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RADIO-FREQUENCY CIRCUIT

Abstract

A radio-frequency circuit **1** includes a power amplifier configured to receive a first signal, a power amplifier configured to receive a second signal that is +90° relative to the first signal, a combiner circuit configured to combine in phase a third signal input from a fourth input port and a fourth signal input from a fifth input port, a phase shifter circuit coupled to a third output port of the power amplifier, a phase shifter circuit coupled to a fourth output port of the power amplifier, the forward phase of a fundamental wave in the phase shifter circuit being −90° relative to the phase shifter circuit, a harmonic phase shifter circuit coupled to the third output port, and a harmonic phase shifter circuit coupled to the fourth output port.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to Japanese Patent Application No. JP 2024-021858 filed on Feb. 16, 2024. The entire contents of the above-identified application, including the specifications, drawings and claims, are incorporated herein by reference in their entirety.

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

[0002] The present disclosure relates to radio-frequency circuits.

2. Description of the Related Art

[0003] Japanese Unexamined Patent Application Publication No. 2012-147352 discloses a semiconductor device (a radio-frequency circuit) including a first amplifier and a second amplifier that constitute a balanced amplifier, a first phase shifter circuit provided in a first output path that connects an output port of the first amplifier and an output terminal, a second phase shifter circuit provided in a second output path that connects an output port of the second amplifier and the output terminal, a resistor coupled to an output port of the first phase shifter circuit and an output port of a second phase shifter circuit, a first inductor coupled between the output port of the first phase shifter circuit and the output terminal, and a second inductor coupled between the output port of the second phase shifter circuit and the output terminal. It is explained that this configuration reduces power combining losses in a power coupler constituted by the resistor, the first inductor, and the second inductor.

SUMMARY OF THE DISCLOSURE

[0004] With the demand for higher output power in mobile phones, there is a need for radio-frequency circuits that mitigate fluctuations in transmission characteristics caused by load variations.

[0005] The present disclosure has been made to solve the problem described above, and a feature thereof is to provide radio-frequency circuits that mitigate fluctuations in transmission characteristics caused by load variations.

[0006] To achieve the feature described above, a radio-frequency circuit according to an embodiment of the present disclosure includes a first antenna terminal, a splitter having a first input port, a first output port, and a second output port, the splitter being configured to split a fundamental signal of a transmit band of a first band that is input to the first input port, configured to output from the first output port a first split signal, and configured to output from the second output port a second split signal that has a phase of +90° relative to the first split signal, a first power amplifier having a second input port and a third output port, the second input port being coupled to the first output port, a second power amplifier having a third input port and a fourth output port, the third input port being coupled to the second output port, the power combiner circuit having the fourth input port, the fifth input port, and the fifth output port, configured to combine in phase the third split signal input from the fourth input port and the fourth split signal input from the fifth input port and output the generated output signal from the fifth output terminal, a first phase shifter circuit coupled between the third output port and the fourth input port, a second phase shifter circuit coupled between the fourth output port and the fifth input port, a first harmonic phase shifter circuit coupled between the third output port and the fourth input port and/or a second harmonic phase shifter circuit coupled between the fourth output port and the fifth input port, and a first filter coupled between the fifth output port and the first antenna terminal, the first filter having a pass band that includes the transmit band. The first phase shifter circuit and the second phase shifter circuit are configured such that a forward phase of a fundamental wave of the transmit band in the second phase shifter circuit in a direction from the fourth output port to the fifth input port is

−90° relative to a forward phase of the fundamental wave in the first phase shifter circuit in a direction from the third output port to the fourth input port. The first phase shifter circuit, the second phase shifter circuit, the first harmonic phase shifter circuit, and the second harmonic phase shifter circuit are configured such that a difference between a first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and a second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°, and a difference between a third reflection phase of at least one of harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and a fourth reflection phase of the at least one of the harmonic waves assuming the fifth output port is observed from the fourth output port is 180°.

[0007] A radio-frequency circuit according to an embodiment of the present disclosure includes a first antenna terminal, a splitter having a first input port, a first output port, and a second output port, the splitter being configured to split a fundamental signal of a transmit band of a first band that is input to the first input port, configured to output from the first output port a first split signal, and configured to output from the second output port a second split signal that has a phase of +90° relative to the first split signal, a first power amplifier having a second input port and a third output port, the second input port being coupled to the first output port, a second power amplifier having a third input port and a fourth output port, the third input port being coupled to the second output port, the power combiner circuit having the fourth input port, the fifth input port, and the fifth output port, configured to combine in antiphase the third split signal input from the fourth input port and the fourth split signal input from the fifth input port and output the generated output signal from the fifth output terminal, a first phase shifter circuit coupled between the third output port and the fourth input port, a second phase shifter circuit coupled between the fourth output port and the fifth input port, a first harmonic phase shifter circuit coupled between the third output port and the fourth input port and/or a second harmonic phase shifter circuit coupled between the fourth output port and the fifth input port, and a first transmit filter coupled between the fifth output port and the first antenna terminal, the first transmit filter having a pass band that includes the transmit band. The first phase shifter circuit and the second phase shifter circuit are configured such that a forward phase of a fundamental wave of the transmit band in the second phase shifter circuit in a direction from the fourth output port to the fifth input port is −90° relative to a forward phase of the fundamental wave in the first phase shifter circuit in a direction from the third output port to the fourth input port. The first phase shifter circuit, the second phase shifter circuit, the first harmonic phase shifter circuit, and the second harmonic phase shifter circuit are configured such that a difference between a first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and a second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°, and a difference between a third reflection phase of at least one of harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and a fourth reflection phase of the at least one of the harmonic waves assuming the fifth output port is observed from the fourth output port is 180°.

[0008] The present disclosure provides radio-frequency circuits that mitigate fluctuations in transmission characteristics caused by load variations.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a circuit configuration diagram of an amplifier circuit, a radio-frequency circuit, and a communication device according to an embodiment;

[0010] FIG. **2**A is a circuit state diagram of the radio-frequency circuit according to the

embodiment in band-A transmission mode;
[0011] FIG. **2**B is a circuit state diagram of the radio-frequency circuit according to the embodiment in band-B transmission mode;
[0012] FIG. **3**A illustrates the fundamental impedances of power amplifiers according to the embodiment;
[0013] FIG. **3**B illustrates the second harmonic impedances of the power amplifiers according to the embodiment;
[0014] FIG. **4**A provides graphs illustrating the gain, error vector magnitude (EVIM), and adjacent channel leakage ratio (ACLR) of the amplifier circuit according to the embodiment;
[0015] FIG. **4**B is a graph illustrating the output characteristics of the second harmonic wave of the amplifier circuit according to the embodiment;
[0016] FIG. **5**A is a circuit configuration diagram of a first phase shifter circuit according to a first modification of the embodiment;
[0017] FIG. **5**B is a circuit configuration diagram of a second phase shifter circuit according to the first modification of the embodiment;
[0018] FIG. **5**C is a circuit configuration diagram of a first harmonic phase shifter circuit according to the first modification of the embodiment;
[0019] FIG. **5**D is a circuit configuration diagram of a second harmonic phase shifter circuit according to the first modification of the embodiment;
[0020] FIG. **6** is a circuit configuration diagram of an amplifier circuit according to a second modification of the embodiment;
[0021] FIG. **7**A illustrates the fundamental impedances of power amplifiers according to the second modification of the embodiment;
[0022] FIG. **7**B illustrates the third harmonic impedances of the power amplifiers according to the second modification of the embodiment;
[0023] FIG. **8** is a graph illustrating the output characteristics of the third harmonic wave of the amplifier circuit according to the second modification of the embodiment;
[0024] FIG. **9** is a circuit configuration diagram of an amplifier circuit and a radio-frequency circuit according to a third modification of the embodiment;
[0025] FIG. **10** is a circuit configuration diagram of an amplifier circuit, a radio-frequency circuit, and a communication device according to a fourth modification of the embodiment; and
[0026] FIG. **11** provides plan views of the amplifier circuit according to the embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0027] Hereinafter, embodiments of the present disclosure will be described in detail with reference to the drawings. It may be noted that the embodiments described below provide comprehensive or specific examples. Details such as numerical values, shapes, materials, constituent elements, and arrangements and connection modes of the constituent elements provided in the following embodiments are illustrative and are not intended to limit the present disclosure.
[0028] The drawings are schematically illustrated with necessary emphasis, omissions, or proportion adjustments to depict the present disclosure and do not necessarily represent exact details; thus, the shapes, positional relationships, and proportions can differ from actual implementations. Identical reference numerals are assigned to substantially the same configuration elements across the drawings, and redundant descriptions of these configuration elements can be omitted or simplified.
[0029] In the drawings described later, the x-axis and the y-axis are perpendicular to each other in a plane parallel to the major surfaces of a mounting substrate. Specifically, assuming the mounting substrate is rectangular in plan view, the x-axis is parallel to a first side of the mounting substrate, and the y-axis is parallel to a second side perpendicular to the first side of the mounting substrate. The z-axis is perpendicular to the major surfaces of the mounting substrate. Along the z-axis, the positive direction indicates upward, and the negative direction indicates downward.

[0030] In the component arrangements of the present disclosure, the expression “a component is disposed at a substrate” includes the case in which the component is disposed at a major surface of the substrate and the case in which the component is disposed within the substrate. The expression “a component is disposed at a major surface of a substrate” applies assuming the component is disposed in contact with the major surface of the substrate and also assuming the component is disposed above the major surface without making contact with the major surface (for example, assuming the component is stacked on another component that is disposed in contact with the major surface). The expression “a component is disposed at a major surface of a substrate” may include the case in which the component is disposed in a depressed portion formed at the major surface. The expression “a component is disposed within a substrate” includes the case in which the component is encapsulated in the module substrate. The expression also includes the case in which the component is entirely positioned between the two major surfaces of the substrate but not fully covered by the substrate. The expression further includes the case in which only a portion of the component is disposed within the substrate.
[0031] In the component layouts of the present disclosure, the term “plan view of a major surface” refers to a situation in which an feature is orthogonally projected on an xy-plane and viewed from the positive side of the z-axis. The expression “A overlaps B in plan view” refers to a situation in which at least a portion of the region of A orthogonally projected on an xy plane coincides with at least a portion of the region of B orthogonally projected on the xy plane. The expression “A is disposed between B and C” refers to a situation in which at least one of the line segments each connecting any given point within B to any given point within C passes through A.
[0032] In the present disclosure, words used to express relationships between elements, such as parallel and vertical, words used to express the shape of an element, such as rectangular, and numerical ranges do not necessarily denote the exact meanings but denote substantially the same meanings involving, for example, several percent differences.
[0033] In the circuit configurations of the present disclosure, the term “couple” applies assuming one circuit element is directly coupled to another circuit element via a connection terminal and/or an interconnect conductor. The term also applies assuming one circuit element is electrically coupled to another circuit element via still another circuit element. The expression “coupled between A and B” means that a circuit element is coupled to both A and B while the circuit element is positioned between A and B.
[0034] In the present disclosure, the term “path” refers to a transmission line formed by, for example, a wire line for transferring radio-frequency signals, an electrode directly coupled to the wire line, and a terminal directly coupled to the wire line or electrode.
[0035] In the present disclosure, the expression “a component A is provided in series in a path B” means that both of the signal input port and the signal output port of the component A are coupled to a wire line, an electrode, or a terminal that constitute the path B.
[0036] As used in the present disclosure, the terms “terminal”, “input port”, and “output port” refer to a point at which a conductor within an element terminates. Assuming the impedance of a conductor between elements is sufficiently low, the “terminal” is interpreted not only as a single point but also as any point in the conductor between the elements, or as the entire conductor.
[0037] Terms describing relationships between elements, such as “parallel” and “vertical”, terms indicating an element's shape, such as “rectangular”, and numerical ranges are not meant to convey only precise meanings. These terms and numerical ranges denote meanings that are substantially the same, involving, for example, about several percent differences.
[0038] The term “pass band of a filter” refers to the portion of the frequency spectrum that can be transferred through the filter and is defined as the frequency range within which the output power is not attenuated by 3 dB or more below the maximum output power. Thus, the higher and lower limits of the pass band of a band pass filter are identified as the higher and lower frequencies of the two points at which the output power is attenuated by 3 dB below the maximum output power.

[0039] The term "transmit band" refers to a frequency band used for transmission in communication devices. The term "receive band" refers to a frequency band used for reception in communication devices. For example, in frequency division duplex (FDD), different frequency bands are used as the transmit band and the receive band; in time division duplex (TDD), the same frequency range is used as the transmit band and the receive band. In particular, assuming the communication devices are installed in user equipments (UEs) for cellular networks, uplink operation bands can be used as the transmit band, and downlink operation bands can be used as the receive band. Assuming the communication devices are installed as base stations (BSs) for cellular networks, downlink operation bands can be used as the transmit band, and uplink operation bands can be used as the receive band.

