Harmonic Analysis Of Gan-Hemts At Different Temperatures For Asymmetric Communication

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Abstract: In this study, the harmonic analysis of GaN-HEMTs are performed for different temperatures between 100K and 600K for asymmetric communication systems. Analysis is based on the expansion of Volterra power series up to third harmonics (kernels) (H1, H2, H3), whose small signal transfer functions are obtained via multi-dimensional Laplace transform. The amplitudes of H1, H2 and H3 transfer functions are obtained in frequency domain depending on the gate-source voltage, $V_{gs}$. The amplitude functions have an inverse amplitude relation between $H1$, $H2$, and $H3$. The use of $H1$ and $H3$ components for asymmetric communication is preferable, since the amplitudes of these harmonics are high. Moreover, the optimal value of $V_{gs}$ is found to be -1V for asymmetric communication applications.

Keywords: HEMT, Asymmetric communication, Volterra series, Temperature, Non-linear, Multi-dimensional Laplace transform

1. Introduction

High Electron Mobility Transistor (HEMT) is a field effect transistor (FET). GaN-HEMTs are used in electronic applications at high frequency due their noise immunity. Analog, digital and wireless communication and industrial applications are the basic areas where GaN-HEMTs are used. The operating frequency of a GaN-HEMT depends on the material used to construct it and varies in the 10-110 GHz range [1].

Numerous studies are published on the estimation of HEMT parameters using small signal analysis. PHEMT parameters [2], GaAs FET ve HEMT parameters estimation using the measured S-parameter [4] are performed via small signal analysis. Crupi et. al make a comparative study of microwave FETs modelling by use of small signal analysis [5]. Equivalent circuits and communication networks with HEMTs are investigated for various properties [3, 6,7,8,9].

The HEMT modelling via large signal analysis is also studied for the design of power amplifiers [10, 11]. Liu presented a precise large signal HEMT model [12]. The small signal analysis is used in very high frequencies in [13]. Simple techniques to get new HEMT models [14] and HEMT equivalent circuits [15] are proposed. Chen et. al. Proposed a method to find a low gate bias model [16]. Since HEMTs are highly nonlinear, nonlinear HEMT models are also studied along with linear models [17, 18, 19, 20, 21, 22]. Another method is to study nonlinear behaviour using linear models by means of harmonic components [19]. Moreover, stability analysis using chaos theory approach is presented [20]. Some researchers apply distortion analysis techniques to HEMTs [23, 24, 25]. Volterra series based analysis methods are among these approaches [24]. Nonlinear systems related works can be found in [26, 27, 28, 29, 30, 31]. Integral transformations have significant roles in these studies. The reader is directed to Brychkow et. al [32] on integral transformations.

Yıldırım studied laser diodes [33, 34, 35, 36] and HEMT applications [37, 38, 39, 40] in communication systems with several researchers.

Recent HEMT related studies are presented in the literature. In these papers, power amplifiers operating at microwave frequencies [41, 19, 44, 45], active harmonik source and load measurements [42], mm wave equivalent circuits for GaN and ALGaN HEMTs [43] and parasitic effects due to temperature [46] are investigated. The GaN HEMT, which is considered in this paper, has a cut-off frequency of 101 GHz and a maximum oscillation frequency of 155 GHz. Other parameters of the HEMT considered can be found in Ahmad et. al. [17, 18].

2. Volterra series analysis of HEMT

Various equivalent circuits are proposed for GaN-HEMT. High and low frequency small and large signal equivalent circuits are examples of these circuits. Due to this, an appropriate equivalent circuit should be selected for the intended study [17-18]. The equivalent circuit used in the analysis is seen in Figure 1.

