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## LEAKAGE CANCELLATION FOR RADIO FREQUENCY TRANSCEIVERS

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### Abstract

Systems and methods for diplexer circuits with leakage cancellation are provided. In one aspect, a diplexer circuit including first and second radio frequency transceiver terminals and a first antenna terminal, and first and second parallel communication paths extending between the first radio frequency transceiver terminal and the first antenna terminal, and third and fourth parallel communication paths extending between the second radio frequency transceiver terminal and the first antenna terminal. The circuit also includes a first phase shifter configured to apply a first phase shift to a first radio frequency transmit signal on the first communication path, a second phase shifter configured to apply a second phase shift to a second radio frequency on the second communication path, and a third phase shifter configured to apply a third phase shift to the first radio frequency transmit signal on the third communication path.

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## Background/Summary

### CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] Any and all applications for which a foreign or domestic priority claim is identified in the Application Data Sheet as filed with the present application are hereby incorporated by reference under 37 CFR 1.57.

### BACKGROUND

#### Field

[0002] Aspects of this disclosure relate to radio frequency (RF) communication systems, and in particular, cancelling signal leakage in such systems.

#### Description of the Related Technology

[0003] RF communication systems typically include an RF front end which couples transmit and receive paths between a baseband processor and one or more antennas. Such RF front ends may include power amplifier(s), low noise amplifier(s), and/or filter(s) to process RF signals transmitted to and received from the antennas. One design considerations for RF front ends is to limit or otherwise reduce the amount of a transmit signal that is leaked onto a receive path.

### SUMMARY

[0004] The systems, methods and devices of this disclosure each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein.

[0005] In one aspect, there is provided a diplexer circuit comprising: first and second radio frequency transceiver terminals and a first antenna terminal; first and second parallel communication paths extending between the first radio frequency transceiver terminal and the first antenna terminal, and third and fourth parallel communication paths extending between the second radio frequency transceiver terminal and the first antenna terminal; a first phase shifter configured to apply a first phase shift to a first radio frequency transmit signal between the first radio frequency transceiver terminal and a first diplexer on the first communication path, a second phase shifter configured to apply a second phase shift to a second radio frequency transmit signal between the first antenna terminal and a second diplexer on the second communication path, and a third phase shifter configured to apply a third phase shift to the first radio frequency transmit signal between the first diplexer and the second radio frequency transceiver terminal on the third communication path.

[0006] The second phase shifter can be further configured to coherently sum the first and second radio frequency transmit signals, and wherein the second phase shifter is further configured to coherently sum third and fourth radio frequency transmit signals received from the second radio frequency transceiver terminal.

[0007] The first phase shifter can be further configured to destructively cancel leakage of third and fourth radio frequency transmit signals received from the second radio frequency transceiver terminal, and wherein the third phase shifter is further configured to destructively cancel leakage of the first and second radio frequency transmit signals received from the first radio frequency transceiver terminal.

[0008] The first phase shifter can include a first hybrid transmit splitter, the second phase shifter can include a second hybrid receive splitter, and the third phase shifter can include a third hybrid antenna splitter.

[0009] The diplexer circuit can further comprise: a third radio frequency transceiver terminal coupled to the first phase shifter; a fourth radio frequency transceiver terminal coupled to the third phase shifter; a second antenna terminal coupled to the second phase shifter; fifth and sixth parallel communication paths extending between the third radio frequency transceiver terminal and the second antenna terminal; and seventh and eighth parallel communication paths extending between the fourth radio frequency transceiver terminal and the second antenna terminal.

[0010] The first phase shifter can be further configured to apply a fourth phase shift to a third radio frequency transmit signal between the third radio frequency terminal and the first diplexer on the fifth communication path, wherein the second phase shifter is further configured to apply a fifth phase shift to a fourth radio frequency transmit signal between the third antenna terminal and the second diplexer on the sixth communication path, and the third phase shifter is further configured to apply a sixth phase shift to the third radio frequency transmit signal between the first diplexer and the second radio frequency transceiver on the seventh communication path.

[0011] The first radio frequency transceiver terminal can be configured to communicate via a cellular signal, and the second radio frequency transceiver terminal can be configured to communicate via a Wi-Fi signal.

[0012] The first phase shifter and the third phase shifter can be configured to provide a phase shift of about  $180^\circ$  to the first radio frequency transmit signal.

[0013] The first phase shifter and the second phase shifter can be configured to provide a phase shift of about  $90^\circ$  to each of the first and second radio frequency transmit signals.

[0014] The third phase shifter can be configured to apply a fourth phase shift to a second radio frequency transmit signal between the second radio frequency terminal and the first diplexer on the third communication path, and the second phase shifter can be configured to apply a fifth phase shift to a fourth radio frequency transmit signal between the first antenna terminal and the first diplexer on the fourth communication path.

[0015] The second phase shifter and the third phase shifter can be configured to provide a phase shift of about  $90^\circ$  to each of the third and fourth radio frequency transmit signals.

[0016] In another aspect, there is provided a method of diplexing radio frequency signals, the method comprising: outputting first and second radio frequency transmit signals onto respective first and second parallel communication paths extending between a first radio frequency transceiver terminal and an antenna; applying a first phase shift to the first radio frequency transmit signal between the first radio frequency terminal and a first diplexer on the first communication path; outputting third and fourth radio frequency transmit signals onto respective third and fourth parallel communication paths extending between a second radio frequency transceiver and the antenna; applying a second phase shift to the second radio frequency transmit signal between the antenna and a second diplexer on the second communication path; and applying a third phase shift to the third radio frequency receive signal between the first diplexer and the second radio frequency transceiver on the third communication path.

[0017] The method can further comprise: combining the first and second radio frequency transmit signals at a splitter; and providing the combined first and second radio frequency transmit signals to the antenna.

[0018] The method can further comprising: combining third and fourth radio frequency transmit

signals received from the second radio frequency transceiver terminal at the splitter; and providing the combined third and fourth radio frequency transmit signals to the antenna.

[0019] The method can further comprise: destructively cancelling the first and second radio frequency transmit signals at a splitter coupled to the second radio frequency transceiver terminal.

[0020] The method can further comprising: destructively cancelling leakage of third and fourth radio frequency transmit signals received from the second radio frequency transceiver terminal at a first splitter coupled to the first radio frequency transceiver terminal; and destructively cancelling leakage of the first and second radio frequency transmit signals at a second splitter coupled to the second radio frequency transceiver terminal.

[0021] In yet another aspect, there is provided a radio frequency system comprising: first and second radio frequency transceivers; a first antenna; and a diplexer circuit includes first and second parallel communication paths extending between the first radio frequency transceiver and the first antenna, third and fourth parallel communication paths extending between the second radio frequency transceiver and the first antenna, a first phase shifter configured to apply a first phase shift to a first radio frequency transmit signal between the first radio frequency transceiver and a first diplexer on the first communication path, a second phase shifter configured to apply a second phase shift to a second radio frequency transmit signal between the first antenna and a second diplexer on the second communication path, and a third phase shifter configured to apply a third phase shift to the first radio frequency transmit signal between the first diplexer and the second radio frequency transceiver on the third communication path.

[0022] The second phase shifter can be further configured to coherently sum the first and second radio frequency transmit signals, and the second phase shifter can be further configured to coherently sum third and fourth radio frequency transmit signals received from the second radio frequency transceiver.

[0023] The first phase shifter can be further configured to destructively cancel leakage of third and fourth radio frequency transmit signals received from the second radio frequency transceiver, and the third phase shifter can be further configured to destructively cancel leakage of the first and second radio frequency transmit signals received from the first radio frequency transceiver.

[0024] The first phase shifter can include a first hybrid transmit splitter, the second phase shifter can include a second hybrid receive splitter, and the third phase shifter can include a third hybrid antenna splitter.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. 1 is a schematic diagram of one example of a communication network.

[0026] FIG. 2 is a schematic diagram of one embodiment of a mobile device.

[0027] FIG. 3 is a schematic diagram of a power amplifier system according to one embodiment.

[0028] FIG. 4 is an example embodiment of a duplexer circuit that can be used in an FDD or TDD radio front-end.

[0029] FIG. 5 is an example embodiment of a duplexer circuit that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure.

[0030] FIG. 6 illustrates an embodiment of a splitter which can be used in accordance with aspects of this disclosure.

[0031] FIG. 7 is another example embodiment of a duplexer circuit that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure.

[0032] FIG. 8 is a flowchart that provides a method for improved RF leakage cancellation for a duplexer circuit used in a radio front-end in accordance with aspects of this disclosure.

[0033] FIG. 9 is an example embodiment of a duplexer circuit that can be used in an FDD or TDD

radio front-end.