[0040] The "forward phase" of a radio-frequency signal between two ports can be determined by applying a measuring RF probe to the two ports and measuring the transfer characteristic (S**21**) using a network analyzer. The "reflection phase" of a radio-frequency signal at a port can be determined by applying a measuring RF probe to the port and measuring the transfer characteristic (S**11**) using a network analyzer.

Embodiment

1 Circuit Configuration of Amplifier Circuit, Radio-Frequency Circuit, and Communication Device

[0041] A circuit configuration of an amplifier circuit **10**, a radio-frequency circuit **1**, and a communication device **4** according to the present embodiment will be described with reference to FIG. **1**. FIG. **1** is a circuit configuration diagram of the amplifier circuit **10**, the radio-frequency circuit **1**, and the communication device **4** according to an embodiment.

1.1 Circuit Configuration of Communication Device **4**

[0042] First, a circuit configuration of the communication device **4** will be described. As illustrated in FIG. **1**, the communication device **4** according to the present embodiment includes the radio-frequency circuit **1**, an antenna **2**, and a radio-frequency signal processing circuit (RFIC: radio frequency integrated circuit) **3**.

[0043] The radio-frequency circuit **1** is operable to transfer radio-frequency signals between the antenna **2** and the RFIC **3**. A detailed circuit configuration of the radio-frequency circuit **1** will be described later.

[0044] The antenna **2** is coupled to an antenna connection terminal **100** (a first antenna terminal) of the radio-frequency circuit **1**. The antenna **2** is operable to transmit radio-frequency signals output from the radio-frequency circuit **1**. The antenna **2** may be operable to receive radio-frequency signals from outside and output the radio-frequency signals to the radio-frequency circuit **1**.

[0045] The RFIC **3** is an example of a signal processing circuit for processing radio-frequency signals.

[0046] Specifically, the RFIC **3** is operable to process, for example by up-conversion, a transmit signal inputted from a baseband signal processing circuit (BBIC; not illustrated in the drawing) and output the transmit signal generated by the signal processing to a transmit path in the radio-frequency circuit **1**. The RFIC **3** is also operable to process, for example by down-conversion, a receive signal inputted through a receive path in the radio-frequency circuit **1** and output the receive signal generated by the signal processing to the BBIC. The RFIC **3** includes a control unit for controlling the radio-frequency circuit **1**. The function of the control unit of the RFIC **3** may be partially or entirely implemented outside the RFIC **3**; for example, the function of the control unit of the RFIC **3** may be partially or entirely implemented in the BBIC or the radio-frequency circuit **1**.

[0047] The RFIC **3** also functions as a control unit for controlling a supply voltage Vcc and a bias current to be supplied to amplifiers included in the amplifier circuit **10**. Specifically, the RFIC **3** outputs control signals to a power supply circuit (not illustrated in the drawing) and a bias circuit (not illustrated in the drawing). The power supply circuit and the bias circuit may be provided in the radio-frequency circuit **1** or the amplifier circuit **10**. The power supply circuit is operable to supply to the amplifiers of the amplifier circuit **10** the supply voltage Vcc that is controlled based on the control signal. The bias circuit is operable to supply to the amplifiers of the amplifier circuit **10** the bias current that is controlled based on the control signal.

[0048] The RFIC **3** also functions as a control unit for controlling connections of switching circuits **41** and **42** included in the radio-frequency circuit **1**, based on the frequency band in use.

[0049] In the communication device **4** according to the present embodiment, the antenna **2** is a non-essential constituent element.

1.2 Circuit Configuration of Radio-Frequency Circuit **1**

[0050] Next, a circuit configuration of the radio-frequency circuit **1** will be described. As illustrated in FIG. **1**, the radio-frequency circuit **1** includes the amplifier circuit **10**, filters **61** and **62**, the switching circuit **42**, inductors **54** to **59**, and the antenna connection terminal **100**.

[0051] The amplifier circuit **10** is a circuit for amplifying transmit signals in bands A and B, inputted from a radio-frequency input terminal **110**. Instead of the amplifier circuit **10**, the radio-frequency circuit **1** may include a first amplifier circuit for amplifying transmit signals in the band A and a second amplifier circuit for amplifying transmit signals in the band B.

[0052] In the present embodiment, the bands A and B represent frequency bands determined by, for example, standards organizations such as the 3rd Generation Partnership Project (3GPP (registered trademark)) and the Institute of Electrical and Electronics Engineers (IEEE)) for communication systems built using a radio access technology (RAT). As the communication system in the present embodiment, for example, a 4th Generation Long Term Evolution (4G LTE) system, 5th Generation New Radio (5G NR) system, and Wireless Local Area Network (WLAN) system may be used, but these are not to be interpreted as limiting.

[0053] The filter **61** is an example of a first filter. The filter **61** is coupled between the switching circuit **41** and the antenna connection terminal **100**. The filter **61** has a pass band that includes the transmit band of the band A (a first band). Specifically, one end of the filter **61** is coupled to a terminal **41***a* of the switching circuit **41**, and the other end of the filter **61** is coupleable to the antenna connection terminal **100** via the inductors **54** and **58** and the switching circuit **42**.

[0054] The filter **62** is an example of a second filter. The filter **62** is coupled between the switching circuit **41** and the antenna connection terminal **100**. The filter **62** has a pass band that includes the transmit band of the band B (a second band). Specifically, one end of the filter **62** is coupled to a terminal **41***b* of the switching circuit **41**, and the other end of the filter **62** is coupleable to the antenna connection terminal **100** via the inductors **56** and **58** and the switching circuit **42**.

[0055] The switching circuit **42** is an example of an antenna switch. The switching circuit **42** has terminals **42***a*, **42***b* and **42***c*. The terminal **42***a* is coupled to the antenna connection terminal **100** via the inductor **58**, the terminal **42***b* is coupled to the filter **61** via the inductor **54**, and the terminal **42***c* is coupled to the filter **62** via the inductor **56**. With the configuration described above, the switching circuit **42** is operable to alternate the connection and disconnection between the antenna connection terminal **100** and the filter **61** and also alternate the connection and disconnection between the antenna connection terminal **100** and the filter **62**.

[0056] The inductor **54** is provided in series in the path connecting the terminal **42***b* of the switching circuit **42** and the filter **61**. The inductor **55** is coupled between the path and ground. The inductors **54** and **55** are operable to provide impedance matching between the switching circuit **42** and the filter **61**. The inductor **56** is provided in series in the path connecting the terminal **42***c* of the switching circuit **42** and the filter **62**. The inductor **57** is coupled between the path and the ground. The inductors **56** and **57** are operable to provide impedance matching between the switching circuit **42** and the filter **62**. The inductor **58** is provided in series in the path connecting the terminal **42***a* of the switching circuit **42** and the antenna connection terminal **100**. The inductor **59** is coupled between the path and ground. The inductors **58** and **59** are operable to provide impedance matching between the switching circuit **42** and the antenna **2**. It may be possible that at least one of the inductors **54** to **59** is not included.

[0057] The circuit configuration described above enables the radio-frequency circuit **1** to transmit radio-frequency signals in the bands A and B.

[0058] It is sufficient for the radio-frequency circuit **1** according to the present disclosure to include at least the amplifier circuit **10** and the filter **61** in the circuit configuration illustrated in FIG. **1**.

1.3 Circuit Configuration of Amplifier Circuit **10**

[0059] Next, a circuit configuration of the amplifier circuit **10** will be described in detail.

[0060] As illustrated in FIG. **1**, the amplifier circuit **10** includes power amplifiers **11** and **12**, phase shifter circuits **21** and **22**, harmonic phase shifter circuits **31** and **32**, the switching circuit **41**, a 90° hybrid **50**, phase shift lines **51** and **52**, a capacitor **53**, and the radio-frequency input terminal **110**.

[0061] The radio-frequency input terminal **110** is coupled to the RFIC **3**. Each of the radio-frequency input terminal **110** and the antenna connection terminal **100** may be a metal conductor such as a metal electrode or metal bump or may be a point (a node) in a metal wire line.

[0062] The 90° hybrid **50** is an example of a splitter. The 90° hybrid **50** has a first input port, a first output port, and a second output port. The first input port is coupled to the radio-frequency input terminal **110**, the first output port is coupled to a second input port of the power amplifier **11**, and the second output port is coupled to a third input port of the power amplifier **12**. The 90° hybrid **50** is configured to split a fundamental signal in the transmit band of the band A or B that is input to the first input port, output a first split signal RF**1** from the first output port, and output a second split signal RF**2**, which has a phase of +90° relative to the first split signal RF**1**, from the second output port.

[0063] The 90° hybrid **50** may be replaced with a phase shifter circuit configured in an alternative manner.

[0064] The power amplifier **11** is an example of a first power amplifier. The power amplifier **11** has the second input port and a third output port. The second input port is coupled to the first output port of the 90° hybrid **50**. The power amplifier **12** is an example of a second power amplifier. The power amplifier **12** has the third input port and a fourth output port. The third input port is coupled to the second output port of the 90° hybrid **50**. The power amplifiers **11** and **12** are able to amplify the radio-frequency signals in the band A or B that are output from the 90° hybrid **50**.

[0065] Each of the power amplifiers **11** and **12** has an amplifier transistor. The amplifier transistor is, for example, a bipolar transistor, such as a heterojunction bipolar transistor (HBT), or a field-effect transistor, such as a metal-oxide-semiconductor field-effect transistor (MOSFET). Assuming the amplifier transistor is a bipolar transistor, the input port of each of the power amplifier **11** and **12** is, for example, the base terminal of the bipolar transistor, and the output port of each of the power amplifiers **11** and **12** is, for example, the collector terminal of the bipolar transistor. Assuming the amplifier transistor is a field-effect transistor, the input port of each of the power amplifiers **11** and **12** is, for example, the gate terminal of the field-effect transistor, and the output port of each of the power amplifiers **11** and **12** is, for example, the drain terminal of the field-effect transistor.

[0066] The phase shifter circuit **21** is an example of a first phase shifter circuit. The phase shifter circuit **21** is coupled between the third output port of the power amplifier **11** and a terminal **41***c* of the switching circuit **41**. The phase shifter circuit **21** includes, for example, capacitors **211** and **212** and an inductor **213**. The capacitor **211** is an example of a first capacitor. The capacitor **211** is coupled between the third output port and the terminal **41***c*. The inductor **213** is an example of a first inductor. The inductor **213** is coupled between ground and the path connecting the capacitor **211** and the terminal **41***c*. The capacitor **212** is provided in series in the path connecting the capacitor **211** and the terminal **41***c*. The phase shifter circuit **21** is configured as a high pass filter. The phase shifter circuit **21** is operable to introduce, for example, a phase shift of +45° (a phase advance of 45°) to the forward phase of the fundamental waves in the bands A and B. The capacitor **212** is a direct-current (DC) blocking capacitor and does not contribute to phase shift. The capacitor **212** is not necessarily included in the phase shifter circuit **21**.

[0067] The phase shifter circuit **22** is an example of a second phase shifter circuit. The phase shifter circuit **22** is coupled between the fourth output port of the power amplifier **12** and a terminal **41***d* of the switching circuit **41**. The phase shifter circuit **22** is configured such that the forward phase of the fundamental waves in the bands A and B in the direction from the fourth output port to the terminal **41***d* is −90° (a phase delay of 90°) relative to the forward phase of the fundamental waves in the bands A and B in the phase shifter circuit **21** in the direction from the third output port to the terminal **41***c*. The phase shifter circuit **22** includes, for example, an inductor **221** and capacitors **222** and **223**. The inductor **221** is an example of a second inductor. The inductor **221** is coupled between the fourth output port and the terminal **41***d*. The capacitor **223** is an example of a second capacitor. The capacitor **223** is coupled between ground and the path connecting the inductor **221** and the terminal **41***d*. The capacitor **222** is provided in series in the path connecting the inductor **221** and the terminal **41***d*. The phase shifter circuit **22** is configured as a low pass filter. The phase shifter circuit **22** is operable to introduce, for example, a phase shift of −45° (a phase delay of 45°) to the forward phase of the fundamental signals in the bands A and B. The capacitor **222** is a DC blocking capacitor and does not contribute to phase shift. The capacitor **222** is not necessarily included in the phase shifter circuit **22**.

[0068] The harmonic phase shifter circuit **31** is an example of a first harmonic phase shifter circuit. The harmonic phase shifter circuit **31** is coupled between the third output port of the power amplifier **11** and the terminal **41***c* of the switching circuit **41**. The harmonic phase shifter circuit **31** includes, for example, a capacitor **311** (a third capacitor) coupled between ground and the path connecting the third output port and the capacitor **211**. The harmonic phase shifter circuit **31** operates as a low pass filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°.

