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TEMPERATURE DEPENDENT ANALYSIS OF HEMT'S BASED ON GAIN, POWER AND ROLLETTI STABILITY

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Abstract

In this study, temperature dependent parameter analysis of HEMTs is performed. Rolletti stability analysis, temperature dependent power and voltage gain are considered. Rolletti stability criterion (K) and Δ (Delta) variation are investigated as a function of temperature and the relation between them are also determined. The critical points for the stability are specified for the frequency regions that the temperature variation is effective. In addition to that, non-linear variation region of Delta, their correspondant values, and boundary spaces are established.

Keywords: HEMT, stability, Rolletti, temperature.

1. Introduction

High Electron Mobility Transistor, HEMT is a field effect transistor that is developed and commercialized by Japanese. HEMTs are commonly used in different areas due to the fact that they work in high frequencies with low noise. The working frequency of HEMT generally varies between 10 to 110 GHz according to their manufacturing material (1-5). HEMT's basic and commonly used areas are analog, numerical and wireless communication systems. In this study, GaN (Gallium Nitrate) based HEMT is analyzed. Power and gain change of HEMT's temperature dependent scattering parameter are examined for this analysis. The cut-off frequency of GaN HEMT is 101GHz and maximum oscillation frequency is 155 GHz [6-7].

In this study gain and S-parameters of HEMT in different temperatures are analyzed. There are different approaches about stability analysis (8-13). Also, a relationship between Roletti stability factor (K) and temperature has been found.

HEMT Analysis

There are a lot of HEMT equivalent circuit models. The major ones are high and low frequency and big and small equivalent signal circuits. Thus, the expedient equivalent circuit is chosen before the analysis of circuit element. (14-16). This chosen equivalent circuit model can be seen in Figure 1. The elements of HEMT equivalent circuit models are analyzed in two groups as intrinsic and extrinsic elements. Extrinsic elements are L_g, L_s, L_d, R_g, R_s and R_d. Intrinsic elements are defined as; gate load resistance R_i, gate-source conductivity g_{ds}, gate-source capacity C_{gs}, dependent current source $G_m = g_m V_{gs}$, drain - source capacity C_{ds} and conductivity (g_m). [4]

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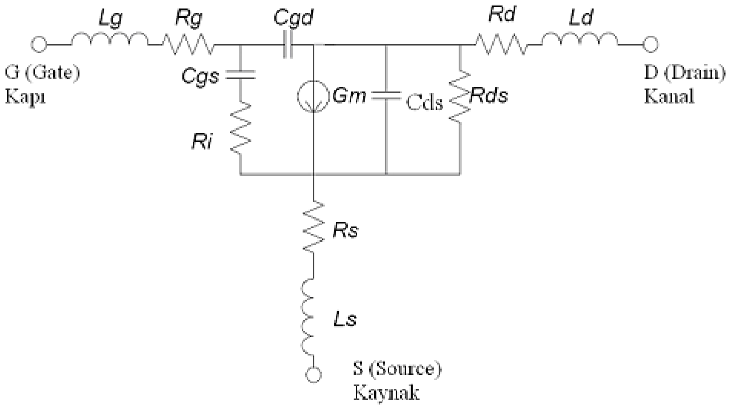


Figure 1. HEMT small signal equivalent circuit model [17].

The values of equivalent circuit model are obtained through the two-port network circuit analysis technique such as scattering S, admittance Y, hybrid H and impedance Z parameters. (18-19). S parameters are defined as:

S_{11}: Input reflection coefficient
S_{12}: Reverse conductivity coefficient (reverse gain and lose)
S_{21}: Forward conductivity coefficient (forward gain)
S_{22}: Output reflection coefficient

The equivalent circuit’s change with temperature shown in Figure 1 can be seen in Table 1.

