An Evaluation of HEMT Potential for Millimeter-Wave Signal Sources Using Interpolation and Harmonic Balance Techniques

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Abstract—**A large-signal analysis method based on harmonic balance technique and 2-D cubic spline interpolation function has been developed and applied to the prediction of InP-based HEMT oscillator performance for frequencies extending up to submillimeter-wave range. The large-signal analysis method uses a limited number of dc and small-signal S-parameter data and allows the accurate characterization of HEMT large-signal behavior. The method has been validated experimentally using load-pull measurement. Oscillation frequency, power performance and load requirements are discussed, predicting the operation capability to 300 GHz using state-of-the-art devices (f_{max} ~ 450 GHz).**

I. Introduction

THREE-TERMINAL devices such as FET's and HBT's are used for a variety of microwave functions. The recent advances in HEMT technology [1] have demonstrated device operation well into the millimeter and submillimeter-wave range. It is, therefore, possible to envisage the development of amplifiers, oscillators and other functions at these very high frequencies. A maximum oscillation frequency of 450 GHz has, for example, been recently reported [2]. A monolithic oscillator using InAlAs/InGaAs HEMT's has also been reported by the authors at 80 GHz [3]. This letter addresses the application of HEMT's in oscillators and examines their potential for millimeter-wave signal generation using a fully numerical nonlinear analysis method based on the experimental data. The study evaluates the operation frequency, output power and load requirements of HEMT oscillators under large signal conditions. The impact of device characteristics is also studied and criteria are given regarding the feasibility of oscillator realization at millimeter/submillimeter-wave frequencies.

II. Simulation Approach Using Interpolation and Harmonic Balance Techniques

The conventional design techniques for high-frequency oscillators are based on either small-signal S-parameters or measured large-signal S-parameters or a combination of S-parameters and time-domain calculations [4]–[6]. However, the small signal S-parameters are not able to predict the steady-state oscillation condition and designs using measured large-signal S-parameters also present certain difficulties arising from measurement accuracy. In order to simulate oscillator performance accurately and easily, a large signal analysis method requiring only a few dc and small-signal data points and employing a numerical scheme to cover the whole data range has been developed in this work.

The oscillator analysis is based on experimental high frequency and dc characteristics of submicron InP based HEMT's using InAlAs/InGaAs heterostructures. Two different HEMT designs were studied with modest (f_{max} ~ 200 GHz, improved performance for structure reported in [7]) and state-of-the-art (f_{max} ~ 450 GHz [2]) characteristics and will in the following be referred to as HEMT A and B, respectively.

DC I–V characteristics were first obtained for the devices and following this, small signal S-parameter measurements were performed at various (V_{ds}, V_{gs}) bias points. A fitting algorithm was used for deriving the value of bias dependent equivalent circuit parameters.

A special modeling program using 2-D cubic spline techniques was developed in order to calculate the two dimensional (V_{gs}, V_{ds}) variations of the equivalent circuit elements. The device model and a set of spline functions representing the device were then combined with a harmonic balance simulator (LIBRA, EEsof) to evaluate the large signal transistor characteristics. An external subroutine is used to evaluate the internal node currents and charges in the nonlinear HEMT model [8]. During execution, the LIBRA simulator (which contains the passive circuit description) reveals these data and minimizes the sums of the node currents and charges by optimizing the voltage waveforms. The use of polynomial fits, although successful for representing the bias-dependence of MESFET's, gives relatively poor fits in HEMT's due to the highly nonlinear characteristics of the latter. It is therefore necessary to seek other alternatives such as for example the interpolation techniques proposed in this letter. This avoids the use of the same predetermined formulae for all bias regions and thus provides larger flexi-

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bility in characterizing strongly nonlinear elements. The 2-D cubic spline function also gives the highest accuracy in terms of interpolation errors compared with polynomial fitting or square root fitting using well-known formulae. This method allows the exact reproduction of experimental microwave data over the bias range of interest even with a limited number of measurements.

As a first step in the device characterization, power saturation characteristics of HEMT's under large signal conditions have been investigated. S_{21} was found to be most sensitive to input power variations compared with the other parameters. Significant S_{21} degradation is observed at high-input power levels due to parasitic MESFET operation of the barrier layer. To validate the modeling approach, the HEMT's were characterized by load-pull measurement with 0 dBm input power level at 10 GHz using a set of FOCUS Inc. computer controlled electromechanical tuners. Fig. 1 shows good agreement between theoretical and measured load-pull characteristics for a 0.1 μm × 150 μm HEMT.

