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COMPACT VOLTAGE COMBINED DOHERTY POWER AMPLIFIER

Abstract

A Doherty power amplifier (PA) includes a main amplifier, an auxiliary amplifier, and a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between the first RF signal and the second RF signal. The Doherty PA also includes a shunt inductor coupled to an output of the main amplifier, a shunt capacitor coupled to an output of the auxiliary amplifier, and a transformer. The transformer includes a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier, and a second inductor magnetically coupled with the first inductor.

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Background/Summary

BACKGROUND

Field

[0001] Aspects of the present disclosure relate generally to wireless communications, and, more particularly, to power amplifiers.

Background

[0002] A wireless device includes a transmitter for transmitting radio frequency (RF) signals via one or more antennas. The transmitter may include power amplifiers for amplifying the RF signals before transmission. One or more of the power amplifiers may be implemented with a Doherty power amplifier, which includes a main amplifier and an auxiliary amplifier.

SUMMARY

[0003] The following presents a simplified summary of one or more implementations in order to provide a basic understanding of such implementations. This summary is not an extensive overview of all contemplated implementations and is intended to neither identify key or critical elements of all implementations nor delineate the scope of any or all implementations. Its sole purpose is to present some concepts of one or more implementations in a simplified form as a prelude to the more detailed description that is presented later.

[0004] A first aspect relates to a Doherty power amplifier (PA). The Doherty PA includes a main amplifier, an auxiliary amplifier, and a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between the first RF signal and the second RF signal. The Doherty PA also includes a shunt inductor coupled to an output of the main amplifier, a shunt capacitor coupled to an output of the auxiliary amplifier, and a transformer. The transformer includes a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier, and a second inductor magnetically coupled with the first inductor.

[0005] A second aspect relates to a system for wireless communications. The system includes a radio frequency front-end (RFFE) module coupled to an antenna. The RFFE circuit includes a main amplifier, an auxiliary amplifier, and a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal. The RFFE module also includes a shunt inductor coupled to an output of the main amplifier, a shunt capacitor coupled to an output of the auxiliary amplifier, and a transformer. The transformer includes a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier, and a second inductor magnetically coupled with the first inductor and coupled to the antenna.

[0006] A third aspect relates to a Doherty power amplifier (PA). The Doherty PA includes a main amplifier, an auxiliary amplifier, and a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal. The Doherty PA also includes a shunt inductor coupled to an output of the main amplifier, a shunt capacitor coupled to an output of the auxiliary amplifier, and a differential load coupled between the output of the main amplifier and the output of the auxiliary amplifier.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** shows an example of a current combined Doherty power amplifier according to certain aspects of the present disclosure.

[0008] FIG. **2** shows an example of a voltage combined Doherty power amplifier according to certain aspects of the present disclosure.

[0009] FIG. **3** shows an example of a Doherty power amplifier including a shunt inductor and a shunt capacitor according to certain aspects of the present disclosure.

[0010] FIG. **4**A shows an exemplary mathematical model of a shunt device according to certain aspects of the present disclosure.

[0011] FIG. **4**B shows an exemplary mathematical model of an output network of a Doherty power amplifier according to certain aspects of the present disclosure.

[0012] FIG. **5** shows an example of a Doherty power amplifier including a transformer providing voltage combining according to certain aspects of the present disclosure.

[0013] FIG. **6** shows another example of a Doherty power amplifier including a transformer providing voltage combining according to certain aspects of the present disclosure.

[0014] FIG. **7** shows an exemplary implementation of a power splitting and phase shifting circuit including a phase shifter according to certain aspects of the present disclosure.

[0015] FIG. **8** shows an exemplary implementation of the phase shifter of FIG. **7** according to certain aspects of the present disclosure.

[0016] FIG. **9** shows an exemplary implementation of a power splitting and phase shifting circuit including a first phase shifter and a second phase shifter according to certain aspects of the present disclosure.

[0017] FIG. **10** shows an exemplary implementation of a power splitting and phase shifting circuit including a power splitter according to certain aspects of the present disclosure.

[0018] FIG. **11** shows an exemplary implementation of a first phase shifter and a second phase shifter according to certain aspects of the present disclosure.

[0019] FIG. **12** shows an exemplary implementation of a main amplifier and an auxiliary amplifier according to certain aspects of the present disclosure.

[0020] FIG. **13** shows another exemplary implementation of a main amplifier and an auxiliary amplifier according to certain aspects of the present disclosure.

[0021] FIG. **14** shows yet another exemplary implementation of a main amplifier and an auxiliary amplifier according to certain aspects of the present disclosure.

[0022] FIG. **15** shows an example where a main amplifier and an auxiliary amplifier include multiple stages according to certain aspects of the present disclosure.

[0023] FIG. **16**A shows an exemplary implementation of a main amplifier including multiple stages according to certain aspects of the present disclosure.

[0024] FIG. **16**B shows an exemplary implementation of an auxiliary amplifier including multiple stages according to certain aspects of the present disclosure.

[0025] FIG. **17**A shows an example of an RF front-end module according to certain aspects of the present disclosure.

[0026] FIG. **17**B shows another example of an RF front-end module according to certain aspects of the present disclosure.

[0027] FIG. **18**A shows an example of the RF front-end module of FIG. **17**A including a shunt capacitor integrated on a die according to certain aspects of the present disclosure.

[0028] FIG. **18**B shows an example of the RF front-end module of FIG. **17**B including a shunt capacitor integrated on a die according to certain aspects of the present disclosure.
[0029] FIG. **19** shows an example of an RF front-end module of including capacitors coupled in parallel with inductors of a transformer according to certain aspects of the present disclosure.
[0030] FIG. **20** shows an exemplary implementation of a transformer according to certain aspects of the present disclosure.
[0031] FIG. **21** shows another exemplary implementation of a transformer according to certain aspects of the present disclosure.
[0032] FIG. **22** shows yet another exemplary implementation of a transformer according to certain aspects of the present disclosure.
[0033] FIG. **23** is a diagram of an environment including an electronic device that includes a transceiver according to certain aspects of the present disclosure.