Table 1. HEMT’s circuit parameters [6-7] in different temperatures (Kelvin, K)

Parameter	T=100K	T=200K	T=300K	T=400K	T=500K	T=600K
$C_{gs\ 1}$ (pF)	0.5795	0.6226	0.6754	0.7309	0.8191	0.9663
$C_{gs\ 2}$ (pF/V)	-0.1581	-0.1814	-0.2086	-0.2315	-0.28	-0.3668
$C_{gs\ 3}$ (pF/V^2)	0.0567	0.0565	0.0573	0.0567	0.0653	0.0878
g_{m1}(mS/mm)	263.75	221.79	177.33	133.73	89.488	51.64
g_{m2}(mS/mm/V)	275.46	244.63	206.74	163.72	115.68	69.768
g_{m3}(mS/mm/V^2)	-49.085	-32.556	-14.5	2.7313	18.302	24.601
r_{ds1}(kΩ)	395.1	491.992	450.457	588.175	851.343	1000
r_{ds2}(kΩ/V)	-316.772	-398.615	-322.077	-421.463	-616.74	-705.210
r_{ds3}(kΩ/V^2)	84.249	104.863	77.955	100.664	146.691	156.079
C_{gd} (pF)	0.07	0.07	0.07	0.07	0.07	0.07
C_{ds} (pF)	0.05	0.05	0.05	0.05	0.05	0.05
R_d (Ω)	2.5	2.5	2.5	2.5	2.5	2.5
Ri (Ω)	1	1	1	1	1	1

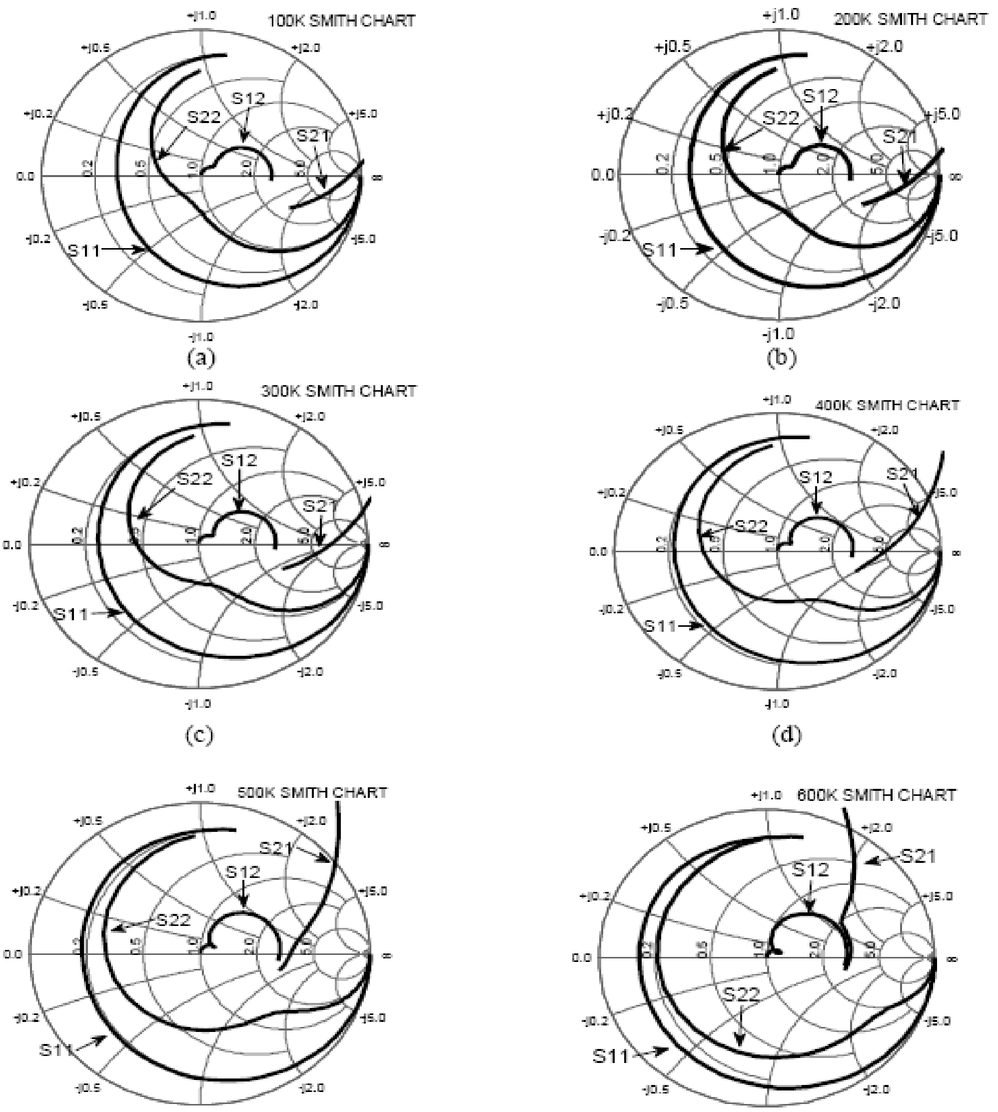
Non-linear output current of HEMT is defined as