[0034] FIG. 10 is an example embodiment of a duplexer circuit that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure.

[0035] FIGS. 11A and 11B provide example embodiments of circuit configurations which can be used to connect the receive port to the duplexer circuit of FIG. 10 in accordance with aspects of this disclosure.

[0036] FIG. 12 is another example embodiment of a duplexer circuit that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure.

[0037] FIGS. 13A and 13B illustrate yet another example embodiment of a duplexer circuit that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure.

[0038] FIG. 14 is an example embodiment of a duplexer circuit that can be used to couple two different communication technologies to an antenna in accordance with aspects of this disclosure.

[0039] FIG. 15 is another example embodiment of a duplexer circuit 400 that can be used to couple two different communication technologies to two antennas in accordance with aspects of this disclosure.

[0040] FIG. 16 is a flowchart that provides a method for improved RF leakage cancellation for a duplexer circuit used in a radio front-end in accordance with aspects of this disclosure.

[0041] FIG. 17 is a flowchart that provides a method for improved RF leakage cancellation for a duplexer circuit in accordance with aspects of this disclosure.

#### DETAILED DESCRIPTION OF EMBODIMENTS

[0042] The following detailed description of certain embodiments presents various descriptions of specific embodiments. However, the innovations described herein can be embodied in a multitude of different ways, for example, as defined and covered by the claims. In this description, reference is made to the drawings where like reference numerals can indicate identical or functionally similar elements. It will be understood that elements illustrated in the figures are not necessarily drawn to scale. Moreover, it will be understood that certain embodiments can include more elements than illustrated in a drawing and/or a subset of the elements illustrated in a drawing. Further, some embodiments can incorporate any suitable combination of features from two or more drawings.

#### Overview of 5G Systems

[0043] The International Telecommunication Union (ITU) is a specialized agency of the United Nations (UN) responsible for global issues concerning information and communication technologies, including the shared global use of radio spectrum.

[0044] The 3rd Generation Partnership Project (3GPP) is a collaboration between groups of telecommunications standard bodies across the world, such as the Association of Radio Industries and Businesses (ARIB), the Telecommunications Technology Committee (TTC), the China Communications Standards Association (CCSA), the Alliance for Telecommunications Industry Solutions (ATIS), the Telecommunications Technology Association (TTA), the European Telecommunications Standards Institute (ETSI), and the Telecommunications Standards Development Society, India (TSDSI).

[0045] Working within the scope of the ITU, 3GPP develops and maintains technical specifications for a variety of mobile communication technologies, including, for example, second generation (2G) technology (for instance, Global System for Mobile Communications (GSM) and Enhanced Data Rates for GSM Evolution (EDGE)), third generation (3G) technology (for instance, Universal Mobile Telecommunications System (UMTS) and High Speed Packet Access (HSPA)), and fourth generation (4G) technology (for instance, Long Term Evolution (LTE) and LTE-Advanced).

[0046] The technical specifications controlled by 3GPP can be expanded and revised by specification releases, which can span multiple years and specify a breadth of new features and evolutions.

[0047] In one example, 3GPP introduced carrier aggregation (CA) for LTE in Release 10. Although initially introduced with two downlink carriers, 3GPP expanded carrier aggregation in Release 14

to include up to five downlink carriers and up to three uplink carriers. Other examples of new features and evolutions provided by 3GPP releases include, but are not limited to, License Assisted Access (LAA), enhanced LAA (eLAA), Narrowband Internet of things (NB-IOT), Vehicle-to-Everything (V2X), and High Power User Equipment (HPUE).

[0048] 3GPP introduced Phase 1 of fifth generation (5G) technology in Release 15, and plans to introduce Phase 2 of 5G technology in Release 16 (targeted for 2019). Subsequent 3GPP releases will further evolve and expand 5G technology. 5G technology is also referred to herein as 5G New Radio (NR).

[0049] 5G NR supports or plans to support a variety of features, such as communications over millimeter wave spectrum, beamforming capability, high spectral efficiency waveforms, low latency communications, multiple radio numerology, and/or non-orthogonal multiple access (NOMA). Although such radio frequency (RF) functionalities offer flexibility to networks and enhance user data rates, supporting such features can pose a number of technical challenges.

[0050] The teachings herein are applicable to a wide variety of communication systems, including, but not limited to, communication systems using advanced cellular technologies, such as LTE-Advanced, LTE-Advanced Pro, and/or 5G NR.

[0051] FIG. 1 is a schematic diagram of one example of a communication network **10**. The communication network **10** includes a macro cell base station **1**, a small cell base station **3**, and various examples of user equipment (UE), including a first mobile device **2a**, a wireless-connected car **2b**, a laptop **2c**, a stationary wireless device **2d**, a wireless-connected train **2e**, a second mobile device **2f**, and a third mobile device **2g**.

[0052] Although specific examples of base stations and user equipment are illustrated in FIG. 1, a communication network can include base stations and user equipment of a wide variety of types and/or numbers.

[0053] For instance, in the example shown, the communication network **10** includes the macro cell base station **1** and the small cell base station **3**. The small cell base station **3** can operate with relatively lower power, shorter range, and/or with fewer concurrent users relative to the macro cell base station **1**. The small cell base station **3** can also be referred to as a femtocell, a picocell, or a microcell. Although the communication network **10** is illustrated as including two base stations, the communication network **10** can be implemented to include more or fewer base stations and/or base stations of other types.

[0054] Although various examples of user equipment are shown, the teachings herein are applicable to a wide variety of user equipment, including, but not limited to, mobile phones, tablets, laptops, IoT devices, wearable electronics, customer premises equipment (CPE), wireless-connected vehicles, wireless relays, and/or a wide variety of other communication devices. Furthermore, user equipment includes not only currently available communication devices that operate in a cellular network, but also subsequently developed communication devices that will be readily implementable with the inventive systems, processes, methods, and devices as described and claimed herein.

[0055] The illustrated communication network **10** of FIG. 1 supports communications using a variety of cellular technologies, including, for example, 4G LTE and 5G NR. In certain implementations, the communication network **10** is further adapted to provide a wireless local area network (WLAN), such as WiFi. Although various examples of communication technologies have been provided, the communication network **10** can be adapted to support a wide variety of communication technologies.

[0056] Various communication links of the communication network **10** have been depicted in FIG. 1. The communication links can be duplexed in a wide variety of ways, including, for example, using frequency-division duplexing (FDD) and/or time-division duplexing (TDD). FDD is a type of radio frequency communications that uses different frequencies for transmitting and receiving signals. FDD can provide a number of advantages, such as high data rates and low latency. In

contrast, TDD is a type of radio frequency communications that uses about the same frequency for transmitting and receiving signals, and in which transmit and receive communications are switched in time. TDD can provide a number of advantages, such as efficient use of spectrum and variable allocation of throughput between transmit and receive directions.

[0057] In certain implementations, user equipment can communicate with a base station using one or more of 4G LTE, 5G NR, and WiFi technologies. In certain implementations, enhanced license assisted access (eLAA) is used to aggregate one or more licensed frequency carriers (for instance, licensed 4G LTE and/or 5G NR frequencies), with one or more unlicensed carriers (for instance, unlicensed WiFi frequencies).

[0058] As shown in FIG. 1, the communication links include not only communication links between UE and base stations, but also UE to UE communications and base station to base station communications. For example, the communication network **10** can be implemented to support self-fronthaul and/or self-backhaul (for instance, as between mobile device **2g** and mobile device **2f**).

[0059] The communication links can operate over a wide variety of frequencies. In certain implementations, communications are supported using 5G NR technology over one or more frequency bands that are less than 6 Gigahertz (GHz) and/or over one or more frequency bands that are greater than 6 GHz. For example, the communication links can serve Frequency Range 1 (FR1), Frequency Range 2 (FR2), or a combination thereof. In one embodiment, one or more of the mobile devices support a HPUE power class specification.

[0060] In certain implementations, a base station and/or user equipment communicates using beamforming. For example, beamforming can be used to focus signal strength to overcome path losses, such as high loss associated with communicating over high signal frequencies. In certain embodiments, user equipment, such as one or more mobile phones, communicate using beamforming on millimeter wave frequency bands in the range of 30 GHz to 300 GHz and/or upper centimeter wave frequencies in the range of 6 GHz to 30 GHz, or more particularly, 24 GHz to 30 GHz.

[0061] Different users of the communication network **10** can share available network resources, such as available frequency spectrum, in a wide variety of ways.