DETAILED DESCRIPTION

[0034] The detailed description set forth below, in connection with the appended drawings, is intended as a description of various configurations and is not intended to represent the only configurations in which the concepts described herein may be practiced. The detailed description includes specific details for the purpose of providing a thorough understanding of the various concepts. However, it will be apparent to those skilled in the art that these concepts may be practiced without these specific details. In some instances, well-known structures and components are shown in block diagram form in order to avoid obscuring such concepts.
[0035] FIG. **1** shows an example of a Doherty power amplifier (PA) **110** according to certain aspects. The Doherty PA **110** may be used in a mobile device or a base station to provide efficient power amplification of a radio frequency (RF) signal having a high peak-to-average power ratio (PAPR). For example, a mobile device or a base station using high- order modulation schemes for high data throughput may generate an RF signal having a high PAPR.
[0036] In this example, the Doherty PA **110** receives an input RF signal (labeled “RF.sub.IN”) at an input **115**, amplifies the RF signal, and outputs the amplified RF signal to a load (labeled “Z.sub.L”). The load may include an antenna, a transmission line, any combination thereof, etc. The input RF signal may come from a mixer (not shown) configured to frequency upconvert a baseband signal or an intermediate frequency (IF) signal into the input RF signal.
[0037] As shown in FIG. **1**, the power of the input RF signal is split between a first path **114** and a second path **116** in the Doherty PA **110**. The first path **114** includes a main amplifier **120** having an input **122** coupled to the input **115** of the Doherty PA **110**. The main amplifier **120** may also be referred to as a carrier amplifier or another term. The second path **116** includes an auxiliary amplifier **130** and a 90-degree phase shifter **150**, in which the 90-degree phase shifter **150** is coupled between the input **115** of the Doherty PA **110** and an input **132** of the auxiliary amplifier **130**. The auxiliary amplifier **130** may also referred to as a peaking amplifier or another term.
[0038] The Doherty PA **110** also includes an impedance inverter **140**. In this example, the impedance inverter **140** is coupled between an output **124** of the main amplifier **120** and the load Z.sub.L, and an output **134** of the auxiliary amplifier **130** is coupled to the load Z.sub.L. The impedance inverter **140** may be implemented with a Pi network, a T network, or a quarter-wavelength transmission line. In the example shown in FIG. **1**, the impedance inverter **140** is implemented with a T network including a first inductor **142**, a second inductor **144**, and a shunt capacitor **146**. The impedance inverter **140** introduces a 90-degree phase shift in the first path **114** (i.e., the main amplifier path). The 90-degree phase shifter **150** in the second path **116** (i.e., auxiliary amplifier path) compensates for the 90 degree phase shift of the impedance inverter **140**.
[0039] The main amplifier **120** may be biased in class AB and may be always on (i.e., active) when the main amplifier **120** is provided with a supply voltage. The auxiliary amplifier **130** is biased in class C. In certain aspects, the auxiliary amplifier **130** may be configured to turn on when the main amplifier **120** is driven into saturation. In this example, the output RF signals from the main

amplifier **120** and the auxiliary amplifier **130** are combined using current combining to drive the load Z.sub.L.

[0040] In operation, when the power level of the input RF signal is low, the auxiliary amplifier **130** is turned off and the main amplifier **120** provides amplification of the input RF signal. As used herein, the power level of the input RF signal is low when the main amplifier **120** is driven below saturation. When the power level of the input RF signal is high enough to drive the main amplifier **120** into saturation or within some range of saturation, the auxiliary amplifier **130** turns on and provides additional amplification of the input RF signal. Thus, when the main amplifier **120** is driven into or close to saturation, both the main amplifier **120** and the auxiliary amplifier **130** contribute to amplification of the input RF signal. The output RF signal of the auxiliary amplifier **130** modulates the impedance at the output **124** of the main amplifier **120** to maintain high power efficiency when the main amplifier **120** operates in the saturation region. In this example, the power efficiency of the Doherty PA **110** as a function of input power may have a first efficiency peak corresponding to a back-off power and a second efficiency peak corresponding to a peak power of the Doherty PA **110**. The back-off power may be the power at which the main amplifier **120** enters saturation. In certain aspects, the back-off power may be approximately 6 dB below the peak power.

[0041] FIG. **1** shows an example in which the output RF signals of the main amplifier **120** and the auxiliary amplifier **130** are combined using current combining to drive a shunt load Z.sub.L. FIG. **2** shows another example in which the output RF signals of the main amplifier **120** and the auxiliary amplifier **130** are combined using voltage combining (also referred to as voltage-mode combining) to drive a series load Z.sub.L. In this example, the impedance inverter **140** is coupled between the output **134** of the auxiliary amplifier **130** and the load Z.sub.L, and the output **124** of the main amplifier **120** is coupled to the load Z.sub.L.

[0042] As shown in FIGS. **1** and **2**, the output network of the Doherty PA **110** includes the impedance inverter **140**, which may be implemented with a Pi -network, a T-network (shown in the example in FIGS. **1** and **2**), or a quarter-wave transmission line. The components (e.g., inductors **142** and **144**) of the impedance inverter **140** may be implemented with surface mount device (SMD) components. The SMD components may be placed on a substrate (e.g., a printed circuit board (PCB), a multi-layer laminate, or the like) of an RF front-end module. However, the SMD components take up space, which may increase the size and cost of the RF front-end module.

[0043] To address this, aspects of the present disclosure provide an output network for a Doherty PA including a shunt inductor coupled to the output of the main amplifier and a shunt capacitor coupled to the output of the auxiliary amplifier. The output network provides a more compact structure compared with an output network including the impedance inverter **140**.

[0044] FIG. **3** shows an exemplary Doherty PA **310** according to aspects of the present disclosure. The Doherty PA **310** includes the main amplifier **120** and the auxiliary amplifier **130** discussed above. The Doherty PA **310** also includes a power splitting and phase shifting circuit **350** coupled to the input **115** of the Doherty PA **310**, the input **122** of the main amplifier **120**, and the input **132** of the auxiliary amplifier **130**. The power splitting and phase shifting circuit **350** is configured to split the power of the RF signal (labeled “RF.sub.IN”) at the input **115** between the main amplifier **120** and the auxiliary amplifier **130**, and provide a phase shift θ between the input **122** of the main amplifier **120** and the input **132** of the auxiliary amplifier **130**. For example, the power splitting and phase shifting circuit **350** may split the RF signal (labeled “RF.sub.IN”) at the input **115** into a first RF signal and a second RF signal, output the first RF signal to the input **122** of the main amplifier **120**, output the second RF signal to the input **132** of the auxiliary amplifier **130**, and provide the phase shift θ between first RF signal and the second RF signal. The power splitting and phase shifting circuit **350** may be implemented with one or more power splitters and one or more phase shifters, as discussed further below.

[0045] Unlike the 90-degree phase shifter **150** shown in FIGS. **1** and **2**, the phase shift θ provided by the power splitting and phase shifting circuit **350** can be different from 90 degrees. As discussed further below, the phase shift θ provides an additional design parameter that can be chosen to improve the power efficiency of the Doherty PA **310**.

[0046] In the example in FIG. **3**, the Doherty PA **310** includes a shunt inductor **346** coupled to the output **124** of the main amplifier **120**. For example, the shunt inductor **346** may be coupled between the output **124** of the main amplifier **120** and ground (or some reference potential). The Doherty PA **310** also includes a shunt capacitor **348** coupled to the output **134** of the auxiliary amplifier **130**. For example, the shunt capacitor **348** may be coupled between the output **134** of the auxiliary amplifier **130** and ground (or some reference potential). In this example, a differential load Z.sub.L is coupled between the output **124** of the main amplifier **120** and the output **134** of the auxiliary amplifier **130**. In certain aspects, the differential load Z.sub.L may include a balun (e.g., a transformer), as discussed further below. In operation, the output RF signals of the main amplifier **120** and the auxiliary amplifier **130** are combined at the differential load Z.sub.L using voltage combining.

[0047] An exemplary approach for choosing an inductance for the shunt inductor **346**, a capacitance for the shunt capacitor **348**, and a phase shift θ for the power splitting and phase shifting circuit **350** will now be discussed according to certain aspects.