[0069] The harmonic phase shifter circuit **32** is an example of a second harmonic phase shifter circuit. The harmonic phase shifter circuit **32** is coupled between the fourth output port of the power amplifier **12** and the terminal **41***d* of the switching circuit **41**. The harmonic phase shifter circuit **32** includes, for example, an inductor **321** and a capacitor **322**. The inductor **321** (a third inductor) and the capacitor **322** (a fourth capacitor) form an LC circuit by being coupled in series with each other. The LC circuit is coupled between ground and the path connecting the fourth output port and the inductor **221**. The harmonic phase shifter circuit **32** operates as a notch filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°.

[0070] The phase shifter circuit **21** and the harmonic phase shifter circuit **31** are configured such that the forward phase of the second harmonic waves in the bands A and B in the circuit formed by combining the phase shifter circuit **21** and the harmonic phase shifter circuit **31** is +45° (a phase advance of 45°). The phase shifter circuit **22** and the harmonic phase shifter circuit **32** are configured such that the forward phase of the second harmonic waves in the circuit formed by combining the phase shifter circuit **22** and the harmonic phase shifter circuit **32** is −45° (a phase delay of 45°).

[0071] The switching circuit **41** is an example of a combiner circuit. The switching circuit **41** has the terminal **41***a* (a fifth output port), the terminal **41***b* (a sixth output port), the terminal **41***c* (a fourth input port), the terminal **41***d* (a fifth input port), and a terminal **41***e* (a monitoring terminal). The switching circuit **41** is operable to alternate between connecting the terminals **41***c* and **41***a* as well as connecting the terminals **41***d* and **41***a* and connecting the terminals **41***c* and **41***b* as well as connecting the terminals **41***d* and **41***b*. With this configuration, the switching circuit **41** outputs from the terminal **41***a* the output signal generated by combining in phase at the terminal **41***a* a third split signal in the band A input from the terminal **41***c* and a fourth split signal in the band A input from the terminal **41***d*. The switching circuit **41** outputs from the terminal **41***b* the output signal generated by combining in phase at the terminal **41***b* a third split signal in the band B input from the terminal **41***c* and a fourth split signal in the band B input from the terminal **41***d*. The terminal

41*a* serves as the signal combining point for combining in phase the band-A third split signal and the band-A fourth split signal. The terminal **41***b* is the signal combining point for combining in phase the band-B third split signal and the band-B fourth split signal.

[0072] The terminal **41***e* (a monitoring terminal) is used, for example, to measure the reflection phase assuming observing the switching circuit **41** side from the collector terminal (a third output port) of the power amplifier **11** or the collector terminal (a third output port) of the power amplifier **12**. Specifically, in the state in which the terminal **41***e* is connected to the terminal **41***c* while the terminal **41***c* is disconnected from the terminals **41***a* and **41***b*, the reflection phases of the fundamental wave and the second harmonic wave of the band A or B can be measured at the terminal **41***e*. The reflection phases measured in the state in which the terminal **41***e* is coupled to the terminal **41***c* is equivalent to the reflection phases of the fundamental wave and the second harmonic wave of the band A or B measured from the collector terminal of the power amplifier **11**. In the state in which the terminal **41***e* is connected to the terminal **41***d* while the terminal **41***d* is disconnected from the terminals **41***a* and **41***b*, the reflection phases of the fundamental wave and the second harmonic wave of the band A or B can be measured at the terminal **41***e*. The reflection phases measured in the state in which the terminal **41***e* is coupled to the terminal **41***d* is equivalent to the reflection phases of the fundamental wave and the second harmonic wave of the band A or B measured from the collector terminal of the power amplifier **12**.

[0073] The phase shift line **51** is provided in series between the third output port of the power amplifier **11** and a supply voltage (Vcc) terminal. The phase shift line **51** is operable to suppress leakage of a first radio-frequency signal, output from the power amplifier **11**, to the Vcc terminal. The phase shift line **52** is provided in series between the fourth output port of the power amplifier **12** and the supply voltage (Vcc) terminal. The phase shift line **52** is operable to suppress leakage of a second radio-frequency signal, output from the power amplifier **12**, to the Vcc terminal. The capacitor **53** is coupled between the Vcc terminal and the ground. The capacitor **53** is operable to inhibit leakage components of the first radio-frequency signal and the second radio-frequency signal from leaking into the Vcc terminal and also inhibit the supply voltage from flowing to ground.

[0074] In the amplifier circuit **10** configured as described above, the phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31** and **32** are configured such that: the difference between a first reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **41***a* is observed from the third output port and a second reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is 180°; and the difference between a third reflection phase of the second harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the third output port and a fourth reflection phase of the second harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is 180°.

[0075] The first reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **41***a* is observed from the third output port is defined as the phase shift of the fundamental wave of the reflected signal reflected at the terminal **41***a* and returned to the third output port, relative to the phase of the fundamental wave of the transmit signal in the band-A transmit band that is output from the third output port, in the state in which the terminal **41***c* is connected to the terminal **41***a* while the terminal **41***a* is disconnected from the filter **61**. The second reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is defined as the phase shift of the fundamental wave of the reflected signal reflected at the terminal **41***a* and returned to the fourth output port, relative to the phase of the fundamental wave of the transmit signal in the band-A transmit band that is output from the fourth output port, in the state in which the terminal **41***d* is connected to the terminal **41***a* while the terminal **41***a* is disconnected from the filter **61**. The third reflection phase of the second harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the third

output port is defined as the phase shift of the second harmonic wave of the reflected signal reflected at the terminal **41***a* and returned to the third output port, relative to the phase of the second harmonic wave of the transmit signal in the band-A transmit band that is output from the third output port, in the state in which the terminal **41***c* is connected to the terminal **41***a* while the terminal **41***a* is disconnected from the filter **61**. The fourth reflection phase of the second harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is defined as the phase shift of the second harmonic wave of the reflected signal reflected at the terminal **41***a* and returned to the fourth output port, relative to the phase of the second harmonic wave of the transmit signal in the band-A transmit band that is output from the fourth output port, in the state in which the terminal **41***d* is connected to the terminal **41***a* while the terminal **41***a* is disconnected from the filter **61**.
[0076] The first reflection phase of the fundamental wave of the band-A transmit band can be obtained by measuring the reflection phase of the fundamental wave of the band A at the terminal **41***a* in the state in which the terminal **41***c* is connected to the terminal **41***a*, the terminal **41***d* is disconnected from the terminal **41***a*, and the terminal **41***a* is disconnected from the filter **61**. The first reflection phase of the fundamental wave of the band-B transmit band can be obtained by measuring the reflection phase of the fundamental wave of the band B at the terminal **41***b* in the state in which the terminal **41***c* is connected to the terminal **41***b*, the terminal **41***d* is disconnected from the terminal **41***b*, and the terminal **41***b* is disconnected from the filter **62**.
[0077] The second reflection phase of the fundamental wave of the band-A transmit band can be obtained by measuring the reflection phase of the fundamental wave of the band A at the terminal **41***a* in the state in which the terminal **41***d* is connected to the terminal **41***a*, the terminal **41***c* is disconnected from the terminal **41***a*, and the terminal **41***a* is disconnected from the filter **61**. The second reflection phase of the fundamental wave of the band-B transmit band can be obtained by measuring the reflection phase of the fundamental wave of the band B at the terminal **41***b* in the state in which the terminal **41***d* is connected to the terminal **41***b*, the terminal **41***c* is disconnected from the terminal **41***b*, and the terminal **41***b* is disconnected from the filter **62**.
[0078] The third reflection phase of the second harmonic wave of the band-A transmit band can be obtained by measuring the reflection phase of the second harmonic wave of the band A at the terminal **41***a* in the state in which the terminal **41***c* is connected to the terminal **41***a*, the terminal **41***d* is disconnected from the terminal **41***a*, and the terminal **41***a* is disconnected from the filter **61**. The third reflection phase of the second harmonic wave of the band-B transmit band can be obtained by measuring the reflection phase of the second harmonic wave of the band B at the terminal **41***b* in the state in which the terminal **41***c* is connected to the terminal **41***b*, the terminal **41***d* is disconnected from the terminal **41***b*, and the terminal **41***b* is disconnected from the filter **62**.
[0079] The fourth reflection phase of the second harmonic wave of the band-A transmit band can be obtained by measuring the reflection phase of the second harmonic wave of the band A at the terminal **41***a* in the state in which the terminal **41***d* is connected to the terminal **41***a*, the terminal **41***c* is disconnected from the terminal **41***a*, and the terminal **41***a* is disconnected from the filter **61**. The fourth reflection phase of the second harmonic wave of the band-B transmit band can be obtained by measuring the reflection phase of the second harmonic wave of the band B at the terminal **41***b* in the state in which the terminal **41***d* is connected to the terminal **41***b*, the terminal **41***c* is disconnected from the terminal **41***b*, and the terminal **41***b* is disconnected from the filter **62**.
[0080] With the configuration described above, assuming unwanted signals at the fundamental and second harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit **1** through the antenna connection terminal **100** from external circuits, the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the second harmonic waves is also 180°. As a result, fluctuations in the transmission characteristics of the radio-frequency circuit **1** in the fundamental and harmonic frequency ranges can be suppressed regardless of load

variations. As such, the amplifier circuit **10** and the radio-frequency circuit **1** is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and harmonic frequency ranges of transmit signals.

[0081] In the amplifier circuit **10** and the radio-frequency circuit **1** according to the present embodiment, the phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31** and **32** control the phase of the fundamental wave and the phase of the second harmonic wave. However, the phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31** and **32** may control the phase of the fundamental wave and the phase of at least one of the nth harmonic waves (n is an integer greater than or equal to 3).

[0082] This means that assuming unwanted signals at the fundamental and nth (n is an integer greater than or equal to 3) harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit through the antenna connection terminal **100** from external circuits, it is sufficient that the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the nth harmonic waves is also 180°. With this configuration, fluctuations in the transmission characteristics of the fundamental and nth harmonic frequency ranges of the radio-frequency circuit can be suppressed regardless of load variations. As such, an amplifier circuit and a radio-frequency circuit are provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and nth harmonic frequency ranges of transmit signals.

1.4 Transmission Characteristics of Radio-Frequency Circuit **1**

[0083] FIG. **2**A is a circuit state diagram of the radio-frequency circuit **1** according to the embodiment in band-A transmission mode. As illustrated in the drawing, in band-A transmission mode, the terminals **41***a* and **41***c* are connected and the terminals **41***a* and **41***d* are connected in the switching circuit **41**. The terminals **42***a* and **42***b* are connected in the switching circuit **42**.

[0084] A band-A transmit signal is split by the 90° hybrid **50** into the first split signal RF**1** and the second split signal RF**2**. The first split signal RF**1** and the second split signal RF**2** are respectively input to the power amplifiers **11** and **12** and amplified into a first signal and a second signal. At the third output port of the power amplifier **11**, the phase of the fundamental wave of the first signal is 0°. At the fourth output port of the power amplifier **12**, the phase of the fundamental wave of the second signal is 90°.

[0085] After the first signal passes through the harmonic phase shifter circuit **31** (with a fundamental-wave forward phase of 0°) and the phase shifter circuit **21** (with a fundamental-wave forward phase of +45°), the phase of the fundamental wave of the first signal is +45° at the terminal **41***a*. After the second signal passes through the harmonic phase shifter circuit **32** (with a fundamental-wave forward phase of 0°) and the phase shifter circuit **22** (with a fundamental-wave forward phase of −45°), the phase of the fundamental wave of the second signal is +45° at the terminal **41***a*. As a result, the band-A first signal and the band-A second signal can be combined in phase at the terminal **41***a*. This configuration enables highly efficient power combining of the fundamental wave with respect to load variations.

[0086] The difference between the first reflection phase (+45°×2=90°) of the fundamental wave of the first signal assuming the terminal **41***a* is observed from the third output port and the second reflection phase (−45°×2=−90°) of the fundamental wave of the second signal assuming the terminal **41***a* is observed from the fourth output port is 1800.

