MAXIMALLY FLAT WAVEFORMS OPERATION OF CLASS-F POWER AMPLIFIERS

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Abstract

The requirements to output network's impedance on higher harmonic components and appropriate input driving for formation maximally flat waveforms of drain current and voltage were presented. Using such waveforms allows obtaining maximal efficiency and output power capability of class-F power amplifiers.

Keywords

class-F, harmonic tuning, high-efficiency amplifier, input drive, power amplifier

1. Introduction

Producing of the short circuit at even and the open circuit at odd harmonics to the active device output (class F operation) allows to substantially increase efficiency of the microwave power amplifier ([1]-[4]). With such a harmonic tuning, the voltage across active device output and current through it does not contain harmonics of the same order simultaneously. In other words, either voltage or current but not both exist at every harmonic frequency.

As was mentioned in [5], minimum power dissipation in the active device could be reached by providing maximally flat waveforms (square-wave, containing only odd harmonics, and half-sinusoid, containing only even harmonics) of the active device output current and voltage (see Fig. 1). In this case, the majority of output current flows when the output voltage is low. Thus such a waveforms are the cause of efficiency increase. In [6] was shown that such an operation also allows obtaining of maximum output power with given DC power.

The following two requirements must be satisfied to provide maximally flat waveforms: 1) only even harmonics can exist in current, and only odd – in voltage (or vice versa); 2) needed relations between magnitudes of remained harmonics are realized. The first requirement is conventional for the described above class F operation. The second requirement, as shown below, can be satisfied by the appropriate input drive.

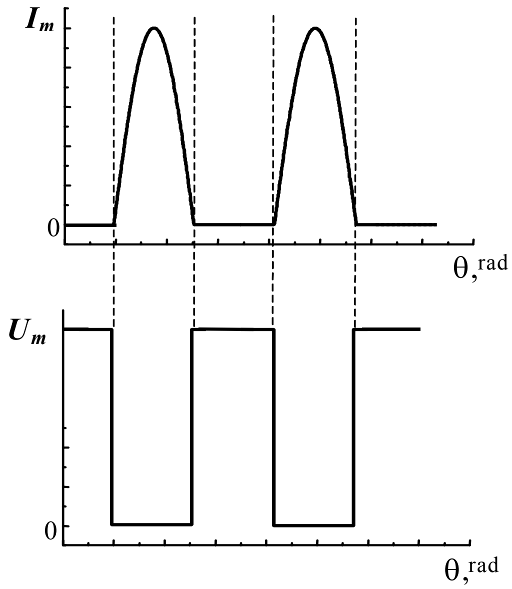

Fig. 1 Maximally flat waveforms consisted of infinite number of harmonics

The idea of using the special input drive to increase amplifier efficiency was presented in recent papers [7], [8]. But in those papers no good explanation was given, why just such a drive was applied.

2. Idealized model

Typically, steady-state class-F amplifier uses the drain voltage that not less than a certain minimum permissible voltage, determined by the characteristics of the active device. The operation with such a drain voltage (which is not least than saturation voltage V_{KNEE}, see Fig. 2) is used to satisfy the assumption that an active device is an ideal current source.

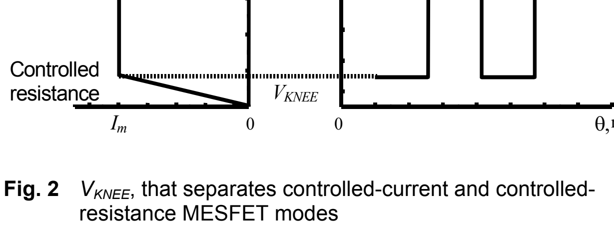

Fig. 2 V_{KNEE}, that separates controlled-current and controlled-resistance MESFET modes

In this case, the drain current depends only on an input drive, and it independents of a drain voltage.

Under this assumption, the active device can be presented for analysis simplicity by ideal current source I_{IS} (that driving by gate-to-source voltage V_{gs}).