[0048] FIG. **4**A shows an example of a shunt device **406** having an admittance of Y, in which the shunt device **406** is between a first port **402** and a second port **404**. The shunt device **406** may be used to model a shunt inductor (e.g., the shunt inductor **346**) or a shunt capacitor (e.g., the shunt capacitor **348**). FIG. **4**A also shows an example of an ABCD matrix **410** modeling the relationship between the voltage and the current at the first port **402** and the voltage and the current at the second port **404** in terms of the admittance Y of the shunt device **406**.

[0049] FIG. **4**B shows an exemplary mathematical model of the impedance Z.sub.m seen at the output **124** of the main amplifier **120** and the impedance Z.sub.a seen at the output **134** of the auxiliary amplifier **130** for the exemplary output network shown in FIG. **3**. The model includes a first ABCD matrix **420** for the shunt inductor **346** where jB.sub.m is the susceptance of the shunt inductor **346** (i.e., imaginary part of admittance) and is a function of the inductance of the shunt inductor **346**. The model includes a second ABCD matrix **430** for the shunt capacitor **348** where jB.sub.a is the susceptance of the shunt capacitor **348** (i.e., imaginary part of admittance) and is a function of the capacitance of the shunt capacitor **348**. The model also include the impedance of the series differential load Z.sub.L between the first ABCD matrix **420** and the second ABCD matrix **430**.

[0050] In this example, the impedance Z.sub.m at the output **124** of the main amplifier **120** and the impedance Z.sub.a at the output **134** of the auxiliary amplifier **130** are a function of the inductance of the shunt inductor **346**, the capacitance of the shunt capacitor **348**, and the phase shift θ based on the exemplary model shown in FIG. **4**B. Thus, the inductance of the shunt inductor **346**, the capacitance of the shunt capacitor **348**, and the phase shift θ provide design parameters that may be chosen to achieve target impedance values for Z.sub.m and Z.sub.a that provide high power efficiency over a wide range.

[0051] For example, the inductance of the shunt inductor **346**, the capacitance of the shunt capacitor **348**, and the phase shift θ may be chosen to achieve target impedance values for Z.sub.m and Z.sub.a that provide high power efficiency at the peak power and the back-off power of the Doherty PA **310**. As discussed above, the Doherty PA **310** may have a first efficiency peak at the back-off power and a second efficiency peak at the peak power.

[0052] For example, a target impedance value for Z.sub.m and a target impedance value for Z.sub.a that provide high power efficiency at the peak power of the Doherty PA **310** may be determined. Also, a target impedance value for Z.sub.m and a target impedance value for Z.sub.a that provide high power efficiency at the back-off power (e.g., 6 dB below the peak power) of the Doherty PA **310** may be determined. The target impedance values may be determined, for example, using a computer simulator that simulates power efficiency at the peak power and the back-off power as a function of the impedance values for Z.sub.m and Z.sub.a. After the target impedances values are determined, an inductance of the shunt inductor **346**, a capacitance of the shunt capacitor **348**, and a phase shift θ may be chosen to achieve the target impedance values (e.g., based on the exemplary model shown in FIG. **4**B).

[0053] In the above examples, the phase shift θ provides an additional degree of freedom in achieving the target impedance values for Z.sub.m and Z.sub.a. In contrast, in the examples in FIGS. **1** and **2**, the phase shift of the 90-degree phase shifter **150** is fixed at 90 degrees and is not used as a design parameter for achieving target impedance values for Z.sub.m and Z.sub.a. Since the phase shift θ of the power splitting and phase shifting circuit **350** is a design parameter that is not fixed at 90 degrees, the phase shift θ may be different from 90 degrees. For example, the phase shift θ may be within a range between 100 degrees and 180 degrees to achieve the target impedance values. However, it is to be appreciated that the phase shift θ is not limited to a phase shift within this exemplary range.

[0054] FIG. **5** shows an example in which the differential load Z.sub.L is a transformer **510**. The transformer **510** may be used as a balun to convert the differential RF signal of the Doherty PA **310** into a single-ended RF signal, as discussed further below.

[0055] In this example, the transformer **510** includes a first inductor **515** and a second inductor **520** magnetically (i.e., inductively) coupled with the first inductor **515**. The first inductor **515** may also be referred to as a primary inductor or winding, and the second inductor **520** may also be referred to as secondary inductor or winding. Each of the inductors **515** and **520** may be implemented with two or more inductors coupled in series and/or parallel. The first inductor **515** has a first terminal **512** coupled to the output **124** of the main amplifier **120**, and a second terminal **516** coupled to the output **134** of the auxiliary amplifier **130**. The second inductor **520** has a first terminal **522** coupled to an antenna **550**, and a second terminal **524** coupled to ground (or some reference potential). It should be appreciated that in some implementations one or more elements or components may be coupled between the second inductor **520** and the antenna such as a filter (e.g., RF filter such as a microacustic filter), an antenna tuner, and the like.

[0056] In operation, the output RF signals of the main amplifier **120** and the auxiliary amplifier **130** are combined at the transformer **510** through voltage combining, and the resulting combined RF signal is output to the antenna **550** for transmission. The voltage combining provides a wider bandwidth compared with current combining at a shunt load. This is because the voltage combining provides the transformer **510** with a larger impedance at the second inductor **520**, which provides better impedance matching with the load impedance (e.g., 50 Ohm) coupled to the second inductor **520**. The load impedance may come from the antenna **550**, and/or a transmission line coupling the antenna **550** to the transformer **510**.

[0057] In the example shown in FIG. **5**, the shunt inductor **346** is coupled between the output **124** of the main amplifier **120** and a supply rail providing a supply voltage Vcc. In this example, the supply voltage Vcc provides DC biasing for the main amplifier **120** through the shunt inductor **346** and DC biasing for the auxiliary amplifier **130** through the shunt inductor **346** and the first inductor **515** of the transformer **510**. The supply rail may act as an AC ground for RF signals.

[0058] FIG. **6** shows another example in which the Doherty PA **310** includes a tap **615** coupling the supply rail (which provides supply voltage Vcc) to the first inductor **515** of the transformer **510**. In this example, DC biasing for the main amplifier **120** and the DC biasing for the auxiliary amplifier **130** are provided by the supply rail coupled to the tap **615**. In some implementations, the tap **615** may be a center tap coupled to the center of the first inductor **515**. However, it is to be appreciated that the tap **615** is not limited to the center of the first inductor **515** and that the tap **615** may be coupled to other locations on the first inductor **515** (i.e., the length between the first terminal **512** and the tap **615** may be different from the length between the tap **615** and the second terminal **516**).

