AMPLIFIER LINEARITY BOOST CIRCUITS AND METHODS FOR POST DISTORTION FEEDBACK CANCELATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 62/694,488, titled "AMPLIFIER LINEARITY BOOST CIRCUITS AND METHODS FOR POST DISTORTION FEEDBACK CANCELATION," filed July 6, 2018, which is incorporated by reference herein in its entirety for all purposes.

BACKGROUND

Many wireless device designs, such as those for smart-phones and tablets, require amplification of a signal without significant distortion. While amplifier architectures have been designed to reduce distortion, practically all wireless device designs will experience some measure of intermodulation distortion. Intermodulation distortion is the amplitude modulation of signals containing two or more different frequencies, and is quantified by the non-harmonic frequencies added to an input signal. Intermodulation distortion often occurs as a result of nonlinearities in an amplifier or pre-amplifier system. When uncontrolled, intermodulation distortion can increase bandwidth and create channel interference, among various other undesirable effects.

SUMMARY

Aspects and examples described herein relate to electronic systems, and in particular, to amplifier circuits for electronic systems and devices. Various examples of the amplifier circuits described herein are configured to reduce an intermodulation distortion in an amplified signal and improve system linearity over a wide range of temperatures and process variations.

According to an aspect of the present ~~invention~~disclosure, an amplifier circuit is provided comprising an amplifier having a signal input and a signal output, the amplifier being configured to produce an amplified signal at the signal output, a feedback path coupled between the signal output and the signal input, and an amplifier linearity boost circuit positioned in the feedback path. The amplifier linearity boost circuit includes a non-linear current generator including a transistor and a biasing circuit coupled to the transistor and configured to selectively bias the

transistor and a phase-shifting circuit including a capacitor coupled in series with a resistor between the non-linear current generator and the signal input~~and a phase-shifting circuit~~, the non-linear current generator being configured to provide a non-linear current

based on the amplified signal, and the phase-shifting circuit being configured to adjust a phase of the non-linear current to reduce an intermodulation distortion of the amplified signal.

In accordance with an ~~embodiment~~example, the non-linear current generator includes a transistor. In accordance with an ~~aspect of this embodiment~~example, the non-linear current generator includes a biasing circuit coupled to the transistor, the biasing circuit being configured to selectively bias the transistor. In accordance with a further ~~aspect of this embodiment~~example, the phase-shifting circuit includes a capacitor coupled in series with a resistor. In accordance with one example, the capacitor is a variable capacitor and the resistor is a variable resistor, and the capacitor and the resistor are coupled between the non-linear current generator and the signal input. In some ~~embodiment~~examples, the transistor is a metal-oxide-semiconductor field-effect transistor (MOSFET), the transistor having a gate, a source, and a drain, the drain being coupled to the signal output and the source being coupled to the phase-shifting circuit. In some examples, the biasing circuit includes a first bias resistor coupled between the gate and an electrical ground, a second bias resistor coupled between the source and the electrical ground, and a bias switch coupled in parallel with a bias capacitor between the gate and the drain. In other examples, the amplifier circuit further comprises a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output. In accordance with some ~~embodiment~~examples, during a feedback mode of operation the bias switch is opened to decouple the gate from the electrical ground.

In other examples, the biasing circuit includes a first bias resistor coupled between the gate and a first bias input, a second bias resistor coupled between the source and a second bias input, and a bias capacitor coupled between the drain and the gate. In some examples, the amplifier circuit further comprises a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output. In accordance with some ~~embodiment~~examples, during a feedback mode of operation the biasing circuit is configured to bias the transistor based at least in part on a first control signal received at the first bias input and a second control signal received at the second bias input.

In still further examples, the biasing circuit includes a bias switch coupled between the gate and an electrical ground, and a current source coupled between the source and the electrical

ground. In some examples, the amplifier circuit further comprises a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output. In accordance with some ~~embodiment~~examples, during a feedback mode of operation the bias switch is opened to decouple the gate from the electrical ground.