[0062] In one example, frequency division multiple access (FDMA) is used to divide a frequency band into multiple frequency carriers. Additionally, one or more carriers are allocated to a particular user. Examples of FDMA include, but are not limited to, single carrier FDMA (SC-FDMA) and orthogonal FDMA (OFDMA). OFDMA is a multicarrier technology that subdivides the available bandwidth into multiple mutually orthogonal narrowband subcarriers, which can be separately assigned to different users.

[0063] Other examples of shared access include, but are not limited to, time division multiple access (TDMA) in which a user is allocated particular time slots for using a frequency resource, code division multiple access (CDMA) in which a frequency resource is shared amongst different users by assigning each user a unique code, space-divisional multiple access (SDMA) in which beamforming is used to provide shared access by spatial division, and non-orthogonal multiple access (NOMA) in which the power domain is used for multiple access. For example, NOMA can be used to serve multiple users at the same frequency, time, and/or code, but with different power levels.

[0064] Enhanced mobile broadband (eMBB) refers to technology for growing system capacity of LTE networks. For example, eMBB can refer to communications with a peak data rate of at least 10 Gbps and a minimum of 100 Mbps for each user. Ultra-reliable low latency communications (uRLLC) refers to technology for communication with very low latency, for instance, less than 2 milliseconds. uRLLC can be used for mission-critical communications such as for autonomous driving and/or remote surgery applications. Massive machine-type communications (mMTC) refers to low cost and low data rate communications associated with wireless connections to everyday objects, such as those associated with Internet of Things (IoT) applications.

[0065] The communication network **10** of FIG. **1** can be used to support a wide variety of advanced communication features, including, but not limited to, eMBB, uRLLC, and/or mMTC.

[0066] FIG. **2** is a schematic diagram of one embodiment of a mobile device **800**. The mobile device **800** includes a baseband system **801**, a transceiver **802**, a front end system **803**, antennas **804**, a power management system **805**, a memory **806**, a user interface **807**, and a battery **808**.

[0067] The mobile device **800** can be used communicate using a wide variety of communications technologies, including, but not limited to, 2G, 3G, 4G (including LTE, LTE-Advanced, and LTE-Advanced Pro), 5G NR, WLAN (for instance, WiFi), WPAN (for instance, Bluetooth and ZigBee), WMAN (for instance, WiMax), and/or GPS technologies.

[0068] The transceiver **802** generates RF signals for transmission and processes incoming RF signals received from the antennas **804**. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in FIG. **2** as the transceiver **802**. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

[0069] The front end system **803** aids in conditioning signals transmitted to and/or received from the antennas **804**. In the illustrated embodiment, the front end system **803** includes antenna tuning circuitry **810**, power amplifiers (PAs) **811**, low noise amplifiers (LNAs) **812**, filters **813**, switches **814**, and signal splitting/combining circuitry **815**. However, other implementations are possible.

[0070] For example, the front end system **803** can provide a number of functionalities, including, but not limited to, amplifying signals for transmission, amplifying received signals, filtering signals, switching between different bands, switching between different power modes, switching between transmission and receiving modes, duplexing of signals, multiplexing of signals (for instance, diplexing or triplexing), or some combination thereof.

[0071] In certain implementations, the mobile device **800** supports carrier aggregation, thereby providing flexibility to increase peak data rates. Carrier aggregation can be used for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), and may be used to aggregate a plurality of carriers or channels. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band or in different bands.

[0072] The antennas **804** can include antennas used for a wide variety of types of communications. For example, the antennas **804** can include antennas for transmitting and/or receiving signals associated with a wide variety of frequencies and communications standards.

[0073] In certain implementations, the antennas **804** support MIMO communications and/or switched diversity communications. For example, MIMO communications use multiple antennas for communicating multiple data streams over a single radio frequency channel. MIMO communications benefit from higher signal to noise ratio, improved coding, and/or reduced signal interference due to spatial multiplexing differences of the radio environment. Switched diversity refers to communications in which a particular antenna is selected for operation at a particular time. For example, a switch can be used to select a particular antenna from a group of antennas based on a variety of factors, such as an observed bit error rate and/or a signal strength indicator.

[0074] The mobile device **800** can operate with beamforming in certain implementations. For example, the front end system **803** can include amplifiers having controllable gain and phase shifters having controllable phase to provide beam formation and directivity for transmission and/or reception of signals using the antennas **804**. For example, in the context of signal transmission, the amplitude and phases of the transmit signals provided to the antennas **804** are controlled such that radiated signals from the antennas **804** combine using constructive and destructive interference to generate an aggregate transmit signal exhibiting beam-like qualities with more signal strength propagating in a given direction. In the context of signal reception, the amplitude and phases are controlled such that more signal energy is received when the signal is



arriving to the antennas **804** from a particular direction. In certain implementations, the antennas **804** include one or more arrays of antenna elements to enhance beamforming.

[0075] The baseband system **801** is coupled to the user interface **807** to facilitate processing of various user input and output (I/O), such as voice and data. The baseband system **801** provides the transceiver **802** with digital representations of transmit signals, which the transceiver **802** processes to generate RF signals for transmission. The baseband system **801** also processes digital representations of received signals provided by the transceiver **802**. As shown in FIG. 2, the baseband system **801** is coupled to the memory **806** of facilitate operation of the mobile device **800**.

[0076] The memory **806** can be used for a wide variety of purposes, such as storing data and/or instructions to facilitate the operation of the mobile device **800** and/or to provide storage of user information.

[0077] The power management system **805** provides a number of power management functions of the mobile device **800**. In certain implementations, the power management system **805** includes a PA supply control circuit that controls the supply voltages of the power amplifiers **811**. For example, the power management system **805** can be configured to change the supply voltage(s) provided to one or more of the power amplifiers **811** to improve efficiency, such as power added efficiency (PAE).

[0078] As shown in FIG. 2, the power management system **805** receives a battery voltage from the battery **808**. The battery **808** can be any suitable battery for use in the mobile device **800**, including, for example, a lithium-ion battery.

[0079] FIG. 3 is a schematic diagram of a power amplifier system **860** according to one embodiment. The illustrated power amplifier system **860** includes a baseband processor **841**, a transmitter/observation receiver **842**, a power amplifier (PA) **843**, a directional coupler **844**, front-end circuitry **845**, an antenna **846**, a PA bias control circuit **847**, and a PA supply control circuit **848**. The illustrated transmitter/observation receiver **842** includes an I/Q modulator **857**, a mixer **858**, and an analog-to-digital converter (ADC) **859**. In certain implementations, the transmitter/observation receiver **842** is incorporated into a transceiver.

[0080] The baseband processor **841** can be used to generate an in-phase (I) signal and a quadrature-phase (Q) signal, which can be used to represent a sinusoidal wave or signal of a desired amplitude, frequency, and phase. For example, the I signal can be used to represent an in-phase component of the sinusoidal wave and the Q signal can be used to represent a quadrature-phase component of the sinusoidal wave, which can be an equivalent representation of the sinusoidal wave. In certain implementations, the I and Q signals can be provided to the I/Q modulator **857** in a digital format. The baseband processor **841** can be any suitable processor configured to process a baseband signal. For instance, the baseband processor **841** can include a digital signal processor, a microprocessor, a programmable core, or any combination thereof. Moreover, in some implementations, two or more baseband processors **841** can be included in the power amplifier system **860**.

[0081] The I/Q modulator **857** can be configured to receive the I and Q signals from the baseband processor **841** and to process the I and Q signals to generate an RF signal. For example, the I/Q modulator **857** can include digital-to-analog converters (DACs) configured to convert the I and Q signals into an analog format, mixers for upconverting the I and Q signals to RF, and a signal combiner for combining the upconverted I and Q signals into an RF signal suitable for amplification by the power amplifier **843**. In certain implementations, the I/Q modulator **857** can include one or more filters configured to filter frequency content of signals processed therein.

[0082] The power amplifier **843** can receive the RF signal from the I/Q modulator **857**, and when enabled can provide an amplified RF signal to the antenna **846** via the front-end circuitry **845**.

[0083] The front-end circuitry **845** can be implemented in a wide variety of ways. In one example, the front-end circuitry **845** includes one or more switches, filters, duplexers, multiplexers, and/or other components. In another example, the front-end circuitry **845** is omitted in favor of the power

amplifier **843** providing the amplified RF signal directly to the antenna **846**. In the embodiment illustrated in FIG. 3, the front-end circuitry **845** includes a duplexing circuit **100** which may include one or more duplexers, as described below.

[0084] The directional coupler **844** senses an output signal of the power amplifier **823**.