The parameters are listed as follows [17,19]:

- Gate inductance, $L_g$ =30 pH; Drain inductance $L_d$=1 pH; Source inductance $L_s$ = 35 pH;
- Gate resistance $R_g$ = 1 $\Omega$; Source-to-channel resistance $R_s$ =1.7 $\Omega$;
- Drain-to-channel resistance $R_d$ =2.5 $\Omega$;
- $C_{gs}$ is gate to channel depletion capacitance with
$C_{g1}=0.6754$ pF; $C_{g2}=-0.2086$ pF; $C_{g3}=-0.0573$ pF.

Charging channel resistance to $C_{gs}$, $R_s=1$ Ω; substrate capacitance $C_{ds}=0.05$ pF.

Drain-to-gate feedback capacitance $C_{gd}=0.07$ pF.

Transconductance $g_m$ with,

$g_m=177.33$ mS/mm; $g_{m2}=206.74$ mS/mm/V; $g_{m3}=-14.5$ mS/mm/V$^2$.

Channel resistance $R_{ds}$ with,

$r_{ds1}=450.457$ kΩ; $r_{ds2}=-322.077$ kΩ/V; $r_{ds3}=77.955$ kΩ/V$^2$.

The circuit parameters at different temperatures for the HEMT considered in this paper is given in [17,18].

The detailed information on Volterra series can be found in [26-32]. Volterra transfer functions $H_1(s_1)$, $H_2(s_1, s_2)$ and $H_3(s_1, s_2, s_3)$ represent the multi-dimensional Laplace transformation or small signal transfer functions of first, second and third kernels, respectively [19]. These are given by:

$$H_1(s_1) = -\frac{g_m}{Y_o(s_1)} H_{1c}(s_1)$$

$$H_2(s_1, s_2) = -\frac{H_{1c}(s_1)H_{1c}(s_2)}{Y_o(s)} \left[ -\frac{g_m \left(1/Z_{gs2}(s_2)\right)}{Y_o(s)} + g_{m2} + \frac{Y_{ds2}(s_2) g_{m1}}{Y_o(s_1) Y_o(s_2)} \right]$$

$$H_3(s_1, s_2, s_3) = -\frac{1}{Y_o(s')} \left[ H_{1c}(s_1) H_{1c}(s_2) H_{1c}(s_3) \left\{ g_{m3} = \frac{g_m \left(1/Z_{gs3}(s_3)\right)}{Y_o(s')} - \frac{Y_{ds3}(s_3) g_{m1}}{Y_o(s_1) Y_o(s_2) Y_o(s_3)} \right\} \right] +$$

$$-\frac{1}{Y_o(s')} \left[ H_{1c}(s_1) H_{2c}(s_1, s_2) \left\{ 2 g_{m2} - \frac{2 \left(1/Z_{gs2}(s_3)\right)}{Y_o(s_2)} \right\} + 2 Y_{ds2}(s_2) H_1(s_1) H_2(s_1, s_2) \right]$$

where:

$$H_{1c}(s_1) = \frac{Y_s(s)}{Y_s(s) + Y_E(s)}$$

$$H_{2c}(s_1, s_2) = -\frac{\left(1/Z_{gs2}\right)}{Y_o(s)} H_{1c}(s_1) H_{1c}(s_2)$$

Figure 1. HEMT small signal equivalent circuit model [17,18].
Using IMD analysis, linear, non-linear and asymmetrical amplitude analyses are studied for single- and multi-tone inputs [33-40].

3. Experimental results

The amplitude of small signal transfer functions of H1, H2 and H3 are shown in Figures 2-4 for GaN-HEMT at 100K. The amplitude graphs for \(V_{gs}=-0.25V\) are seen in Figure 2. For \(V_{gs}=-0.25V\), amplitude of the first harmonic is 48 dB, the ratio H2/H1, which is the ratio of the second harmonic amplitude to the first harmonic amplitude, is -95 dB, the ratio H3/H1 is 8 dB and the ratio H3/H2 is 100 dB. The difference between the second and third harmonics are 106 dB. Considering the maximum values, the difference becomes 198 dB. This shows that the effect of the third harmonic is much larger than that of the second harmonic.
Figure 2. The output amplitude graphs for $V_{gs}=-0.25\,\text{V}$ at $T=100\,\text{K}$.