[0087] The forward phase of the second harmonic wave of the first signal in the circuit formed by combining the harmonic phase shifter circuit **31** and the phase shifter circuit **21** is +45°. The forward phase of the second harmonic wave of the second signal in the circuit formed by combining the harmonic phase shifter circuit **32** and the phase shifter circuit **22** is −45°. In other words, the difference between the third reflection phase (+45°×2=90°) of the second harmonic wave of the first signal assuming the terminal **41***a* is observed from the third output port and the fourth reflection phase (−45°×2=−90°) of the second harmonic wave of the second signal assuming

the terminal **41***a* is observed from the fourth output port is 1800.
[0088] FIG. **2**B is a circuit state diagram of the radio-frequency circuit **1** according to the embodiment in band-B transmission mode. As illustrated in the drawing, in band-B transmission mode, the terminals **41***b* and **41***c* are connected and the terminals **41***b* and **41***d* are connected in the switching circuit **41**. The terminals **42***a* and **42***c* are connected in the switching circuit **42**.
[0089] A band-B transmit signal is split by the 90° hybrid **50** into the first split signal RF**1** and the second split signal RF**2**. The first split signal RF**1** and the second split signal RF**2** are respectively input to the power amplifiers **11** and **12** and amplified into a first signal and a second signal. At the third output port of the power amplifier **11**, the phase of the fundamental wave of the first signal is 0°. At the fourth output port of the power amplifier **12**, the phase of the fundamental wave of the second signal is 90°.
[0090] After the first signal passes through the harmonic phase shifter circuit **31** (with a fundamental-wave forward phase of 0°) and the phase shifter circuit **21** (with a fundamental-wave forward phase of +45°), the phase of the fundamental wave of the first signal is +45° at the terminal **41***b*. After the second signal passes through the harmonic phase shifter circuit **32** (with a fundamental-wave forward phase of 0°) and the phase shifter circuit **22** (with a fundamental-wave forward phase of −45°), the phase of the fundamental wave of the second signal is +45° at the terminal **41***b*. As a result, the band-B first signal and the band-A second signal can be combined in phase at the terminal **41***b*. This configuration enables highly efficient power combining of the fundamental wave with respect to load variations.
[0091] The difference between the first reflection phase (+45°×2=90°) of the fundamental wave of the first signal assuming the terminal **41***b* is observed from the third output port and the second reflection phase (−45°×2=−90°) of the fundamental wave of the second signal assuming the terminal **41***b* is observed from the fourth output port is 1800.
[0092] The forward phase of the second harmonic wave of the first signal in the circuit formed by combining the harmonic phase shifter circuit **31** and the phase shifter circuit **21** is +45°. The forward phase of the second harmonic wave of the second signal in the circuit formed by combining the harmonic phase shifter circuit **32** and the phase shifter circuit **22** is −45°. In other words, the difference between the third reflection phase (+45°×2=90°) of the second harmonic wave of the first signal assuming the terminal **41***b* is observed from the third output port and the fourth reflection phase (−45°×2=−90°) of the second harmonic wave of the second signal assuming the terminal **41***b* is observed from the fourth output port is 1800.
[0093] FIG. **3**A illustrates the fundamental impedances of the power amplifiers **11** and **12** according to the embodiment. FIG. **3**B illustrates the second harmonic impedances of the power amplifiers **11** and **12** according to the embodiment. FIG. **3**A illustrates the impedance of the band-A fundamental wave (frequencies f.sub.L1 to f.sub.H1) at the third output port of the power amplifier **11** (PA**11**) and the impedance of the band-A fundamental wave at the fourth output port of the power amplifier **12** (PA**12**) in polar coordinates. FIG. **3**B illustrates the impedance of the band-A second harmonic wave (frequencies f.sub.L2 to f.sub.H2) at the third output port of the power amplifier **11** (PA**11**) and the impedance of the band-A second harmonic wave at the fourth output port of the power amplifier **12** (PA**12**) in polar coordinates.
[0094] As illustrated in FIG. **3**A, the difference between the first reflection phase of the fundamental wave and the second reflection phase of the fundamental wave is 180°. As a result, a consistent phase difference of 180° is maintained between the fundamental impedance of the power amplifier **11** and the fundamental impedance of the power amplifier **12** across the band-A fundamental frequency range (frequencies f.sub.L1 to f.sub.H1). Thus, the radio-frequency circuit **1** cancels out load variations in the band-A fundamental frequency range and achieves stable transmission output characteristics across the fundamental frequency range.
[0095] As illustrated in FIG. **3**B, the difference between the third reflection phase of the second harmonic wave and the fourth reflection phase of the second harmonic wave is 180°. As a result, a

consistent phase difference of 180° is maintained between the second harmonic impedance of the power amplifier **11** and the second harmonic impedance of the power amplifier **12** across the band-A second harmonic frequency range (frequencies f.sub.L2 to f.sub.H2). Thus, the radio-frequency circuit **1** cancels out load variations in the band-A second harmonic frequency range and achieves stable transmission output characteristics across the second harmonic frequency range.
[0096] FIG. **4**A provides graphs illustrating the gain, error vector magnitude (EVIM), and adjacent channel leakage ratio (ACLR) of the amplifier circuit **10** according to the embodiment. FIG. **4**B is a graph illustrating the output characteristics of the second harmonic wave of the amplifier circuit **10** according to the embodiment. The upper portion of FIG. **4**A illustrates the fundamental impedance with a load impedance of F=0.2 on Smith charts with contour plots of (a) gain, (b) EVM, and (c) ACLR from load-pull measurements. The lower portion of FIG. **4**A illustrates the results of mapping the contour plots on the fundamental impedance.
[0097] As illustrated in FIG. **4**A, the gain, EVM, and ACLR of each of the power amplifiers **11** and **12**, fluctuate with load variations (phase variations). However, because the difference between the first reflection phase of the fundamental wave and the second reflection phase of the fundamental wave is 180°, variations in the gain, EVM, and ACLR of the combined fundamental wave from the power amplifiers **11** and **12** are suppressed. As a result, the amplifier circuit **10** achieves stable transmission output characteristics of the fundamental wave, regardless of the presence of load variations.
[0098] As illustrated in FIG. **4**B, the second harmonic outputs of the power amplifiers **11** and **12** fluctuate with load variations (phase variations). However, because the difference between the third reflection phase of the second harmonic wave and the fourth reflection phase of the second harmonic wave is 180°, variations in the combined second harmonic output formed by combining the second harmonic waves from the power amplifiers **11** and **12** are suppressed. As a result, the amplifier circuit **10** achieves stable transmission output characteristics of the second harmonic wave, regardless of the presence of load variations.
[0099] Known amplifier circuits with balanced first and second power amplifiers have a 90° fundamental phase difference at the output ports of the first and second power amplifiers, perform in-phase combining at the combining point, and suppress harmonic waves.
[0100] However, under the circumstance where high output power performance is desired, an issue arises: the need to operate with both the fundamental wave and the harmonic wave while stably outputting the fundamental wave and the harmonic wave regardless of load variations. To address the issue, it is highly effective and significant to maintain a reflection phase difference of 180° at the output ports of the power amplifiers **11** and **12** in the two frequency ranges of the fundamental wave and the harmonic wave, as in the amplifier circuit **10** and the radio-frequency circuit **1** according to the present embodiment.
[0101] It may be noted that in the amplifier circuit **10** according to the present embodiment, either the harmonic phase shifter circuit **31** or **32** may be excluded. It is sufficient for the amplifier circuit according to the present disclosure to have a circuit configuration that achieves a 180° phase difference between the reflection phase of the second harmonic wave of the first signal in the path connecting the third output port of the power amplifier **11** and the terminal **41***a* (combining point) and the reflection phase of the second harmonic wave of the second signal in the path connecting the fourth output port of the power amplifier **12** and the terminal **41***a*.
[0102] In the present embodiment, the numerical values for forward phase, reflection phase, and reflection phase difference do not necessarily represent exact values but represent substantially the same values involving, for example, about 30% differences.
2 Circuit Configuration of Amplifier Circuit According to First Modification
[0103] An amplifier circuit according to a first modification will be described. The amplifier circuit according to the present modification includes power amplifiers **11** and **12**, phase shifter circuits **21**A and **22**A, harmonic phase shifter circuits **31**A and **32**A, a switching circuit **41**, a 90° hybrid **50**,

phase shift lines **51** and **52**, a capacitor **53**, and a radio-frequency input terminal **110**. The amplifier circuit according to the present modification differs from the amplifier circuit **10** according to the embodiment in the circuit configuration of the phase shifter circuit and the harmonic phase shifter circuit. The following describes the amplifier circuit according to the present modification, focusing on the phase shifter circuits **21**A and **22**A and the harmonic phase shifter circuits **31**A and **32**A, which are different configurational features from the amplifier circuit **10** according to the embodiment, and descriptions of the same configurational features as the amplifier circuit **10** according to the embodiment will not be repeated.

[0104] FIG. **5**A is a circuit configuration diagram of the phase shifter circuit **21**A according to the first modification of the embodiment. The phase shifter circuit **21**A is an example of a first phase shifter circuit. The phase shifter circuit **21**A is coupled between a third output port of the power amplifier **11** and a terminal **41***c* of the switching circuit **41**. The phase shifter circuit **21**A includes capacitors **211**, **212**, and **214**, an inductor **213**, and a switch **215**. The capacitor **211** is an example of a first capacitor. The capacitor **211** is coupled between terminals **201** and **202**. The inductor **213** is an example of a first inductor. The inductor **213** is coupled between ground and the path connecting the capacitor **211** and the terminal **202**. The capacitor **212** is provided in series in the path connecting the capacitor **211** and the terminal **202**. The switch **215** (a fifth switch) and the capacitor **214** are coupled in series with each other to form a first variable circuit. The first variable circuit is coupled between the terminals **201** and **202**. The phase shifter circuit **21**A is configured as a high pass filter. The phase shifter circuit **21**A is operable to introduce, for example, a phase shift of +450 (a phase advance of 45°) to the forward phase of the fundamental waves in the bands A and B. The capacitor **212** is a DC blocking capacitor and does not contribute to phase shift. The capacitor **212** is not necessarily included in the phase shifter circuit **21**A. The forward phase of the fundamental wave can be changed by switching between the closed state and the open state of the switch **215**. For example, the switch **215** can be closed or open depending on whether the amplifier circuit according to the present modification transfers band-A or band-B transmit signals. In other words, the phase shifter circuit **21**A is configured such that the forward phase can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*. This configuration highly precisely controls the reflection phase shift of the fundamental wave to match the band being transferred.

[0105] FIG. **5**B is a circuit configuration diagram of the phase shifter circuit **22**A according to the first modification of the embodiment. The phase shifter circuit **22**A is an example of a second phase shifter circuit. The phase shifter circuit **22**A is coupled between terminals **203** and **204**. The phase shifter circuit **22**A is configured such that the forward phase of the fundamental waves in the bands A and B is −90° (a phase delay of 90°) relative to the phase shifter circuit **21**A. The phase shifter circuit **22**A includes an inductor **221**, capacitors **222**, **223**, and **224**, and a switch **225**. The inductor **221** is an example of a second inductor. The inductor **221** is coupled between the terminals **203** and **204**. The capacitor **223** is an example of a second capacitor. The capacitor **223** is coupled between ground and the path connecting the inductor **221** and the terminal **204**. The capacitor **222** is provided in series in the path connecting the inductor **221** and the terminal **204**. The switch **225** (a sixth switch) and the capacitor **224** are coupled in series with each other to form a second variable circuit. The second variable circuit is coupled between the terminal **204** and ground. The phase shifter circuit **22**A is configured as a low pass filter. The phase shifter circuit **22**A is operable to introduce, for example, a phase shift of −45° (a phase delay of 45°) to the forward phase of the fundamental signals in the bands A and B. The capacitor **222** is a DC blocking capacitor and does not contribute to phase shift. The capacitor **222** is not necessarily included in the phase shifter circuit **22**A. The forward phase of the fundamental wave can be changed by switching between the closed state and the open state of the switch **225**. For example, the switch **215** can be closed or open depending on whether the amplifier circuit according to the present modification transfers band-A or band-B transmit signals. In other words, the phase shifter circuit **22**A is configured such that the forward phase can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*. This configuration highly precisely controls the reflection phase shift of the fundamental wave to match the band being transferred.

[0106] FIG. **5**C is a circuit configuration diagram of the harmonic phase shifter circuit **31**A according to the first modification of the embodiment. The harmonic phase shifter circuit **31**A is an example of a first harmonic phase shifter circuit. The harmonic phase shifter circuit **31**A is coupled between the third output port and the terminal **41***c*. The harmonic phase shifter circuit **31**A includes capacitors **311** and **312** and a switch **313**. The capacitor **311** is coupled between ground and the path connecting the third output port and the capacitor **211**. The switch **313** (a seventh switch) and the capacitor **312** are coupled in series with each other to form a third variable circuit. The third variable circuit is coupled between the path described above and ground. The harmonic phase shifter circuit **31**A operates as a low pass filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°. The forward phase of the second harmonic wave can be changed by switching between the closed state and the open state of the switch **313**. For example, the switch **313** can be closed or open depending on whether the amplifier circuit according to the present modification transfers band-A or band-B transmit signals. In other words, the harmonic phase shifter circuit **31**A is configured such that the forward phase can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*. This configuration highly precisely controls the reflection phase shift of the second harmonic wave to match the band being transferred.