Additionally, the sensed output signal from the directional coupler **844** is provided to the mixer **858**, which multiplies the sensed output signal by a reference signal of a controlled frequency. The mixer **858** operates to generate a downshifted signal by downshifting the sensed output signal's frequency content. The downshifted signal can be provided to the ADC **859**, which can convert the downshifted signal to a digital format suitable for processing by the baseband processor **841**.

Including a feedback path from the output of the power amplifier **843** to the baseband processor **841** can provide a number of advantages. For example, implementing the baseband processor **841** in this manner can aid in providing power control, compensating for transmitter impairments, and/or in performing digital pre-distortion (DPD). Although one example of a sensing path for a power amplifier is shown, other implementations are possible.

[0085] The PA supply control circuit **848** receives a power control signal from the baseband processor **841**, and controls supply voltages of the power amplifier **843**. In the illustrated configuration, the PA supply control circuit **848** generates a first supply voltage V.sub.CC1 for powering an input stage of the power amplifier **843** and a second supply voltage V.sub.CC2 for powering an output stage of the power amplifier **843**. The PA supply control circuit **848** can control the voltage level of the first supply voltage V.sub.CC1 and/or the second supply voltage V.sub.CC2 to enhance the power amplifier system's PAE.

[0086] The PA supply control circuit **848** can employ various power management techniques to change the voltage level of one or more of the supply voltages over time to improve the power amplifier's power added efficiency (PAE), thereby reducing power dissipation.

[0087] One technique for improving efficiency of a power amplifier is average power tracking (APT), in which a DC-to-DC converter is used to generate a supply voltage for a power amplifier based on the power amplifier's average output power. Another technique for improving efficiency of a power amplifier is envelope tracking (ET), in which a supply voltage of the power amplifier is controlled in relation to the envelope of the RF signal. Thus, when a voltage level of the envelope of the RF signal increases the voltage level of the power amplifier's supply voltage can be increased. Likewise, when the voltage level of the envelope of the RF signal decreases the voltage level of the power amplifier's supply voltage can be decreased to reduce power consumption.

[0088] In certain configurations, the PA supply control circuit **848** is a multi-mode supply control circuit that can operate in multiple supply control modes including an APT mode and an ET mode. For example, the power control signal from the baseband processor **841** can instruct the PA supply control circuit **848** to operate in a particular supply control mode.

[0089] As shown in FIG. 3, the PA bias control circuit **847** receives a bias control signal from the baseband processor **841**, and generates bias control signals for the power amplifier **843**. In the illustrated configuration, the bias control circuit **847** generates bias control signals for both an input stage of the power amplifier **843** and an output stage of the power amplifier **843**. However, other implementations are possible.

#### Example Duplexing Filter Circuits With Transmit Signal Cancellation

[0090] FIG. 4 is an example embodiment of a duplexer circuit **100** that can be used in an FDD or TDD radio front-end. As shown in FIG. 4, the duplexer circuit **100** is connected between a transmit (Tx) port **102**, a receive (Rx) port **104**, and an antenna (ANT) port **106**. The transmit port **102** includes one or more power amplifiers (PAs) **843** configured to amplify an RF signal and provide the amplified RF signal to an antenna connected to the antenna port **106**. Although not illustrated, the receive port **104** may include one or more LNAs (e.g., the LNAs **812** of FIG. 2) and the antenna port **106** may include an antenna (e.g., the antenna **804** of FIG. 2 or the antenna **846** of FIG. 3).

[0091] The duplexer circuit **100** includes a duplexer **108** including a transmit (Tx) filter **108a** and a

receive (Rx) filter **108b** coupled together at a common node, such as an antenna node coupled to the antenna port **106**. An isolation path **107** is formed between the transmit port **102** and the receive port **104**. In some implementations, the duplexer **108** can be implemented as a surface acoustic wave (SAW) duplexer, which can provide relatively wide bandwidth. However, this disclosure is not limited thereto and in other implementations, the duplexer **108** can be implemented as an LC filter or any other type of appropriate filter technology.

[0092] The transmit and receive filters **108a** and **108b** can be bandpass filters that respectively allow signals having the frequencies of the transmit and receive bands to reject or attenuate frequencies outside of the respective pass bands. Since the transmit and receive bands do not have overlapping frequencies, the RF transmit signals received from the power amplifier can be attenuated by the combination of the transmit and receive filters **108a** and **108b** such that the RF transmit signal is prevented from reaching the LNA on the receive port **104**. That is, the duplexer **100** is configured to substantially block all frequencies along the isolation path **107** from the transmit port **102** to the receive port **104**.

[0093] However, in practice there may be a certain amount of leakage of the RF signals through one or more of the transmit and receive filters **108a** and **108b** forming the duplexer circuit **100**. In FDD and/or TDD radio front-ends, performance can be limited due to leakage of noise and/or interference through the duplexing filters **108a** and **108b**. For instance, the amplified RF signal received from the transmit port **102** may leak through the duplexer **108** to the duplexer receive output ports and onto the receive port **104**. The leakage of noise and interferences through the duplexing filters **108a** and **108b** to the receive port **104** can include all the gained up transceiver noise in the receive band, the power amplifier **843** added noise in the receive band, as well as the transmit carrier leakage that is provided from the transmit port **102** to the transmit input of the duplexer **100** which can leak unintentionally across the duplexer **100** to the receive port **104**. The transmit carrier leakage can result in a significant performance impact.

[0094] One technique for reducing leakage through the duplexer **100** is to provide stronger attenuation of the duplexer **100** in order to reach desired isolation values. Filter which provide stronger out-of-band attenuation typically also have higher the insertion loss within-band for both the transmit and receive filters **108a** and **108b**. In addition, such filters once phased properly within the duplexer **100** itself also provide better transmit-to-receive isolation. Single filters have invested in higher Q technology in order to achieve steeper skirts and better isolation, especially for comparatively difficult bands with a relatively narrow duplex gap and a relatively small frequency spacing between the transmit and receive bands.

[0095] Duplex spacing or duplex distance generally refers to the space between the transmit and receive frequencies. As the duplex spacing decreases, the band gap (e.g., the space between the transmit and receive bands) also decreases. In 5G, the duplex spacing for many bands may be in the range of about 40-300 MHz, which may be relatively tight compared to legacy network technologies.

[0096] Aspects of this disclosure relate to a duplexer circuit **100** that can reduce leakage from the transmit port **102** to the receive port **104** without adjusting the out-of-band attenuation of the filters used in the duplexer circuit **100**. FIG. 5 is an example embodiment of a duplexer circuit **100** that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure. The duplexer circuit **100** is coupled to a transmit port **102**, a receive port **104**, and an antenna port **106**. The duplexer circuit **100** includes a transmit splitter **110**, a receive splitter **112**, and an antenna splitter **114**, respectively coupled to the transmit port **102**, the receive **104** port, and the antenna port **106**.

[0097] The duplexer circuit **100** further includes a first phase shifter **116**, a second phase shifter **118**, a third phase shifter **120**, a first duplexer **122**, and a second duplexer **124**. In addition, a first isolation path **107** and a second isolation path **109** are formed between the transmit port **102** and the receive port **104**. In certain implementations, each of the first to third phase shifters **116-120** is

configured to provide a substantially 90° phase shift. The first and second duplexers **122** and **124** may be substantially matched and each include a transmit filter **122a**, **124a** and a receive filter **122b**, **124b**.

[0098] As shown in FIG. 5, the use of the splitters **110-114** provides parallel paths between each of the transmit port **102**, the receive port **104**, and the antenna port **106**. The first to third phase shifters **116-120** are located such that the parallel paths cancel RF signals between the transmit port **102** and the receive port **104** and sum coherently between the antenna port **106** and each of the transmit and receive ports **102** and **104**. For example, the first and second splitters **110** and **112**, the first and second phase shifters **116** and **118**, and the first and second duplexers **122** and **124** form the first and second isolation paths **107** and **109**. In detail, the first and second phase shifter **116** and **118** are both formed on the first isolation path **107** while no phase shift is applied on the second isolation path **109**. Thus, the first isolation path **107** provides a 180° phase shift compared to the second isolation path **109** such that the RF leakage signal along the first isolation path **107** cancels the RF leakage signal along the second isolation path **109**. By providing cancelation of the RF leakage signals along the first and second isolation paths **107** and **109**, the isolation between the transmit port **102** and the receive port **104** is increased without altering the construction of the first and second duplexers **122** and **124**.

[0099] The duplexer circuit **100** further provides constructive summing of the paths between the transmit port **102** and the antenna port **106**, as well as between the antenna port **106** and the receive port **104**. For example, the first phase shifter **116** and the third phase shifter **120** are placed on respective paths such that the RF signals transmitted on the parallel paths between the transmit port **102** and the antenna port **106** are both phase shifted by 90° and thus sum constructively. Similarly, the second phase shifter **118** and the third phase shifter **120** are placed on respective paths such that the RF signals transmitted on the parallel paths between the antenna port **106** and the receive port **102** are both phase shifted by 90° and thus sum constructively.