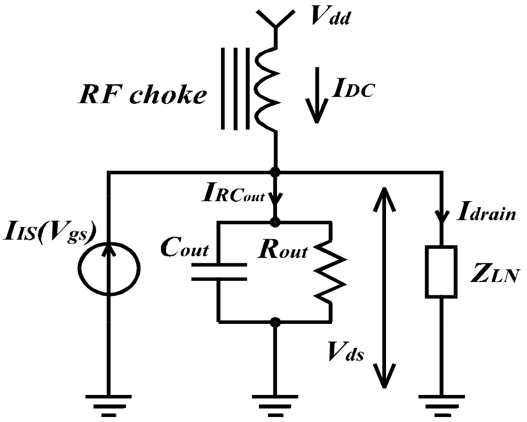

Fig. 3 The equivalent circuit of power amplifier with MESFET that operates in controlled-current mode

The equivalent circuit for such an idealized model is shown in Fig. 3. Here C_{out} and R_{out} present the output impedance of the active device, Z_{LN} presents the input impedance of load network. In case of class-F operation, Z_{LN} should provide matching mode at fundamental frequency, short circuit mode at even harmonics and open circuit mode at odd harmonics. Assuming that drain current I_{drain} and drain voltage V_{ds} (see Fig. 3) have the maximally flat waveforms, needed waveform of $I_{IS}(V_{gs})$, and then (by resolving return task) needed waveform of V_{gs} can be found:

$$I_{IS}\left(V_{gs}\right)=I_{RCout}+I_{drain} \tag{1}$$

Here $I_{IS}(V_{gs})$, I_{RCout} and I_{drain} means the spectral components of given harmonic. Taking into account that

$$V_{ds}=I_{drain}\cdot Z_{LN}$$

$$I_{RCout}=V_{ds}\frac{pC_{out}R_{out}+1}{R_{out}}$$

(there, $p = jn\omega_0$ is given complex frequency, ω_0 fundamental frequency, n – higher harmonic number) obtains:

$$I_{IS}\left(V_{gs}\right)=I_{drain}\left(1+\frac{Z_{LN}}{R_{out}}\left(1+pC_{out}R_{out}\right)\right) \tag{2}$$

Simulated I_{RCout} and $I_{IS}(V_{gs})$ waveforms with fifth-harmonic peaking is shown in Fig.4. It can be seen, that special waveform of $I_{IS}(V_{gs})$ current and hence, special gate driving should be used to formation maximally flat drain current.

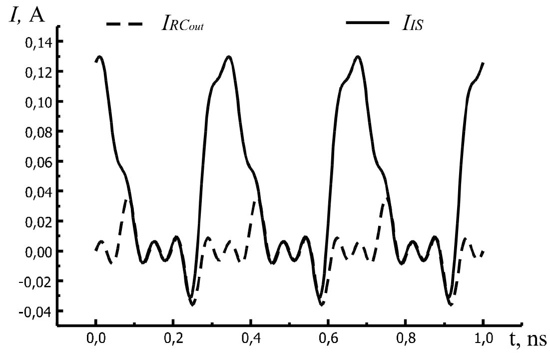

Fig. 4 Simulated I_{RCout} and $I_{IS}(V_{gs})$ waveforms with fifth-harmonic peaking

3. Physically-based model

The equivalent circuit of amplifier with physically based MESFET model is shown in Fig.1.

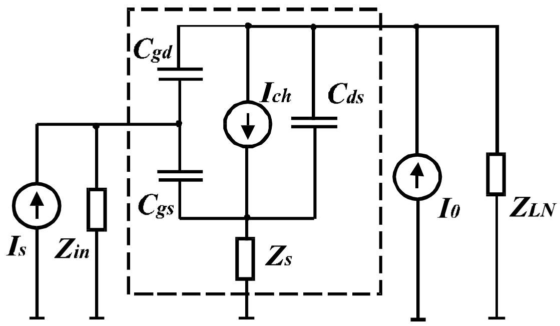

Fig. 5 The equivalent circuit of the considered amplifier

Here Z_{in} and Z_{LN} are input impedances of the input and output networks (including gate and drain parasitic elements of an active device package), respectively; I_S is an ideal ac current source; I_0 is dc supply current source. GaAs MESFET model presented in [9] was used for the amplifier analysis. In Fig.1 the dashed line shows it. For more simplification only average values of capacities were taken into consideration.

