The UHF oscillators based on a HEMT structure with negative conductivity

Andriy Semenov, Olena Semenova
Faculty of Radio Engineering, Telecommunication and Instrument Engineering
Vinnytsia National Technical University
Vinnytsia, Ukraine
Semenov79@ukr.net

Oleksandr Osadchuk
Faculty of Radio Engineering, Telecommunication and Instrument Engineering
Vinnytsia National Technical University
Vinnytsia, Ukraine
Osadchuk69@mail.ru

Abstract—The article considers a possibility of constructing microwave oscillators on a transistor structure with negative conductivity based on two HEMT. Obtained non-linear equations can be used to model microwave oscillator parameters and characteristics with an error not more than 10%.

Keywords—oscillator; HEMT; negative conductivity; transistor structure

I. INTRODUCTION

UHF (ultra high frequency) voltage-controlled oscillators are widely used in radio engineering and electronics. Their construction can be considerably simplified using impedance properties of a transistor structure with negative conductivity. In such case control voltage changes oscillation frequency in limits (3,0..9,5)% at small non-linear distortions of harmonic oscillations. HEMT utilization allows increasing oscillation frequency in the voltage-controlled oscillator (VCO) and considerable decreasing the total harmonic distortion (THD<0,297%). The urgent problem of the oscillator projecting is the transistor structure based on the HEMT I/V curve approximation problem.

II. OSCILLATOR ON THE TWO-ELECTRODE HEMT STRUCTURE

The UHF oscillator on the two-electrode HEMT structure is shown on fig.1. The obtained equation of the two-electrode HEMT structure I/V curve is expressed by (1). The equation of the differential conductivity is expressed by (2). Their diagrams are shown on fig. 2.

![Electric circuit of the UHF oscillator on the two-electrode HEMT structure](image)

Fig. 1. The electric circuit of the UHF oscillator on the two-electrode HEMT structure

\[
I(U) = \frac{U}{R_1 + R_2} + \frac{I_{so}}{\tanh M \left(1 - \frac{U}{2U_0} \cdot \frac{R_1}{R_1 + R_2}\right)} \tanh \left[M \frac{U / 2U_0}{1 - \frac{U}{2U_0} \cdot \frac{R_1}{R_1 + R_2}}\right]
\]

(1)

\[
G_{\text{d}}^{-1}(U) = \frac{dI}{dU} = \frac{1}{R_1 + R_2} - \frac{I_{so}}{2U_0} \left(\frac{2R_1}{R_1 + R_2} \left[1 - \frac{U}{2U_0} \cdot \frac{R_1}{R_1 + R_2}\right] \tanh \left[M \frac{U / 2U_0}{1 - \frac{U}{2U_0} \cdot \frac{R_1}{R_1 + R_2}}\right]\right),
\]

(2)

where \(I_{so}\) is the source current at \(U_{gd} = 0, U_{sd} = U_0\); \(U_{gd}, U_{sd}\) are the voltages on the gate-drain and source-drain electrodes respectively; \(U_0\) is the cutoff voltage [1].

The parameter of \(M\) is evaluated from the equation

\[
M = \frac{S_{\text{max}} U_0}{I_{so}},
\]

where \(S_{\text{max}} = \frac{dI}{dU_{sd}}\) is the drain characteristics conductance of a FET at \(U_{sd} = U_{gd} = 0\) [1].

![Approximated I/V curve and differential conductivity](image)

Fig. 2. The approximated I/V curve (a) and differential conductivity dependences (b) of the two-electrode HEMT structure

The generated current equation is
Second harmonic is on a level of -53 dB, others are less.