[0100] Aspects of this disclosure which provide parallel isolation paths **107** and **109** for which one of the paths **107** and **109** is phase shifted by 180° can provide broadband active cancellation that can greatly improve the degradation of the reference sensitivity for the partnered band. As used herein, reference sensitivity generally refers to the sensitivity at the receiver even when the transmitter is off. The active transmit cancellation described herein can also potentially relax the overall filter requirements of each of the first and second duplexers **122** and **124**, even for relatively small duplex spacing scenarios. Reflection from antenna port **106** mismatch may degrade the effectiveness of the cancellation, however, the cancellation is optimized with higher out-of-band attenuations. According to aspects of this disclosure, the duplexer circuit **100** may be a band-dedicated implementation.

[0101] While the use of a duplexer circuit **100** such as that of FIG. 5 may involve a larger area and/or cost compared to other techniques, the active canceling of leakage signals using matched duplexers **122** and **124** enable greater improved performance in bands that are previously only well addressed by extremely expensive (and potentially large as well) duplexers in different technologies. Thus, aspects of this disclosure can allow a lower cost and smaller duplexer circuit **100** approach to be used with higher performance for reference sensitivity.

[0102] FIG. 6 illustrates an embodiment of a splitter **110** which can be used in accordance with aspects of this disclosure. In particular, the splitter **110** is a passive power splitter that includes an impedance **126** (e.g., a dissipation resistor) connected between the two output legs of the splitter **110**. In certain implementations, the splitter **110** can be embodied as a Wilkinson power splitter. In particular, a simple T-junction may function well if both sides are balanced, however, if the impedances of the legs of the T-junction are not matched, cancellation may not be as good. The use of a splitter **110** such as a Wilkinson power splitter can address this issue. The impedance **126** can dissipate impedance match between the two branches of the splitter **110**.

[0103] FIG. 7 is another example embodiment of a duplexer circuit **100** that can be used in an FDD

or TDD radio front-end in accordance with aspects of this disclosure. Similar to FIG. 5, the duplexer circuit **100** of FIG. 7 is coupled to a transmit port **102**, a receive port **104**, and an antenna port **106**. The duplexer circuit **100** includes a transmit hybrid splitter **130**, an antenna hybrid splitter **132**, a receive hybrid splitter **134**, first to third resistors **136-140**, a first duplexer **142**, and a second duplexer **144**. The transmit, antenna, and receive hybrid splitters **130-134** are respectively connected to the transmit, antenna, and receive ports **102-106**. In addition, each of the transmit, antenna, and receive hybrid splitters **130-134** are connected to ground via a corresponding one of the first to third resistors **136-140**.

[0104] The transmit, antenna, and receive hybrid splitters **130-134** may be implemented as 90° 3 dB hybrid splitters (for example, the hybrid splitters **130-134** may be implemented as hybrid baluns). With reference to the transmit hybrid splitter **130** as an example, the transmit hybrid splitter **130** receives an RF signal from the transmit port **102** as an input and splits the RF signal into two RF signals, a first one of the split RF signals has no phase shift and a second one of the split RF signals has a 90° phase shift. The two RF signals output from the transmit hybrid splitter **130** are provided to the first and second duplexers **142**.

[0105] Any leakage from the first split RF signal (e.g., having no phase shift) through the first duplexer **142** is applied to the third hybrid splitter **134** and undergoes no phase shift for the portion that is split to the receive port **106**. Further, any leakage from the second split RF signal (e.g., having a 90° phase shift) through the second duplexer **144** is applied to the third hybrid splitter **134** and undergoes a further 90° phase shift for the portion that is split to the receive port **106**. Thus, the leakage signals from the first and second split RF signals have a phase shift of 180° with respect to each other, and thus, cancel at the receive port **106**.

[0106] The connections between the first to third hybrid splitters **130-134** and the first and second duplexers **142** and **144** provide for constructive interference between the transmit port **102** and the antenna port **104** as well as between the antenna port **104** and the receive port **106**. Portions of the signals split via any one of the first to third hybrid splitters **130-134** which are not used for either cancelling leaking or constructive interference of the RF signals are grounded via the first to third resistors **136-140**.

[0107] By providing active RF leakage cancellation between the transmit port **102** and the receive port **106**, the FIG. 7 implementation may have the same advantages as discussed above in connection with the FIG. 6 implementation.

[0108] FIG. 8 is a flowchart that provides a method for improved RF leakage cancellation for a duplexer circuit used in a radio front-end in accordance with aspects of this disclosure. The method **200** can be performed using the duplexer circuit **100** of either FIG. 6 or FIG. 7.

[0109] The method **200** starts at block **201**. At block **202**, the method **200** involves outputting first and second radio frequency transmit signals onto respective first and second parallel transmit paths extending between a power amplifier and an antenna. At block **204**, the method **200** involves applying a first phase shift to the first radio frequency transmit signal between the power amplifier and a first duplexer on the first transmit path. At block **206**, the method **200** involves outputting first and second radio frequency receive signals onto respective first and second parallel receive paths extending between the antenna and a receive splitter. At block **208**, the method **200** involves applying a second phase shift to the first radio frequency receive signal between the antenna and a second duplexer on the first receive path. At block **210**, the method **200** involves applying a third phase shift to the second radio frequency receive signal between the first duplexer and the receive splitter on the second receive path. The method **200** ends at block **212**.

#### Further Example Duplexing Filter Circuits With Transmit Signal Cancellation

[0110] Frequency division duplex (FDD) operation involves concurrent transmit and receive, separated in frequency offset of the duplex spacing and the low noise receive path is protected from the transmit impairments by the isolation provided by the filter isolation of the duplexer. This isolation may come at the cost of insertion loss in the transmit signal (e.g., higher DC consumption

and lower power capability at the antenna) and in the receive signal (degraded sensitivity even when the transmitter is off, so-called “reference sensitivity”). As the transmit power levels increase and transmit channel bandwidths increase, these challenges to protect the receiver from the transmit impairments becomes more difficult.

[0111] Transmit impairments include but are not limited to: 1) transmit leakage of modulated carrier power, 2) adjacent channel leakage ratio (ACLR) and spectral emissions regrowth falling directly onto the active receive channel, 3) ACLR that leaks through the transmit-to-receive isolation (e.g., mid-duplex gap isolation) in the form of a concentrated high amplitude intermodulation distortion (IMD) spurious, 4) receive band noise (white noise) generated in the power amplifier, 5) receive band noise (white noise) generated by the transceiver gained up by the power amplifier, 6) reverse intermodulation created at the power amplifier output from back-injected blocker mixing with the forward transmit carrier power to produce IMD that can fall onto the receive channel, and 7) farther offset harmonics or general spurious that can additionally degrade the active receive.

[0112] As described above, one technique for reducing leakage through the duplexer **100** involves providing stronger attenuation and isolation of the transmit-to-receive properties of the duplex filter (e.g., see the duplexer **108** of FIG. **4**), which come at some trade-off and sacrifice to degrade (increase) the insertion loss of the transmit and receive paths. This technique may involve leveraging phase cancellation and brute force isolation properties of the duplexer to address the attenuation of the transmit impairments.

[0113] Even using stronger attenuation, there may be unavoidable transmitter power leak. Relatively high power blockers may be out of the low-noise amplifier intended pass band. Further, the typical transmit power level may be so large as to saturate the low-noise amplifier. One or more of ACLR emissions, white noise out of band, and noise components may fall directly into the active receive channel. In addition, the non-linearity of the power amplifier can create spectral regrowth.

[0114] FIG. **9** is an example embodiment of a duplexer circuit **300** that can be used in an FDD or TDD radio front-end. As shown in FIG. **9**, the duplexer circuit **300** is connected between a power amplifier (PA) **302** connected to a transmit port **301**, a low-noise amplifier (LNA) **304** connected to a receive port **305**, and an antenna **306**. The power amplifier **302** is configured to amplify an RF signal received from the transmit port **301** and provide the amplified RF signal to the antenna **306** via the duplexer circuit **300**. The low-noise amplifier **304** is configured to receive an RF signal from the antenna **306** via the duplexer circuit **300**.