In accordance with other examples, the biasing circuit includes a current source coupled to the drain via a first bias switch, a bias resistor coupled between the source and an electrical ground, and a second bias switch coupled between the gate and the electrical ground. In some examples, the amplifier circuit further comprises a direct current blocking component positioned in the feedback path and interposed between the amplifier linearity boost circuit and the signal output. The amplifier circuit may further comprise a bypass switch positioned in feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output. In accordance with some ~~embodiment~~examples, during a feedback mode of operation the first bias switch is closed to couple the current source to the drain, and the second bias switch is opened to decouple the gate from the electrical ground.

In accordance with some ~~embodiment~~examples, the amplifier is configured to apply a variable gain to a signal received at the signal input to produce the amplified signal at the signal output.

In some ~~embodiment~~examples, the phase-shifting circuit is configured to shift the phase of the non-linear current based at least in part on a gain setting of the amplifier, and the phase-shifting circuit includes a variable capacitor coupled in series with a variable resistor. In at least one ~~embodiment~~example, at least one of the variable capacitor and the variable resistor are adjustable to vary the phase of the non-linear current. In accordance with some ~~embodiment~~examples, the amplifier circuit further comprises a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output based at least in part on a gain setting of the amplifier. In at least some ~~embodiment~~examples, at least one of the variable capacitor and the variable resistor are adjustable to vary the magnitude of the non-linear current.

In accordance with an ~~aspect~~ example of the present ~~invention~~disclosure, the amplifier circuit may be included in a module, and the module may be included in an electronic device. In accordance with an ~~aspect~~ example of the present ~~invention~~disclosure, the amplifier circuit may be included in a system that

includes an antenna to transmit and/or receive a signal, a transceiver, and the amplifier circuit coupled between at least the antenna and the transceiver.

In accordance with another aspect of the present ~~invention~~disclosure, an amplifier feedback method is provided. The method includes receiving a signal at a signal input of an amplifier, amplifying the signal to provide an amplified signal at a signal output of the amplifier, electrically coupling the signal output to the signal input responsive to a first gain setting of the amplifier to apply~~applying~~ a non-linear current to the signal received at the signal input based on the amplified signal, and shift~~ing~~ a phase of the non-linear current to reduce an intermodulation distortion of the amplified signal, and electrically decoupling the signal output from the signal input responsive to a second gain setting of the amplifier. ~~-~~In accordance with one ~~aspect~~example, shifting the phase of the non-linear current includes adjusting a complex impedance of a phase-shifting circuit, and adjusting the complex impedance of the phase-shifting circuit includes adjusting a value of at least one of a capacitor and a resistor. In accordance with another ~~aspect~~example, applying a non-linear current to the signal received at the signal input includes coupling a transistor in a feedback path between the signal input and the signal output, and applying the non-linear current with the transistor. In accordance with a still further ~~aspect~~example, the method may further includes adjusting a magnitude of the non-linear current to reduce the intermodulation distortion of the amplified signal, and adjusting the magnitude of the non-linear current includes adjusting a complex impedance of a phase-shifting circuit. In some ~~embodiment~~examples, adjusting the magnitude of the non-linear current includes adjusting the magnitude of the non-linear current based on a gain setting of the amplifier, and in some ~~embodiment~~examples, shifting the phase of the non-linear current includes shifting the phase based on a gain setting of the amplifier.

In accordance with yet a further aspect of the present ~~invention~~disclosure, an amplifier feedback method ~~may include~~ comprises amplifying a signal at a signal input of an amplifier to provide an amplified signal at a signal output of ~~an~~ the amplifier, producing a non-linear current based on the amplified signal, adjusting a complex impedance of a phase-shifting circuit to adjust at least one of a magnitude and a phase of the non-linear current, electrically coupling the signal output to the signal input responsive to a first gain setting of the amplifier to apply~~and applying~~ the non-linear current to the signal at a signal input of the amplifier to reduce an intermodulation

distortion of the amplified signal, and electrically decoupling the signal output from the signal input responsive to a second gain setting of the amplifier.