[0107] FIG. **5**D is a circuit configuration diagram of the harmonic phase shifter circuit **32**A according to the first modification of the embodiment. The harmonic phase shifter circuit **32**A is an example of a second harmonic phase shifter circuit. The harmonic phase shifter circuit **32**A is coupled between the fourth output port and the terminal **41***d*. The harmonic phase shifter circuit **32**A includes an inductor **321**, capacitors **322** and **323**, and a switch **324**. The inductor **321** and the capacitor **322** form an LC circuit by being coupled in series with each other. The LC circuit is coupled between ground and the path connecting the fourth output port and the inductor **221**. The switch **324** (an eighth switch) and the capacitor **323** are coupled in series with each other to form a fourth variable circuit. The fourth variable circuit is coupled in parallel with the capacitor **322**. The harmonic phase shifter circuit **32**A operates as a notch filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°. The forward phase of the second harmonic wave can be changed by switching between the closed state and the open state of the switch **324**. For example, the switch **324** can be closed or open depending on whether the amplifier circuit according to the present modification transfers band-A or band-B transmit signals. In other words, the harmonic phase shifter circuit **32**A is configured such that the forward phase can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*. This configuration highly precisely controls the reflection phase shift of the second harmonic wave to match the band being transferred.

[0108] In the present modification, the numerical values for forward phase, reflection phase, and reflection phase difference do not necessarily represent exact values but represent substantially the same values involving, for example, about 30% differences.

3 Configuration of Amplifier Circuit **10***b* According to Second Modification

[0109] An amplifier circuit **10**B according to a second modification will be described. FIG. **6** is a circuit configuration diagram of the amplifier circuit **10**B according to the second modification of the embodiment. As illustrated in the drawing, the amplifier circuit **10**B includes power amplifiers **11** and **12**, phase shifter circuits **21** and **22**, harmonic phase shifter circuits **31**B and **32**B, the switching circuit **41**, a 90° hybrid **50**, phase shift lines **51** and **52**, a capacitor **53**, and a radio-

frequency input terminal **110**. The amplifier circuit **10**B according to the present modification differs from the amplifier circuit **10** according to the embodiment in the circuit configuration of the harmonic phase shifter circuit. The following describes the amplifier circuit **10**B according to the present modification, focusing on the harmonic phase shifter circuits **31**B and **32**B, which are different configurational features from the amplifier circuit **10** according to the embodiment, and descriptions of the same configurational features as the amplifier circuit **10** according to the embodiment will not be repeated.
[0110] The harmonic phase shifter circuit **31**B is an example of a first harmonic phase shifter circuit. The harmonic phase shifter circuit **31**B is coupled between the third output port of the power amplifier **11** and the terminal **41***c* of the switching circuit **41**. In the present modification, one end of the harmonic phase shifter circuit **31**B is coupled between the third output port of the power amplifier **11** and the connection point of the phase shift line **51** and the phase shifter circuit **21**. The harmonic phase shifter circuit **31**B is coupled near the third output port to suppress parasitic inductance and parasitic capacitance, because the reflection phase of the third harmonic wave at the third output port, which is in a higher frequency band, needs to be controlled with high precision. The harmonic phase shifter circuit **31**B includes, for example, a third capacitor coupled between ground and the path connecting the third output port and the capacitor **211**. The harmonic phase shifter circuit **31**B operates as a low pass filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°.
[0111] The harmonic phase shifter circuit **32**B is an example of a second harmonic phase shifter circuit. The harmonic phase shifter circuit **32**B is coupled between the fourth output port of the power amplifier **12** and the terminal **41***d* of the switching circuit **41**. In the present modification, one end of the harmonic phase shifter circuit **32**B is coupled between the fourth output port of the power amplifier **12** and the connection point of the phase shift line **52** and the phase shifter circuit **22**. The harmonic phase shifter circuit **32**B is coupled near the fourth output port to suppress parasitic inductance and parasitic capacitance, because the reflection phase of the third harmonic wave at the fourth output port, which is in a higher frequency band, needs to be controlled with high precision. The harmonic phase shifter circuit **32**B includes, for example, a third inductor and a fourth capacitor. The third inductor and the fourth capacitor form an LC circuit by being coupled in series with each other. The LC circuit is coupled between ground and the path connecting the fourth output port and the second inductor. The harmonic phase shifter circuit **32**B operates as a notch filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°.
[0112] The phase shifter circuit **21** and the harmonic phase shifter circuit **31**B are configured such that the forward phase of the third harmonic waves in the bands A and B in the circuit formed by combining the phase shifter circuit **21** and the harmonic phase shifter circuit **31**B is +45° (a phase advance of 45°). The phase shifter circuit **22** and the harmonic phase shifter circuit **32**B are configured such that the forward phase of the third harmonic waves in the circuit formed by combining the phase shifter circuit **22** and the harmonic phase shifter circuit **32**B is −45° (a phase delay of 45°).
[0113] In the amplifier circuit **10**B configured as described above, the phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31**B and **32**B are configured such that: the difference between the first reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **41***a* is observed from the third output port and the second reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is 180°; and the difference between the third reflection phase of the third harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the third output port and the fourth reflection phase of the third harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is 180°.

[0114] The third reflection phase of the third harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the third output port is defined as the phase shift of the third harmonic wave of the reflected signal reflected at the terminal **41***a* and returned to the third output port, relative to the phase of the third harmonic wave of the transmit signal in the band-A transmit band that is output from the third output port, in the state in which the terminal **41***c* is connected to the terminal **41***a* while the terminal **41***a* is disconnected from the filter **61**. The fourth reflection phase of the third harmonic wave of the band-A transmit band assuming the terminal **41***a* is observed from the fourth output port is defined as the phase shift of the third harmonic wave of the reflected signal reflected at the terminal **41***a* and returned to the fourth output port, relative to the phase of the third harmonic wave of the transmit signal in the band-A transmit band that is output from the fourth output port, in the state in which the terminal **41***d* is connected to the terminal **41***a* while the terminal **41***a* is disconnected from the filter **61**.
[0115] The third reflection phase of the third harmonic wave of the band-A transmit band can be obtained by measuring the reflection phase of the third harmonic wave of the band A at the terminal **41***a* in the state in which the terminal **41***c* is connected to the terminal **41***a*, the terminal **41***d* is disconnected from the terminal **41***a*, and the terminal **41***a* is disconnected from the filter **61**. The third reflection phase of the third harmonic wave of the band-B transmit band can be obtained by measuring the reflection phase of the third harmonic wave of the band B at the terminal **41***b* in the state in which the terminal **41***c* is connected to the terminal **41***b*, the terminal **41***d* is disconnected from the terminal **41***b*, and the terminal **41***b* is disconnected from the filter **62**.
[0116] The fourth reflection phase of the third harmonic wave of the band-A transmit band can be obtained by measuring the reflection phase of the third harmonic wave of the band A at the terminal **41***a* in the state in which the terminal **41***d* is connected to the terminal **41***a*, the terminal **41***c* is disconnected from the terminal **41***a*, and the terminal **41***a* is disconnected from the filter **61**. The fourth reflection phase of the third harmonic wave of the band-B transmit band can be obtained by measuring the reflection phase of the third harmonic wave of the band B at the terminal **41***b* in the state in which the terminal **41***d* is connected to the terminal **41***b*, the terminal **41***c* is disconnected from the terminal **41***b*, and the terminal **41***b* is disconnected from the filter **62**.
[0117] FIG. **7**A illustrates the fundamental impedances of the power amplifiers **11** and **12** according to the second modification of the embodiment. FIG. **7**B illustrates the third harmonic impedances of the power amplifiers **11** and **12** according to the second modification of the embodiment. FIG. **7**A illustrates the impedance of the band-A fundamental wave (frequencies f.sub.L1 to f.sub.H1) at the third output port of the power amplifier **11** (PA**11**) and the impedance of the band-A fundamental wave at the fourth output port of the power amplifier **12** (PA**12**) in polar coordinates. FIG. **7**B illustrates the impedance of the band-A third harmonic wave (frequencies f.sub.L3 to f.sub.H3) at the third output port of the power amplifier **11** (PA**11**) and the impedance of the band-A third harmonic wave at the fourth output port of the power amplifier **12** (PA**12**) in polar coordinates.
[0118] As illustrated in FIG. **7**A, the difference between the first reflection phase of the fundamental wave and the second reflection phase of the fundamental wave is 180°. As a result, a consistent phase difference of 180° is maintained between the fundamental impedance of the power amplifier **11** and the fundamental impedance of the power amplifier **12** across the band-A fundamental frequency range (frequencies f.sub.L1 to f.sub.H1). Thus, the radio-frequency circuit according to the present modification cancels out load variations in the band-A fundamental frequency range and achieves stable transmission output characteristics across the fundamental frequency range.
[0119] As illustrated in FIG. **7**B, the difference between the third reflection phase of the third harmonic wave and the fourth reflection phase of the third harmonic wave is 180°. As a result, a consistent phase difference of 180° is maintained between the third harmonic impedance of the power amplifier **11** and the third harmonic impedance of the power amplifier **12** across the band-A

third harmonic frequency range (frequencies f.sub.L3 to f.sub.H3). Thus, the radio-frequency circuit according to the present modification cancels out load variations in the band-A third harmonic frequency range and achieves stable transmission output characteristics across the third harmonic frequency range.

[0120] FIG. **8** is a graph illustrating the output characteristics of the third harmonic wave of the amplifier circuit **10**B according to the second modification of the embodiment. As illustrated in the drawing, the third harmonic outputs of the power amplifiers **11** and **12** fluctuate with load variations (phase variations). However, because the difference between the third reflection phase of the third harmonic wave and the fourth reflection phase of the third harmonic wave is 180°, variations in the combined third harmonic output formed by combining the third harmonic waves from the power amplifiers **11** and **12** are suppressed. As a result, the amplifier circuit **10**B achieves stable transmission output characteristics of the third harmonic wave, regardless of the presence of load variations.

[0121] As described above, in the amplifier circuit **10**B and the radio-frequency circuit according to the present modification, assuming unwanted signals at the fundamental and third harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit through the antenna connection terminal **100** from external circuits, the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the third harmonic waves is also 180°. As a result, fluctuations in the transmission characteristics of the fundamental and harmonic frequency ranges of the radio-frequency circuit can be suppressed regardless of load variations. As such, the amplifier circuit **10**B and the radio-frequency circuit are provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and harmonic frequency ranges of transmit signals.

[0122] It may be noted that in the amplifier circuit **10**B according to the present modification, either the harmonic phase shifter circuit **31**B or **32**B may be excluded. It is sufficient for the amplifier circuit according to the present disclosure to have a circuit configuration that achieves a 180° phase difference between the reflection phase of the third harmonic wave of the first signal in the path connecting the third output port of the power amplifier **11** and the terminal **41***a* (combining point) and the reflection phase of the third harmonic wave of the second signal in the path connecting the fourth output port of the power amplifier **12** and the terminal **41***a*.

[0123] In the amplifier circuit **10**B according to the present modification, at least one of the phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31**B and **32**B may include a variable circuit having a variable forward phase. The circuit configurations illustrated in FIGS. **5**A to **5**D are examples of specific circuit configurations that include the above variable circuit. For example, the circuit state of the variable circuit can be changed depending on whether the amplifier circuit **10**B according to the present modification transfers band-A or band-B transmit signals. In other words, at least one of the phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31**B and **32**B may be configured such that the forward phase of the fundamental wave and the third harmonic wave can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*. This configuration highly precisely controls the reflection phase shift of the third harmonic wave to match the band being transferred.

[0124] In the present modification, the numerical values for forward phase, reflection phase, and reflection phase difference do not necessarily represent exact values but represent substantially the same values involving, for example, about 30% differences.

4 Configuration of Amplifier Circuit **10***c* According to Third Modification

[0125] An amplifier circuit **10**C according to a third modification will be described. FIG. **9** is a circuit configuration diagram of the amplifier circuit **10**C and a radio-frequency circuit according to the third modification of the embodiment. As illustrated in the drawing, the amplifier circuit **10**C includes power amplifiers **11** and **12**, phase shifter circuits **21**C and **22**C, harmonic phase shifter circuits **31**C and **32**C, a transformer **45**, a switching circuit **46**, a 90° hybrid **50**, phase shift lines **51** and **52**, a capacitor **53**, and a radio-frequency input terminal **110**. The amplifier circuit **10**C according to the present modification differs from the amplifier circuit **10** according to the embodiment primarily in incorporating the transformer **45**. The following describes the amplifier circuit **10**C according to the present modification with a main focus on configurational features different from the amplifier circuit **10** according to the embodiment, and descriptions of the same configurational features as the amplifier circuit **10** according to the embodiment will not be repeated. The radio-frequency circuit according to the present modification differs from the radio-frequency circuit **1** according to the embodiment in the configuration of the amplifier circuit.

