HEMT Models for S-Parameter and Noise Parameter Extrapolation

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Abstract

Four models have been developed and assessed for fitting the measured noise parameters up to 26GHz and S-parameters up to 40GHz, for a commercial HEMT chip. The first treats the intrinsic noise sources as uncorrelated, thermal sources. The second is an extension of this, allowing a better fit to be achieved by including the distributed nature of the gate and drain electrodes using a semidistributed, sliced model. The third model neglects the distributed effect but takes into account the partial correlation of the gate and drain noise sources. This causes a larger improvement in the quality of fit, allowing the model to fit the measured data within reasonable measurement limits. Fourthly, the addition of the distributed effect to the correlated model allows a further marginal improvement, but the conditioning of the problem and the accuracy of the data appear to be insufficient to allow accurate extraction of the additional parameters needed.

Introduction

Accurate scattering and noise parameter data are essential for the design of low noise amplifiers. Scattering parameters for transistors are routinely measured up to 40GHz and beyond, but experimental determination of noise parameters at such high frequencies is extremely difficult and prone to large errors. The only noise parameter commonly published for frequencies above about 26GHz is the minimum noise figure, F_{min}. This provides insufficient information for the design of an amplifier, since the source reflection coefficient for minimum noise figure, Γ_{OPT}, and the equivalent noise resistance, r_n, are also required. The parameter r_n determines the sensitivity of the noise figure to deviations of the source reflection coefficient from Γ_{OPT}.

This paper compares four models which have been applied to the problem of fitting the manufacturer's measured noise parameters, up to 26GHz, and S-parameters, up to 40GHz, for the Toshiba HEMT chip, type JS8900-AS. The objective of this exercise was to generate realistic noise parameter data for 26 to 40GHz.

The models employed were :

1. A simple equivalent circuit in which the HEMT intrinsic noise sources are accounted for by the thermal noise of the gate to source and drain to source resistances, held at elevated temperatures. This is essentially the approach adopted by Pospiezalski [1].

2. An extension of the model 1, to include the effect of the distributed nature of the gate and drain electrodes at higher frequencies. This is achieved by introducing a sliced structure, similar to that used by Escotte and Mollier [2], with the first slice differing to allow for field differences in the gate feed region, as reported elsewhere by the authors [3].

3. An enhancement of the model 1 by the addition of a gate noise source, correlated with the drain noise, as described in detail in the next section.

4. A further development of model 3, by the incorporation of the correlated model into the sliced HEMT structure.

Details of the Unsliced Model with Correlated Noise Sources

The equivalent circuit model used is shown in Fig.1. Apart from R_{ds}, all resistances are at temperature $T_{dev} = 23°C$, so that in the noise analysis they each contain implicit, uncorrelated noise current generators giving mean square noise currents of $4kT_{dev}\Delta f/R$. R_{ds} is at temperature absolute zero, and all noise generated in the drain is accounted for in the explicit noise generator, i_d. An additional explicit noise generator, i_g, partially correlated with i_d, is connected in parallel with R_{gs}. The correlation is brought about by the capacitive coupling of the gate circuit to noise sources in the drain circuit [4]. To facilitate comparison with parameters arising in the earlier models [3], the mean square gate and drain noise currents are related to effective temperatures T_g and T_d as follows :

$$\overline{|i_g|^2} = \frac{4\,k\,T_g\,\Delta f}{R_{gs}}$$

and

$$\overline{|i_d|^2} = \frac{4\,k\,T_d\,\Delta f}{R_{ds}}$$

IF1

The correlation coefficient is defined by the relationship:

$$C = \frac{\overline{i_g\, i_d^*}}{\sqrt{\overline{|i_g|^2}\;\overline{|i_d|^2}}}$$

The model was analyzed and optimized using the EEsof program LIBRA. Using the facility in that program for relating element values to variables, which in turn can be made mathematical functions of other variables, the noise sources referred to above were related to the temperature variables T_g and T_d, and to the magnitude and angle of C. In this way, the paradoxical condition allowed in the EEsof correlated noise source model, where the magnitude of C can become greater than unity, was avoided.

Optimization and Results

The unsliced correlated model was optimized to fit the measured S-parameters and noise parameters for the Toshiba HEMT chip type JS8900-AS. The optimization was partitioned as follows. Firstly the electrical element values were estimated by minimizing the S-parameter error function, consisting of the sum of the squared moduli of the differences between the measured and modelled S-parameters, summed over 2 to 40GHz in 2GHz steps. The electrical element values were then temporarily fixed at these values whilst the noise source element values were determined, by minimizing the noise parameter error function. This consisted of the sums of the squares of the deviations in F_{min}, r_n, and the real and imaginary parts of Γ_{OPT}, calculated at 14, 18, 22, 24 and 26GHz. A final optimization was then performed, in which the values of the electrical elements and the noise source elements were all allowed to vary in order to minimize the sum of the two error functions.