[0115] The duplexer circuit **300** includes a duplexer **308** including a transmit filter **308A** and a receive filter **308B**, which are respectively coupled to the power amplifier **302** and the low-noise amplifier **304**. The transmit filter **308A** and the receive filter **308B** are coupled together at a common node, such as an antenna node coupled to the antenna **306**. In some implementations, the duplexer **308** can be implemented as a surface acoustic wave (SAW) duplexer, which can provide relatively wide bandwidth. However, this disclosure is not limited thereto and in other implementations, the duplexer **308** can be implemented as an LC filter or any other type of appropriate filter technology.

[0116] As shown in FIG. **9**, there may be a certain amount of leakage **320** through the duplexer **308** from the power amplifier **302** to the low-noise amplifier **304**. The transmit carrier leakage through the duplexer **308** can result in a significant performance impact. Some amount of leakage **320** may be present no matter how good the rejection of the duplexer **308**. Thus, aspects of this disclosure relate to techniques for cancelling the leakage **320** from the transmit port **301** and the power amplifier **302** to the low-noise amplifier **304** and the receive port **305**.

[0117] Aspects of this disclosure provide a matched path for the transmit leakage **320**, and does not require the use of a receive channel or the antenna based out of band blocker. By amplitude and phase adjusting the matched filter leakage **320** path, cancellation of these unwanted impairments

can be provided. Thus, aspects of this disclosure provide for enhanced cancellation of substantially all transmit impairments described herein, and can effectively provide much lower receive de-sense as a result, with less impact to insertion loss and even low transmit power performance.

[0118] Aspects of this disclosure can address one or all of the above-identified issues. FIG. 10 is an example embodiment of a duplexer circuit 300 that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure. With reference to FIG. 10, the duplexer circuit 300 is connected between a power amplifier 302 connected to a transmit port 301; a first low-noise amplifier 304A, a phase shifter 312, a second low-noise amplifier 304B, and a splitter 314 connected to a receive port 305; and an antenna 306. The power amplifier 302 is configured to amplify an RF signal received from the transmit port 301 and provide the amplified RF signal to the antenna 306 via the duplexer circuit 300. The first low-noise amplifier 304A is configured to receive an RF signal from the antenna 306 via the duplexer circuit 300. Further details on the functionality of the first and second low-noise amplifiers 304A and 304B, the phase shifter 312, and the splitter 314 are provided below.

[0119] The duplexer circuit 300 includes a first transmit filter 308A and a first receive filter 308B, which may be substantially similar to the transmit and receive filters 308A and 308B of FIG. 9. The duplexer circuit 300 of FIG. 10 further includes a second receive filter 310B and a second transmit filter 310A which are electrically coupled to provide a second path 322 between the transmit port 301 and the receive port 305. The second path 322 (e.g., including the second receive filter 310B and a second transmit filter 310A) is substantially matched to a primary path which includes the first transmit filter 308A and the first receive filter 308B. Thus, the leakage current 320 flowing through the first transmit filter 308A and the first receive filter 308B may be substantially matched by a second leakage current flowing through the second path 322.

[0120] The first low-noise amplifier 304A, the phase shifter 312, the second low-noise amplifier 304B, and the splitter 314 are arranged between the duplexer circuit 300 and the receive port 305 and are configured to cancel the leakage current 320 and the second leakage current. In detail, the phase shifter 312 can be configured to shift the second leakage current by substantially 180° and the first and second low-noise amplifiers 304A and 304B are configured to respectfully amplify the first and second leakage currents by the same amount. However, in other embodiments, the phase shifter 312 may be configured to provide a different amount of phase shift or may be omitted from the circuit as described herein.

[0121] Finally, the splitter 314 (functioning as a mixer) is configured to combine the amplified leakage currents, which results in cancellation since the two leakage currents are phase offset by 180° and have substantially the same amplitude.

[0122] While a certain amount of leakage current may also be present between the transmit port 301 and the antenna 306 as well as between the antenna 306 and the receive port 305, this leakage current may be insignificant compared to the desired RF signals being communicated. For example, an RF receive signal received at the antenna 306 is provided to the first low noise amplifier 304A via the first receive filter 308B. An RF receive leakage signal must travel through the first transmit filter 308A, the second receive filter 310B, and the second transmit filter 310A before arriving at the phase shifter 312. Because the pass bands of these three filters do not overlap, the amplitude of the RF receive leakage signal will be significantly lower than the RF receive signal received at the first low noise amplifier 304A, and thus, the signal-to-noise ratio of the RF receive signal is not significantly affected by the RF receive leakage current. An RF transmit signal provided from the transmit port 301 to the antenna 306 is similarly not significantly affected by an RF transmit leakage signal.

[0123] FIGS. 11A and 11B provide example embodiments of circuit configurations which can be used to connect the receive port 305 to the duplexer circuit 300 of FIG. 10 in accordance with aspects of this disclosure. With reference to the embodiment illustrated in FIG. 11A, the splitter 314 can include a balun 316 having a first loop connected between the receive port 305 and ground

and a second loop connected between the first and second low-noise power amplifiers **304A** and **304B**. Because the balun **316** is configured to receive a balance input, the leakage signals provided by the first and second low-noise power amplifiers **304A** and **304B** do not need to be phase offset in order for the balun **316** to cancel the matched leakage signals. Thus, the phase shifter **312** of the FIG. **11A** embodiment can be configured to provide no phase shift (e.g.,  $0^\circ$  phase shift) or can be omitted from the circuit such that the second low-noise power amplifier **304B** is directly connected to the duplexer circuit **300**.

[0124] With reference to the embodiment illustrated in FIG. **11B**, the splitter **314** can include a passive power splitter **318** (e.g., such as the splitter **110** illustrated in FIG. **6**) configured to function as a mixer that combines the RF signals respectively received from the first and second low-noise amplifiers **304A** and **304B**. For example, the power splitter **318** can include an impedance **319** coupled between the inputs connected to the first and second low-noise amplifiers **304A** and **304B**. In the FIG. **11B** embodiment, the phase shifter **312** can be configured to provide about a  $180^\circ$  phase shift such that the leakage currents input into the splitter **312** are substantially cancelled before reaching the receive port **305**.

[0125] FIG. **12** is another example embodiment of a duplexer circuit **300** that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure. Similar to the FIG. **10** embodiment, the duplexer circuit **300** is connected between a power amplifier **302** connected to a transmit port **301**; a first low-noise amplifier **304A**, a phase shifter **312**, a second low-noise amplifier **304B**, and a splitter **314** connected to a receive port **305**; and an antenna **306**. The power amplifier **302** is configured to amplify an RF signal received from the transmit port **301** and provide the amplified RF signal to the antenna **306** via the duplexer circuit **300**. The first low-noise amplifier **304A** is configured to receive an RF signal from the antenna **306** via the duplexer circuit **300**.

[0126] In contrast to the FIG. **10** embodiment, the duplexer **300** of FIG. **12** includes a transmit filter **308A**, a first receive filter **308B**, and a second receive filter **310B**, omitting the second transmit filter **310A** of FIG. **10**. The second receive filter **310B** is coupled to the phase shifter **312**. Although a second leakage current flowing through the second receive filter **310B** does not flow through a second transmit filter **310A**, the second leakage current may still have substantially the same amplitude as a first leakage current flowing through the transmit filter **308A** and the receive filter **308B**. Thus, the first low-noise amplifier **304A**, the phase shifter **312**, the second low-noise amplifier **304B**, and the splitter **314** can be configured to cancel the first and second leakage currents before the leakage currents reach the receive port **305**. In some embodiments, splitter **314** can be implemented using one of the embodiments of FIGS. **11A** and **11B**.

#### Example Duplexing Filter Circuits With EM Coupling Cancellation

[0127] FIGS. **13A** and **13B** illustrate yet another example embodiment of a duplexer circuit **300** that can be used in an FDD or TDD radio front-end in accordance with aspects of this disclosure. In particular, FIG. **13A** illustrates the duplexer **300** with a circuit diagram oriented similar to that of FIGS. **10** and **12**, while FIG. **13B** illustrates an alternative view of the circuit diagram for the duplexer **300** of FIG. **13A**.

[0128] With reference to FIGS. **13A** and **13B**, the duplexer circuit **300** is connected between a power amplifier **302** connected to a transmit port **301**; a first low-noise amplifier **304A**, a second low-noise amplifier **304B**, and a splitter **314** connected to a receive port **305**; and an antenna **306**. The power amplifier **302** is configured to amplify an RF signal received from the transmit port **301** and provide the amplified RF signal to the antenna **306** via the duplexer circuit **300**. The first low-noise amplifier **304A** is configured to receive an RF signal from the antenna **306** via the duplexer circuit **300**.