[0126] The phase shifter circuit **21**C is an example of a first phase shifter circuit. The phase shifter circuit **21**C is coupled between the third output port of the power amplifier **11** and a terminal **45***b* of the transformer **45**. The phase shifter circuit **21**C includes, for example, an inductor **221** and capacitors **222** and **223**. The inductor **221** is an example of a first inductor. The inductor **221** is coupled between the fourth output port and the terminal **45***b*. The capacitor **223** is an example of a first capacitor. The capacitor **223** is coupled between ground and the path connecting the inductor **221** and the terminal **45***b*. The capacitor **222** is provided in series in the path connecting the inductor **221** and the terminal **45***b*. The phase shifter circuit **21**C is configured as a low pass filter. The phase shifter circuit **21**C is operable to introduce, for example, a phase shift of −45° (a phase delay of 45°) to the forward phase of the fundamental signals in the bands A and B. The capacitor **222** is a DC blocking capacitor and does not contribute to phase shift. The capacitor **222** is not necessarily included in the phase shifter circuit **21**C.

[0127] The phase shifter circuit **22**C is an example of a second phase shifter circuit. The phase shifter circuit **22**C is coupled between the fourth output port of the power amplifier **12** and a terminal **45***c* of the transformer **45**. The phase shifter circuit **22**C is configured such that the forward phase of the fundamental waves in the bands A and B is +90° (a phase advance of 90°) relative to the phase shifter circuit **21**C. The phase shifter circuit **22**C includes, for example, capacitors **211** and **212** and an inductor **213**. The capacitor **211** is an example of a second capacitor. The capacitor **211** is coupled between the third output port and the terminal **45***c*. The inductor **213** is an example of a second inductor. The inductor **213** is coupled between ground and the path connecting the capacitor **211** and the terminal **45***c*. The capacitor **212** is provided in series in the path connecting the capacitor **211** and the terminal **45***c*. The phase shifter circuit **22**C is configured as a high pass filter. The phase shifter circuit **22**C is operable to introduce, for example, a phase shift of +450 (a phase advance of 45°) to the forward phase of the fundamental waves in the bands A and B. The capacitor **212** is a DC blocking capacitor and does not contribute to phase shift. The capacitor **212** is not necessarily included in the phase shifter circuit **22**C.

[0128] The harmonic phase shifter circuit **31**C is an example of a first harmonic phase shifter circuit. The harmonic phase shifter circuit **31**C is coupled between the third output port of the power amplifier **11** and the terminal **45***b* of the transformer **45**. The harmonic phase shifter circuit **31**C includes, for example, an inductor **321** and a capacitor **322**. The inductor **321** (a third inductor) and the capacitor **322** (a third capacitor) form an LC circuit by being coupled in series with each other. The LC circuit is coupled between ground and the path connecting the third output port and the inductor **221**. The harmonic phase shifter circuit **31**C operates as a notch filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°.

[0129] The harmonic phase shifter circuit **32**C is an example of a second harmonic phase shifter circuit. The harmonic phase shifter circuit **32**C is coupled between the fourth output port of the power amplifier **12** and the terminal **45***c* of the transformer **45**. The harmonic phase shifter circuit **32**C includes, for example, a capacitor **311** (a fourth capacitor) coupled between ground and the path connecting the fourth output port and the capacitor **211**. The harmonic phase shifter circuit

32C operates as a low pass filter with a pass band that corresponds to the fundamental frequency ranges of the bands A and B. The forward phase of the fundamental waves is, for example, 0°.
[0130] The phase shifter circuit **21**C and the harmonic phase shifter circuit **31**C are configured such that the forward phase of the second harmonic waves in the bands A and B in the circuit formed by combining the phase shifter circuit **21**C and the harmonic phase shifter circuit **31**C is −45° (a phase delay of 45°). The phase shifter circuit **22**C and the harmonic phase shifter circuit **32**C are configured such that the forward phase of the second harmonic waves in the circuit formed by combining the phase shifter circuit **22**C and the harmonic phase shifter circuit **32**C is +45° (a phase advance of 45°).
[0131] The transformer **45** is an example of a combiner circuit. The transformer **45** includes a primary coil, a secondary coil, a terminal **45***a* (a fifth output port), which is one end of the primary coil, the terminal **45***b* (a fourth input port), which is the other end of the primary coil, and the terminal **45***c* (a fifth input port), which is one end of the secondary coil. The transformer **45** is operable to combine in antiphase the third split signal input from the terminal **45***b* and the fourth split signal input from the terminal **45***c* and output the generated output signal from the terminal **45***a*. The transformer **45** serves as the signal combining point for combining in antiphase the band-A third split signal and the band-A fourth split signal and combining in antiphase the band-B third split signal and the band-B fourth split signal.
[0132] The switching circuit **46** operates as a band alteration switch. The switching circuit **46** has terminals **46***a*, **46***b*, and **46***c*. The switching circuit **46** is operable to alternate between connecting the terminals **46***a* and **46***b* and connecting the terminals **46***a* and **46***c*.
[0133] With the configuration described above, a band-A transmit signal is split by the 90° hybrid **50** into the first split signal RF**1** and the second split signal RF**2**. The first split signal RF**1** and the second split signal RF**2** are respectively input to the power amplifiers **11** and **12** and amplified into a first signal and a second signal. At the third output port of the power amplifier **11**, the phase of the fundamental wave of the first signal is 0°. At the fourth output port of the power amplifier **12**, the phase of the fundamental wave of the second signal is 90°.
[0134] After the first signal passes through the harmonic phase shifter circuit **31**C (with a fundamental-wave forward phase of 0°) and the phase shifter circuit **21**C (with a fundamental-wave forward phase of −45°), the phase of the fundamental wave of the first signal is −45° at the terminal **45***b*. After the second signal passes through the harmonic phase shifter circuit **32**C (with a fundamental-wave forward phase of 0°) and the phase shifter circuit **22**C (with a fundamental-wave forward phase of +45°), the phase of the fundamental wave of the second signal is +1350 at the terminal **45***c*. As a result, the band-A first signal and the band-A second signal can be combined in antiphase at the transformer **45**. This configuration enables highly efficient power combining of the fundamental wave with respect to load variations.
[0135] The difference between the first reflection phase (−45°×2=−90°) of the fundamental wave of the first signal assuming the terminal **45***b* is observed from the third output port and the second reflection phase (45°×2=+90°) of the fundamental wave of the second signal assuming the terminal **45***c* is observed from the fourth output port is 1800.
[0136] The forward phase of the second harmonic wave of the first signal in the circuit formed by combining the harmonic phase shifter circuit **31**C and the phase shifter circuit **21**C is −45°. The forward phase of the second harmonic wave of the second signal in the circuit formed by combining the harmonic phase shifter circuit **32**C and the phase shifter circuit **22**C is +45°. In other words, the difference between the third reflection phase (−45°×2=−90°) of the second harmonic wave of the first signal assuming the terminal **45***b* is observed from the third output port and the fourth reflection phase (45°×2=+90°) of the second harmonic wave of the second signal assuming the terminal **45***c* is observed from the fourth output port is 1800.
[0137] In the amplifier circuit **10**C configured as described above, the phase shifter circuits **21**C and **22**C and the harmonic phase shifter circuits **31**C and **32**C are configured such that: the

difference between the first reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **45***b* is observed from the third output port and the second reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **45***c* is observed from the fourth output port is 180°; and the difference between the third reflection phase of the second harmonic wave of the band-A transmit band assuming the terminal **45***b* is observed from the third output port and the fourth reflection phase of the second harmonic wave of the band-A transmit band assuming the terminal **45***c* is observed from the fourth output port is 180°.
[0138] With the configuration described above, assuming unwanted signals at the fundamental and second harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit through the antenna connection terminal **100** from external circuits, the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the second harmonic waves is also 180°. As a result, fluctuations in the transmission characteristics of the fundamental and harmonic frequency ranges of the radio-frequency circuit can be suppressed regardless of load variations. As such, the amplifier circuit **10**C and the radio-frequency circuit are provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and harmonic frequency ranges of transmit signals.
[0139] It may be noted that in the amplifier circuit **10**C according to the present modification, either the harmonic phase shifter circuit **31**C or **32**C may be excluded. It is sufficient for the amplifier circuit according to the present disclosure to have a circuit configuration that achieves a 180° phase difference between the reflection phase of the second harmonic wave of the first signal in the path connecting the third output port of the power amplifier **11** and the terminal **45***b* and the reflection phase of the second harmonic wave of the second signal in the path connecting the fourth output port of the power amplifier **12** and the terminal **45***c*.
[0140] In the amplifier circuit **10**C according to the present modification, the phase shifter circuits **21**C and **22**C and the harmonic phase shifter circuits **31**C and **32**C may be configured such that: the difference between the first reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **45***b* is observed from the third output port and the second reflection phase of the fundamental wave of the band-A transmit band assuming the terminal **45***c* is observed from the fourth output port is 180°; and the difference between the third reflection phase of the third harmonic wave of the band-A transmit band assuming the terminal **45***b* is observed from the third output port and the fourth reflection phase of the third harmonic wave of the band-A transmit band assuming the terminal **45***c* is observed from the fourth output port is 180°.
[0141] With the configuration described above, assuming unwanted signals at the fundamental and third harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit through the antenna connection terminal **100** from external circuits, the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the third harmonic waves is also 180°. As a result, fluctuations in the transmission characteristics of the fundamental and harmonic frequency ranges of the radio-frequency circuit can be suppressed regardless of load variations.
[0142] In the present modification, the numerical values for forward phase, reflection phase, and reflection phase difference do not necessarily represent exact values but represent substantially the same values involving, for example, about 30% differences.

5 Configuration of Amplifier Circuit, Radio-Frequency Circuit, and Communication Device According to Fourth Modification

[0143] Amplifier circuits **10**Da and **10**Db, a radio-frequency circuit **1**D, and a communication device **4**D according to a fourth modification will be described. FIG. **10** is a circuit configuration diagram of the amplifier circuits **10**Da and **10**Db, the radio-frequency circuit **1**D, and the communication device **4**D according to the fourth modification of the embodiment. As illustrated in the drawing, the communication device **4**D according to the present modification includes the

radio-frequency circuit **1**D, antennas **2***a* and **2***b*, and an RFIC **3**.
[0144] The antenna **2***a* is coupled to an antenna connection terminal **100***a* (a first antenna terminal) of the radio-frequency circuit **1**D. The antenna **2***a* is operable to transmit radio-frequency signals outputted from the radio-frequency circuit **1**D and to receive radio-frequency signals from outside and output the radio-frequency signals to the radio-frequency circuit **1**D.
[0145] The antenna **2***b* is coupled to an antenna connection terminal **100***b* (a second antenna terminal) of the radio-frequency circuit **1**D. The antenna **2***b* is operable to transmit radio-frequency signals outputted from the radio-frequency circuit **1**D and to receive radio-frequency signals from outside and output the radio-frequency signals to the radio-frequency circuit **1**D.
[0146] The radio-frequency circuit **1**D includes amplifier circuits **10**Da and **10**Db, filters **61***a*, **61***b*, **62***a*, and **62***b*, a switching circuit **43**, and the antenna connection terminals **100***a* and **100***b*. The radio-frequency circuit **1**D according to the present modification differs from the radio-frequency circuit **1** according to the embodiment primarily in additionally incorporating a receive circuit and incorporating two amplifier circuits. The following describes the radio-frequency circuit **1**D according to the present modification with a main focus on configurational features different from the radio-frequency circuit **1** according to the embodiment, and descriptions of the same configurational features as the radio-frequency circuit **1** according to the embodiment will not be repeated.
[0147] The amplifier circuit **10**Da includes power amplifiers **11***a* and **12***a*, phase shifter circuits **21**Da and **22**Da, harmonic phase shifter circuits **31**Da and **32**Da, a switching circuit **44***a*, a 90° hybrid **50***a*, and a radio-frequency input terminal **110***a*. The amplifier circuit **10**Da has the same circuit configuration as the amplifier circuit **10** according to the embodiment. The phase shifter circuits **21**Da and **22**Da and the harmonic phase shifter circuits **31**Da and **32**Da are configured such that: the difference between the first reflection phase of the fundamental wave of the band-A transmit band assuming the switching circuit **44***a* is observed from the output port of the power amplifier **11***a* and the second reflection phase of the fundamental wave of the band-A transmit band assuming the switching circuit **44***a* is observed from the output port of the power amplifier **12***a* is 180°; and the difference between the third reflection phase of the second harmonic wave of the band-A transmit band assuming the switching circuit **44***a* is observed from the output port of the power amplifier **11***a* and the fourth reflection phase of the second harmonic wave of the band-A transmit band assuming the switching circuit **44***a* is observed from the output port of the power amplifier **12***a* is 180°.
[0148] The amplifier circuit **10**Db includes power amplifiers **11***b* and **12***b*, phase shifter circuits **21**Db and **22**Db, harmonic phase shifter circuits **31**Db and **32**Db, a switching circuit **44***b*, a 90° hybrid **50***b*, and a radio-frequency input terminal **110***b*. The power amplifiers **11***b* and **12***b* are an example of a third power amplifier. The amplifier circuit **10**Db has the same circuit configuration as the amplifier circuit **10** according to the embodiment. The phase shifter circuits **21**Db and **22**Db and the harmonic phase shifter circuits **31**Db and **32**Db are configured such that: the difference between the first reflection phase of the fundamental wave of the band-A transmit band assuming the switching circuit **44***b* is observed from the output port of the power amplifier **11***b* and the second reflection phase of the fundamental wave of the band-A transmit band assuming the switching circuit **44***b* is observed from the output port of the power amplifier **12***b* is 180°; and the difference between the third reflection phase of the second harmonic wave of the band-A transmit band assuming the switching circuit **44***b* is observed from the output port of the power amplifier **11***b* and the fourth reflection phase of the second harmonic wave of the band-A transmit band assuming the switching circuit **44***b* is observed from the output port of the power amplifier **12***b* is 180°.
[0149] The filter **61***a* is an example of a first filter. The filter **61***a* is coupled between the switching circuit **44***a* and the antenna connection terminal **100***a*. The filter **61***a* has a pass band that includes the band A. Specifically, one end of the filter **61***a* is coupled to the switching circuit **44***a*, and the

other end of the filter **61***a* is coupleable to the antenna connection terminal **100***a* via the switching circuit **43**. As illustrated in FIG. **10**, receive filters having pass bands that include the band A and low-noise amplifiers may be coupled to the node in the path connecting the filter **61***a* and the switching circuit **43**.