[0059] In the example in FIG. **6**, the Doherty PA **310** also includes a coupling capacitor **610**

coupled between the shunt inductor **346** and ground. The coupling capacitor **610** is used to block DC voltages (e.g., the supply voltage Vcc from the supply rail) while providing an AC short to ground for RF signals.
[0060] It is to be appreciated that the present disclosure is not limited to the examples shown in FIGS. **5** and **6**, and that the main amplifier **120** and the auxiliary amplifier **130** may be DC biased using other techniques.
[0061] FIG. **7** shows an exemplary implementation of the power splitting and phase shifting circuit **350** according to certain aspects. In this example, the power splitting and phase shifting circuit **350** includes a power splitter **710** and a phase shifter **730**. The power splitter **710** has input **712** coupled to the input **115**, a first output **714**, and a second output **716**. In this example, the power splitter **710** is implemented with conductive routing (e.g., metal routing) that splits into a first branch providing the first output **714** and a second branch providing the second output **716**. In this example, the power splitting and phase shifting circuit **350** splits the RF signal (labeled “RF.sub.IN”) at the input **115** into the first RF signal at the first output **714** and the second RF signal at the second output **716**.
[0062] In this example, the first output **714** of the power splitter **710** is coupled to the input **122** of the main amplifier **120**, and the phase shifter **730** is coupled between the second output **716** of the power splitter **710** and the input **132** of the auxiliary amplifier **130**. The phase shifter **730** may be configured to shift the phase of the second RF signal by the phase shift θ before inputting the second RF signal to the auxiliary amplifier **130**. Although one phase shifter is shown in the example in FIG. **7**, it is to be appreciated that the power splitting and phase shifting circuit **350** may include more than one phase shifter, as discussed further below.
[0063] FIG. **8** shows an exemplary implementation of the phase shifter **730**. In this example, the phase shifter **730** includes a series inductor **810** and shunt capacitors **815** and **820**. In this example, the inductance of the series inductor **810** and the capacitances of the shunt capacitors **815** and **820** may be chosen to achieve the desired phase shift θ. It is to be appreciated that the phase shifter **730** is not limited to the exemplary implementation shown in FIG. **8**.
[0064] FIG. **9** shows another exemplary implementation of the power splitting and phase shifting circuit **350** according to certain aspects. In this example, power splitting and phase shifting circuit includes a first phase shifter **910** and a second phase shifter **920**. The first phase shifter **910** is between coupled between the first output **714** of the power splitter **710** and the input **122** of the main amplifier **120**, and the second phase shifter **920** is coupled between the second output **716** of the power splitter **710** and the input **132** of the auxiliary amplifier **130**.
[0065] In this example, the first phase shifter **910** is configured to shift the phase of the first RF signal by a first phase shift before the first RF signal is input to the main amplifier **120**, and the second phase shifter **920** is configured to shift the phase of the second RF signal by a second phase shift before the second RF signal is input to the auxiliary amplifier **130**. The first phase shift of the first phase shifter **910** and the second phase shift of the second phase shifter **920** may be chosen such that the phase shift between the first RF signal at the input **122** of the main amplifier **120** and the second RF signal at the input of the **132** of the auxiliary amplifier **130** is equal to the phase shift θ discussed above. Thus, the phase shift θ between the input **122** of the main amplifier **120** and the input **132** of the auxiliary amplifier **130** is achieved using the first phase shifter **910** and the second phase shifter **920** in combination in this example. In other words, each of the first phase shifter **910** and the second phase shifter **920** contribute to the phase shift θ between the first RF signal and the second RF signal.
[0066] FIG. **10** shows another exemplary implementation of the power splitting and phase shifting circuit **350** according to certain aspects. In this example, the power splitter **710** is implemented with a Wilkinson power splitter. However, it is to be appreciated that the power splitter **710** (also referred to as a power divider) is not limited to a Wilkinson power splitter.
[0067] In the example in FIG. **10**, the power splitter **710** includes a first quarter-wavelength

transmission line **1020** coupled between the input **712** and the first output **714**, a second quarter-wavelength transmission line **1025** coupled between the input **712** and the second output **716**, and a resistor **1030** coupled between the first output **714** and the second output **716**. In this example, the power splitter **710** is configured to receive the input RF signal (labeled "RF.sub.IN") at the input **712**, split the input RF signal into the first RF signal and the second RF signal, output the first RF signal at the first output **714**, and output the second RF signal at the second output **716**.

[0068] It is to be appreciated that the power splitting and phase shifting circuit **350** is not limited to the example shown in FIG. **10**. For example, in some implementations, the first output **714** of the power splitter **710** may be coupled to the input **122** of the main amplifier **120** with the first phase shifter **910** omitted. In this example, the phase shifter **730** may be coupled between the second output **716** of the power splitter **710** and the input **132** of the auxiliary amplifier **130** to provide the phase shift θ.

[0069] FIG. **11** shows an exemplary implementation of the first phase shifter **910** and the second phase shifter **920** according to certain aspects. In this example, the first phase shifter **910** includes a series capacitor **1110** and shunt inductors **1115** and **1120**. The second phase shifter **920** includes the series inductor **810** and the shunt capacitors **815** and **820** shown in the example in FIG. **8**. In this example, the inductances of the inductors **810**, **1115**, and **1120** and the capacitances of the capacitors **815**, **820**, and **1110** may be chosen to achieve the desired phase shift θ between the input **122** of the main amplifier **120** and the input **132** of the auxiliary amplifier **130**. It is to be appreciated that the first phase shifter **910** and the second phase shifter **920** are not limited to the exemplary implementation shown in FIG. **11**.

[0070] FIG. **12** shows an exemplary implementation of the main amplifier **120** and the auxiliary amplifier **130** according to certain aspects. In this example, the main amplifier **120** includes a first bipolar junction transistor (BJT) **1210** and a first coupling capacitor **1212**. The collector of the first BJT **1210** is coupled to the output **124** of the main amplifier **120**, and the emitter of the first BJT **1210** is coupled to ground (or some reference potential). The base of the first BJT **1210** is coupled to a main bias circuit **1218** configured to bias the base of the first BJT **1210**. The first coupling capacitor **1212** is coupled between the input **122** of the main amplifier **120** and the base of the first BJT **1210**. The first coupling capacitor **1212** is configured to couple the RF signal at the input **122** to the base of the first BJT **1210** while blocking the bias voltage from the main bias circuit **1218**. The collector of the first BJT **1210** may be biased by the supply voltage Vcc in FIG. **5** or FIG. **6**.

[0071] In this example, the auxiliary amplifier **130** includes a second BJT **1220** and a second coupling capacitor **1222**. The collector of the second BJT **1220** is coupled to the output **134** of the auxiliary amplifier **130**, and the emitter of the second BJT **1220** is coupled to ground (or some reference potential). The base of the second BJT **1220** is coupled to an auxiliary bias circuit **1228** configured to bias the base of the second BJT **1220**. For example, the auxiliary bias circuit **1228** may be configured to bias the second BJT **1220** in Class C. The second coupling capacitor **1222** is coupled between the input **132** of the auxiliary amplifier **130** and the base of the second BJT **1220**. The second coupling capacitor **1222** is configured to couple the RF signal at the input **132** to the base of the second BJT **1220** while blocking the bias voltage from the auxiliary bias circuit **1228**. The collector of the second BJT **1220** may be biased by the supply voltage Vcc in FIG. **5** or FIG. **6**.

