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~~certain embodiments~~, 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~~s~~ relation to an envelope of the radio frequency signal, 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 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.

[0005] In various examples~~embodiments~~, the enhancement mode field-effect transistor is a metal oxide semiconductor transistor.

[0006] In a number of examples~~embodiments~~, the enhancement mode field-effect transistor is a short channel n-type metal oxide semiconductor transistor.

[0007] In several examples~~embodiments~~, the depletion mode field-effect transistor is a Schottky gate field-effect transistor.

[0008] In some examples~~embodiments~~, 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~~embodiments~~, a gate of the depletion mode transistor is biased by the ground voltage. In accordance with several examples~~embodiments~~, a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

[0009] In various examples~~embodiments~~, 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.

[0010] In several examples~~embodiments~~, 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.

[0011] In some examples~~embodiments~~, 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.

[0012] In various examples~~embodiments~~, 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.

[0013] In another aspect~~certain embodiments~~, 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~~s~~ relation to an envelope of a radio frequency signal, 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~~embodiments~~, the enhancement mode field-effect transistor is a metal oxide semiconductor transistor.

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

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

[0017] In various examples~~embodiments~~, 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~~embodiments~~, a gate of the depletion mode transistor is biased by the ground voltage. In accordance with several examples~~embodiments~~, a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

[0018] In some examples~~embodiments~~, 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~~embodiments~~, 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~~embodiments~~, 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~~embodiments~~, 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~~certain embodiments~~, 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~~s~~ relation to an envelope of a radio frequency signal using an envelope tracker, 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~~embodiments~~, the enhancement mode field-effect transistor is a metal oxide semiconductor transistor.

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

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

[0026] In some examples~~embodiments~~, 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~~embodiments~~, a gate of the depletion mode transistor is biased by the ground voltage. In accordance with several examples~~embodiments~~, a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

[0027] In various examples~~embodiments~~, 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~~embodiments~~, the method further includes providing a gate bias voltage to a gate of the enhancement mode field-effect transistor using a gate bias inductor.

[0029] In some examples~~embodiments~~, generating the power amplifier supply voltage includes outputting a plurality of regulated voltages from a DC-to-DC converter, generating a modulator output voltage based on the plurality of regulated voltages and the envelope of the radio frequency signal using a modulator, and filtering the modulator output voltage to generate the power amplifier supply voltage using a modulator output filter.

[0030] In various examples~~embodiments~~, generating the power amplifier supply voltage includes tracking the envelope using a DC-to-DC converter and an error amplifier operating in parallel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] Figure 1 is a schematic diagram of one embodiment of a mobile device.

[0032] Figure 2 is a schematic diagram of one embodiment of a transmit system for transmitting radio frequency (RF) signals from a mobile device.

[0033] Figure 3 is a schematic diagram of a power amplifier according to one embodiment.

[0034] Figure 4A is a graph of one example of power gain versus output power for a common source n-type metal oxide semiconductor (NMOS) power amplifier.

[0035] Figure 4B is a graph of one example of power gain versus output power for a composite cascode power amplifier.

[0036] Figure 4C is a graph of one example of quiescent drain current versus supply voltage for a common source NMOS power amplifier.

[0037] Figure 4D is a graph of one example of quiescent drain current versus supply voltage for a composite cascode power amplifier.

[0038] Figure 5A is a graph of one example of gain versus output power for a composite cascode power amplifier.

[0039] Figure 5B is a graph of one example of power added efficiency (PAE) versus output power for a composite cascode power amplifier.

[0040] Figure 5C is a graph of one example of quiescent current versus power amplifier supply voltage for a composite cascode power amplifier.

[0041] Figure 6 is a schematic diagram of a power amplifier according to another embodiment.

[0053] Figure 1 is a schematic diagram of one example of a mobile device 100. The mobile device 100 includes a baseband system 1, a transceiver 2, a front end system 3, antennas 4, a power management system 5, a memory 6, a user interface 7, and a battery 8.

