large periphery devices measured below 26 GHz [1]. Because of the inaccuracies in the noise models and the need to both scale and extrapolate to higher frequencies, the use of the resultant model invariably leads to several design iterations.

The accuracy of the noise parameter measurements depends substantially on the accuracy of the S-parameter calibration. The experimental data reveals that changes in the calibration kit parameters that only slightly affect the S-parameters produce significant changes in the shape of the optimum noise source impedance over frequency. Also, it is difficult to extract the value of gate resistance exactly. Errors in the value of gate resistance that are inconsequential below 26 GHz can have a significant effect at higher frequencies.

In this paper, we shall present a novel procedure that significantly improves the accuracy of noise models of HEMT devices at millimeter wave frequencies. In this procedure, on-wafer prematched noise test structures are designed, fabricated and tested at microwave (2 to 26.5 GHz) and millimeter-wave frequencies (33-50 GHz). An accurate device model is developed using the microwave frequency test data and then scaled and verified with the millimeter-wave frequency test data. This approach incorporates device scaling and provides a thoroughly verified noise model which can be extrapolated to V- and W-band frequencies.

Calibration Improvements

Noise parameter measurements depend heavily on the S-parameter calibration. The low frequency noise parameter tests were done using the ATN NP5 noise parameter test set. The test algorithm depends heavily on S-parameter data to determine the source impedances presented to the device by the tuner, device S-parameters and the load impedance. As a result, the measured noise parameters are sensitive to S-parameter calibration [9]. Figure 1 shows the effect of changing the s-parameter calibration kit in the network analyzer on both the s-parameters and the noise parameters. The original calibration that produced the upper Zopt curve in figure 1 was based on electromagnetic simulations only and the lower curve resulted when the open circuit capacitance of the original calibration was adjusted slightly to place the measurement of an offset open precisely on the edge of the Smith Chart. A calibration kit change that only slightly affects the S-parameters produces significant changes in the value of optimum noise source impedance. Also, extrapolation of the two sets of data in figure 1 to millimeter wave frequencies would clearly give quite different values for the optimum source impedance.

A verified calibration kit was developed to reduce

CH3577-4/95/0000-0939$01.00 © 1995 IEEE

errors in the noise parameters due to the S-parameter calibration. The calibration kit was developed using a TRL (thru, reflect, line) calibration to measure the SOLT (short, open, load, thru) standards. The SOLT standards are preferred for on wafer calibration because they are compact. However, the impedance standards must all be well known for the calibration to be correct and analysis of planar impedance standards is difficult, especially for a resistive load [2]. The TRL standards require relatively long line standards, but produce a more accurate calibration. For TRL, only the characteristic impedance of the thru and line standards need be known exactly [4]. These quantities are more easily calculated or measured.

We calculated the characteristic impedance for our coplanar thru and line standards using Sonnet electromagnetic simulation software [5]. The reflect standard was a coplanar short offset 10um from the probe pads. After calibration by the TRL method, we measured the S-parameters of our SOLT standards. Using the measured S-parameters of the SOLT standards we developed an new calibration kit. The new SOLT calibration kit was then used to measure noise parameters of 100 and 200um devices from 2-26 GHz using the ATN noise parameter test set. Further investigation of the calibration kit will include measurements of offset short, open and loads as verification standards.

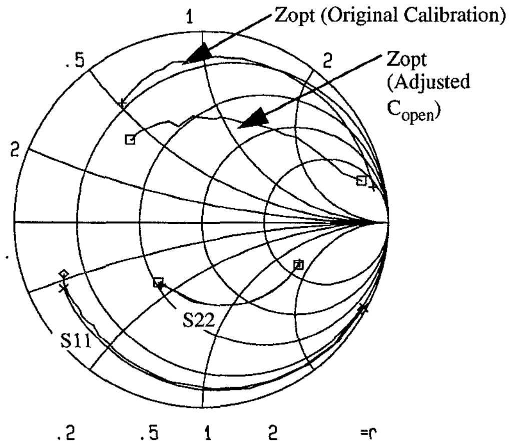


Fig. 1. Optimum source impedance, S11 and S22 for a 200um HEMT at 2V, 40% peak Gm current, from 2-26 GHz measured with two different sets of s-parameter calibration parameters.