[0072] FIG. **13** shows another exemplary implementation of the main amplifier **120** and the auxiliary amplifier **130** according to certain aspects. In this example, the main amplifier **120** includes a first field effect transistor (FET) **1310** and a first coupling capacitor **1312**. The drain of the first FET **1310** is coupled to the output **124** of the main amplifier **120**, and the source of the first FET **1310** is coupled to ground (or some reference potential). The gate of the first FET **1310** is coupled to a main bias circuit **1318** configured to bias the gate of the first FET **1310**. The first coupling capacitor **1312** is coupled between the input **122** of the main amplifier **120** and the gate of the first FET **1310**. The first coupling capacitor **1312** is configured to couple the input RF signal from the input **122** to the gate of the first FET **1310** while blocking the bias voltage from the main bias circuit **1318**. The drain of the first FET **1310** may be biased by the supply voltage Vcc in FIG. **5** or FIG. **6**.

[0073] In this example, the auxiliary amplifier **130** includes a second FET **1320** and a second coupling capacitor **1322**. The drain of the second FET **1320** is coupled to the output **134** of the auxiliary amplifier **130**, and the source of the second FET **1320** is coupled to ground (or some reference potential). The gate of the second FET **1320** is coupled to an auxiliary bias circuit **1328** configured to bias the gate of the second FET **1320**. For example, the auxiliary bias circuit **1328** may be configured to bias the second FET **1320** in Class C. The second coupling capacitor **1322** is coupled between the input **132** of the auxiliary amplifier **130** and the gate of the second FET **1320**. The second coupling capacitor **1322** is configured to couple the input RF signal at the input **132** to the gate of the second FET **1320** while blocking the bias voltage from the auxiliary bias circuit **1328**. The drain of the second FET **1320** may be biased by the supply voltage Vcc in FIG. **5** or FIG. **6**.

[0074] FIG. **14** shows another exemplary implementation of the main amplifier **120** and the auxiliary amplifier **130** according to certain aspects. In this example, the main amplifier **120** is implemented with a cascode amplifier including a first FET **1410**, a second FET **1415**, and the first coupling capacitor **1412**. The drain of the second FET **1415** is coupled to the output **124** of the main amplifier **120**. The drain of the first FET **1410** is coupled to the source of the second FET **1415** and the source of the first FET **1410** is coupled to ground (or some reference potential). The gate of the first FET **1410** is coupled to a first main bias circuit **1420** configured to bias the gate of the first FET **1410**. The first coupling capacitor **1412** is coupled between the input **122** of the main amplifier **120** and the gate of the first FET **1410**. The first coupling capacitor **1412** is configured to couple the input RF signal at the input **122** to the gate of the first FET **1410** while blocking the bias voltage from the first main bias circuit **1420**. The gate of the second FET **1415** is coupled to a second main bias circuit **1430** configured to bias the gate of the second FET **1415**. In this example, the second FET **1415** functions as a common gate amplifier. The drain of the second FET **1415** may be biased by the supply voltage Vcc in FIG. **5** or FIG. **6**.

[0075] In this example, the auxiliary amplifier **130** is implemented with a cascode amplifier including a third FET **1440**, a fourth FET **1445**, and the second coupling capacitor **1442**. The drain of the fourth FET **1445** is coupled to the output **134** of the auxiliary amplifier **130**. The drain of the third FET **1440** is coupled to the source of the fourth FET **1445** and the source of the third FET **1440** is coupled to ground (or some reference potential). The gate of the third FET **1440** is coupled to a first auxiliary bias circuit **1450** configured to bias the gate of the third FET **1440** in Class C. The second coupling capacitor **1442** is coupled between the input **132** of the auxiliary amplifier **130** and the gate of the third FET **1440**. The second coupling capacitor **1442** is configured to couple the input RF signal at the input **132** to the gate of the third FET **1440** while blocking the bias voltage from the first auxiliary bias circuit **1450**. The gate of the fourth FET **1445** is coupled to a second auxiliary bias circuit **1460** configured to bias the gate of the fourth FET **1445**. In this example, the fourth FET **1445** functions as a common gate amplifier. The drain of the fourth FET **1445** may be biased by the supply voltage Vcc in FIG. **5** or FIG. **6**.

[0076] It is to be appreciated that the main amplifier **120** and the auxiliary amplifier **130** may each be implemented with multi-stage amplifiers in some implementations. In this regard, FIG. **15** shows an example in which the main amplifier **120** includes two or more stages **1510-1** to **1510-***n* and the auxiliary amplifier **130** includes two or more stages **1520-1** to **1520-**according to certain aspects.

[0077] FIGS. **16**A and **16**B show an exemplary implementation in which the main amplifier **120** includes a first stage **1510-1** and a second stage **1510-2**, and the auxiliary amplifier **130** includes a first stage **1520-1** and a second stage **1520-2** according to certain aspects. Referring to FIG. **16**A, the first stage **1510-1** includes a first BJT **1610**, a first coupling capacitor **1615** coupled between the input **1612** of the first stage **1510-1** and the base of the first BJT **1610**, and a load inductor **1625** coupled between a supply rail and the collector of the first BJT **1610**. The supply rail provides a supply voltage Vcc_m which may be the same as the supply voltage Vcc or different. The emitter of the first BJT **1610** is coupled to ground (or some reference potential) and the output **1618** of the first stage **1510-1** is taken between the collector of the first BJT **1610** and the load inductor **1625**. The input **1612** is coupled to the input **122** of the main amplifier **120** via a first impedance matching network **1620**, and the base of the first BJT **1610** is biased by a first main bias circuit **1640**.

[0078] The second stage **1510-2** includes a second BJT **1630** and a second coupling capacitor **1635** coupled between the input **1632** of the second stage **1510-2** and the base of the second BJT **1630**. The emitter of the second BJT **1630** is coupled to ground (or some reference potential), the collector of the second BJT **1630** is coupled to the output **1638** of the second stage **1510-2**, and the base of the second BJT **1630** is biased by a second main bias circuit **1645**. The input **1632** is coupled to the output **1618** of the first stage **1510-1** via a second impedance matching network **1628**.

[0079] Referring to FIG. **16**B, the first stage **1520-1** includes a first BJT **1660**, a first coupling capacitor **1665** coupled between the input **1662** of the first stage **1520-1** and the base of the first BJT **1660**, and a load inductor **1675** coupled between a supply rail and the collector of the first BJT **1660**. The supply rail provides a supply voltage Vcc_a which may be the same as the supply voltage Vcc or different. The emitter of the first BJT **1660** is coupled to ground (or some reference potential) and the output **1668** of the first stage **1520-1** is taken between the collector of the first BJT **1660** and the load inductor **1675**. The input **1662** is coupled to the input **132** of the auxiliary amplifier **130** via a first impedance matching network **1670**, and the base of the first BJT **1660** is biased by a first auxiliary bias circuit **1690**.

[0080] The second stage **1520-2** includes a second BJT **1680** and a second coupling capacitor **1685** coupled between the input **1682** of the second stage **1520-2** and the base of the second BJT **1680**. The emitter of the second BJT **1680** is coupled to ground (or some reference potential), the collector of the second BJT **1680** is coupled to the output **1688** of the second stage **1520-2**, and the base of the second BJT **1680** is biased by a second auxiliary bias circuit **1695**. The input **1682** is coupled to the output **1668** of the first stage **1520-1** via a second impedance matching network **1678**.