Still other aspects, examples, and advantages of these exemplary aspects and implementations are discussed in detail below. Examples disclosed herein may be combined with other examples in any manner consistent with at least one of the principles disclosed herein, and references to "an example," "some example," "an alternate example," "various examples," "one example" or the like are not necessarily mutually exclusive and are intended to indicate that a

CLAIMS

1. An amplifier circuit comprising:

an amplifier having a signal input and a signal output, the amplifier being configured to produce an amplified signal at the signal output;

a feedback path coupled between the signal output and the signal input; and

an amplifier linearity boost circuit positioned in the feedback path, the amplifier linearity boost circuit including a non-linear current generator ~~and a phase-shifting circuit~~including a transistor and a biasing circuit coupled to the transistor and configured to selectively bias the transistor and a phase-shifting circuit including a capacitor coupled in series with a resistor between the non-linear current generator and the signal input, the non-linear current generator being configured to provide a non-linear current based on the amplified signal, and the phase-shifting circuit being configured to adjust a phase of the non-linear current to reduce an intermodulation distortion of the amplified signal.

~~2. The amplifier circuit of claim 1 wherein the non-linear current generator includes a biasing circuit coupled to a transistor, the biasing circuit being configured to selectively bias the transistor.~~

~~3. The amplifier circuit of claim 2 wherein the phase-shifting circuit includes a capacitor coupled in series with a resistor and wherein the capacitor and the resistor are coupled between the non-linear current generator and the signal input.~~

2~~4~~. The amplifier circuit of claim 1~~3~~ wherein the transistor is a metal-oxide-semiconductor field-effect transistor, the transistor having a gate, a source, and a drain, the drain being coupled to the signal output and the source being coupled to the phase-shifting circuit.

~~5~~3. The amplifier circuit of claim 4~~2~~ wherein the biasing circuit includes a first bias resistor coupled between the gate and an electrical ground, a second bias resistor coupled between the source and the electrical ground, and a bias switch selectively coupled in parallel with a bias capacitor between the gate and the drain.

4. The amplifier circuit of claim 3 further comprising a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output.

5~~6~~. The amplifier circuit of claim 3~~5~~ wherein during a feedback mode of operation the bias switch is opened to decouple the gate from the electrical ground.

~~7~~6. The amplifier circuit of claim ~~4~~2 wherein the biasing circuit includes a first bias resistor coupled between the gate and a first bias input, a second bias resistor coupled between the source and a second bias input, and a bias capacitor coupled between the drain and the gate.

7. The amplifier circuit of claim 6 further comprising a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output.

8. The amplifier circuit of claim ~~7~~6 wherein during a feedback mode of operation the biasing circuit is configured to bias the transistor based at least in part on a first control signal received at the first bias input and a second control signal received at the second bias input.

9. The amplifier circuit of claim ~~4~~2 wherein the biasing circuit includes a bias switch coupled between the gate and an electrical ground, and a current source coupled between the source and the electrical ground.

10. The amplifier circuit of claim 9 further comprising a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output.

11. The amplifier circuit of claim 9 wherein during a feedback mode of operation the bias switch is opened to decouple the gate from the electrical ground.

~~11~~12. The amplifier circuit of claim ~~4~~2 wherein the biasing circuit includes a current source coupled to the drain via a first bias switch, a bias resistor coupled between the source and an electrical ground, and a second bias switch coupled between the gate and the electrical ground.

~~12~~13. The amplifier circuit of claim ~~11~~12 further comprising a direct current blocking component positioned in the feedback path and interposed between the amplifier linearity boost circuit and the signal output.

~~13. The amplifier circuit of claim 11 wherein during a feedback mode of operation the first bias switch is closed to couple the current source to the drain, and the second bias switch is opened to decouple the gate from the electrical ground.~~

14. The amplifier circuit of ~~any of claims 1-~~claim 13 further comprising a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output.