The resulting S-parameter predictions show very good agreement over the full frequency range. The main parameters which are improved when compared with models 1 and 2 are S_{12} and S_{22}. Plots of S_{12} and S_{22} for models 1 and 2 are given in Fig.2a, where the annotations 1 and 2 indicate unsliced and sliced models respectively. The improvement brought about by the introduction of correlation can be seen in Fig.2b.

The noise parameters of model 3 also show excellent agreement. In particular the fit of r_n is significantly improved, compared to the uncorrelated, unsliced model, and marginally improved compared to model 2. This can be seen by comparing Figs.3a and 3b. Fig.3a shows the measured and modelled values of r_n and F_{min} for models 1 and 2. The corresponding data for the unsliced model with correlated noise sources are shown in Fig.3b. In all figures, the measured data are shown by asterisks, and the model predictions are shown by continuous lines.

The element values for the fully optimised unsliced correlated noise source model (Fig.1) are given in Table 1.

Combining the Sliced and Correlated Effects into the Same Model

The next natural extension of the modelling work described above was to incorporate the single FET model with correlation into the sliced model [3], and to repeat the optimisation routine. This was done, using five slices, the first being allowed to differ to account for differences in the gate feed region. This model gave a further reduction in the combined error function of 25%, resulting mainly from a further slight improvement in the fit of r_n, as seen in Fig.3c. However, it can also be seen from Fig.3c that the introduction of the slicing effect has caused a significant increase in the predicted value of F_{min} at 40 GHz.

Discussion

A simple model without correlation or distributed effects can be optimised to give a very good fit to the S-parameters of a HEMT, up to 40GHz. However, to fit the four noise parameters simultaneously, using uncorrelated gate and drain noise sources, it is necessary to perturb the element values such that the fit to the S-parameters is degraded. This is particularly noticeable in S_{22}. The introduction of distributed effects improves this situation somewhat, as shown in Figs.2a and 3a, and in [3].

Further significant improvements can be achieved in the simultaneous fitting of scattering and noise parameters by introducing correlation between the drain noise and the gate noise. This is similar to the model of Pucel et al [4], except that here the excess noise source in the gate is in parallel with R_{gs}, instead of with the series combination of C_{gs} and R_{gs}. Alternatively, it can be viewed as an enhancement of the Pospiezalski model [1] by the addition of a correlated noise source to the gate circuit. This gives rise to a 70% reduction in error function compared to the sliced, uncorrelated model, the improvement being dominated by the improved fit of S_{22}. Since the correlated unsliced model contains fewer parameters than the uncorrelated sliced model, it represents a better working tool for use in the microwave and low mm-wave region.

The further addition of the distributed effect, using the sliced model structure, gives an additional improvement of 25% in the error function. However, from Fig.3c it can be seen that this new model causes F_{min} at 40GHz to rise unrealistically to 3.2dB, putting it well in excess of the manufacturer's suggested value of 2.5dB. It is thus clear that noise parameters at high frequency are sensitive to the distributed effect. The semidistributed model is expected to give a good approximation to this effect but further work is required to allow accurate element values to be determined for this model. This would require either a set of measurements at higher frequencies and the derivation of an efficient parameter extraction procedure, or a physics based approach to determining the effects of field differences near the gate feed and the transmission line parameters of the gate and drain electrodes.

Conclusions

Four HEMT models have been assessed for their ability to fit simultaneously, the S-parameters up to 40 GHz and the noise parameters up to 26GHz for a commercial HEMT chip. A simple model based on thermal, uncorrelated noise sources [1] can be improved by the introduction of the distributed effects [3]. A greater improvement is achieved by introducing correlation between gate and drain noise sources and omitting the distributed effect. When both correlation and distributed effects are included a further improvement in fit can be achieved, but the high frequency noise parameters then become very sensitive to element values which cannot be determined accurately from the low frequency measurements. Therefore the unsliced, correlated model is considered to be the most suitable tool for extrapolation of noise data into the low mm-wave range.