[0081] It is to be appreciated that the main amplifier **120** and the auxiliary amplifier **130** may also be implemented with multiple stages including FETs.

[0082] FIG. **17**A shows an example of an RF front-end module **1720** including the Doherty PA **310** according to certain aspects. In this example, the RF front-end module **1720** includes a substrate **1715** (e.g., PCB) and a die **1710** (e.g., GaAs die, silicon die, etc.) mounted on the substrate **1715** (e.g., flip-chip mounted on the substrate **1715**). The die **1710** includes the main amplifier **120** and the auxiliary amplifier **130**. For example, for the exemplary implementation where the main amplifier **120** and the auxiliary amplifier **130** include the first BJT **1210** and the second BJT **1220**, respectively, the die **1710** includes the first BJT **1210** and the second BJT **1220**. For the exemplary implementation where the main amplifier **120** and the auxiliary amplifier **130** include the first FET **1310** and the second FET **1320**, respectively, the die **1710** includes the first FET **1310** and the second FET **1320**. An RF front-end module may also be referred to as an RFFE module or RFFE circuit.

[0083] In the example in FIG. **17**A, the shunt inductor **346**, the shunt capacitor **348**, and transformer **510** may be placed on the substrate **1715** and/or embedded in the substrate **1715**. Although the transformer **510** is shown as being part of the RF front-end module **1720** in the example in FIG. **17**A, it is to be appreciated that the transformer **510** may be located outside of the RF front-end module **1720** is some implementations.

[0084] In the example in FIG. **17**A, the main amplifier **120** and the auxiliary amplifier **130** are biased by the supply rail through the shunt inductor **346**. FIG. **17**B shows another example of the

RF front-end module **1720** in which the main amplifier **120** and the auxiliary amplifier **130** are biased by the supply rail through the tap **615** of the first inductor **515** of the transformer **510**.
[0085] FIG. **18**A shows an example of the exemplary implementation of the RF front-end module **1720** of FIG. **17**A in which the shunt capacitor **348** is integrated on the die **1710** with the auxiliary amplifier **130**. FIG. **18**B shows an example of the exemplary implementation of the RF front-end module **1720** of FIG. **17**B in which the shunt capacitor **348** is integrated on the die **1710**. It is to be appreciated that, in each of the examples shown in FIGS. **18**A and **18**B, the die **1710** may also include an integrated shunt capacitor (not shown) coupled to the output **124** of the main amplifier **120**.
[0086] FIG. **19** shows an example in which the Doherty PA **310** also includes a first capacitor **1910** coupled in parallel with the first inductor **515** of the transformer **510**, and a second capacitor **1915** coupled in parallel with the second inductor **520** of the transformer **510**. In this example, the capacitances of the capacitors **1910** and **1915** may be chosen to enhance the transfer of power from the first inductor **515** to the second inductor **520** for a desired center frequency of the output RF signal. In some implementations, one of the capacitors **1910** and **1915** may be omitted.
[0087] FIG. **19** also shows an example of a third capacitor **1920** coupled between a tap **1922** on the first inductor **515** of the transformer **510** and ground to provide an AC short to ground. The tap **1922** may be a center tap located at the center of the first inductor **515** or a tap located at another location on the first inductor **515**.
[0088] FIG. **20** shows an exemplary implementation of the transformer **510** according to certain aspects. In this example, the first inductor **515** is implemented with a first planar loop inductor formed from a first metal layer (e.g., using a lithographic and etching process). The left half of FIG. **20** shows a top view of the first inductor **515** without the second inductor **520**.
[0089] In this example, the second inductor **520** is implemented with a second planar loop inductor formed from a second metal layer (e.g., using a lithographic and etching process). The second metal layer may be above or below the first metal layer with an insulating layer interposed between the first metal layer and the second metal layer. For the exemplary RF front-end module **1720**, the first metal layer and the second metal layer may be placed on the substrate **1715** and/or embedded in the substrate **1715**.
[0090] The right half of FIG. **20** shows a top view of an example in which the second inductor **520** overlaps the first inductor **515** to form the transformer **510**. In this example, the overlap of the first inductor **515** and the second inductor **520** provides the magnetic (i.e., inductive) coupling between the first inductor **515** and the second inductor **520**.
[0091] In the example in FIG. **20**, the first inductor **515** and the second inductor **520** are formed from different metal layers. FIG. **21** shows another exemplary implementation in which the first inductor **515** and the second inductor **520** are formed from the same metal layer. In this example, the first inductor **515** is implemented with a first planar loop inductor and the second inductor **520** is implemented with a second planar inductor. The second inductor **520** is located within the inner loop of the first inductor **515** to provide the magnetic (i.e., inductive) coupling between the first inductor **515** and the second inductor **520**.
[0092] Although not shown in FIGS. **20** and **21**, it is to be appreciated that the first inductor **515** may include the tap **615** extending from a location (e.g., center location) on the first inductor **515**.
[0093] FIG. **22** shows another exemplary implementation of the transformer **510** in which the transformer has a turn ratio higher than 1:1 according to certain aspects. In this example, the first inductor **515** is implemented with a first planar loop inductor formed from a first metal layer (e.g., using a lithographic and etching process). The left half of FIG. **22** shows a top view of the first inductor **515** without the second inductor **520**.
[0094] In this example, the second inductor **520** has two turns for a turn ratio of 1:2. The second inductor **520** includes first portion **2210** and a second portion **2215** formed from a second metal layer (e.g., using a lithographic and etching process), and a bridge **2220** formed from a third metal

layer (e.g., using a lithographic and etching process). The bridge **2220** crosses over the first portion **2210** and is coupled to the first portion **2210** and the second portion **2215** by vias (not shown) between the second metal layer and the third metal layer.

[0095] The right half of FIG. **22** shows a top view of an example in which the second inductor **520** overlaps the first inductor **515** to form the transformer **510**. In this example, the overlap of the first inductor **515** and the second inductor **520** provides the magnetic (i.e., inductive) coupling between the first inductor **515** and the second inductor **520**.

[0096] FIG. **23** is a diagram of an environment **2300** that includes an electronic device **2302** and a base station **2304**. The electronic device **2302** includes a wireless transceiver **2396**, which may include the Doherty PA **310**.

[0097] In the environment **2300**, the electronic device **2302** communicates with the base station **2304** through a wireless link **2306**. As shown, the electronic device **2302** is depicted as a smart phone. However, the electronic device **2302** may be implemented as any suitable computing or other electronic device, such as a cellular base station, a broadband router, an access point, a cellular or mobile phone, a gaming device, a navigation device, a media device, a laptop computer, a desktop computer, a tablet computer, a server computer, a network-attached storage (NAS) device, a smart appliance, a vehicle-based communication system, an Internet of Things (IoT) device, a sensor or security device, an asset tracker, and so forth.