Millimeter-Wave Noise Parameters

On-wafer noise prematched structures were developed to measure noise parameters of 40, 60 and 80um devices at 39 and 44 GHz. The test structures consist of an input 6 dB pad, an input matching circuit, the HEMT device and an output matching circuit. For each frequency and device size of interest, five test structures were designed. Each of the five structures had the same input pad and output matching circuit. The input pad serves to reduce the effect of probe VSWR on the source impedance presented to the device and the output matching circuit helps raise the gain of the structure. The design of the input matching circuits was based on noise parameters extrapolated by the previous method. One of the structures was designed for minimum noise figure and the others for noise figures going up from the minimum in 0.5 dB steps.

The noise figure of the test structures was measured using a commercially available Q-band high ENR noise source and an existing TRW MMIC Q-band low noise amplifier as a post amplifier. A commercially available Q-band downconverter was used to bring the IF to 30 MHz for reading by an HP 8970B noise figure meter. The 39 GHz structures were measured from 35 to 43 GHz and the 44 GHz structures were measured from 40 to 48 GHz. The bias was applied through a pair of external bias tees. The loss of the wafer probes was taken into account by measuring the total loss of both probes with an on-wafer microstrip thru and assuming that each probe accounted for half of the loss. No attempt was made to measure the impedance of the input probe or account for its effect on the noise figure measurements. Figure 2 shows a typical measurement over frequency of the noise figure of a set of five 44 GHz, 60um test structures. The measurement ripple is due to VSWR effects between the input probe and the 6 dB pad.

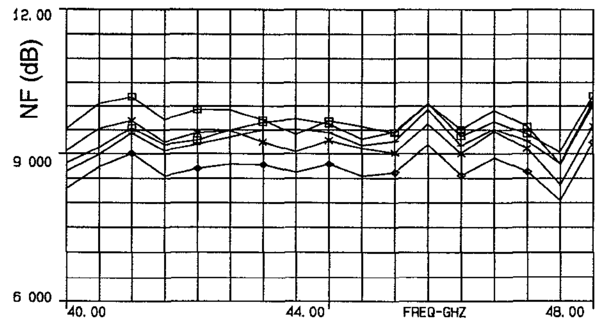


Fig. 2. Raw NF vs. frequency for a set of five pre-matched noise figure test structures each presenting a different source to a 60um HEMT biased at 2V and 40% of the peak Gm current.

Noise parameters for the HEMT device were then calculated from the measurements of the test structures noise figures. The 6 dB pads, input matching circuits and output matching circuits were all simulated using Sonnet [5] electromagnetic simulation software. The effects of the pad, input matching circuit and output matching circuit on the measured noise figure were removed using the well known system noise temperature equation using

T/To=1/(available gain)

for the effective noise temperature of the passive circuits. An existing small signal model for the device was used to calculate the noise parameters of the device. Since the source impedances were found entirely by calculation, they were assumed to have no random error and the noise parameters were found by a least square fit to the device noise figures using the conjugate gradient method [6].

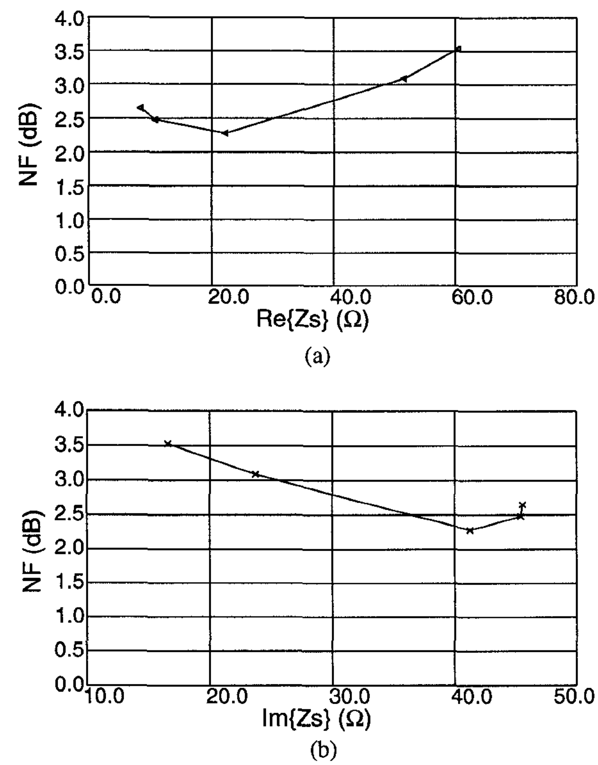
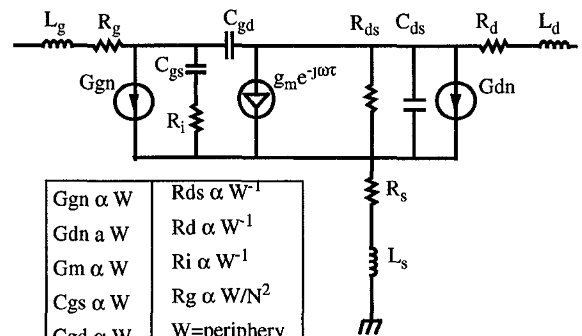