References

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Table 1 Model Element Values

Parameter	Value
T_d	1438 K
T_g	107 K
C	0.985 ∠ -29°
C_{gs}	0.165pF
R_{gs}	5.88Ω
L_s	0.025nH
R_s	0.66Ω
C_{ds}	0.070pF
R_{ds}	219Ω
C_{dg}	0.020pF
L_g	0.134nH
L_d	0.156nH
R_g	1.67Ω
R_d	5.02Ω
g_m	50.2mA/V
τ	1.99ps

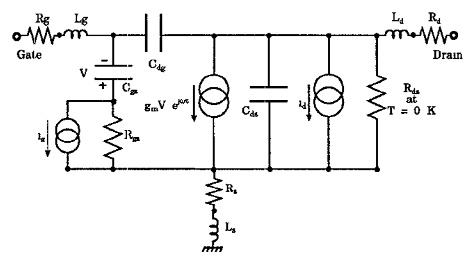
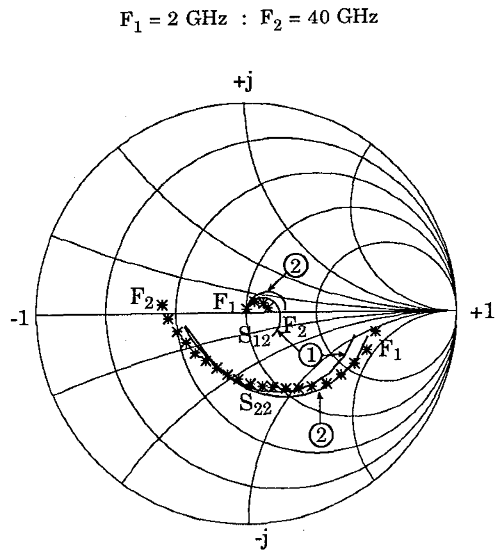


Fig.1 HEMT Model Equivalent Circuit Structure



Fig,2(a) Uncorrelated Model

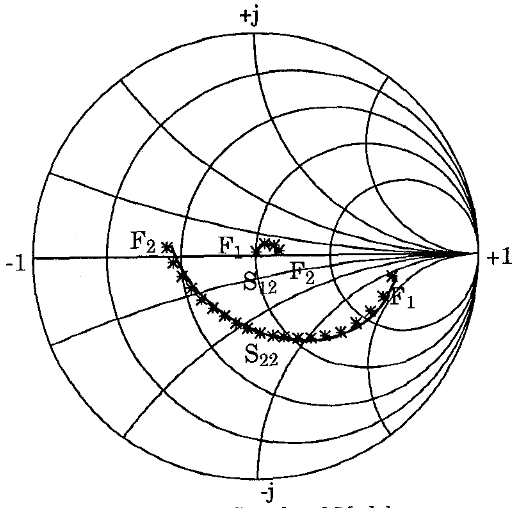


Fig.2(b) Correlated Model

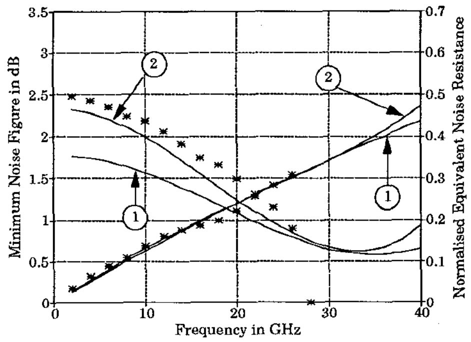


Fig.3(a) Uncorrelated Model

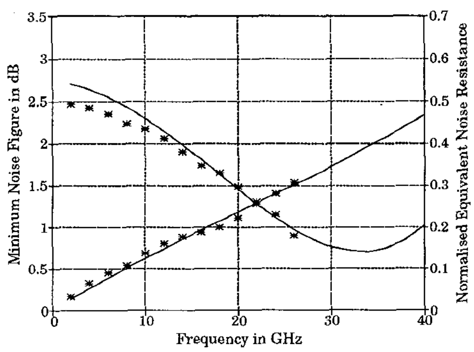


Fig.3(b) Correlated Model

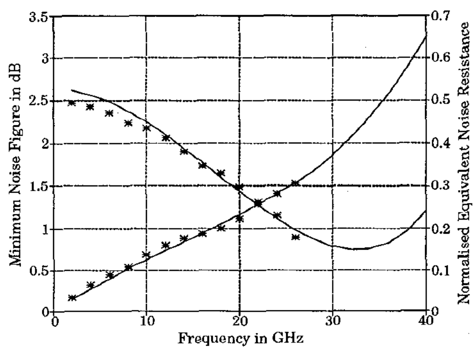


Fig.3(c) Correlated Sliced Model

Fig.2 Measured and Predicted values of S_{12} and S_{22}

Fig.3 Measured and Predicted Minimum Noise Figure and Equivalent Noise Resistance