[0098] The base station **2304** communicates with the electronic device **2302** via the wireless link **2306**, which may be implemented as any suitable type of wireless link. Although depicted as a base station tower of a cellular radio network, the base station **2304** may represent or be implemented as another device, such as a satellite, a terrestrial broadcast tower, an access point, a peer-to-peer device, a mesh network node, a fiber optic line, another electronic device generally as described above, and so forth. Hence, the electronic device **2302** may communicate with the base station **2304** or another device via a wired connection, a wireless connection, or a combination thereof. The wireless link **2306** can include a downlink of data or control information communicated from the base station **2304** to the electronic device **2302** and an uplink of other data or control information communicated from the electronic device **2302** to the base station **2304**. The wireless link **2306** may be implemented using any suitable communication protocol or standard, such as 3rd Generation Partnership Project Long-Term Evolution (3GPP LTE, 3GPP NR 5G), IEEE 2302.11, IEEE 2302.11, Bluetooth™, and so forth.

[0099] The electronic device **2302** includes a processor **2380** and a memory **2382**. The memory **2382** may be or form a portion of a computer readable storage medium. The processor **2380** may include any type of processor, such as an application processor or a multi-core processor, that is configured to execute processor-executable instructions (e.g., code) stored by the memory **2382**. The memory **2382** may include any suitable type of data storage media, such as volatile memory (e.g., random access memory (RAM)), non-volatile memory (e.g., Flash memory), optical media, magnetic media (e.g., disk or tape), and so forth. In the context of this disclosure, the memory **2382** is implemented to store instructions **2384**, data **2386**, and other information of the electronic device **2302**.

[0100] The electronic device **2302** may also include input/output (I/O) ports **2390**. The I/O ports **2390** enable data exchanges or interaction with other devices, networks, or users or between components of the device.

[0101] The electronic device **2302** may further include a signal processor (SP) **2392** (e.g., such as a digital signal processor (DSP)). The signal processor **2392** may function similar to the processor **2380** and may be capable of executing instructions and/or processing information in conjunction with the memory **2382**.

[0102] For communication purposes, the electronic device **2302** also includes a modem **2394**, the wireless transceiver **2396** (e.g., the Doherty PA **310** and/or the RF front-end module **1720**), and one or more antennas (e.g., the antenna **550**). The wireless transceiver **2396** provides connectivity to respective networks and other electronic devices connected therewith using RF wireless signals. The wireless transceiver **2396** may facilitate communication over any suitable type of wireless network, such as a wireless local area network (LAN) (WLAN), a peer to peer (P2P) network, a mesh network, a cellular network, a wireless wide area network (WWAN), a navigational network (e.g., the Global Positioning System (GPS) of North America or another Global Navigation Satellite System (GNSS)), and/or a wireless personal area network (WPAN).

[0103] Implementation examples are described in the following numbered clauses: [0104] 1. A Doherty power amplifier (PA), comprising: [0105] a main amplifier; [0106] an auxiliary amplifier; [0107] a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal; [0108] a shunt inductor coupled to an output of the main amplifier; [0109] a shunt capacitor coupled to an output of the auxiliary amplifier; and [0110] a transformer, the transformer comprising: [0111] a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier; and [0112] a second inductor magnetically coupled with the first inductor. [0113] 2. The Doherty PA of clause 1, wherein the phase shift is between 100 degrees and 180 degrees. [0114] 3. The Doherty PA of clause 1 or 2, wherein the second inductor is coupled between an antenna and a ground. [0115] 4. The Doherty PA of any one of clauses 1 to 3, wherein the shunt inductor is coupled between the output of the main amplifier and a voltage supply rail. [0116] 5. The Doherty PA of clause 4, wherein the shunt capacitor is coupled between the output of the auxiliary amplifier and a ground. [0117] 6. The Doherty PA of any one of clauses 1 to 3, wherein the first inductor includes a tap coupled to a voltage supply rail. [0118] 7. The Doherty PA of clause 6, further including a coupling capacitor, wherein the coupling capacitor is coupled between the shunt inductor and a ground, and the shunt inductor is coupled between the output of the main amplifier and the coupling capacitor. [0119] 8. The Doherty PA of clause 7, wherein the shunt capacitor is coupled between the output of the auxiliary amplifier and a ground. [0120] 9. The Doherty PA of any one of clauses 6 to 8, wherein the tap is located at a center of the first inductor. [0121] 10. The Doherty PA of any one of clauses 1 to 9, further comprising a first capacitor coupled in parallel with the first inductor. [0122] 11. The Doherty PA of clause 10, further comprising a second capacitor coupled in parallel with the second inductor. [0123] 12. The Doherty PA of any one of clauses 1 to 11, wherein the main amplifier, the auxiliary amplifier, and the shunt capacitor are integrated on a die. [0124] 13. The Doherty PA of any one of clauses 1 to 12, wherein the power splitting and phase shifting circuit comprises: [0125] a power splitter having an input coupled to an input of the Doherty PA, a first output coupled to the input of the main amplifier, and a second output; and [0126] a phase shifter coupled between the second output of the power splitter and the input of the auxiliary amplifier, wherein the phase shifter is configured to shift a phase of the second RF signal by the phase shift. [0127] 14. The Doherty PA of anyone of clauses 1 to 12, wherein the power splitting and phase shifting circuit comprises: [0128] a power splitter having an input coupled to an input of the Doherty PA, a first output, and a second output; [0129] a first phase shifter coupled between the first output and the input of the main amplifier; and [0130] a second phase shifter coupled between the second output and the input of the auxiliary amplifier, wherein each of the first phase shifter and the second phase shifter contributes to the phase shift between the first RF signal and the second RF signal. [0131] 15. The Doherty PA of any one of clauses 1 to 14, wherein the auxiliary amplifier is configured to turn on when the main amplifier is driven into saturation. [0132] 16. The Doherty PA of any one of clauses 1 to 15, wherein the first inductor comprises a first planar inductor in a first metal layer, and the second inductor comprises a second planar inductor in a second metal layer and overlapping the first planar inductor. [0133] 17. The Doherty PA of any one of clauses 1 to 15, wherein the first inductor comprises a first planar inductor, and the second inductor comprises a second planar inductor located within the first planar inductor. [0134] 18. A system for wireless communications, comprising: [0135] a radio frequency front-end (RFFE) module coupled to an antenna and comprising: [0136] a main amplifier; [0137] an auxiliary amplifier; [0138] a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal; [0139] a shunt inductor coupled to an output of the main amplifier; [0140] a shunt capacitor coupled to an output of the auxiliary amplifier; and [0141] a transformer, the transformer comprising: [0142] a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier; and [0143] a second inductor magnetically coupled with the first inductor and coupled to the antenna. [0144] 19. The system of clause 18, wherein the phase shift is between 100 degrees and 180 degrees. [0145] 20. The system of clause 18 or 19, wherein the RFFE module comprises a die, and the main amplifier, the auxiliary amplifier, and the shunt capacitor are integrated on the die. [0146] 21. The system of clause 20, wherein the RFFE module comprises a substrate, the die is mounted on the substrate, and the transformer is on the substrate. [0147] 22. The system of any one of clauses 18 to 21, wherein the first inductor comprises a first planar inductor in a first metal layer, and the second inductor comprises a second planar inductor in a second metal layer and overlapping the first planar inductor. [0148] 23. The system of any one of clauses 18 to 21, wherein the first inductor comprises a first planar inductor, and the second inductor comprises a second planar inductor located within the first planar inductor. [0149] 24. A Doherty power amplifier (PA), comprising: [0150] a main amplifier; [0151] an auxiliary amplifier; [0152] a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal; [0153] a shunt inductor coupled to an output of the main amplifier; [0154] a shunt capacitor coupled to an output of the auxiliary amplifier; and [0155] a differential load coupled between the output of the main amplifier and the output of the auxiliary amplifier. [0156] 25. The Doherty PA of clause 24, wherein the phase shift is between 100 degrees and 180 degrees. [0157] 26. The Doherty PA of clause 24 or 25, wherein the shunt inductor is coupled between the output of the main amplifier and a voltage supply rail. [0158] 27. The Doherty PA of clause 26, wherein the shunt capacitor is coupled between the output of the auxiliary amplifier and a ground. [0159] 28. The Doherty PA of any one of clauses 24 to 27, wherein the power splitting and phase shifting circuit comprises: [0160] a power splitter having an input coupled to an input of the Doherty PA, a first output coupled to the input of the main amplifier, and a second output; and [0161] a phase shifter coupled between the second output of the power splitter and the input of the auxiliary amplifier, wherein the phase shifter is configured to shift a phase of the second RF signal by the phase shift. [0162] 29. The Doherty PA of any one of clauses 24 to 27, wherein the power splitting and phase shifting circuit comprises: [0163] a power splitter having an input coupled to an input of the Doherty PA, a first output, and a second output; [0164] a first phase shifter coupled between the first output and the input of the main amplifier; and [0165] a second phase shifter coupled between the second output and the input of the auxiliary amplifier, wherein each of the first phase shifter and the second phase shifter contributes to the phase shift between the first RF signal and the second RF signal. [0166] 30. The Doherty PA of any one of clauses 24 to 29, wherein the auxiliary amplifier is configured to turn on when the main amplifier is driven into saturation. [0167] 31. The Doherty PA of any one of clauses 24 to 30, wherein the differential load comprises a transformer, the transformer comprising: [0168] a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier; and [0169] a second inductor magnetically coupled with the first inductor.