The oscillator analysis was based on a circuit set-up consisting of the HEMT amplifying unit and a frequency selective feedback loop. A simple common source series feedback topology was used for this purpose. An ideal coupler is placed between the HEMT and the feedback loop to initiate and monitor the oscillation. The initiating signal is then increased until the gain of the HEMT saturates and the following oscillation condition is reached:

$$G(j\omega, A) \cdot H(j\omega) = 1,$$

where $G(j\omega, A)$ is the gain of the HEMT as a function of frequency (ω) and power (A) and $H(j\omega)$ is the transfer function of the feedback loop. The initial condition for the simulation is set by the linear small-signal calculation results. This method provides the possibility of predicting the oscillator behavior under both small and large-signal conditions and obtaining a good understanding of transient and steady state oscillation phenomena, as related to the device characteristics.

III. Evaluation of HEMT Potential for Millimeter/Submillimeter-Wave Oscillation

The simulation method was applied to study the common-source oscillator performance using submicron InAlAs/InGaAs HEMT's. Devices with two different f_{max} values were used for this purpose (HEMT A: 200 GHz/HEMT B: 450 GHz). The results confirmed a drop of negative resistance at the output port as the frequency increases and translates therefore to a requirement of smaller load impedance values at high frequencies. The output power dependence on the termination impedance is calculated and is shown in Fig. 2 for HEMT A (2 × 45-μm gate periphery) at various oscillation frequencies. The large signal analysis indicates that an optimum output power level is obtained when the load impedance is of the order of 1/2 to 1/4 of the small signal negative resistance at frequencies not too close to maximum frequency of oscillation (f_{max}). At very high frequencies, the load impedance determined by the above criteria is reduced to very low values (below 5 Ω) which are difficult to implement in practice. This termination load requirement sets the practical limit of upper frequency at which the oscillator circuit can be implemented. These effects were studied and design criteria were established based on practical realization constraints of load terminations exceeding 5 Ω.

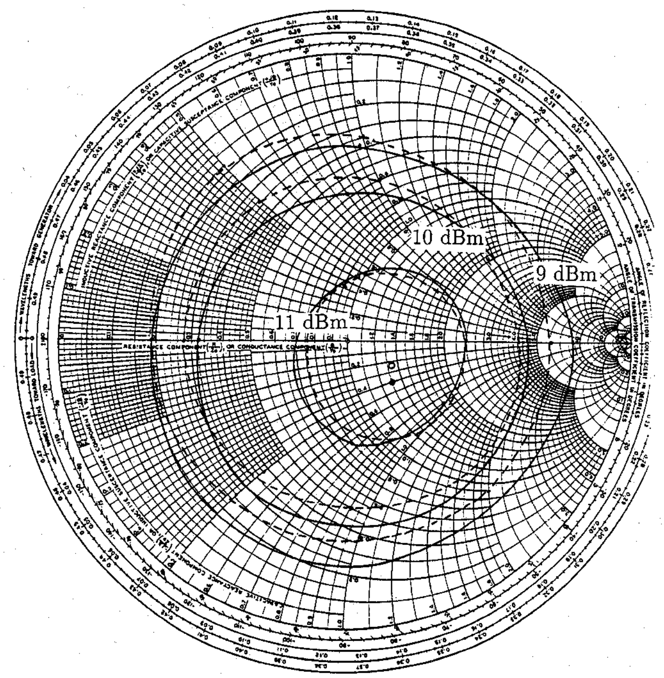

Fig. 1. Comparison of theoretical (---) and experimental (—) load-pull characteristics of 0.1 μm × 150 μm InAlAs/InGaAs HEMT at 10 GHz with an input power level of 0 dBm.