$$i_d(v_g, v_d) = \frac{\partial I_d}{\partial V_g} v_g + \frac{\partial I_d}{\partial V_d} v_d + \frac{1}{2}\frac{\partial I_d}{\partial V_g^2} v_g^2 + \frac{1}{2}\frac{\partial^2 I_d}{\partial V_g \partial V_d} v_g v_d + \frac{1}{6}\frac{\partial^3 I_d}{\partial V_g^3} v_g^3 + \frac{1}{2}\frac{\partial^3 I_d}{\partial V_g^2 \partial V_d} v_g^2 v_d + \frac{1}{6}\frac{\partial^3 I_d}{\partial V_d^3} v_d^3 + \frac{1}{2}\frac{\partial^3 I_d}{\partial V_d^2 \partial V_g} v_d^2 v_g \qquad (1)$$

[13].

Output conductivity is stated as $g_m = g_{m1} + g_{m2} v_{gs} + g_{m3} v^2$. The change values of gm_1, gm_2 *and* gm_3 decrease as % 19.579, %25.327 and %50.119 respectively. As a result of this, output current decreases and affects the gain directly. Output resistor (drain-source) is stated as $r_{ds} = r_{ds1} + r_{ds2} v_{gs} + r_{ds3} v^2$. Furthermore, the variation of output resistor increases at the rates of %263.004, %222.655 and 185.259 respectively. Gate-resource capacity change is defined as $C_{gs} = C_{gs1} + C_{gs2} v_{gs} + C_{gs3} v^2$. Variation rates C_{gs1}, C_{gs2} for the values of C_{gs3} increase at the rates of %166.747, %232.005 and %154.850 respectively. As a result of this, working frequency of HEMT is changed.

HEMT's Smith Chart curves in various Kelvin (K) temperatures are shown in Figure 2. It can be seen that S_{11} parameter in 2GHz passes from positive reactance to negative reactance area, and in 57GHz it passes from negative reactance to positive reactance area. Additionally, it's in capacitive area up to 13 GHz and in inductive area between 13GHz and 70GHz. It can also be seen that output reaction coefficient S_{22} passes from positive reactance area to negative reactance area in 1.7 GHz, negative reactance to positive reactance in 70 GHz, is capacitive up to 36 GHz and is inductive between 36 GHz and 70 GHz.



(a) (b) (c) (d) (e) (f)

Figure 2. HEMT's Smith Chart curves in various temperatures a)100K b)200K c)300K d)400K e)500K f)600 K

2. Gain Parameters

Transfer function is often used in system analysis. When maximum power transfer is desired, generally the signal power is used. The load impedance in double pin system (Z_L), source impedance (Z_S) is characterized by scattering matrix [8] and chain matrix [ABCD]. The transducer power gain (g_T) represents load power (P_L) power got from the source (P_{AVS}), input Γ_{IN} , output Γ_{OUT} ,load (Γ_L) and source (Γ_S) reflection coefficients. Also, the transducer power gain is defined as

$$g_T = \frac{P_L}{P_{AVS}} = \frac{|S_{21}|^2 (1-|\Gamma_L|^2)(1-|\Gamma_S|^2)}{|1-\Gamma_{IN}\Gamma_S|^2 |1-S_{22}\Gamma_L|^2} \tag{2}$$

Transfer power gain depends on load and source impedance. Available power gain (G_A) depends on the rate of available power in two-port network (P_{AVN}) to available power of source (P_{AVS}). Available power gain (G_A) is defined as

$$G_A = \frac{P_{AVN}}{P_{AVS}} = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2} |S_{21}|^2 \frac{1}{1-|\Gamma_{OUT}|^2} \tag{3}$$

The relationship between source signal voltage V_s and transfer power and voltage related to output voltage V_0 is defined as in the equality below:

$$V_g^{\,2} = \frac{V_0^{\,2}}{V_S^{\,2}} = \frac{V_0^{\,2} / R_L}{V_S^{\,2} / 4R_S} \frac{R_L}{4R_S} = g_T \frac{R_L}{4R_S} \tag{4}$$

Additionally, it's defined as R_L load resistor and R_S source serial resistor. [8, 11, 12].