[0170] Within the present disclosure, the word “exemplary” is used to mean “serving as an example, instance, or illustration.” Any implementation or aspect described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other aspects of the disclosure. Likewise, the term “aspects” does not require that all aspects of the disclosure include the discussed feature, advantage or mode of operation. The term “coupled” is used herein to refer to the direct or indirect electrical coupling between two structures. It is also to be appreciated that the term “ground” may refer to a DC ground or an AC ground, and thus the term “ground” covers both possibilities. It is also to be appreciated that an “inductor” may include multiple inductors coupled in series. It is also to be appreciated than an “input” may be a single-ended input, a differential input, or one of two inputs of a differential input, and an “output” may be a single-ended output, a differential output, or one of two outputs of a differential output.

[0171] The previous description of the disclosure is provided to enable any person skilled in the art to make or use the disclosure. Various modifications to the disclosure will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other variations without departing from the spirit or scope of the disclosure. Thus, the disclosure is not intended to be limited to the examples described herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

Claims

1. A Doherty power amplifier (PA), comprising: a main amplifier; an auxiliary amplifier; a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal; a shunt inductor coupled to an output of the main amplifier; a shunt capacitor coupled to an output of the auxiliary amplifier; and a transformer, the transformer comprising: a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier; and a second inductor magnetically coupled with the first inductor.

2. The Doherty PA of claim 1, wherein the phase shift is between 100 degrees and 180 degrees.

3. The Doherty PA of claim 1, wherein the second inductor is coupled between an antenna and a ground.

4. The Doherty PA of claim 1, wherein the shunt inductor is coupled between the output of the main amplifier and a voltage supply rail.

5. The Doherty PA of claim 4, wherein the shunt capacitor is coupled between the output of the auxiliary amplifier and a ground.

6. The Doherty PA of claim 1, wherein the first inductor includes a tap coupled to a voltage supply rail.

7. The Doherty PA of claim 6, further including a coupling capacitor, wherein the coupling capacitor is coupled between the shunt inductor and a ground, and the shunt inductor is coupled between the output of the main amplifier and the coupling capacitor.

8. The Doherty PA of claim 7, wherein the shunt capacitor is coupled between the output of the auxiliary amplifier and a ground.

9. The Doherty PA of claim 6, wherein the tap is located at a center of the first inductor.

10. The Doherty PA of claim 1, further comprising a first capacitor coupled in parallel with the first inductor.

11. The Doherty PA of claim 10, further comprising a second capacitor coupled in parallel with the second inductor.

12. The Doherty PA of claim 1, wherein the main amplifier, the auxiliary amplifier, and the shunt capacitor are integrated on a die.

13. The Doherty PA of claim 1, wherein the power splitting and phase shifting circuit comprises: a power splitter having an input coupled to an input of the Doherty PA, a first output coupled to the input of the main amplifier, and a second output; and a phase shifter coupled between the second output of the power splitter and the input of the auxiliary amplifier, wherein the phase shifter is configured to shift a phase of the second RF signal by the phase shift.

14. The Doherty PA of claim 1, wherein the power splitting and phase shifting circuit comprises: a power splitter having an input coupled to an input of the Doherty PA, a first output, and a second output; a first phase shifter coupled between the first output and the input of the main amplifier; and a second phase shifter coupled between the second output and the input of the auxiliary amplifier, wherein each of the first phase shifter and the second phase shifter contributes to the phase shift between the first RF signal and the second RF signal.

15. The Doherty PA of claim 1, wherein the auxiliary amplifier is configured to turn on when the main amplifier is driven into saturation.

16. A system for wireless communications, comprising: a radio frequency front-end (RFFE) module coupled to an antenna and comprising: a main amplifier; an auxiliary amplifier; a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal; a shunt inductor coupled to an output of the main amplifier; a shunt capacitor coupled to an output of the auxiliary amplifier; and a transformer, the transformer comprising: a first inductor coupled between the output of the main amplifier and the output of the auxiliary amplifier; and a second inductor magnetically coupled with the first inductor and coupled to the antenna.

17. The system of claim 16 wherein the phase shift is between 100 degrees and 180 degrees.

18. The system of claim 16, wherein the RFFE module comprises a die, and the main amplifier, the auxiliary amplifier, and the shunt capacitor are integrated on the die.

19. The system of claim 18, wherein the RFFE module comprises a substrate, the die is mounted on the substrate, and the transformer is on the substrate.

20. A Doherty power amplifier (PA), comprising: a main amplifier; an auxiliary amplifier; a power splitting and phase shifting circuit configured to receive an input radio frequency (RF) signal, split the input RF signal into a first RF signal and a second RF signal, output the first RF signal to an input of the main amplifier, output the second RF signal to an input of the auxiliary amplifier, and provide a phase shift between first RF signal and the second RF signal; a shunt inductor coupled to an output of the main amplifier; a shunt capacitor coupled to an output of the auxiliary amplifier; and a differential load coupled between the output of the main amplifier and the output of the auxiliary amplifier.