In Figure 3, the amplitude graphs for the case $V_{gs}=-1\,\text{V}$ at $T=100\,\text{K}$ is given. In this case, the amplitude of the first harmonic decreases by 10 dB to 38 dB, which corresponds to 20.83 % reduction in the amplitude. On the other hand, the third harmonic amplitude increases by 10 dB to 18 dB corresponding to 225% increase. The second harmonic amplitude decreases to 85 dB with 10.53 % decrease.

Figure 3. The output amplitude graphs for $V_{gs}=-1\,\text{V}$ at $T=100\,\text{K}$.

Figure 4 demonstrates the output amplitudes for $V_{gs}=-0.5\,\text{V}$ at $T=100\,\text{K}$. Here, the increase in the first harmonic is 26.31 % and it increases to 48 dB from 38 dB, while third harmonic decreases to 2 dB from 18 dB with 900% and second harmonic decreases by -100 dB with 17.64 %. This means that the third and second harmonics are attenuated up to 10 dB and -99.5 dB. This result corresponds to a good attenuation of harmonics in the communication. However, this is not preferred for asymmetric communication.

Figure 4. The output amplitude graphs for $V_{gs}=-1.5\,\text{V}$ at $T=100\,\text{K}$.

It can be observed that for $V_{gs}=-3.5\,\text{V}$, the amplitude of the first harmonic increases to 58 dB with a rate of 20.83 %, while the amplitudes of the second and third harmonics decrease to -120 dB and -18 dB with respective rates of 20% and 1000 %. When $V_{gs}$ increases in the negative direction, the amplitudes of second and third harmonics decrease. In this case, the amplitude of the first harmonic increases by approximately 10 dB while the second and third harmonic amplitudes decreases below -150 dB and -50 dB, respectively.
The figures 5-7 give the amplitude graphs for GaN-HEMT operation temperature $T=200$ K, which can be tolerated by the living things. Under this condition, Figure 4 gives the amplitudes of first, second and third harmonics for $V_{gs}=-0.25V$. The amplitudes for first, second, third and $H3/H2$ are 45 dB, -80 dB, 5 dB and 94 dB, respectively.

![Figure 5. The output amplitude graphs for $V_{gs}=-0.25V$ at $T=200K$.](image)

Figure 5 shows the amplitude graphs for $V_{gs}=-1V$. The amplitudes are 35 dB, -82 dB, 11 dB and 92 dB for first, second, third and $H3/H2$ values, respectively. The rates of change with respect to $V_{gs}=-0.25V$ are found to be 22.22 %, 2.5 %, 222.22 % and 2.22 % in the first, second, third and $H3/H2$ values, respectively. The change in the third harmonic is remarkable.

![Figure 6. The output amplitude graphs for $V_{gs}=-1V$ at $T=200K$.](image)

In Figure 7, the same graphs are given for $V_{gs}=-1.5V$ at $T=200K$. The respective amplitudes are found to be 45 dB, 95 dB, 12 dB and 92 dB. The rate of changes with respect to the values at $V_{gs}=-1V$, 28.57 %, 14.63 %, 9% and approximately 2 %.

![Figure 7. The output amplitude graphs for $V_{gs}=-1.5V$ at $T=200K$.](image)

The amplitudes for $T=300K$ (room temperature) are given in Figures 8-11. The respective amplitudes of first, second, third harmonics and the ratio $H3/H2$ are detected as 42 dB, -85 dB, 0 dB and 83 dB for $V_{gs}=-0.25V$ (Figure 8).
The respective values for \( V_{gs} = -1 \text{V} \) can be found as 32 dB, -80 dB, 8 dB and 83 dB (Figure 9). The rates of changes with respect to the values for \( V_{gs} = -0.25 \text{V} \) are estimated as 23.8, 5.88, 800 and 1 in percentage. The highest change rate is in the third harmonic amplitude with 800 %.