Power gain curve of HEMT in various temperatures is acquired in Figure3. Power gain for 600K is more than 20GHz, for 500K more than 37GHz, for 400K more than 55GHz, lastly for 100K, 200K and 300K more than70GHz. The power gain of 20GHz varies 7dB between 100K and 600k. This power gain is important to gain frequency value for high frequencies. The cut off frequency difference for the same range is more than 50GHz or the cut off frequency increases more than 350%.

As the temperature increases it corresponds to attenuation for all the values. Approximately, all temperature values up to 160 MHz are the same in low frequency.

That is to say, temperature variation in this frequency region doesn't affect HEMT's gain.

The acquired available power curve is shown in Figure 4. It has been found out that the value got from the curve analysis is 25 GHz for 600 K, –3dB; for 500K, 0dB; for 400K, 2.3dB; for 300K, 3dB; for 200K, 4dB and for 100K, 4.8dB. The biggest variation in temperature is the situation in 600K. The gain difference between 600K and 100K temperatures is 7.8dB.

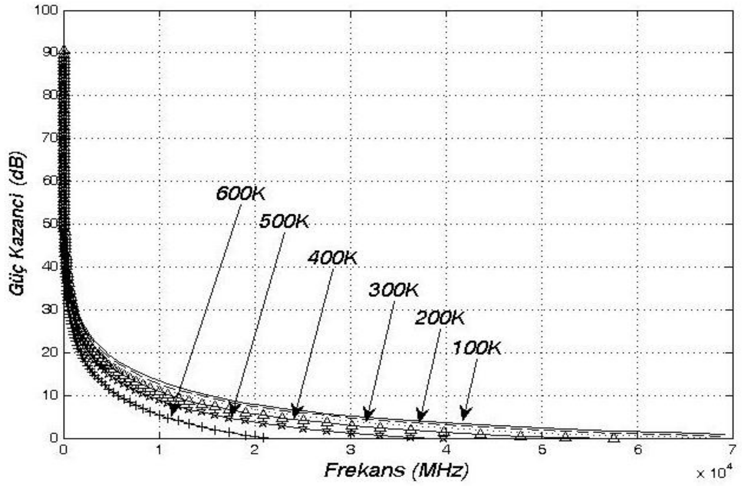


Figure 3. HEMT's power gain in various temperatures

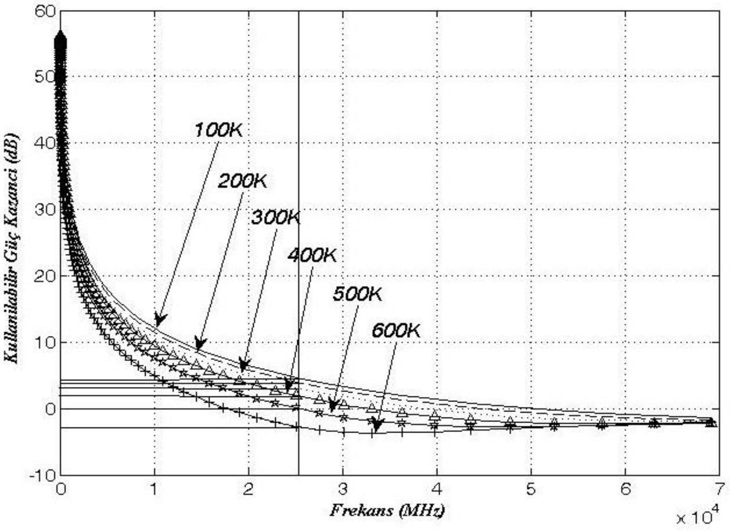


Figure 4. HEMT's available power gain in various temperatures

The acquired transfer power frequency gain curves of HEMT in various temperatures are shown in Figure 5. It can be seen that there is a close relationship between power gain and temperature. It has been found out that the value got from the curve analysis is 30 GHz for 600 K, –6.2dB; for 500K, -2.5dB; for 400K, 0dB; for 300K, 1.70dB; for 200K, 2.5dB and for 100K, 3.40dB. The difference of power gain between 600K and 100K in 30GHz is 9.60dB.

The biggest cut off frequency values corresponding to 100K is 42GHz, and the smallest one corresponding to 600K is 12.1GHz. Temperature increase affects transfer power gain and cut off frequency dramatically. In addition, the effect of temperature can be seen in frequency and transfer power gain.