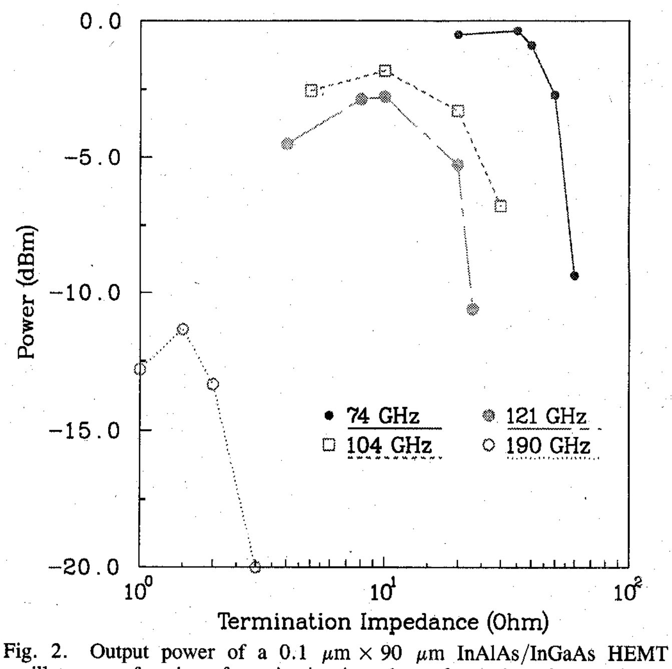

Fig. 2. Output power of a 0.1 μm × 90 μm InAlAs/InGaAs HEMT oscillator as a function of termination impedance for various frequencies of operation.

The available oscillation power was evaluated at different frequencies using optimum termination conditions. The results are shown in Fig. 3. The oscillation power level decreases first slowly and shows a more dramatic degradation at high frequencies close to f_{max}. This corresponds to the degradation of maximum available gain and thus negative resistance at high frequencies. The reduced negative resistance imposes a smaller value of termination load with the result of less power delivered to the load. The overall characteristics suggest that generation of reasonable power levels is feasible up to a frequency of 2/3 of $f_{\max}$. More than 2.5 dBm of output power can be expected up to 300 GHz out of 0.1 μm HEMT's with six 22.5-μm gate fingers assuming an $f_{\max}$ of 450 GHz. This prediction does not include any parasitic effects coming from mismatches, losses of transmission lines and source grounding.

Fig. 3 also shows the characteristics of devices with different gate widths and the effect of gate periphery on the output power level. Larger devices provide higher oscillation power at low frequencies because of their larger periphery and thus current. They are, however, harder to implement in oscillator circuits. This is due to their lower induced negative resistance, which implies very small termination impedance requirements. Since larger periphery devices have increased shunt capacitance values and require reduced load impedances, the role of series (loss) resistance becomes predominant compared to the load. As a result, the net power delivered to the load degrades faster with frequency and the power may not scale with periphery at the upper end of their frequency operation capabilities. A compromise has consequently to be made between the oscillation power and ease of realization when choosing the device periphery.

It should finally be noted that the simulation results in Fig. 3 were obtained using a simple series feedback topology and the evaluated oscillation power values do not, therefore, necessarily reflect the maximum power capability of the devices. The simulation method presented in this letter has also been applied to the design of heterostructure MMIC oscillator chips. These had complex feedback schemes and have been experimentally characterized at 35 GHz [9] and 76 GHz [8]; the predicted power levels were within 2 dB of the experimental results.

In summary, a large-signal analysis approach was developed for FET's using interpolation and harmonic balance techniques. The method is applied to InAlAs/InGaAs HEMT's in order to evaluate their potential as signal sources at submillimeter-wave frequencies. Signal generation with more than 2.5 dBm output power is expected up to 300 GHz using devices with a maximum oscillation frequency of 450 GHz.

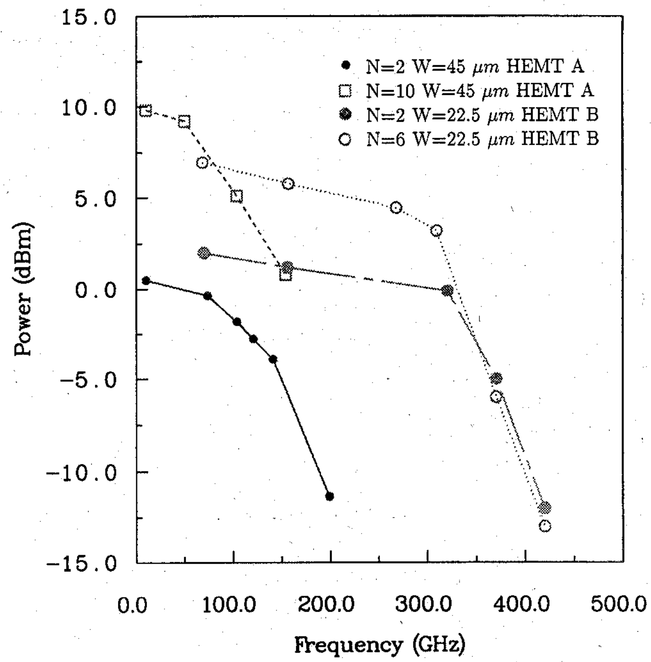

Fig. 3. Power delivered by a InAlAs/InGaAs HEMT oscillator as a function of frequency, device design (A or B), width (W) and number of fingers (N).

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