The increase in the first harmonic is 42 dB with a rate of 31.25 % (Figure 10) for \( V_{gs} = -0.5 \text{V} \) at T=300K. The other values are recorded as -90 dB with 12.5 % increase, -3 dB with 138.75 % decrease and 83 dB with 0% for second harmonic, third harmonic and \( H3/H2 \), respectively.

In Figure 11, the graphs for \( V_{gs} = -3.5 \text{V} \) is seen. The amplitudes of first, second and third harmonics along with \( H3/H2 \) are found to be 51 dB, -110 dB, -21 db and 82 dB, respectively. Comparing with the values for \( V_{gs} = -1.5 \text{V} \), the first harmonic increases with 26.19 %, the second harmonic increases with a rate of 22.22 % and the third harmonic decreases with 600%. This suggests that \( V_{gs} \) should be increased in negative polarity to attenuate the harmonics. In other words, the larger Vgs is, the larger the harmonic attenuation in IMD applications. However, it is important to remember that \( V_{gs} \) should be relatively small in reverse polarity for IMD applications.
We investigate the characteristics for T=400K, since the semiconductor material may be exposed to such temperatures due to heating as result of a fault or overloading. In Figures 12-14, the characteristics at T=400 K for several $V_{gs}$ voltages. Figure 12 shows the amplitudes under $V_{gs}$=-0.25V. The amplitudes of first, second and third harmonics along with H3/H2 ratio are 40 dB, -80 dB, -5 dB and 71 dB, respectively. When compared to the same voltage at T=300 K, the amplitude of the third harmonic decreases by a ratio of 500 %. Practically, this means that the third harmonic is attenuated effectively.

![Figure 12](image12.png)

**Figure 12.** The output amplitude graphs for $V_{gs}$=-0.25V at T=400K.

Figure 13 gives the amplitudes for $V_{gs}$=-1V. The amplitudes for first, second and third harmonics along with H3/H2 are 28 dB, -70 dB, 5 dB and 71 dB. Comparing with the values for $V_{gs}$=-1V at T=300 K, the amplitudes reduced with percentages of 12.5 %, 12.5 %, 37.5 % and 15.66 % given in the above order. The reduction in the third harmonic is significant.

![Figure 13](image13.png)

**Figure 13.** The output amplitude graphs for $V_{gs}$=-1V at T=400K.

In Figure 14, the amplitudes of first, second and third harmonics along with H3/H2 can be estimated as 38 dB, -80 dB, -10 dB and 71 dB, respectively, for $V_{gs}$=-0.5V. Comparison of these values with the ones at T=300 K gives the percentage reductions of amplitudes with 9.52 %, -11.11 %, 233.33 % and 14.45 %.

![Figure 14](image14.png)

**Figure 14.** The output amplitude graphs for $V_{gs}$=-0.5V at T=400K.

In Figure 15, the amplitudes are given for $V_{gs}$=-0.25V at T=500K. The amplitudes are found as 35 dB, -70 dB, -12, dB and 55 dB for first, second and third harmonics along with H3/H2, respectively. The second harmonic amplitude is larger than the third harmonic amplitude by 14.5 dB at 1.5 GHz. Taking into account the maximum amplitudes, the difference of second and third harmonics is -12.5 dB and the second harmonic is -70 dB. The resonant frequency is around 28.5 GHz. However, the second harmonic amplitude increases while the first and third harmonics decreases after 55 GHz.
Figure 15. The output amplitude graphs for $V_{gs} = -0.25V$ at T=500K.