For low frequency values, there are 12.5dB differences of gain at the beginning and 9.6dB in 30GHz. Besides, it has been found out that the difference of gain between those two values is 2.9dB.

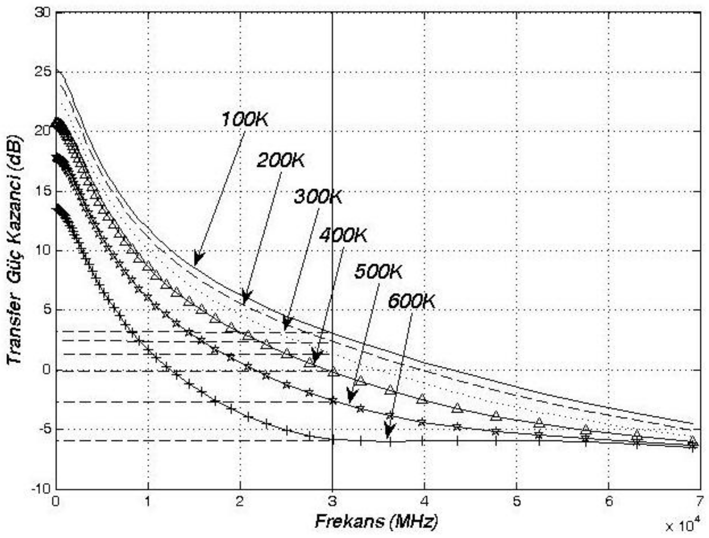


Figure 5. HEMT's transfer power gain in various temperatures

The acquired HEMT's transfer power gain in various temperatures is shown in Figure 6. It has been found out that the correspondent values which have 30GHz frequency values for 600K -4.5dB; for 500K, -0.9dB; for 400K, 2.4dB; for 300K, 3.7 dB; for 200K, 5dB and for 100K, 6.3dB amplitude. The biggest cut off frequency for 100K is 43 GHz and the smallest one for 600 K is 23 GHz.

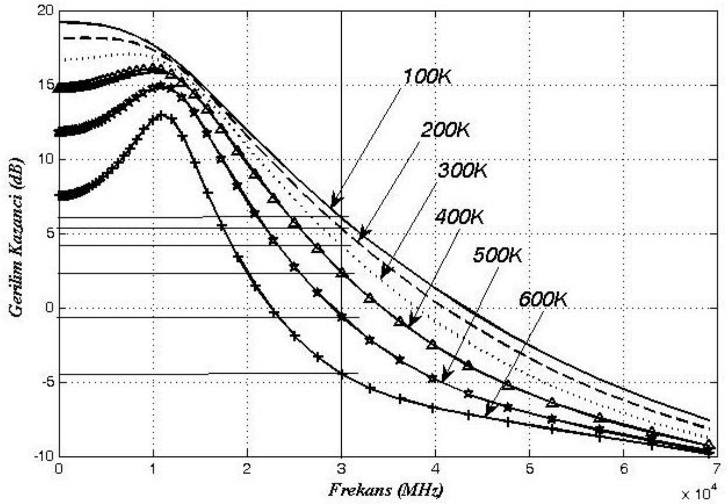


Figure 6. HEMT's transfer voltage gain in various temperatures

3. HEMT's Stability Analysis

The stability in systems is defined as limited input to limited output. There are a lot of measures in stability analysis. They are Nyguist, Root-locus, Hurtwizt, Roletti, Linville, Stern and the others. These stability measures are generally different. Some of them can be used in the analysis of control system as well. There are some different measures in non-linear systems. They can be called as Lyapunov I-II, Pointcare and the others.

Along with the theoretical advantages, it sometimes has very limited outcomes in practical applications as well. In other words, the design of practically high scale non-linear systems and the analysis are the major ones. [8-12].

In stability analysis, input-output reflection constants of HEMT are taken into account. These constants are defined as input reflection Γ_I and output Γ_{OUT} . Stability of HEMT is correlated with conditions of below one (1) for these two values. For two-port network system, these values are accepted as stable when they are below one. Instability condition is the situation whose reflection coefficients are above one. Stability statements are defined as

$$|\Gamma_{IN}| = \left| S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \right| < 1 \tag{5}$$

$$|\Gamma_{OUT}| = \left| S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} \right| < 1 \tag{6}$$

[8, 10-11]. If the condition of Rollet is fulfilled, stability factor K is stable as unconditioned circuit. Accordingly,

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{21}S_{12}|} > 1 \tag{7}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} < 1 \tag{8}$$

In order to calculate the stability of a system by using S-parameters, intermediate value of Δ (Delta) and then Rollet stability factor K is calculated [10]. If the value is K > ,it is accepted as unconditionally stabile. Conversely, it can be potentially instable. For K < 1, the element is potentially instable and probably creates oscillation in most of the combinations of load impedance and source in many cases.

