COMPOSITE CASCODE POWER AMPLIFIERS FOR ENVELOPE TRACKING APPLICATIONS

BACKGROUND

Field

[0001] Embodiments of the invention relate to electronic systems, and in particular, to power amplifiers for use in radio frequency (RF) electronics.

Description of the Related Technology

[0002] Power amplifiers are used in radio frequency (RF) communication systems to amplify RF signals for transmission via antennas. It is important to manage the power of RF signal transmissions to prolong battery life and/or provide a suitable transmit power level.

[0003] Examples of RF communication systems with one or more power amplifiers include, but are not limited to, mobile phones, tablets, base stations, network access points, customer-premises equipment (CPE), laptops, and wearable electronics. For example, in wireless devices that communicate using a cellular standard, a wireless local area network (WLAN) standard, and/or any other suitable communication standard, a power amplifier can be used for RF signal amplification. An RF signal can have a frequency in the range of about 30 kHz to 300 GHz, for instance, in the range of about 410 MHz to about 7.125 GHz for Fifth Generation (5G) cellular communications in Frequency Range 1 (FR1) or in the range of about 24.250 GHz to about 52.600 GHz for Frequency Range 2 (FR2) of the 5G communication standard.

SUMMARY

[0004] In one aspect, the present disclosure relates to a mobile device including a transceiver configured to generate a radio frequency signal, a power management system including an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of the radio frequency signal, wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier support voltage, and a front end system including

a composite cascode power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage. The composite cascode

[0013] In another aspect, the present disclosure relates to an envelope tracking system. The envelope tracking system includes an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal, wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier support voltage, and a composite cascode power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage. The composite cascode power amplifier includes an enhancement mode field-effect transistor configured to receive the radio frequency signal and a depletion mode field-effect transistor in cascode with the enhancement-mode field-effect transistor.

[0014] In various examples, the enhancement mode field-effect transistor is a metal oxide semiconductor transistor.

[0015] In several examples, the enhancement mode field-effect transistor is a short channel n-type metal oxide semiconductor transistor.

[0016] In some examples the depletion mode field-effect transistor is a Schottky gate field-effect transistor.

[0017] In various examples, a source of the enhancement mode field-effect transistor is connected to a ground voltage, and a drain of the enhancement mode field-effect transistor is connected to an output terminal of the composite cascode power amplifier through the depletion mode field-effect transistor. According to a number of embodiments, a gate of the depletion mode transistor is biased by the ground voltage. In accordance with several embodiments, a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

[0018] In some examples, the composite cascode power amplifier further includes a choke inductor electrically connected between the power amplifier supply voltage and a drain of the depletion mode field-effect transistor.

[0019] In several examples, the composite cascode power amplifier further includes a gate bias inductor configured to provide a gate bias voltage to a gate of the enhancement mode field-effect transistor.

[0020] In various examples, the envelope tracker includes a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage at an output based on the plurality of regulated voltages

and the envelope of the radio frequency signal, and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage.

[0021] In some examples, the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier supply voltage.

[0022] In another aspect, the present disclosure relates to a method of radio frequency signal amplification in a mobile device. The method includes generating a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal using an envelope tracker, wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier support voltage, powering a composite cascode power amplifier using the power amplifier supply voltage, the composite cascode power amplifier including an enhancement mode field-effect transistor and a depletion mode field-effect transistor in cascode with the enhancement-mode field-effect transistor, and amplifying the radio frequency signal using the composite cascode power amplifier.

[0023] In various examples, the enhancement mode field-effect transistor is a metal oxide semiconductor transistor.

[0024] In a number of examples, the enhancement mode field-effect transistor is a short channel n-type metal oxide semiconductor transistor.

[0025] In several examples, the depletion mode field-effect transistor is a Schottky gate field-effect transistor.

[0026] In some examples, a source of the enhancement mode field-effect transistor is connected to a ground voltage, and a drain of the enhancement mode field-effect transistor is connected to an output terminal of the composite cascode power amplifier through the depletion mode field-effect transistor. According to a number of examples, a gate of the depletion mode transistor is biased by the ground voltage. In accordance with several examples, a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

[0027] In various examples, the method further includes providing the power amplifier supply voltage to a drain of the depletion mode field-effect transistor using a choke inductor.

[0028] In several examples, the method further includes providing a gate bias voltage to a gate of the enhancement mode field-effect transistor using a gate bias inductor.

FET with a positive voltage can provide a mechanism for balancing between gain variation and PAE.

[0088] A D-MODE~~An E-MODE~~ transistor is also referred to herein as a normally ON transistor, since the D-MODE~~E-MODE~~ transistor conducts when operating with a gate-to-source voltage of 0 V. An E-MODE~~A D-MODE~~ transistor is referred to herein as a normally OFF transistor.

[0089] Figure 3 is a schematic diagram of a power amplifier 250 according to one embodiment. The power amplifier 250 includes an E-MODE MOS transistor 241, a D-MODE Schottky gate FET 242, an input DC blocking capacitor 243, an output DC blocking capacitor 244, a gate bias inductor 245, and a choke inductor 246.

[0090] Although Figure 3 depicts one embodiment of a composite cascode power amplifier, the teachings herein are applicable to composite cascode power amplifiers implemented in a wide variety of ways.