Requirement impedance of the output network $Z_{LN}(n\omega_0)$ can be found as:

$$Z_{LN}=\frac{V_{out}}{I_{out}}= \\ =\frac{V_{ds}+Z_s\left(C_{gs}pV_{gs}+C_{ds}pV_{ds}+I_{ch}\right)}{C_{gd}pV_{gs}-(C_{gd}+C_{ds})pV_{ds}-I_{ch}} \tag{3}$$

Here, V_{gs}, V_{ds} and I_{ch} are given harmonic components of the gate and drain voltages and the channel current, respectively, V_{out} and I_{out} are voltage and current at the active device output. Z_{LN} can be found at the odd harmonic frequencies by substitution of the maximally drain current waveform:

$$Z_{LN(odd)} = \infty \tag{4}$$

and on the even harmonic frequencies – by substitution of the maximally flat drain voltage waveform:

$$Z_{LN(even)} = Z_s \frac{C_{gs} p V_{gs} + I_{ch}}{C_{gd} p V_{gs} - I_{ch}} \tag{5}$$

Note, that $Z_{LN(even)}$ in (5) differs from the generally used zero value, but it approaches this value if Z_S is zero. The obtaining of square-wave form just of the intrinsic drain voltage V_{ds} (what does not include voltage drop on a source parasitic element Z_S of an active device package) is cause of such a difference.

Expressions (4) and (5) are the first of two conditions, mentioned in Introduction. The second condition can be obtained if we take into account that output impedance found by substitution of half-sinusoid and by substitution of square-wave must be similar. Thus gate voltage harmonics content, that provides needed relations (to achieve maximally flat waveforms) between remained harmonics of the drain current and voltage can be obtained by equating those impedances. It means, that Z_{LN} obtained from (3) by substitution non-zero $V_{ds(odd)}$ must be infinite at the odd harmonic frequencies (see (4)); and Z_{LN} obtained from (3) by substitution non-zero $I_{out(even)}$ must be same as (5) at the even harmonic frequencies. Under these proposals, harmonics content of driving waveform V_{gs} was obtained:

$$V_{gs(1)} = \frac{\frac{I_{d\max}}{2} + \frac{2V_{d\max}}{\pi} p(C_{gd} + C_{ds}) + I_{ch}}{C_{gd} p}$$

$$V_{gs(even)} = \frac{I_{ch}}{C_{gd} p} - \frac{I_{d\max}\alpha_n}{C_{gd} p} \tag{6}$$

$$V_{gs(odd)} = \frac{I_{ch}}{C_{gd} p} - \frac{C_{gd} + C_{ds}}{C_{gd}} V_{d\max}\beta_n$$

Here, α_n, β_n are Fourier coefficients of half-sinusoid and square-wave, respectively; $I_{d\ max}$ and $V_{d\ max}$ are maximal values of the drain current and voltage correspondingly. It is a set of the transcendental equations – definition of any I_{ch} component requires all V_{gs} components to be known (in general, I_{ch} is depend on both V_{gs} and V_{ds} harmonics content, but V_{ds} was already given as square-wave). Equation for fundamental component $V_{gs(1)}$ in (6) was obtained under assumption of matching between active device output and load at this frequency.

By the numerical solution of set (6) the gate voltage waveform was simulated. Simplex Nelder-Mead optimization routine was used and harmonics up to five was taken into account. Obtained waveform is presented in Fig. 6.

Then the sets of the transcendental equations similar (6) for definition of the drain voltage and current were compounded and numerically resolved.

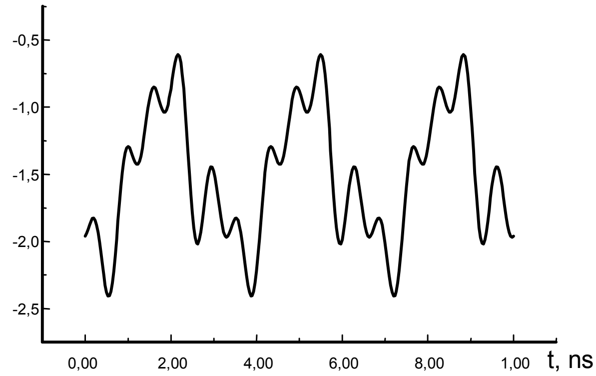

Fig. 6 Simulated gate voltage waveform with fifth-harmonic peaking

The obtained drain current and voltage waveforms appropriated to the simulated before gate driving (see Fig. 6) are shown in Fig. 7. It can be seen, that these waveforms are close to the maximally flat (with the fifth-harmonic peaking).