[0129] FIG. **13A** further illustrates an embodiment of the splitter **314**, which can be combined with any other embodiment disclosed herein. In this embodiment, the splitter **314** includes a first phase shifter **330**, a second phase shifter **332**, and a mixer **334**. The first phase shifter **330** can be



configured to apply a positive 45° phase shift and the second phase shifter 332 can be configured to apply a negative 45° phase shift. Accordingly, the two signals received at the mixer 334 have a relative phase shift of 180° and are cancelled before reaching the receive port 305.

[0130] The duplexer 300 includes a first transmit filter 308A, a first receive filter 308B, a second transmit filter 310A, a second receive filter 310B, a first impedance 350A and a second impedance 350B. In the embodiment of FIGS. 13A and 13B, the filters 308A, 308B, 310A, and 310B are connected by conductive traces. The filters 308A, 308B, 310A, and 310B and conductive traces are arranged in order to match radiative coupling of EM therebetween. The first and second impedances 350A and 350B can be configured to improve impedance and loading effects.

[0131] With reference to FIG. 13A, five nodes 1-5 are illustrated at points on the conductive traces. A first EM coupling 340 may be formed between node 1 and node 4 and a second EM coupling 342 may be formed between node 1 and node 3. A first leakage current 344 and a second leakage current 346 from the transmit port 301 to the receive port 305 are also shown in FIG. 13A.

[0132] In order to substantially match the first and second EM couplings 340 and 342, the duplexer 300 may be physically laid out as shown in FIG. 13B. As shown in FIG. 13B, the filters 308A, 308B, 310A, and 310B, conductive traces, and first and second impedances 350A and 350B are arranged substantially symmetrically such that the first and second EM couplings 340 and 342 will substantially cancel at the splitter 314 before arriving at the receive port 305.

[0133] In some embodiments, the first impedance 350A may include a shunt inductor, which is applied at the common port 2 of the first transmit filter 308A and the first receive filter 308B. The shunt inductor together with a capacitor for the first transmit filter 308A can function as a parallel LC circuit, which may be resonant over a first frequency range. The LC circuit may be designed to function as an open circuit at frequencies of interest. The second impedance 350B is configured to substantially match the first impedance 350A. In some implementations, matching the first and second impedances 350A and 350B may involve tuning one or more of the first and second impedances 350A and 350B to obtain a sufficient match therebetween. That is, one or more of the first and second impedances 350A and 350B may be tunable to improve the EM coupling cancellation of the duplexer 300. In some embodiments, one or more of the first and second impedances 350A and 350B may have a programmable impedance via a switched parallel inductor coupled to ground.

#### Example Duplexing Filter Circuits With Signal Cancellation Between Different Communication Technologies

[0134] FIG. 14 is an example embodiment of a diplexer circuit 400 that can be used to couple two different communication technologies to an antenna in accordance with aspects of this disclosure. The diplexer circuit 400 of FIG. 14 is coupled to a cellular port 402, a Wi-Fi port 404, and an antenna port 406. Thus, the diplexer circuit 400 is configured to selectively connect one of the cellular port 402 and the Wi-Fi port 404 to the antenna port 406 for wireless communication. The diplexer circuit 400 is further connected to ground via a plurality of resistors 408, 410, and 412.

[0135] The diplexer circuit 400 includes first and second diplex filters 414 and 416, a cellular hybrid splitter 418, a Wi-Fi hybrid splitter 420, and an antenna hybrid splitter 422. The cellular, Wi-Fi, and antenna hybrid splitters 418-422 are respectively connected to the cellular, Wi-Fi, and antenna ports 402-406. In addition, each of the cellular, Wi-Fi, and antenna hybrid splitters 418-422 are connected to ground via a corresponding one of the first to third resistors 408-412.

[0136] Similar to the FIG. 7 embodiment, the cellular, Wi-Fi, and antenna hybrid splitters 418-422 may be implemented as 90° 3 dB hybrid splitters (for example, the hybrid splitters 418-422 may be implemented as hybrid baluns). The diplexer circuit 400 is configured to reduce leakage signals between the cellular port 402 and the Wi-Fi port 404 by providing two paths therebetween with the leakage signals on the two paths cancelling each other.

[0137] With reference to the cellular hybrid splitter 418 as an example, the cellular hybrid splitter 418 receives an RF signal from the cellular port 402 as an input and splits the RF signal into two

RF signals. A first one of the split RF signals has no phase shift and is provided to the first diplexer **414** and a second one of the split RF signals has a 90° phase shift and is provided to the second diplexer **416**.

[0138] Any leakage from the first split RF signal (e.g., having no phase shift) through the first diplexer **142** is applied to the Wi-Fi hybrid splitter **420** and undergoes no phase shift for the portion that is split to the Wi-Fi port **404**. Further, any leakage from the second split RF signal (e.g., having a 90° phase shift) through the second diplexer **422** is applied to the Wi-Fi hybrid splitter **420** and undergoes a further 90° phase shift for the portion that is split to the Wi-Fi port **404**. Thus, the leakage signals from the first and second split RF signals have a phase shift of 180° with respect to each other, and thus, cancel at the Wi-Fi port **404**. Signal originating from the Wi-Fi port **404** undergo a similar cancellation on the path to the cellular port **402**.

[0139] The connections between the cellular, Wi-Fi, and antenna hybrid splitters **418-422** and the first and second diplexers **414** and **416** provide for constructive interference between the cellular port **402** and the antenna port **406** as well as between the Wi-Fi port **404** and the antenna port **406**. Portions of the signals split via any one of the cellular, Wi-Fi, and antenna hybrid splitters **418-422** which are not used for either cancelling leaking or constructive interference of the RF signals are grounded via the first to third resistors **408-412**.

[0140] By providing active RF leakage cancellation between the cellular port **402** and the Wi-Fi port **410**, the FIG. **14** implementation may have the same advantages as discussed above in connection with the implementations of FIGS. **6** and **7**.

[0141] The embodiment of FIG. **14** can address limited isolation and impedance termination challenges that limit low loss diplexing (impedance loading of one path depends on impedance loading other path, which can result in “suck-outs” and poor impedance loading depending on frequency-dependent phase of the complex terminations) by employing balanced configuration that substantially guarantees 50 Ohm. In other implementations, the diplexer isolation may be relaxed, which results in this problem and eventually the diplexer is unusable due to this variability in the application.

[0142] The embodiment of FIG. **14** can also enhance the isolation between the cellular port **402** and the Wi-Fi port **404** by the isolation property of the hybrid splitters **418-422** (e.g., which may have 20-25 dB isolation). The first to third resistors **408-412** may provide a substantially ideal match for the diplexers **414** and **416** to the antenna **406**. The isolation may be above a threshold within a given range of the band edge for the transmit and receive bands. The transmit leakage and receive band can be suppressed in both directions (e.g., from cellular to Wi-Fi and from Wi-Fi to cellular). By providing this cancellation, aspects of this disclosure can provide higher isolation with a difficult impedance loading vs. out of band attenuation trade-off than compared to other approaches.

[0143] When the bandwidth of the hybrid splitters **418-422** is wider than a threshold value, the second harmonics can also be phase cancelled in both directions (e.g., from cellular to Wi-Fi and from Wi-Fi to cellular).

[0144] One example implementation is between band B40 (e.g., 2.3-2.4 GHz) and B41 (e.g., 2.496-2.69 GHz) for LTE for the cellular signal and 2.4 GHz Wi-Fi that is in between B40 and B41 (e.g., 2.403-2.495 GHz). Aspects of this disclosure enables 20-25 dB enhanced isolation for this extremely challenging coexistence case, and potentially greatly relaxes the filter attenuation required (e.g., less impedance loading).

[0145] According to aspects of this disclosure, the termination **402-406** may be used for sensing the reflected/non-coherent desired signals, and potentially used in further signal cancellation schemes for advantage in coexistence by the radio.

[0146] FIG. **15** is another example embodiment of a diplexer circuit **400** that can be used to couple two different communication technologies to two antennas in accordance with aspects of this disclosure. The diplexer circuit **400** of FIG. **15** is coupled to a first cellular port **402A**, a second

cellular port **402B**, a first Wi-Fi port **404A**, a second Wi-Fi port **404B**, an first antenna port **406A**, and a second antenna port **406B**. The diplexer circuit **400** is configured to selectively connect one of the first cellular port **402A** and the first Wi-Fi port **404A** to the first antenna port **406A** as well as one of the second cellular port **402B** and the second Wi-Fi port **404B** to the second antenna port **406B**.