Curves in Figure 7 have been acquired using HEMT equivalent circuit in Figure 1 and values in Table 1. In modeling, Rollet stability factor (K) and Delta curves have been acquired in 10MHz-500GHz frequency range and different temperatures.

Δ and stability factor have reverse relationship in different temperatures until HEMT becomes totally stable. In low frequency ranges (10-400 MHz), Delta gets the maximum values, whereas stability factor gets minimum values. This situation is same for all temperatures. However, it can be accepted as initial point of dissociation according to temperatures which are used after 1GHz between Delta and Rollet factor. Dissociation between 1-11 GHz is observed for Rollet factor. Yet, 11GHz critical frequency Delta value is 0.09. Unconditional Rollet factor of HEMT becomes stable between 60-100 GHz in various temperatures. It reaches to “1”, after Rollet and Delta values of 300 GHz. However, for HEMT frequency value used for HEMT, it is more than cut-off frequency (150 GHz). Theoretically, the system is stable for the frequencies after 100 GHz. Delta and K values reach to one (1) value in 400GHz. The frequency range corresponding to Rollet stability establishment time is between 11 and 60 GHz. It has been found out that Rolletti criteria are 80GHz for 600K, 87 GHz for 500K, 92GHz for 400K, 95GHz for 300K, 97 GHz for 200K, 100GHz for 100K. For Delta values it also reaches to “1” after the value of 400GHz.

For the ideal usable stable region 300 K, it operates in stable way between 60 and 150 GHz. This temperature corresponds to room temperature.

As the temperature increases, the Delta frequency decreases. Consequently, as the temperature increases, the value of Rollet factor decreases to smaller frequencies.

Δ (Delta, D)'s change which affects Roletti stability factor can be seen when Figure 8 and 9 analyzed together. These variables are obtained from S_{11}, S_{12}, S_{21} and S_{22} values. The scattering variables affecting Delta factor have been analyzed with multiplication of a.(S_{11} *S_{22}) and b.(S_{12} * S_{21}) in two parts. Figure 8 has been acquired in order to calculate the Δ with scattering parameters.

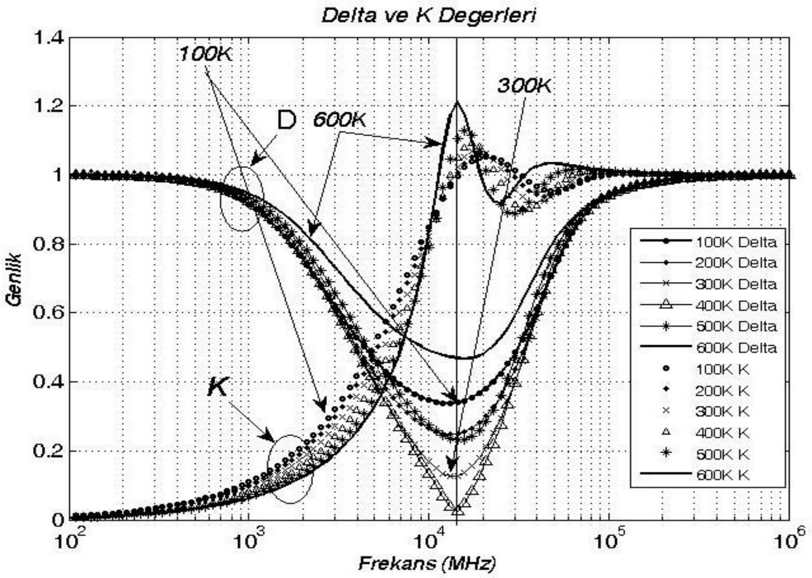


Figure 7. The relationship between Delta-K and HEMT in various temperatures

The curve is made up of three important points. They are;

1. When the situation is (S_{11}* S_{22}=1), it corresponds to (S_{12}* S_{21}=0). In this situation, the system is unconditionally instable.
2. If the value of (S_{12}* S_{21}) equals to "1", then the value of (S_{11}* S_{22}) equals to zero.
3. It corresponds to (S_{11}* S_{22}=0.4) and (S_{11}* S_{22}=0.14) values in flexion point.