Fig. 3. Noise figure vs. source impedance at 44GHz after de-embedding device from the test structure. Data is for a 60um HEMT at 2V, 40% peak Gm current.(a) vs. Re{Zs} (b) vs. Im{Zs}

Device Model Development

A device model was developed using the topology of figure 4 [1,7]. Other HEMT noise model topologies have been proposed which may more accurately reflect the device physics [8] and these are also under investigation. The linear model parameters were chosen to fit to S-parameter data taken on the 60, 80 and 200um device sizes from 50 MHz to 50 GHz. The noise currents and correlation coefficient were chosen for the best fit possible to 2-26 GHz noise parameter data taken on the 200um devices and to the 35 and 44 Ghz data taken on the 60 um and 80 um devices (figure 6).



Ggn α W	Rds α W^{-1}
Gdn a W	Rd α W^{-1}
Gm α W	Ri α W^{-1}
Cgs α W	Rg α W/N^2
Cgd α W	W=periphery
Cds α W	N=no. fingers

Fig. 4. Device model topology and scaling equations.

Conclusion

A novel and accurate procedure for development of HEMT noise models was presented. This procedure overcomes errors that were inherent in previous millimeter wave noise models. The noise models can be scaled and extrapolated to millimeter wave frequencies with confidence. This model is currently being used for V- and W- band LNA designs.

References

[1] B. Nelson, et. al., "Octave Band InGaAs HEMT MMIC Low Noise Amplifiers to 40 GHz," 12th Annual IEEE GaAs IC Symposium, New Orleans, LA, Oct. 7-10, 1990, pp.165-168.

[2] D. F. Williams and R. B. Marks, "On-Wafer Impedance Measurement on Lossy Substrates," IEEE Microwave and Guided Wave Lett., vol. 4, no. 6, pp. 175-176, June 1994.

[3] V. Adamian and A. Uhlir Jr., "A Novel Procedure for Receiver Noise Characterization," IEEE Trans. on Instr. and Meas., vol. IM-22, no.2, pp. 181-182, June, 1973.

[4] R. B. Marks, "A Multiline Method of Network Analyzer Calibration," IEEE Trans. Microwave Theory and Tech., vol. 39, pp. 1205-1215, 1991.

[5] Sonnet Software. Sonnet Software, Inc., Liverpool, NY.

[6] W. Press, et al., *Numerical Recipes in C: The Art of Scientific Computing,* Cambridge University Press, Cambridge, MA, 1992.

[7] R. A. Pucel, H. A. Haus and H. Statz, "Signal and Noise Properties of Gallium Arsenide Microwave Field Effect Transistors", Advances in Electronics and Electron Physics, v. 38, 1975, pp. 195-265.

[8] M. Pospieszalski, "Modeling of Noise Parameters of MESFET's and MODFET's and Their Frequency and Temperature Dependence," IEEE Trans. Microwave Theory and Tech., vol. 37, no 9, Sept., 1989, pp. 1340-1350.

[9] J. R. Fenton, "Noise Parameter Data Comparison While Varying the On-Wafer S-Parameter Calibration Technique", 44th ARFTG Conference, Boulder, CO, Dec. 1994, pp. 89-97.