The amplitude balance differential equation is

\[
T \frac{dU}{dT} = \left( \frac{R_{eq}}{R_1 + R_2} + \frac{I_{so}R_{eq}}{2U_0 \tanh M} \right) U + \frac{I_{so}R_{eq}}{2U_0 \tanh M} \left( \frac{R_1}{R_1 + R_2} \right)^2 - \frac{1}{3} M^2 \times U \tan \tau + \ldots
\]

(3)

(4)

The oscillator autoexcitation condition is

\[
\frac{R_{eq}}{R_1 + R_2} + \frac{I_{so}R_{eq}}{2U_0 \tanh M} > 1.
\]

(5)

The oscillator stationary vibration amplitude is

\[
U_{cr} = \sqrt{\frac{2U_0 \left( 1 - \frac{R_{eq}}{R_1 + R_2} \right) - \frac{I_{so}R_{eq}}{2U_0 \tanh M}}{\frac{I_{so}R_{eq}}{2U_0 \tanh M}}} \left( \frac{R_1}{R_1 + R_2} \right)^2 - \frac{1}{3} M^2 \times U \tan \tau + \ldots
\]

(6)

Dependence of the oscillation amplitude \( U \) on time (at the generation establishing stage)

\[
U(t) = \frac{U(0)e^\gamma t}{\sqrt{1 + (U^2(0)/U_{cr}^2)(\exp 2\gamma t - 1)}},
\]

where \( U(0) \) is the oscillation initial amplitude,

\[
\gamma = \left( \frac{R_{eq}}{R_1 + R_2} + \frac{I_{so}R_{eq}}{2U_0 \tanh M} \right) ^{-1} / T.
\]

(7)

(8)

III. OSCILLATOR ON THE THREE-ELECTRODE HEMT STRUCTURE

The electric circuit of the UHF oscillator on the three-electrode HEMT structure is shown on fig. 3 [2].

![Fig. 3. The electric circuit of the UHF oscillator on the HEMT structure](image)

The experimental I/V curve of the three-electrode HEMT structure is shown on fig. 4 [3].

![Fig. 4. The I/V curve of the three-electrode HEMT structure of the UHF oscillator at: 1) U=0.2 V; 2) U=0.25 V; 3) U=0.3 V; 4) U=0.35 V; 5) U=0.4 V; 6) U=0.45 V](image)

The equation of the three-electrode HEMT structure I/V curve is expressed by (9). The equation of its negative conductivity is expressed by (10)

\[
I(U_1,U_2) = \frac{U_2}{R_2 + R_3} + I_{so} \left( 1 - P(U_1,U_2) \right) \times \left( \tanh M \right)^{-1} \left( \frac{U_2}{U_0} \right) \left[ \frac{U_2}{U_0} / \left( 1 - P(U_1,U_2) \right) \right] +
\]

(9)

where

\[
P(U_1,U_2) = \frac{U_1}{U_0} - \frac{U_2}{U_0} - \frac{bU_1}{U_0} \left( \frac{R_3}{R_2 + R_3} \right)^2 - 1.
\]

(10)

![Fig. 5. Approximated static I/V curves of the three-electrode HEMT structure at 1) U=0.2 V; 2) U=0.3 V; 3) U=0.4 V](image)
The generated current equation is

\[ i_0(u) = \frac{1}{R_2 + R_1} \left( \frac{I_{eq}}{U_0} \right) M \left( P_2 - \frac{U^2}{U_0^2} \left( \frac{R_1}{R_1 + R_3} \right)^2 \right) U \cos \tau + ... \]

(11)

where

\[ P_2 = (1 + S R_i + S^2 R_i^2)^2 - 3 S R_i \]

\[ P_3 = (1 + S R_i + S^2 R_i^2)(S^2 R_i^2 - 2 b U_i(1 + S R_i)) + S R_i(b U_i - 1). \]

The amplitude balance differential equation is

\[ T \frac{dU}{dt} = \left( \frac{R_{eq}}{R_2 + R_1} + \frac{I_{eq} R}{\tanh M} \frac{1}{U_0^2} P_2 - 1 \right) U - I_{eq} R M \frac{U^3}{\tanh M} \left( \frac{R_1}{R_1 + R_3} \right)^2. \]

(12)

The oscillator autoexcitation condition is

\[ \frac{R_{eq}}{R_2 + R_1} + \frac{I_{eq} R}{\tanh M} \frac{1}{U_0^2} P_2 > 1. \]

(13)

The oscillator stationary vibration amplitude is

\[ U_{ct} = U_0 \left( \frac{R_{eq}}{R_2 + R_1} + \frac{I_{eq} R}{U_0} \frac{1}{\tanh M} \frac{P_2 - 1}{U_0^2} \right). \]

(14)

