LOAD-LINE SWITCHING FOR PUSH-PULL POWER AMPLIFIERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 62/736,540 titled LOAD-LINE SWITCHING FOR PUSH-PULL POWER AMPLIFIERS, filed September 26, 2018, which is incorporated by reference herein in its entirety.

BACKGROUND

In mobile applications, such as cellular, it can be very important to prolong battery life to allow mobile devices to operate for relatively long periods of time without being recharged. Power amplification is one of the functions that consumes a significant amount of battery power in mobile applications. Several system and circuit implementations have been directed at reducing current consumption to prolong battery life as well as to improve the thermal reliability of mobile devices. Some common methods used to improve the efficiency of power amplifiers for cellular or other mobile applications include Average Power Tracking (APT), Envelope Tracking (ET), and dynamic load-line tuning. However, these methods can involve complex processing and calibration and therefore are not always desirable in certain applications.

SUMMARY ~~OF INVENTION~~

The examples~~Aspects and embodiments~~ described herein are directed to a method and circuit implementations for providing programmable load-line impedance tuning in a push-pull power amplifier.

In one aspect~~According to one embodiment~~, a push-pull power amplifier system having an input, an output, and a variable load-line impedance comprise~~s~~ an input amplifier coupled to the input of the push-pull power amplifier system to receive an unbalanced radio frequency (RF) input signal and provide an unbalanced amplified RF signal at an output of the input amplifier~~a power amplifier having an input to receive a radio frequency (RF) input signal and an output, the power amplifier configured to amplify the RF input signal and provide at the output an RF output signal that is an amplified version of the RF input signal~~, an input transformer having a primary winding coupled to the output of the input amplifier and having a secondary winding to provide a pair of

balanced RF signals based on the unbalanced amplified RF signal, an output transformer having a primary winding to receive a respective amplified balanced RF signal of the pair of amplified balanced RF signals and a secondary winding ~~coupled to the output of the power amplifier and configured~~ to provide ~~the~~an unbalanced amplified RF output signal on a load-line coupled to the output of the push-pull power amplifier system, a switchable shunt capacitance switchably connected between the load-line and a reference potential, and a switch configured to selectively connect the switchable shunt capacitance to the reference potential and

disconnect the switchable shunt capacitance from the reference potential to vary an impedance of the load-line to match an impedance at the primary winding of the output transformer.

In one example, the power amplifier includes a pair of complementary transistors.

In one example, the impedance of the load-line is varied to tune a power level of the RF output signal.

In one example, the switchable shunt capacitance includes a single fixed-value capacitor.

In another example, the switchable shunt capacitance includes a variable capacitor.

In another example, the switchable shunt capacitance includes a plurality of capacitors configured to be selectively connected together in series and/or parallel to provide a selected capacitance value.

In one example, the push-pull power amplifier system further comprises an input transformer coupled to the input of the power amplifier. The input transformer may be configured to receive the RF input signal, to split the RF input signal into a pair of balanced RF input signals, and to provide the pair of balanced RF input signals to the power amplifier, and the output transformer may be configured to receive a pair of balanced RF output signals from the power amplifier, and to recombine the pair of balanced RF output signals to provide the RF output signal on the load-line. In another example, the push-pull power amplifier system further comprises an input amplifier coupled to an input of the input transformer such that the input transformer is connected between the input amplifier and the power amplifier.

In another example, ~~According to another embodiment~~ a power amplifier system comprises a push-pull power amplifier having an input to receive a radio frequency (RF) input signal and an output, the power amplifier configured to amplify the RF input signal and provide at the output an RF output signal that is an amplified version of the RF input signal, a switchable shunt capacitance switchably connected between a load-line coupled to the output of the push-pull power amplifier and a reference potential, a switch configured to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential to vary an impedance of the load-line, and a controller coupled to the switch and configured to control the switch to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential.

In one example, the impedance of the load-line is varied to tune a power level of the RF output signal.

In one example, the controller is further coupled to the push-pull power amplifier and configured to control one or more parameters of the push-pull power amplifier. In another example, the controller is configured to control the one or more parameters of the push-pull power amplifier and the switch using a mobile industry processor interface (MIPI) control protocol.