[0091] The power amplifier 250 receives an RF input signal RF_{IN} at an RF input terminal, and provides an amplified RF output signal RF_{OUT} to an RF output terminal. In the illustrated embodiment, the input DC blocking capacitor 243 is connected between the RF input terminal and the gate of the E-MODE MOS transistor 241 to allow biasing of the gate voltage of the E-MODE MOS transistor 241 separately from the DC voltage of the RF input terminal. Additionally, the output DC blocking capacitor 244 is connected between the drain of the D-MODE Schottky gate FET 242 and the RF output terminal to decouple the drain voltage of the FET 242 from the DC voltage of the RF output terminal.

[0092] As shown in Figure 3, the choke inductor 246 provides the power amplifier supply voltage V_{PA} to the drain of the D-MODE Schottky gate FET 242. The power amplifier supply voltage V_{PA} can be generated by an envelope tracker including, but not limited to, any of the envelope trackers disclosed herein.

[0093] The E-MODE MOS transistor 241 includes a gate that receives the RF input signal RF_{IN}. The D-MODE FET 242 operates in cascode with the E-MODE MOS transistor 241 to generate the RF output signal RF_{OUT}. In the illustrated embodiment, the gate of the E-MODE MOS transistor 241 is biased by a gate bias voltage V_{GBIAS} provided by the gate bias inductor 245, while the gate of the D-MODE Schottky gate FET 242 is biased by a ground

voltage (ground). In certain implementations, the E-MODE MOS transistor 241 is a short channel n-type metal oxide semiconductor (NMOS) transistor.

WHAT IS CLAIMED IS:

1. A mobile device comprising:

a transceiver configured to generate a radio frequency signal;

a power management system including an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of the radio frequency signal, wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier support voltage; and

a front end system including a composite cascode power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the composite cascode power amplifier including an enhancement mode field-effect transistor configured to receive the radio frequency signal and a depletion mode field-effect transistor in cascode with the enhancement-mode field-effect transistor.

2. The mobile device of claim 1 wherein the enhancement mode field-effect transistor is a metal oxide semiconductor transistor.

3. The mobile device of claim 1 wherein the depletion mode field-effect transistor is a Schottky gate field-effect transistor.

4. The mobile device of claim 1 wherein a source of the enhancement mode field-effect transistor is connected to a ground voltage, and a drain of the enhancement mode field-effect transistor is connected to an output terminal of the composite cascode power amplifier through the depletion mode field-effect transistor.

5. The mobile device of claim 4 wherein a gate of the depletion mode transistor is biased by the ground voltage.

6. The mobile device of claim 4 wherein a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

7. The mobile device of claim 1 wherein the composite cascode power amplifier further includes a choke inductor electrically connected between the power amplifier supply voltage and a drain of the depletion mode field-effect transistor.

8. The mobile device of claim 1 wherein the composite cascode power amplifier further includes a gate bias inductor configured to provide a gate bias voltage to a gate of the enhancement mode field-effect transistor.

9. The mobile device of claim 1 wherein the ~~envelope tracker includes a~~ DC-to-DC converter is configured to output a plurality of regulated voltages, and the envelope tracker includes a modulator configured to generate a modulator output voltage at an output based on the plurality of regulated voltages and the envelope of the radio frequency signal, and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage.

~~10. The mobile device of claim 1 wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier supply voltage.~~

~~11.~~10. An envelope tracking system comprising:

an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal, wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier supply voltage; and

a composite cascode power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the composite cascode power amplifier including an enhancement mode field-effect transistor configured to receive the radio frequency signal and a depletion mode field-effect transistor in cascode with the enhancement-mode field-effect transistor.

~~12.~~11. The envelope tracking system of claim 10~~11~~ wherein the enhancement mode field-effect transistor is a short channel n-type metal oxide semiconductor transistor.

~~13.~~12. The envelope tracking system of claim 10~~11~~ wherein a source of the enhancement mode field-effect transistor is connected to a ground voltage, and a drain of the enhancement mode field-effect transistor is connected to an output terminal of the composite cascode power amplifier through the depletion mode field-effect transistor.

~~14.~~13. The envelope tracking system of claim 12~~13~~ wherein a gate of the depletion mode transistor is biased by the ground voltage.

~~15.~~14. The envelope tracking system of claim 12~~13~~ wherein a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

~~16.~~15. The envelope tracking system of claim 10~~11~~ wherein the ~~envelope tracker includes a~~ DC-to-DC converter is configured to output a plurality of regulated voltages, and the envelope tracker includes a modulator configured to generate a modulator output voltage at an output based on the plurality of regulated voltages and the envelope of the radio frequency signal, and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage.

~~17. The envelope tracking system of claim 11 wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier supply voltage.~~

~~18.~~16. A method of radio frequency signal amplification in a mobile device, the method comprising:

generating a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal using an envelope tracker, wherein the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier support voltage;

powering a composite cascode power amplifier using the power amplifier supply voltage, the composite cascode power amplifier including an enhancement mode field-effect transistor and a depletion mode field-effect transistor in cascode with the enhancement-mode field-effect transistor; and

amplifying the radio frequency signal using the composite cascode power amplifier.

~~19.~~17. The method of claim 16~~18~~ wherein the enhancement mode field-effect transistor is a metal oxide semiconductor transistor, and the depletion mode field-effect transistor is a Schottky gate field-effect transistor.

~~20.~~18. The method of claim 16~~18~~ wherein a source of the enhancement mode field-effect transistor is connected to a ground voltage, the method further comprising biasing a gate of the depletion mode transistor using a positive voltage above the ground voltage.