Dependence of the oscillation amplitude \( U \) on time (at the generation establishing stage)

\[ U(t) = U(0) \exp(\gamma t) \left( 1 + (U_0^2 / U_{ct}^2) \exp(2\gamma t - 1) \right). \]

(15)

where \( U(0) \) is the oscillation initial amplitude,

\[ \gamma = \left( \frac{R_{eq}}{R_2 + R_1} + \frac{I_{eq} R}{U_0} \frac{1}{\tanh M} \frac{P_2 - 1}{U_0^2} \right)^{1/2}. \]

(16)

IV. OPTIC-CONTROLLED OSCILLATOR ON THE HEMT STRUCTURE

The diagram of the optic-controlled oscillator on the HEMT structure is shown on fig. 8.

In the UHF range the HEMT source current is a sum of two components, they are 2D electron gas and AlGaAs electrons. Each of them may be expressed as

\[ I_{ci} = q Z n_i(x) v_i(x), \quad i = 1, 2, \]

(17)

where \( Z \) is a gate width; \( q \) is an electron charge module; \( v_i \) is an electron drift rate; \( U_i \) is a model parameter. The drift rate dependence on field strength allowing saturation effect is

\[ v_i(x) = \begin{cases} \mu_i E(x), & E(x) < E_{Hi}; \\ 1 + E(x)/E_{Hi}, & E(x) \geq E_{Hi}; \end{cases} \]

(18)

where \( \mu_i \) is a mobility in weak field; \( E_{Hi} \) is a critical electric field when the saturation takes place; \( V_{Hi} \) is the saturation electron rate at \( E_i = E_{Hi} \).

The HEMT source currents in linear and saturation modes are expressed (21) add (22) respectively
\[ I_{\text{in}} = \frac{A_i}{L + U_{\text{in}}} \times \left[ B_i U_{\text{in}} - \ln \cosh \frac{U_{\text{gs}} - U_{\text{m}} - U_{\text{in}}}{U_{\text{ui}}} + \ln \cosh \frac{U_{\text{gd}} - U_{\text{m}}}{U_{\text{ui}}} \right] \]  
\[ j_{\text{in}} = \frac{A_i}{L_{\text{ij}} + U_i / A_{\text{ij}}} \times \left[ B_i U_{\text{in}} - \ln \cosh \frac{U_{\text{gs}} - U_{\text{m}} - U_{\text{in}}}{U_{\text{ui}}} + \ln \cosh \frac{U_{\text{gd}} - U_{\text{m}}}{U_{\text{ui}}} \right], \]  
where

\[ A_i = q \mu Z \eta (1 - \alpha_i) U_{\text{in}} \]
\[ B_i = \alpha_i / (1 - \alpha_i) U_{\text{in}}, \]

\[ U_{\text{in}} \] is the channel potential in the saturation point, \( L_{\text{ij}} \) is the saturation useful channel length calculated from the equation

\[ L_{\text{ij}} = L - \frac{2d_i}{\pi} \sinh^{-1} \left( \frac{\pi (U_{\text{in}} - U_i)}{2d_i E_i} \right). \]

Experimental diagrams of the oscillation frequency sensitivity dependence on the radiating power change are shown on fig. 9.

![F, MHz vs. U, В](image1.png)

![F, MHz vs. P, мВ/см²](image2.png)

Fig. 9. Diagram of the oscillation frequency change with the supply voltage (a) and radiating power density (b)

The conversion function of radiating power density into the oscillation frequency is obtained

\[ F_0 = 0.1125 \sqrt{B_i + \left[ R_i^2 + 4L_{\text{eq}} R_i^2 (P_{\text{in}}) \right] \left[ R_i^2 N_i (P_{\text{in}}) \right]}, \]

where

\[ B_i = R_i^2 (P_{\text{in}}) \left[ N_i (P_{\text{in}}) \right] + C_{\text{eq}} R_i^2 (P_{\text{in}}) N_i (P_{\text{in}}) - L_{\text{eq}}. \]

From figs. 9, 10 oscillation frequency relative optical tuning is claimed to be 9,88% while electrical tuning is claimed to be 3,7%.

Fig. 10. Dependence of sensitivity of the UHF optic-controlled oscillator on the HEMT structure on the radiating power density at different values of the supply voltage

REFERENCES