In one example, the switchable shunt capacitance includes a single fixed-value capacitor. In another example, the switchable shunt capacitance includes a variable capacitor. In one example, the controller is coupled to the variable capacitor and configured to tune a capacitance value of the variable capacitor. In another example, the switchable shunt capacitance includes a plurality of capacitors and a plurality of switches configured to selectively connect together selected ones of the plurality of capacitors in series and/or parallel to provide a selected capacitance value for the switchable shunt capacitance. In one example, the controller is coupled to the plurality of switches and configured to control the plurality of switches to connect together the selected ones of the plurality of capacitors to provide the selected capacitance value.

In another example, ~~According to another embodiment~~ a method of operating a power amplifier system having at least two modes of operation comprises receiving a radio frequency (RF) input signal at an input of the power amplifier system, amplifying, via a push-pull power amplifier, the RF input signal to provide an amplified RF signal to a load-line, adjusting an impedance of the load-line based on the mode of operation of the power amplifier system, and providing the amplified RF signal to an output of the power amplifier system via the load-line.

In one example, adjusting the impedance of the load-line includes connecting a shunt capacitance between the load-line and a reference potential during at least one mode of operation. In another example, adjusting the impedance of the load-line includes tuning a capacitance value of a variable shunt capacitor coupled between the load-line and a reference potential. In one example, adjusting the impedance of the load-line includes controlling a plurality of switches to connect together selected ones of a plurality of shunt capacitors coupled between the load-line and a reference potential.

In one example, the impedance of the load-line is adjusted based on the mode of operation to tune a power level of the amplified RF signal to a target output power level. Another ~~embodiment~~example is directed to a radio frequency (RF) front-end module comprising a transceiver configured to provide an RF transmit signal and to receive and process an RF received signal, a duplexer, an antenna switch coupled to the duplexer, the antenna switch and the duplexer

together being configured to switch operation of the RF front-end module between a transmit mode and a receive mode, and a push-pull power amplifier coupled between the transceiver and the duplexer and configured to receive and amplify the RF transmit signal, the push-pull power amplifier including a shunt capacitance switchably connected between an output load-line of the push-pull power amplifier and a reference potential, and a switch configured to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential to vary an impedance of the output load-line.

In one example, the switchable shunt capacitance includes a single fixed-value capacitor. In another example, the switchable shunt capacitance includes a variable capacitor. In another example, the switchable shunt capacitance includes a plurality of capacitors configured to be selectively connected together in series and/or parallel to provide a selected capacitance value.

In one example, the transceiver includes a transmitter circuit configured to provide the RF transmit signal and a receiver circuit configured to receive and process the RF received signal. The RF front-end module may further comprise a low-noise amplifier coupled between the duplexer and the receiver circuit and configured to amplify the RF received signal.

In another example, ~~According to another embodiment~~ a wireless device comprises an antenna, a transceiver configured to provide RF transmit signals and to receive and process RF received signals, an antenna switch module coupled between the transceiver and the antenna and configured to switch operation of the wireless device between a transmit mode and a receive mode, and a power amplifier module coupled between the transceiver and the antenna switch module and configured to receive and amplify the RF transmit signals, the power amplifier module including at least one push-pull power amplifier having a variable load-line impedance, the at least one push-pull power amplifier including a shunt capacitance switchably connected between a load-line of the at least one push-pull power amplifier and a reference potential, and a switch configured to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential to vary the load-line impedance.

In one example, the switchable shunt capacitance includes a single fixed-value capacitor. In another example, the switchable shunt capacitance includes a variable capacitor. In another example, the switchable shunt capacitance includes a plurality of capacitors configured to be selectively connected together in series and/or parallel to provide a selected capacitance value.

The wireless device may further comprise a power management system coupled to the power amplifier module and configured to control the switch of the at least one push-pull power amplifier to selectively vary the load-line impedance. In one example, the power management system is further coupled to the transceiver and configured to control at least one operating parameter of the transceiver.

The wireless device may further comprise a directional coupler connected between the power amplifier module and the antenna switch module, the directional coupler being configured to extract a portion of each of the RF transmit signals by electromagnetic coupling to provide RF coupled signals. In one example, the wireless device further comprises a sensor coupled to the directional coupler and to the transceiver, the sensor being configured to receive the RF coupled signals and to provide feedback information to the transceiver to regulate an output power level of the power amplifier module based on the Rf coupled signals.

The wireless device may further comprise a low-noise amplifier coupled between the antenna switch module and the transceiver and configured to amplify the RF received signals during the receive mode.