   The critical points of Delta correspond to:

   1. $S_{11} * S_{22} = 0.373$, $S_{12} * S_{21} = 0.3$ and $\Delta = 0.2$,
   2. $S_{11} * S_{22}$ =1, $S_{12} * S_{21} = 0.07$ and $\Delta = 1$
   3. $S_{11} * S_{22}$ =0.96, $S_{12} * S_{21} = 0.3$ and $\Delta = 0.55$.

These points correspond to critical turning points in HEMT's operation process. It has been observed that depending on HEMT's scattering variables, the values between $S_{11} * S_{22}$ =0.1-0.2, $S_{12} * S_{21}$ = 0.2-0.4 and $\Delta = 0.25–0.4$ correspond to high level non-linear dimension. On the other hand, the corresponding values of Δ's (in 15GHz for 300K in figure 7) minimum and Rolet factor's maximum values are $S_{11} * S_{22}$ =0.373, $S_{12} * S_{21}$ = 0.25. As can be seen in Figure 8, there is no linear situation among the variables that make up Δ any of the regions. On the contrary, there is a non-linear situation in high level.

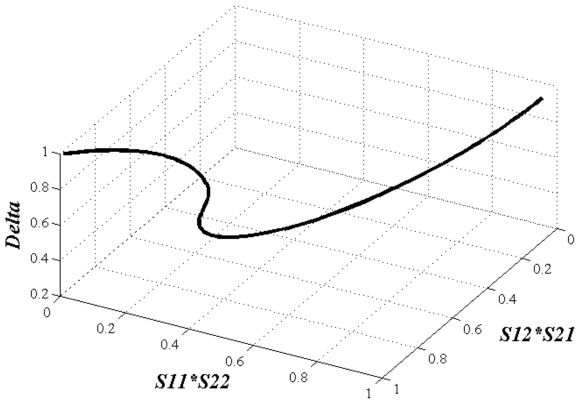


Figure 8. The change according to delta's scattering parameters

4. Conclusion

At the end of this study, correlated to temperature variation, it has been concluded that;

1. As the temperature increases Delta values increase and the frequency of Roletti stability criteria decreases. Additionally, for the highest temperature 600K, the oscillation fluctuation reaches to high values and the stability establishment time gets bigger. On the other hand, stable available probable band-width gets smaller.
2. In low level of temperature (100K), stability establishment time and oscillation fluctuation are shorter.
3. In 400K temperature, Delta value reaches to the smallest value. On the contrary, Rollet (K) value is lower and oscillation establishment time is shorter.
4. At 15GHz, in all temperatures, Delta value gets the lowest value. This frequency is the most sensitive frequency to the temperature. However, a Roletti criterion becomes unconditionally stable when HEMT works in this area. On the other hand, it is the most sensitive frequency to temperature and the environment temperature will certainly have a big effect on it.
5. Power variation has a direct relationship with the temperature. As the temperature increases, the power values reduce. There is a difference of 10.8dB between two different temperatures (100K-600 K). There is a difference of 31dB in transfer power gain. This value is important for high frequency applications.
6. As in critical temperature 400K, delta reaches to minimum level, and in 600K it reaches to maximum level. These two temperature values constitute HEMT's extreme points of operation temperatures.

In this study, it has been found out that in order for HEMT to work stable, the most sensitive frequency to temperature is 15GHz. The best operating temperature is 300K. This is because the voltage gain-up to 10GHz- is approximately accepted as stable. As a result, HEMT operates unconditionally stable after 11GHz. The variables sensitive to temperature -output inductivity $g_m=g_{m1}+g_{m2}v_{gs}+g_{m3}v^2_{gs}$, output inductivity $r_{ds}= r_{ds1}+r_{ds2}v_{gs}+r_{ds3}v^2_{gs}$ and gate-source $c_{gs}=c_{gs1}+c_{gs2}v_{gs}+c_{gs3}v^2_{gs}$ -are capacity change. As a result of the change of those variables, HEMT's characteristics operation varies. Consequently, according to Roletti criterion, HEMT operates unconditionally instable between 140MHz-11GHz and unconditionally stable between 11-30GHz. The best -3dB band width corresponds to 300K temperature value.

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