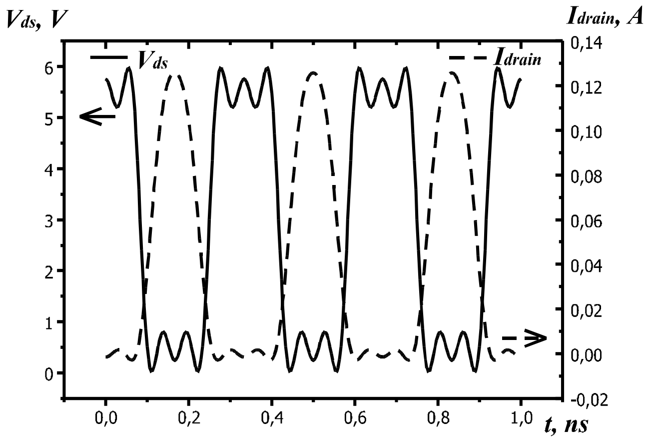

Fig. 7 Simulated drain current and voltage waveforms that appropriate to special gate driving

So, using special input drive is able to provide the maximally flat waveforms of an active device output current and voltage in a microwave class-F power amplifier.

Simulated drain current and voltage waveforms what were obtained with conventional sinusoidal gate driving are shown in Fig. 8.

It can be seen, that drain current waveform (see Fig. 8 and Fig. 9) substantially differs from maximally flat. Note, that even rising of number of harmonic peaking not able to decrease such a difference.

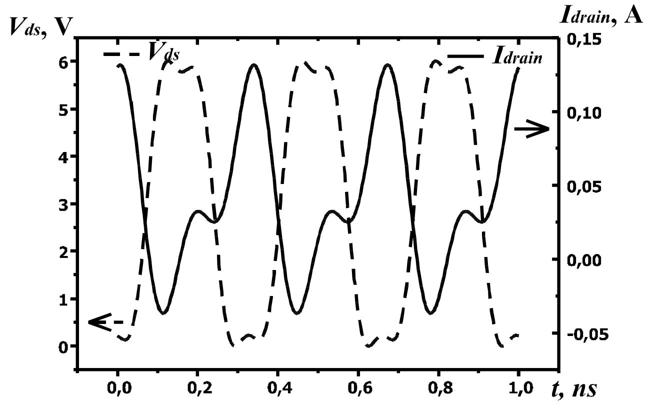

Fig. 8 Simulated drain current and voltage waveforms with a fifth-harmonic peaking that appropriate to the sinusoidal gate driving

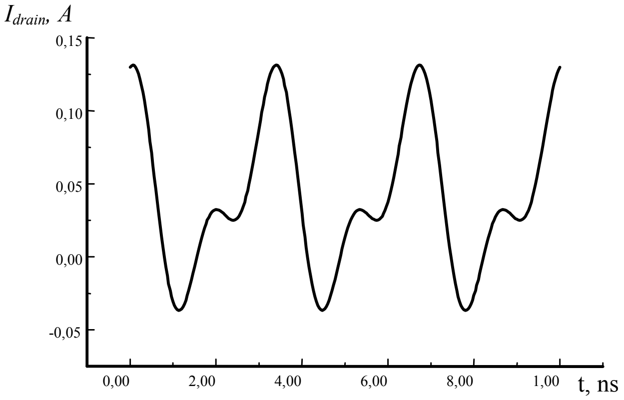

Fig. 9 Simulated drain current waveform with a third-harmonic peaking that appropriate to the sinusoidal gate driving

4. Conclusions

As it was already mentioned, conventional requirement to achieve maximally flat waveforms in microwave class-F amplifier is not sufficient, because it provides just the absence of the odd harmonics in current and even harmonics in voltage of the active device output. An important thing in achieving maximally flat waveforms is needed relation between magnitudes of the remained harmonics. In this paper it was shown that such relations could be reached by using special input drive.

The method to define which input drive is needed to achieve maximally flat waveforms was also presented on the example of the class-F power amplifier on GaAs MESFET. This method will allow to design the amplifiers with the highest efficiency, because the using of such waveforms provides the reducing of power dissipation and hence the increasing of efficiency.

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