[0150] The filter **62***a* is an example of a second filter. The filter **62***a* is coupled between the switching circuit **44***a* and the antenna connection terminal **100***a*. The filter **62***a* has a pass band that includes the band B. Specifically, one end of the filter **62***a* is coupled to the switching circuit **44***a*, and the other end of the filter **62***a* is coupleable to the antenna connection terminal **100***a* via the switching circuit **43**. As illustrated in FIG. **10**, receive filters having pass bands that include the band B and low-noise amplifiers may be coupled to the node in the path connecting the filter **62***a* and the switching circuit **43**.

[0151] The filter **61***b* is an example of a third filter. The filter **61***b* is coupled between the switching circuit **44***b* and the antenna connection terminal **100***b*. The filter **61***b* has a pass band that includes the band A. Specifically, one end of the filter **61***b* is coupled to the switching circuit **44***b*, and the other end of the filter **61***b* is coupleable to the antenna connection terminal **100***b* via the switching circuit **43**. As illustrated in FIG. **10**, receive filters having pass bands that include the band A and low-noise amplifiers may be coupled to the node in the path connecting the filter **61***b* and the switching circuit **43**.

[0152] The filter **62***b* is an example of a second filter. The filter **62***b* is coupled between the switching circuit **44***b* and the antenna connection terminal **100***b*. The filter **62***b* has a pass band that includes the band B. Specifically, one end of the filter **62***b* is coupled to the switching circuit **44***b*, and the other end of the filter **62***b* is coupleable to the antenna connection terminal **100***b* via the switching circuit **43**. As illustrated in FIG. **10**, receive filters having pass bands that include the band B and low-noise amplifiers may be coupled to the node in the path connecting the filter **62***b* and the switching circuit **43**.

[0153] The switching circuit **43** is an example of an antenna switch. The switching circuit **43** has terminals **43***a*, **43***b*, **43***c*, **43***d*, **43***e*, **43***f*, **43***g*, and **43***h*. The terminal **43***a* is coupled to the antenna connection terminal **100***a*. The terminal **43***b* is coupled to the antenna connection terminal **100***b*. The terminal **43***c* is coupled to the filter **61***a*. The terminal **43***d* is coupled to the filter **62***a*. The terminal **43***f* is coupled to the filter **61***b*. The terminal **43***g* is coupled to the filter **62***b*. With the configuration described above, the switching circuit **43** is operable to alternate the connection and disconnection between the antenna connection terminal **100***a* and the filter **61***a*, the connection and disconnection between the antenna connection terminal **100***a* and the filter **62***a*, the connection and disconnection between the antenna connection terminal **100***b* and the filter **61***b*, and the connection and disconnection between the antenna connection terminal **100***b* and the filter **62***b*. The switching circuit **43** is able to couple the antenna connection terminal **100***a* to the filter **61***a* while also coupling the antenna connection terminal **100***b* to the filter **61***b*. The switching circuit **43** is able to couple the antenna connection terminal **100***a* to the filter **62***a* while also coupling the antenna connection terminal **100***b* to the filter **62***b*. This means that the communication device **4**D is able to output from the antenna **2***a* band-A transmit signals output from the amplifier circuit **10**Da, while outputting from the antenna **2***b* band-A transmit signals output from the amplifier circuit **10**Db. The communication device **4**D is able to output from the antenna **2***a* band-B transmit signals output from the amplifier circuit **10**Da, while outputting from the antenna **2***b* band-B transmit signals output from the amplifier circuit **10**Db.

[0154] With this configuration, band-A transmit signals output from the amplifier circuit **10**Db may leak into the amplifier circuit **10**Da through the antenna connection terminal **100***b* (the antenna **2***b*) and the antenna connection terminal **100***a* (the antenna **2***a*). Also in this case, the reflection phase difference of the band-A fundamental and harmonic waves assuming observed from the output ports of the balanced power amplifiers **11***a* and **11***b* is 180°. Thus, load variations in the fundamental and harmonic frequency ranges can be suppressed. As such, the radio-frequency circuit **1**D is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and harmonic frequency ranges of transmit signals.

[0155] In the present modification, the numerical values for forward phase, reflection phase, and reflection phase difference do not necessarily represent exact values but represent substantially the same values involving, for example, about 30% differences.

6 Component Layout of Amplifier Circuit **10**

[0156] Next, a component layout of the amplifier circuit **10** according to the embodiment will be described. FIG. **11** provides plan views of the amplifier circuit **10** according to the embodiment. In FIG. **11**, (a) illustrates a layout of circuit components assuming a major surface **90***a* of a mounting substrate **90** is viewed from the front side in the positive direction of the z-axis. In FIG. **11**, (b) is a cutaway view of the layout of circuit components assuming a major surface **90***b* of the mounting substrate **90** is viewed from the front side in the positive direction of the z-axis. In FIG. **11**, some wires connecting the mounting substrate **90** and the circuit components are not illustrated.

[0157] The amplifier circuit **10** illustrated in FIG. **11** includes the mounting substrate **90** for the amplifier circuit **10** illustrated in FIG. **1**.

[0158] The mounting substrate **90** has the major surfaces **90***a* and **90***b* that are opposite to each other. The circuit components constituting the amplifier circuit **10** are mounted at the mounting substrate **90**. For example, a low temperature co-fired ceramics (LTCC) substrate having a layered structure of a plurality of dielectric layers, a high temperature co-fired ceramics (HTCC) substrate, a component-embedded substrate, a substrate including a redistribution layer (RDL), or a printed-circuit board is used as the mounting substrate **90**.

[0159] As illustrated in FIG. **11**, the 90° hybrid **50**, the power amplifiers **11** and **12**, the inductors **213**, **221** and **321**, and the capacitors **211**, **212**, **222**, **223**, **311**, **322**, and **53** are disposed at the major surface **90***a*. The switching circuit **41** is disposed at the major surface **90***b*.

[0160] In this arrangement, the circuit components are disposed separately at the major surface **90***a* or **90***b* of the mounting substrate **90**. This arrangement thus reduces the size of the amplifier circuit **10**.

[0161] The 90° hybrid **50** and the power amplifiers **11** and **12** are included in a semiconductor integrated circuit (IC) **71**. The switching circuit **41** is included in a semiconductor IC **72**.

[0162] In this arrangement, the 90° hybrid **50** and the power amplifiers **11** and **12** are formed as a single chip, and the switching circuit **41** is formed as a single chip. This arrangement thus reduces the size of the amplifier circuit **10**.

[0163] The semiconductor ICs **71** and **72** are made using, for example, complementary metal oxide semiconductor (CMOS). Specifically, the semiconductor ICs **71** and **72** may be manufactured using a silicon on insulator (SOI) process. The semiconductor ICs **71** and **72** may be made from at least one of GaAs, SiGe, and GaN. The semiconductor material of the semiconductor ICs **71** and **72** is not limited to the materials presented above.

[0164] The switching circuit **41** includes the terminals **41***a*, **41***b*, **41***c*, **41***d*, and **41***e* and switches **411**, **412**, **413**, **414**, **415**, and **416**.

[0165] The switch **411** is an example of a first switch. The switch **411** is coupled between the terminals **41***c* and **41***a*. The switch **413** is an example of a second switch. The switch **413** is coupled between the terminals **41***c* and **41***b*. The switch **412** is an example of a third switch. The switch **412** is coupled between the terminals **41***d* and **41***a*. The switch **414** is an example of a fourth switch. The switch **414** is coupled between the terminals **41***d* and **41***b*. The switch **415** is coupled between the terminals **41***e* and **41***c*. The switch **416** is coupled between the terminals **41***e* and **41***d*.

[0166] Assuming the major surface of the semiconductor IC **72** is viewed in plan view, the switches **411** and **412** are positioned between the terminals **41***c* and **41***d*, and the terminal **41***a* is positioned between the switches **411** and **412**. The switches **413** and **414** are positioned between the terminals **41***c* and **41***d*, and the terminal **41***b* is positioned between the switches **413** and **414**.

[0167] In this configuration, the line length from the terminal **41***c* to the terminal **41***a* and the line length from the terminal **41***d* to the terminal **41***a*, which carry band-A signals, are equal; the line length from the terminal **41***c* to the terminal **41***b* and the line length from the terminal **41***d* to the terminal **41***b*, which carry band-B signals, are also equal. This configuration helps highly precisely set the difference between the reflection phase from the third output port of the power amplifier **11** to the terminal **41***a* and the reflection phase from the fourth output port of the power amplifier **12** to the terminal **41***a*. This configuration also helps highly precisely set the difference between the reflection phase from the third output port of the power amplifier **11** to the terminal **41***b* and the reflection phase from the fourth output port of the power amplifier **12** to the terminal **41***b*.

[0168] The amplifier circuit according to the first modification has the same component layout illustrated in FIG. **11**, except that the first variable circuit of the phase shifter circuit **21**A is included in the semiconductor IC **72** and coupled to the terminal **41***c*, while the second variable circuit of the phase shifter circuit **22**A is included in the semiconductor IC **72** and coupled to the terminal **41***d*.

[0169] In this configuration, the variable circuits of the phase shifter circuits **21**A and **22**A can be included in the semiconductor IC **72** having the switching circuit **41**. This configuration reduces the size of the amplifier circuit and the radio-frequency circuit.

[0170] Additionally, the third variable circuit of the harmonic phase shifter circuit **31**A is included in the semiconductor IC **72**. The fourth variable circuit of the harmonic phase shifter circuit **32**A is included in the semiconductor IC **72**.

[0171] In this configuration, the variable circuits of the harmonic phase shifter circuit **31**A and **32**A can be included in the semiconductor IC **72** having the switching circuit **41**. This configuration reduces the size of the amplifier circuit and the radio-frequency circuit.

7 Effects

[0172] As described above, the radio-frequency circuit **1** according to the present embodiment includes the antenna connection terminal **100**, the 90° hybrid **50** configured to split a fundamental signal of the transmit band of the band A that are input to the first input port, output the first split signal from the first output port, and output the second split signal, which has a phase of +90° relative to the first split signal, from the second output port, the power amplifier **11** having the second input port and the third output port, the second input port being coupled to the first output port, the power amplifier **12** having the third input port and the fourth output port, the third input port being coupled to the second output port, the combiner circuit having the fourth input port, the fifth input port, and the fifth output port, configured to combine in phase the third split signal input from the fourth input port and the fourth split signal input from the fifth input port to generate an output signal and configured to output the output signal from the fifth output port, the phase shifter circuit **21** coupled between the third output port and the fourth input port, the phase shifter circuit **22** coupled between the fourth output port and the fifth input port, the harmonic phase shifter circuit **31** coupled between the third output port and the fourth input port and/or the harmonic phase shifter circuit **32** coupled between the fourth output port and the fifth input port, and the filter **61** coupled between the fifth output port and the antenna connection terminal **100**, having a pass band that includes the transmit band. The phase shifter circuits **21** and **22** are configured such that the forward phase of the fundamental wave of the transmit band in the phase shifter circuit **22** in the direction from the fourth output port to the fifth input port is −90° relative to the forward phase of the fundamental wave in the phase shifter circuit **21** in the direction from the third output port to the fourth input port. The phase shifter circuits **21** and **22** and the harmonic phase shifter circuits **31** and **32** are configured such that: the difference between the first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and the second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°; and the difference between the third reflection phase of at least one of the harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and the fourth reflection phase of the at least one of the harmonic waves of the transmit band assuming the fifth output port is observed from the fourth output port is 180°.