In another example, ~~According to another embodiment an~~ the amplifier system comprises a push-pull power amplifier having an input to receive a radio frequency (RF) input signal and an output, the push-pull power amplifier being configured to amplify the RF input signal and provide at the output an RF output signal that is an amplified version of the RF input signal, a switchable shunt capacitance switchably connected between a load-line connected to the output of the push-pull power amplifier and a reference potential, and a switch configured to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential to vary an impedance of load-line.

In one example, the switchable shunt capacitance includes a single fixed-value capacitor. In another example the switchable shunt capacitance includes a variable capacitor. In another example the switchable shunt capacitance includes a plurality of capacitors configured to be selectively connected together in series and/or parallel to provide a selected capacitance value.

Further examples~~Still other aspects, embodiments,~~ and advantages ~~of these exemplary aspects and embodiments~~ are discussed in detail below. ~~Embodiments~~Examples disclosed herein may be combined with other ~~embodiments~~examples in any manner consistent with at least one of

the principles disclosed herein, and references to "an ~~embodiment~~example," "some ~~embodiments~~examples," "an alternate ~~embodiment~~example," "various

~~embodiments~~examples," "one ~~embodiment~~example" or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described may be included in at least one ~~embodiment~~example. The appearances of such terms herein are not necessarily all referring to the same ~~embodiment~~example.

BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of the invention. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

FIG. 1 is a simplified circuit diagram of one example of a push-pull amplifier incorporating load-line switching according to aspects of the present invention;

FIG. 2 is a block diagram of one example of an amplifier system according to aspects of the present invention;

FIG. 3A is a smith chart showing simulated results for an example of the push-pull amplifier shown in FIG. 1, according to aspects of the present invention;

FIG. 3B is a smith chart showing further simulated results for the example of the push-pull amplifier shown in FIG. 1, according to aspects of the present invention;

FIG. 4A is a block diagram showing another example of the amplifier system of FIG. 2 in which the switchable capacitor is variable, according to aspects of the present invention;

FIG. 4B is a block diagram of one example of a capacitor bank arrangement that may be used to implement the switchable capacitor in FIGS. 1 and 2, according to aspects of the present invention;

FIG. 5 is a block diagram of one example of an RF front-end module incorporating a push-pull power amplifier according to aspects of the present invention; and

FIG. 6 is a block diagram of one example of a wireless device incorporating one or more push-pull power amplifiers according to aspects of the present invention.

CLAIMS

1. A push-pull power amplifier system having an input, an output, and a variable load-line impedance comprising:

an input amplifier coupled to the input of the push-pull power amplifier system to receive an unbalanced radio frequency (RF) input signal and provide an unbalanced amplified RF signal at an output of the input amplifier;

~~a power amplifier having an input to receive a radio frequency (RF) input signal and an output, the power amplifier configured to amplify the RF input signal and provide at the output an RF output signal that is an amplified version of the RF input signal;~~

an input transformer having a primary winding coupled to the output of the input amplifier and having a secondary winding to provide a pair of balanced RF signals based on the unbalanced amplified RF signal;

a pair of complementary amplifiers to receive a respective balanced RF signal of the pair of balanced RF signals and provide a pair of amplified balanced RF signals;

an output transformer having a primary winding to receive a respective amplified balanced RF signal of the pair of amplified balanced RF signals and a secondary winding ~~coupled to the output of the power amplifier and configured~~ to provide ~~the~~an unbalanced amplified RF output signal on a load-line coupled to the output of the push-pull power amplifier system;

a switchable shunt capacitance switchably connected between the load-line and a reference potential; and

a switch configured to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential to vary an impedance of the load-line to match an impedance at the primary winding of the output transformer.

2. The push-pull power amplifier system of claim 1 wherein the impedance of the load-line is varied to tune a power level of the unbalanced amplified RF output signal.

3. The push-pull power amplifier system of claim 1 wherein the switchable shunt capacitance includes a single fixed-value capacitor.

4. The push-pull power amplifier system of claim 1 wherein the switchable shunt capacitance includes a variable capacitor.

5. The push-pull power amplifier system of claim 1 wherein the switchable shunt capacitance includes a plurality of capacitors configured to be selectively connected together in series and/or parallel to provide a selected capacitance value.

6. The push-pull power amplifier system of claim 1 further comprising a fixed-value capacitor non-switchably coupled between the load-line and the reference potential, wherein the switchable shunt capacitance includes a plurality of capacitors switchably connected together in parallel with the fixed-value capacitor to provide a selected capacitance value.