[0147] The communication between the first cellular port **402A** and the first Wi-Fi port **404A** to the first antenna port **406A** is substantially similar to that described above in connection with FIG. **14**. In addition, the communication between the second cellular port **402B** and the second Wi-Fi port **404B** to the second antenna port **406B** function similarly to the communication between the first ports **402A**, **404A**, and **406A**. Further, cross communications between the first ports **402A**, **404A**, and **406A** and the second ports **402B**, **404B**, and **406B** are substantially insignificant by providing cancellation of any leakage signals from the first cellular/Wi-Fi ports **402A**, **404A**, and **406A** and the second antenna **406B** as well as cancellation of any leakage signals from the second cellular/Wi-Fi ports **402B**, **404B**, and **406B** and the first antenna **406A**.

[0148] In implementations of the FIG. **15** embodiment, by driving the additional ports of the hybrid splitters **418-422** compared to FIG. **14**, additional signals can be routed through the diplexers **414** and **422** concurrently, and substantially optimally with much less loss to multiple antenna configurations. This can enable low loss carrier aggregation of closely spaced bands and channels to multiple antennas with the afore described benefits of FIG. **14** of high isolation and lower insertion loss. In one example, the impedance presented to the ports **402A-406B** may be substantially ideal if close to 50 Ohm to preserve the isolation characteristics of the hybrid splitters **418-422** and balanced architecture.

[0149] FIG. **16** is a flowchart that provides a method for improved RF leakage cancellation for a diplexer circuit used in a radio front-end in accordance with aspects of this disclosure. The method **500** can be performed using the diplexer circuit **300** of any one of either FIGS. **10**, **13A**, and **13B**.

[0150] The method **500** starts at block **501**. At block **502**, the method **500** involves outputting a first radio frequency transmit signal to a first transmit filter positioned between a power amplifier and an antenna. At block **504**, the method **500** involves amplifying the first radio frequency transmit signal at a first low-noise amplifier received from the first transmit filter via a first receive filter. At block **506**, the method **500** involves outputting a second radio frequency transmit signal to a cancellation path including a second receive filter and a second transmit filter. At block **508**, the method **500** involves applying a phase shift to one or both the second radio frequency transmit signal received from the cancellation path. At block **510**, the method **500** involves amplifying the phase shifted second radio frequency at a second low-noise amplifier. The method **500** ends at block **512**.

[0151] FIG. **17** is a flowchart that provides a method for improved RF leakage cancellation for a diplexer circuit in accordance with aspects of this disclosure. The method **600** can be performed using the diplexer circuit **400** of any one of either FIGS. **14** and **15**.

[0152] The method **600** starts at block **601**. At block **602**, the method **600** involves outputting first and second radio frequency transmit signals onto respective first and second parallel communication paths extending between a first radio frequency transceiver terminal and an antenna. At block **604**, the method **600** involves applying a first phase shift to the first radio frequency transmit signal between the first radio frequency terminal and a first diplexer on the first communication path. At block **606**, the method **600** involves outputting third and fourth radio frequency transmit signals onto respective third and fourth parallel communication paths extending between a second radio frequency transceiver and the antenna. At block **608**, the method **600** involves applying a second phase shift to the second radio frequency transmit signal between the antenna and a second diplexer on the second communication path. At block **610**, the method **600** involves applying a third phase shift to the first radio frequency transmit signal between the first diplexer and the second radio frequency transceiver on the third communication path. The method

**CONCLUSION**

[0153] Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise,” “comprising,” and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to.” The word “coupled”, as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Likewise, the word “connected”, as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words “herein,” “above,” “below,” and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word “or” in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

[0154] Moreover, conditional language used herein, such as, among others, “can,” “could,” “might,” “can,” “e.g.,” “for example,” “such as” and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or states are included or are to be performed in any particular embodiment.

[0155] The above detailed description of embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise form disclosed above. While specific embodiments of, and examples for, the invention are described above for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. For example, while processes or blocks are presented in a given order, alternative embodiments may perform routines having steps, or employ systems having blocks, in a different order, and some processes or blocks may be deleted, moved, added, subdivided, combined, and/or modified. Each of these processes or blocks may be implemented in a variety of different ways. Also, while processes or blocks are at times shown as being performed in series, these processes or blocks may instead be performed in parallel, or may be performed at different times.

[0156] The teachings of the invention provided herein can be applied to other systems, not necessarily the system described above. The elements and acts of the various embodiments described above can be combined to provide further embodiments.

[0157] While certain embodiments of the inventions have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosure. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosure.

**Claims**

1. (canceled)
2. A radio frequency front end system comprising: a first receive amplifier, a second receive

amplifier, and a transmit amplifier configured to output an amplified radio frequency transmit signal; and a bi-directional filter including: a transmit path including a first filter and connected between the transmit amplifier and an antenna; a receive path including a second filter and connected between the antenna and the first receive amplifier; a leakage path through which a leakage signal caused by the amplified radio frequency transmit signal passes to the receive path; and a cancellation path including a third filter and connected between the transmit amplifier and the second receive amplifier.

**3.** The radio frequency front end system of claim 2 further comprising a first circuit configured to process a signal that is output by the receive path together with a signal output with the cancellation path.

**4.** The radio frequency front end system of claim 3 further comprising phase shifter circuitry included in one or more of the receive path and the cancellation path.

**5.** The radio frequency front end system of claim 3 wherein the first circuit is configured to destructively cancel the leakage signal and a cancellation signal output by the cancellation path.

**6.** The radio frequency front end system of claim 3 wherein the first circuit is a splitter.

**7.** The radio frequency front end system of claim 3 wherein the first circuit includes a mixer.

**8.** The radio frequency front end system of claim 2 wherein the cancellation path further includes a fourth filter configured to filter a cancellation signal output by the cancellation path, wherein the first filter and the fourth filter each have a passband corresponding to a transmit frequency band and the second filter and the third filter each have a passband corresponding to a receive frequency band.

**9.** The bi-directional filter of claim 8 wherein the first filter, the second filter, the third filter, and the fourth filter are arranged substantially symmetrically.

**10.** The bi-directional filter of claim 2 wherein the bi-directional filter is configured such that the leakage path is matched to the cancellation path.

**11.** A radio frequency system comprising: an antenna port; a transmit path including a first filter and connected between a transmit port and the antenna port; a receive path including a second filter and connected between the antenna port a receive port; a leakage path through which a leakage signal caused by an amplified radio frequency transmit signal passes to the receive path; and a cancellation path including a third filter and connected to the transmit port.

**12.** The radio frequency system of claim 11 wherein the radio frequency system is a duplexer, the antenna port is a bi-directional port of the duplexer, the transmit port is an input port of the duplexer, the receive port is a first output port of the duplexer, and the radio frequency system further includes a second output port coupled to an output of the cancellation path.

**13.** The radio frequency system of claim 11 further comprising cancellation circuitry configured to receive an output of the receive path and an output of the cancellation path, and to generate a processed receive signal in which the leakage signal is cancelled or reduced.

**14.** The radio frequency system of claim 13 further comprising a first receive amplifier connected in the receive path between the second filter and the cancellation circuitry, a second receive amplifier connected in the cancellation path between the third filter and the cancellation circuitry, and a transmit amplifier coupled to the transmit port and configured to output the amplified radio frequency transmit signal.

**15.** The radio frequency system of claim 13 further comprising phase shifter circuitry included in the receive path between the second filter and the cancellation circuitry, in the cancellation path between the third filter and the cancellation circuitry, or in both.

**16.** The radio frequency system of claim 11 wherein the cancellation path further includes a fourth filter configured to filter a cancellation signal output by the cancellation path, wherein the first filter and the fourth filter each have a passband corresponding to a transmit frequency band and the second filter and the third filter each have a passband corresponding to a receive frequency band.

**17.** The radio frequency system of claim 16 wherein the first filter, the second filter, the third filter,

and the fourth filter are arranged substantially symmetrically.

**18.** A mobile device comprising: an antenna; and a radio frequency front end connected to the antenna including a first receive amplifier; a second receive amplifier, a transmit amplifier configured to output an amplified radio frequency transmit signal, and a bi-directional filter including: a transmit path connected between the transmit amplifier and the antenna, the transmit path including a first filter; a receive path connected between the antenna and the first receive amplifier, the receive path including a second filter; a leakage path through which a leakage signal caused by the amplified radio frequency transmit signal passes to the receive path; and a cancellation path connected between the transmit amplifier and the second receive amplifier.

**19.** The mobile device of claim 18 wherein the radio frequency front end further includes a first circuit configured to process a signal output by the receive path together with a signal output with the cancellation path.

**20.** The mobile device of claim 19 further comprising phase shifter circuitry included in one or more of the receive path and the cancellation path.

**21.** The mobile device of claim 19 wherein the first circuit is configured to destructively cancel the leakage signal and a cancellation signal output by the cancellation path.

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