In Figure 16, the amplitudes are seen for $V_{gs} = -1V$. The first and second harmonic amplitudes approaches each other in this case. The amplitudes of interest are 16 dB, -51 dB, 3 dB and 53 dB. At 15 GHz, the second and third harmonic amplitudes are same. After this the third harmonic amplitude starts to increase up to 3 dB. Comparing to the values for $V_{gs} = -0.25V$, the first and second harmonic amplitudes decrease by 45.71 % and 26.72 % while the third harmonic amplitude increases by 124.5 %. The highest changes in amplitudes are in the first and third harmonic amplitudes.

Figure 16. The output amplitude graphs for $V_{gs} = -1V$ at T=500K.

The analysis is also carried out for T=600K even though it is not practical to reach this value, however this temperature is used for test of HEMT. For $V_{gs} = -0.25V$, the amplitudes are found to be 29 dB, -54 dB, -24 dB and 29 dB. It should be noted that the amplitudes for the first and third harmonics are same. The third harmonic is attenuated significantly with respect to the previous cases (Figure 17).

Figure 17. The output amplitude graphs for $V_{gs} = -0.25V$ at T=600K.

In Figure 18, the amplitudes are given for $V_{gs} = -1V$. The amplitudes are 13 dB, -41 dB, -11 dB and 29 dB. But for frequencies less than the resonance frequency, the second harmonic amplitude reaches to 23 dB. In this case, the second harmonic amplitude is 176.92 % larger than the first harmonic amplitude.

Figure 18. The output amplitude graphs for $V_{gs} = -1V$ at T=600K.
The studies on symmetric and asymmetric communication systems can be found in [33-42]. In this study, the amplitudes of the first, second and third harmonic amplitudes are investigated against \( V_{gs} \) and temperature. For \( V_{gs} = -1 \) V, the third harmonic amplitudes are larger than 0 dB and it is larger than the second harmonic amplitudes in all cases. The third harmonic is more dominant than the second harmonic. In case of increasing temperature, the second harmonic amplitudes are larger than the first harmonic amplitude at low frequencies. For classical communication systems, this is an undesired situation and the harmonics should be attenuated. If the GaN-HEMT IMD and the asymmetric communication systems are used together, the second harmonic components should not be used, because the amplitudes of second and third harmonics behaves in opposition, which makes the overall amplitude smaller. Due to this, the use of the first and second harmonic components produce a better result probably. The best (or optimum) results for the third harmonic components are obtained for \( V_{gs} = -1 \) V. The third harmonic amplitude is always higher than the second harmonic component for \( V_{gs} = -1 \) V. The advantage of high third harmonic is to allow less amplifier in the communication system and operation costs will be reduced seriously. This provides a sustainable and economic operation of the system. The Table 1 summarizes the amplitude changes. The percentages are calculated with reference to the values at T=300 K.

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<th>Table 1. Amplitude changes</th>
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<td>( V_{gs} ) (V)</td>
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From Table 1, it can easily be seen that the HEMT gain increases for low temperatures (i.e. 100K and 200K) while it decreases for high temperatures (400K, 500K, 600K) with reference to T=300 K. This means that the gain increases when HEMT is cooled and decreases when HEMT is heated.

4. Result and discussion

In this study, the harmonic amplitudes are investigated against \( V_{gs} \) and temperature changes. With reference to T=300 K, the second and third harmonic amplitudes increase at 100K and 200K. However at high temperatures (400K, 500K, 600K), the amplitudes decreases significantly. The optimum \( V_{gs} \) value appears to be -1 V for asymmetric communication systems. Depending on the output amplitude of GaN-HEMT, power gain, useful power and voltage gain decrease by increasing temperature. For the positive percentage values for H1, H2 and H3 correspond to the increase in power and voltage gain, while the negative percentages corresponds to the decrease in power and voltage gains. The gain of GaN-HEMT decrease by increasing temperature. It should be preferable to use the first and third harmonic components (H1 and H3) for symmetric and asymmetric communication systems. Because the signs of these harmonics are same. This results an increase in the amplitude of frequency components and the system hardware costs less.
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