7. The push-pull power amplifier system of claim 1 further comprising at least one capacitor coupled to a center tap of the primary winding of the output transformer.

8. The push-pull power amplifier system of claim 7 wherein the at least one capacitor is coupled between the center tap of the primary winding of the output transformer and the reference potential.

9. The push-pull power amplifier system of claim 8 wherein the secondary winding of the output transformer has a first end to provide the unbalanced amplified RF output signal and a second end that is coupled to the reference potential through a capacitor.

10. The push-pull power amplifier system of claim 1 wherein the secondary winding of the output transformer has a first end to provide the unbalanced amplified RF output signal and a second end that is coupled to the reference potential through a capacitor.

~~6. The push-pull power amplifier system of any one of claims 1-5 further comprising an input transformer coupled to the input of the power amplifier.~~

~~7. The push-pull power amplifier system of claim 6 wherein the input transformer is configured to receive the RF input signal, to split the RF input signal into a pair of balanced RF input signals, and to provide the pair of balanced RF input signals to the power amplifier; and~~

~~wherein the output transformer is configured to receive a pair of balanced RF output signals from the power amplifier, and to recombine the pair of balanced RF output signals to provide the RF output signal on the load-line.~~

~~8. The push-pull power amplifier system of claim 6 further comprising an input amplifier coupled to an input of the input transformer such that the input transformer is connected between the input amplifier and the power amplifier.~~

~~9. A power amplifier system comprising:~~

~~a push-pull power amplifier having an input to receive a radio frequency (RF) input signal and an output, the power amplifier configured to amplify the RF input signal and provide at the output an RF output signal that is an amplified version of the RF input signal;~~

~~a switchable shunt capacitance switchably connected between a load-line coupled to the output of the push-pull power amplifier and a reference potential;~~

~~a switch configured to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential to vary an impedance of the load-line; and~~

~~a controller coupled to the switch and configured to control the switch to selectively connect the switchable shunt capacitance to the reference potential and disconnect the switchable shunt capacitance from the reference potential.~~

~~10. The power amplifier system of claim 9 wherein the impedance of the load-line is varied to tune a power level of the RF output signal.~~

~~11. The power amplifier system of claim 9 wherein the controller is further coupled to the push-pull power amplifier and configured to control one or more parameters of the push-pull power amplifier.~~

12. The power amplifier system of claim 11 wherein the controller is configured to control the one or more parameters of the push-pull power amplifier and the switch using a mobile industry processor interface (MIPI) control protocol.

13. The power amplifier system of any one of claims 9-12 wherein the switchable shunt capacitance includes a single fixed-value capacitor.

14. The power amplifier system of any one of claims 9-12 wherein the switchable shunt capacitance includes a variable capacitor.

15. The power amplifier system of claim 14 wherein the controller is coupled to the variable capacitor and configured to tune a capacitance value of the variable capacitor.

16. The power amplifier system of any one of claims 9-12 wherein the switchable shunt capacitance includes a plurality of capacitors and a plurality of switches configured to selectively connect together selected ones of the plurality of capacitors in series and/or parallel to provide a selected capacitance value for the switchable shunt capacitance.

17. The power amplifier system of claim 16 wherein the controller is coupled to the plurality of switches and configured to control the plurality of switches to connect together the selected ones of the plurality of capacitors to provide the selected capacitance value.

18. A method of operating a power amplifier system having at least two modes of operation, the method comprising:

receiving a radio-frequency (RF) input signal at an input of the power amplifier system;

amplifying, via a push-pull power amplifier, the RF input signal to provide an amplified RF signal to a load-line;

adjusting an impedance of the load-line based on the mode of operation of the power amplifier system; and

providing the amplified RF signal to an output of the power amplifier system via the load-line.

~~19. The method of claim 18 wherein adjusting the impedance of the load-line further includes connecting a shunt capacitance between the load-line and a reference potential during at least one mode of operation.~~

~~20. The method of claim 18 wherein adjusting the impedance of the load-line further includes tuning a capacitance value of a variable shunt capacitor coupled between the load-line and a reference potential.~~

~~21. The method of claim 18 wherein adjusting the impedance of the load-line further includes controlling a plurality of switches to connect together selected ones of a plurality of shunt capacitors coupled between the load-line and a reference potential.~~

~~22. The method of any one of claims 18-21 wherein the impedance of the load-line is adjusted based on the mode of operation to tune a power level of the amplified RF signal to a target output power level.~~