[0054] The mobile device 100 can be used communicate using a wide variety of communications technologies, including, but not limited to, 2G, 3G, 4G (including LTE, LTE-Advanced, and LTE-Advanced Pro), 5G, WLAN (for instance, Wi-Fi), WPAN (for instance, Bluetooth and ZigBee), WMAN (for instance, WiMax), and/or GPS technologies.

[0055] The transceiver 2 generates RF signals for transmission and processes incoming RF signals received from the antennas 4. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in Figure 1 as the transceiver 2. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

[0056] The front end system 3 aids ins conditioning signals transmitted to and/or received from the antennas 4. In the illustrated embodiment, the front end system 3 includes power amplifiers (PAs) 11, low noise amplifiers (LNAs) 12, filters 13, switches 14, and duplexers 15. However, other implementations are possible.

[0057] For example, the front end system 3 can provide a number of functionalities, including, but not limited to, amplifying signals for transmission, amplifying received signals, filtering signals, switching between different bands, switching between different power modes, switching between transmission and receiving modes, duplexing of signals, multiplexing of signals (for instance, diplexing or triplexing), or some combination thereof.

[0058] In certain implementations, the mobile device 100 supports carrier aggregation, thereby providing flexibility to increase peak data rates. Carrier aggregation can be used for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), and may be used to aggregate a plurality of carriers or channels. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band and/or in different bands.

[0059] The antennas 4 can include antennas used for a wide variety of types of communications. For example, the antennas 4 can include antennas associated transmitting

[0063] The memory 6 can be used for a wide variety of purposes, such as storing data and/or instructions to facilitate the operation of the mobile device 100 and/or to provide storage of user information.

[0064] The power management system 5 provides a number of power management functions of the mobile device 100. The power management system 5 of Figure 1 includes an envelope tracker 60. As shown in Figure 1, the power management system 5 receives a battery voltage fromorm the battery 8. The battery 8 can be any suitable battery for use in the mobile device 100, including, for example, a lithium-ion battery.

[0065] The mobile device 100 of Figure 1 illustrates one example of an RF communication system that can include power amplifier(s) implemented in accordance with one or more features of the present disclosure. However, the teachings herein are applicable to RF communication systems implemented in a wide variety of ways.

[0066] Figure 2 is a schematic diagram of one embodiment of a transmit system 130 for transmitting RF signals from a mobile device. The transmit system 130 includes a battery 101, an envelope tracker 102, a power amplifier 103, a directional coupler 104, a duplexing and switching circuit 105, an antenna 106, a baseband processor 107, a signal delay circuit 108, a digital pre-distortion (DPD) circuit 109, an I/Q modulator 110, an observation receiver 111, an intermodulation detection circuit 112, an envelope delay circuit 121, a coordinate rotation digital computation (CORDIC) circuit 122, a shaping circuit 123, a digital-to-analog converter 124, and a reconstruction filter 125.

[0067] The transmit system 130 of Figure 2 illustrates one example of an RF communication system that can include power amplifier(s) implemented in accordance with one or more features of the present disclosure. However, the teachings herein are applicable to RF communication systems implemented in a wide variety of ways.

[0068] The baseband processor 107 operates to generate an I signal and a Q signal, which correspond to signal components of a sinusoidal wave or signal of a desired amplitude, frequency, and phase. For example, the I signal can be used to represent an in-phase component of the sinusoidal wave and the Q signal can be used to represent a quadrature-phase component of the sinusoidal wave, which can be an equivalent representation of the sinusoidal wave. In certain implementations, the I and Q signals are provided to the I/Q modulator 110 in a digital format. The baseband processor 107 can be any suitable processor configured to

providing DC-to-DC conversion of a battery voltage V_{BATT}. Although an example with three regulated voltages is shown, the multi-output boost switcher 625 can generate more or fewer regulated voltages. In certain implementations, at least a portion of the regulated voltages are boosted relative to the battery voltage V_{BATT}. In some configurations, one or more of the regulated voltages is a buck voltage having a voltage lower than the battery voltage V_{BATT}.

[0126] The capacitor bank 630 aids in stabilizing the regulated voltages generated by the multi-output boost switcher 625. For example, the capacitors 631-633 operate as decoupling capacitors.