15. The amplifier circuit of claim 12 wherein during a feedback mode of operation the first bias switch is closed to couple the current source to the drain, and the second bias switch is opened to decouple the gate from the electrical ground.

16. The amplifier circuit of claim 1 wherein the amplifier is configured to apply a variable gain to a signal received at the signal input to produce the amplified signal at the signal output.

~~16~~17. The amplifier circuit of claim ~~15~~16 wherein the phase-shifting circuit is configured to shift the phase of the non-linear current based at least in part on a gain setting of the amplifier.

~~17~~18. The amplifier circuit of claim ~~16~~17 wherein the phase-shifting circuit includes a variable capacitor coupled in series with a variable resistor, and wherein at least one of the variable capacitor and the variable resistor are adjustable to vary the phase of the non-linear current.

19. The amplifier circuit of claim 18 further comprising a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output based at least in part on a gain setting of the amplifier.

20~~18~~. The amplifier circuit of claim 16~~15~~ wherein the phase-shifting circuit is configured to adjust a magnitude of the non-linear current based at least in part on a gain setting of the amplifier.

~~19~~21. The amplifier circuit of claim ~~18~~20 wherein the phase-shifting circuit includes a variable capacitor coupled in series with a variable resistor, and wherein at least one of the variable capacitor and the variable resistor are adjustable to vary the magnitude of the non-linear current.

~~20. The amplifier circuit of any of claims 15-19 further comprising a bypass switch positioned in the feedback path and interposed between the signal output and the non-linear current generator, the bypass switch being configured to selectively decouple the amplifier linearity boost circuit from the signal output based at least in part on a gain setting of the amplifier.~~

~~21. A module comprising the amplifier circuit of any one of claims 1—13 or 15-19.~~

~~22. An electronic device comprising the module of claim 21.~~

~~23~~22. An amplifier feedback method comprising:

receiving a signal at a signal input of an amplifier;

amplifying the signal to provide an amplified signal at a signal output of the amplifier;

~~applying~~electrically coupling the signal output to the signal input responsive to a first gain setting of the amplifier to

apply a non-linear current to the signal received at the signal input based on the amplified signal~~;~~ and

~~shifting~~ shift a phase of the non-linear current to reduce an intermodulation distortion of the amplified signal~~.~~; and

electrically decoupling the signal output from the signal input responsive to a second gain setting of the amplifier.

23. The amplifier feedback method of claim ~~23~~22 wherein shifting the phase of the non-linear current includes adjusting a complex impedance of a phase-shifting circuit.

~~25~~24. The amplifier feedback method of claim ~~23~~22 further comprising, responsive to the first gain setting, adjusting a magnitude of the non-linear current to reduce the intermodulation distortion of the amplified signal.

~~26~~25. The amplifier feedback method of claim ~~25~~24 wherein adjusting the magnitude of the non-linear current includes adjusting a complex impedance of a phase-shifting circuit.

~~27~~26. The amplifier feedback method of claim ~~25~~24 wherein adjusting the magnitude of the non-linear current includes adjusting the magnitude of the non-linear current based on ~~a~~the first gain setting of the amplifier.

~~28~~27. The amplifier feedback method of claim ~~25~~24 wherein shifting the phase of the non-linear current includes shifting the phase based on ~~a~~the first gain setting of the amplifier.

~~29~~28. An amplifier feedback method comprising:

amplifying a signal at a signal input of an amplifier to provide an amplified signal at a signal output of ~~an~~the amplifier;

producing a non-linear current based on the amplified signal;

adjusting a complex impedance of a phase-shifting circuit to adjust at least one of a magnitude and a phase of the non-linear current; ~~and~~

~~applying~~electrically coupling the signal output to the signal input responsive to a first gain setting of the amplifier to apply the non-linear current to the signal at ~~a~~the signal input of the amplifier to reduce an intermodulation distortion of the amplified signal~~.~~; and

electrically decoupling the signal output from the signal input responsive to a second gain setting of the amplifier.