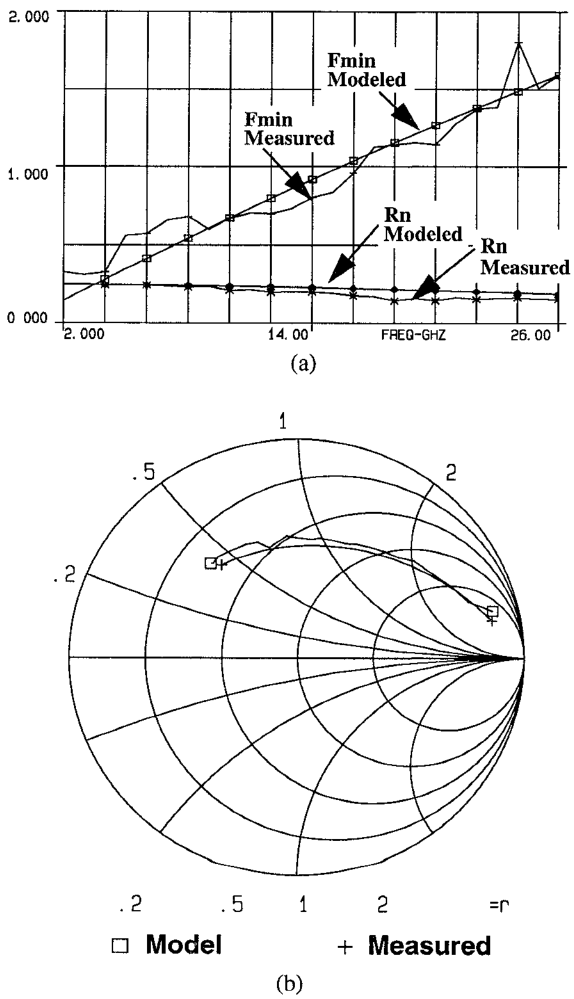


Fig. 5. Modelled vs. measured noise parameters for the 200um HEMT at 2V, 40% peak Gm, 2-26 GHz. (a) Fmin and Rn. (b) Optimum source impedance.

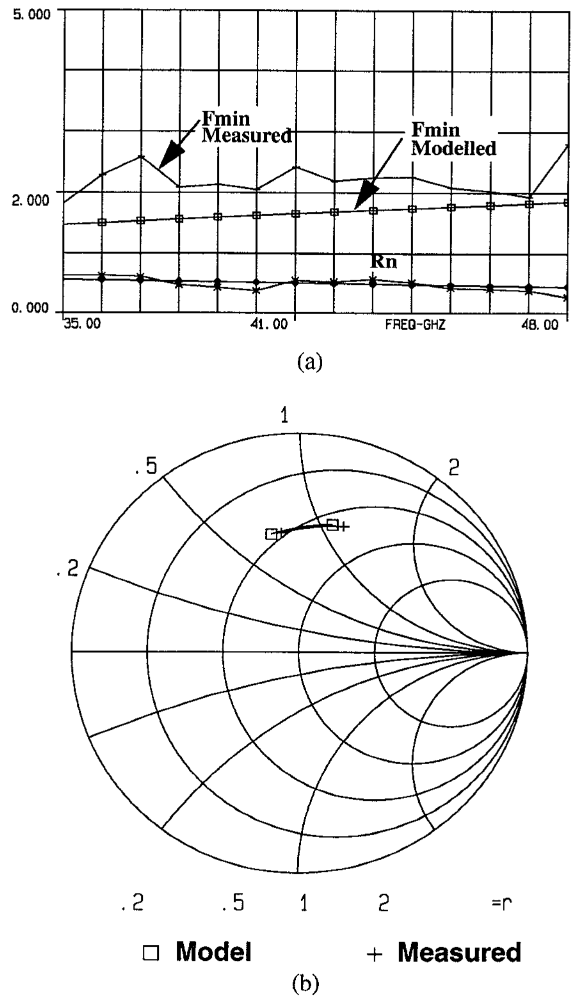


Fig. 6. Modelled vs. measured noise parameters for the 60um HEMT at 2V, 40% peak Gm, 35-48GHz. (a) Fmin and Rn. (b) Optimum source impedance.