[0127] The filter 626 processes the output of the switch bank 627 to generate the power amplifier supply voltage V_{PA}. By controlling the selection of the switches 641-643 over time based on the envelope signal, the power amplifier supply voltage V_{PA} is generated to track the envelope signal.

[0128] Figure 11A is a schematic diagram of one embodiment of a packaged module 800. Figure 11B is a schematic diagram of a cross-section of the packaged module 800 of Figure 11A taken along the lines 11B–11B.

[0129] The packaged module 800 includes an IC or die 801, surface mount components 803, wirebonds 808, a package substrate 820, and encapsulation structure 840. The package substrate 820 includes pads 806 formed from conductors disposed therein. Additionally, the die 801 includes pads 804, and the wirebonds 808 have been used to electrically connect the pads 804 of the die 801 to the pads 806 of the package substrate 8200~~1~~.

[0130] The die 801 includes a power amplifier 846, which can be implemented in accordance with any of the embodiments herein.

[0131] The packag~~e~~ing substrate 820 can be configured to receive a plurality of components such as the die 801 and the surface mount components 803, which can include, for example, surface mount capacitors and/or inductors.

[0132] As shown in Figure 11B, the packaged module 800 is shown to include a plurality of contact pads 832 disposed on the side of the packaged module 800 opposite the side used to mount the die 801. Configuring the packaged module 800 in this manner can aid in connecting the packaged module 800 to a circuit board such as a phone board of a wireless device. The example contact pads 832 can be configured to provide RF signals, bias signals, power low voltage(s) and/or power high voltage(s) to the die 801 and/or the surface mount

components 803. As shown in Figure 11B, the electrically connections between the contact pads 832 and the die 801 can be facilitated by connections 833 through the package substrate 820. The connections 833 can represent electrical paths formed through the package substrate 820, such as connections associated with vias and conductors of a multilayer laminated package substrate.

[0133] In some embodiments, the packaged module 800 can also include one or more packaging structures to, for example, provide protection and/or facilitate handling of the packaged module 800. Such a packaging structure can include overmold or encapsulation structure 840 formed over the packag~~e~~ing substrate 820 and the components and die(s) disposed thereon.

[0134] It will be understood that although the packaged module 800 is described in the context of electrical connections based on wirebonds, one or more features of the present disclosure can also be implemented in other packaging configurations, including, for example, flip-chip configurations.

[0135] Figure 12 is a schematic diagram of one embodiment of a phone board 900. The phone board 900 includes the module 800 shown in Figures 1~~10~~A-1~~10~~B attached thereto. Although not illustrated in Figure 12 for clarity, the phone board 9~~8~~00 can include additional components and structures.

Applications

[0136] Some of the embodiments described above have provided examples in connection with wireless devices or mobile phones. However, the principles and advantages of the embodiments can be used for any other systems or apparatus that have needs for power amplifiers.

[0137] Such envelope trackers can be implemented in various electronic devices. Examples of the electronic devices can include, but are not limited to, consumer electronic products, parts of the consumer electronic products, electronic test equipment, etc. Examples of the electronic devices can also include, but are not limited to, memory chips, memory modules, circuits of optical networks or other communication networks, and disk driver circuits. The consumer electronic products can include, but are not limited to, a mobile phone, a telephone, a television, a computer monitor, a computer, a hand-held computer, a personal

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~~s~~ relation to an envelope of the radio frequency signal; 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 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.

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. An envelope tracking system comprising:

an envelope tracker configured to generate a power amplifier supply voltage that changes in~~s~~ relation to an envelope of a radio frequency signal; 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. The envelope tracking system of claim 11 wherein the enhancement mode field-effect transistor is a short channel n-type metal oxide semiconductor transistor.

13. The envelope tracking system of claim 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. The envelope tracking system of claim 1 wherein a gate of the depletion mode transistor is biased by the ground voltage.

15. The envelope tracking system of claim 1 wherein a gate of the depletion mode transistor is biased by a positive voltage above the ground voltage.

16. The envelope tracking system of claim 11 wherein 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.

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

generating a power amplifier supply voltage that changes in~~s~~ relation to an envelope of a radio frequency signal using an envelope tracker;

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. The method of claim 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. The method of claim 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.