[0173] With the configuration described above, assuming unwanted signals at the fundamental and second harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit **1** through the antenna connection terminal **100** from external circuits, the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the second harmonic waves is also 180°. As a result, fluctuations in the transmission characteristics of the fundamental and harmonic frequency ranges of the radio-frequency circuit **1** can be suppressed regardless of load variations. As such, the amplifier circuit **10** and the radio-frequency circuit **1** are provided in the manner that mitigates fluctuations in transmission characteristics caused by load variations.

[0174] In an example, in the radio-frequency circuit **1**, the harmonic wave corresponds to the second harmonic wave having a frequency twice the fundamental wave.

[0175] With this configuration, the radio-frequency circuit **1** is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and second harmonic frequency ranges of transmit signals.

[0176] In an example, in the radio-frequency circuit according to the second modification, the harmonic wave corresponds to the third harmonic wave having a frequency three times the fundamental wave.

[0177] With this configuration, the radio-frequency circuit is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and third harmonic frequency ranges of transmit signals.

[0178] In an example, in the radio-frequency circuit **1**, the phase shifter circuit **21** is configured such that the forward phase of the fundamental wave is +45°. The phase shifter circuit **22** is configured such that the forward phase of the fundamental wave is −45°. The phase shifter circuit **21** and the harmonic phase shifter circuit **31** are configured such that the forward phase of the harmonic wave in the circuit formed by combining the phase shifter circuit **21** and the harmonic phase shifter circuit **31** is +45°. The phase shifter circuit **22** and the harmonic phase shifter circuit **32** are configured such that the forward phase of the harmonic wave in the circuit formed by combining the phase shifter circuit **22** and the harmonic phase shifter circuit **32** is −45°.

[0179] With this configuration, the first signal and the second signal, which are two band-A radio-frequency signals, can be combined in phase at the fifth output port. This configuration enables highly efficient power combining of the fundamental wave with respect to load variations. This configuration achieves a 180° difference between the first reflection phase (+45°×2=90°) of the fundamental wave of the first signal assuming the fifth output port is observed from the third output port and the second reflection phase (−45°×2=−90°) of the fundamental wave of the second signal assuming the fifth output port is observed from the fourth output port. This configuration achieves a 180° difference between the third reflection phase (+45°×2=90°) of the second harmonic wave of the first signal assuming the fifth output port is observed from the third output port and the fourth reflection phase (−45°×2=−90°) of the second harmonic wave of the second signal assuming the fifth output port is observed from the fourth output port.

[0180] In an example, in the radio-frequency circuit **1**, the phase shifter circuit **21** includes the capacitor **211** coupled between the third output port and the fourth input port, and the inductor **213** coupled between ground and the path connecting the capacitor **211** and the fourth input port. The phase shifter circuit **22** includes the inductor **221** coupled between the fourth output port and the fifth input port, and the capacitor **223** coupled between ground and the path connecting the inductor **221** and the fifth input port.

[0181] With this configuration, the phase shifter circuit **21** is configured as a high pass filter. This configuration achieves a +45° forward phase of the fundamental wave of the band A. The phase shifter circuit **22** is configured as a low pass filter. This configuration achieves a −45° forward phase of the fundamental wave of the band A.

[0182] In an example, in the radio-frequency circuit **1**, the harmonic phase shifter circuit **31** includes the capacitor **311** coupled between ground and the path connecting the third output port and the capacitor **211**. The harmonic phase shifter circuit **32** includes an LC circuit including the inductor **321** and the capacitor **322** that are coupled in series with each other. The LC circuit is coupled between ground and the path connecting the fourth output port and the inductor **221**.
[0183] With this configuration, the harmonic phase shifter circuit **31** operates as a low pass filter with a pass band that corresponds to the fundamental frequency range of the band A. This configuration achieves a 0° forward phase of the fundamental wave of the band A. The harmonic phase shifter circuit **32** operates as a notch filter with a pass band that corresponds to the fundamental frequency range. This configuration achieves a 0° forward phase of the fundamental wave.
[0184] In an example, the radio-frequency circuit **1** further includes the filter **62** having a pass band that includes the band-B transmit band. The combiner circuit includes the switching circuit **41** having the terminal **41***c* (the fourth input port), the terminal **41***d* (the fifth input port), the terminal **41***a* (the fifth output port), and the terminal **41***b* (the sixth output port), configured to alternate between connecting the terminals **41***c* and **41***a* as well as connecting the terminals **41***d* and **41***a* and connecting the terminals **41***c* and **41***b* as well as connecting the terminals **41***d* and **41***b*. The filter **62** is coupled to the terminal **41***b*.
[0185] With this configuration, the radio-frequency circuit **1** is provided in the manner that supports multiple bands and enables outputting band-A transmit signals and band-B transmit signals. Furthermore, the terminals **41***a* and **41***b* of the switching circuit **41** serve as signal combining points, and the switching circuit also serves as a combiner circuit. This configuration reduces the size of the radio-frequency circuit **1**.
[0186] In an example, in the radio-frequency circuit **1**, the switching circuit **41** is included in the semiconductor IC **72**. The switching circuit **41** includes the switch **411** coupled to the terminals **41***c* and **41***a*, the switch **413** coupled to the terminals **41***c* and **41***b*, the switch **412** coupled to the terminals **41***d* and **41***a*, and the switch **414** coupled to the terminals **41***d* and **41***b*. Assuming the major surface of the semiconductor IC **72** is viewed in plan view, the switches **411** and **412** are positioned between the terminals **41***c* and **41***d*, the terminal **41***a* is positioned between the switches **411** and **412**, the switches **413** and **414** are positioned between the terminals **41***c* and **41***d*, and the terminal **41***b* is positioned between the switches **413** and **414**.
[0187] In this configuration, the line length from the terminal **41***c* to the terminal **41***a* and the line length from the terminal **41***d* to the terminal **41***a*, which carry band-A signals, are equal; the line length from the terminal **41***c* to the terminal **41***b* and the line length from the terminal **41***d* to the terminal **41***b*, which carry band-B signals, are also equal. This configuration helps highly precisely set the difference between the reflection phase from the third output port of the power amplifier **11** to the terminal **41***a* and the reflection phase from the fourth output port of the power amplifier **12** to the terminal **41***a*. This configuration also helps highly precisely set the difference between the reflection phase from the third output port of the power amplifier **11** to the terminal **41***b* and the reflection phase from the fourth output port of the power amplifier **12** to the terminal **41***b*.
[0188] In an example, in the radio-frequency circuit **1**, the switching circuit **41** further includes the terminal **41***e*. The terminal **41***e* is coupleable to the terminal **41***c* in the state in which the terminal **41***c* is disconnected from the terminals **41***a* and **41***b* or coupleable to the terminal **41***d* in the state in which the terminal **41***d* is disconnected from the terminals **41***a* and **41***b*.
[0189] With this configuration, the reflection phase of the fundamental and second harmonic waves of the band A or B can be measured at the terminal **41***e*.
[0190] In an example, in the radio-frequency circuit according to the second modification, at least one of the phase shifter circuits **21**A and **22**A is configured such that the forward phase can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*.

[0191] This configuration highly precisely controls the reflection phase shift of the fundamental wave to match the band being transferred.
[0192] In an example, in the radio-frequency circuit according to the second modification, the switching circuit **41** is included in the semiconductor IC **72**. The phase shifter circuit **21**A includes the first variable circuit having the switch **215** and at least one of an inductor and a capacitor coupled to the switch **215**. The phase shifter circuit **22**A includes the second variable circuit having the switch **225** and at least one of an inductor and a capacitor coupled to the switch **225**. The first variable circuit is coupled to the terminal **41***c* and included in the semiconductor IC **72**. The second variable circuit is coupled to the terminal **41***d* and included in the semiconductor IC **72**.
[0193] In this configuration, the variable circuits of the phase shifter circuits **21**A and **22**A can be included in the semiconductor IC **72** having the switching circuit **41**. This configuration reduces the size of the amplifier circuit and the radio-frequency circuit.
[0194] In an example, in the radio-frequency circuit according to the second modification, at least one of the harmonic phase shifter circuits **31**A and **32**A is configured such that the forward phase can be changed by alternating between connecting the terminals **41***c* and **41***d* to the terminal **41***a* and connecting the terminals **41***c* and **41***d* to the terminal **41***b*.
[0195] This configuration highly precisely controls the reflection phase shift of the second harmonic wave to match the band being transferred.
[0196] In an example, in the radio-frequency circuit according to the second modification, the switching circuit **41** is included in the semiconductor IC **72**. The harmonic phase shifter circuit **31**A includes the third variable circuit having the switch **313** and at least one of an inductor and a capacitor coupled to the switch **313**. The harmonic phase shifter circuit **32**A includes the fourth variable circuit having the switch **324** and at least one of an inductor and a capacitor coupled to the switch **324**. The third variable circuit and the fourth variable circuit are included in the semiconductor IC **72**.
[0197] In this configuration, the variable circuits of the harmonic phase shifter circuit **31**A and **32**A can be included in the semiconductor IC **72** having the switching circuit **41**. This configuration reduces the size of the amplifier circuit and the radio-frequency circuit.
[0198] In an example, the radio-frequency circuit **1**D according to the fourth modification includes the antenna connection terminals **100***a* and **100***b*, the amplifier circuit **10**Da coupled to the antenna connection terminal **100***a* and including the power amplifiers **11***a* and **12***a*, the amplifier circuit **10**Db coupled to the antenna connection terminal **100***b* and including the power amplifiers **11***b* and **12***b*, the filter **61***a* coupled between the antenna connection terminal **100***a* and the amplifier circuit **10**Da, and the filter **61***b* coupled between the antenna connection terminal **100***b* and the amplifier circuit **10**Db.
[0199] With this configuration, assuming the band A transmit signals output from the amplifier circuit **10**Db leak into the amplifier circuit **10**Da through the antenna connection terminals **100***b* and **100***a*, the reflection phase difference between the band-A fundamental wave and the band-A harmonic wave assuming observed from the output ports of the balanced power amplifiers **11***a* and **11***b* is 180°. This configuration thus suppresses load variations in the fundamental and harmonic frequency ranges. As such, the radio-frequency circuit **1**D is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and harmonic frequency ranges of transmit signals.
[0200] The radio-frequency circuit according to the third modification includes the antenna connection terminal **100**, the 90° hybrid **50** configured to split a fundamental signal of the transmit band of the band A that are input to the first input port, output the first split signal from the first output port, and output the second split signal, which has a phase of +90° relative to the first split signal RF**1**, from the second output port, the power amplifier **11** having the second input port and the third output port, the second input port being coupled to the first output port, the power amplifier **12** having the third input port and the fourth output port, the third input port being

coupled to the second output port, the combiner circuit having the fourth input port, the fifth input port, and the fifth output port, configured to combine in antiphase the third split signal input from the fourth input port and the fourth split signal input from the fifth input port to generate an output signal and configured to output the output signal from the fifth output port, the phase shifter circuit **21**C coupled between the third output port and the fourth input port, the phase shifter circuit **22**C coupled between the fourth output port and the fifth input port, the harmonic phase shifter circuit **31**C coupled between the third output port and the fourth input port and/or the harmonic phase shifter circuit **32**C coupled between the fourth output port and the fifth input port, and the filter **61** coupled between the fifth output port and the antenna connection terminal **100**, having a pass band that includes the transmit band. The phase shifter circuits **21**C and **22**C are configured such that the forward phase of the fundamental wave of the transmit band in the phase shifter circuit **22**C in the direction from the fourth output port to the fifth input port is −90° relative to the forward phase of the fundamental wave in the phase shifter circuit **21**C in the direction from the third output port to the fourth input port. The phase shifter circuits **21**C and **22**C and the harmonic phase shifter circuits **31**C and **32**C are configured such that: the difference between the first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and the second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°; and the difference between the third reflection phase of the harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and the fourth reflection phase of the harmonic waves of the transmit band assuming the fifth output port is observed from the fourth output port is 180°.

[0201] With the configuration described above, assuming unwanted signals at the fundamental and second harmonic frequencies of the band-A transmit band leak into the radio-frequency circuit through the antenna connection terminal **100** from external circuits, the reflection phase difference between the fundamental waves observed from the output ports of the two balanced power amplifiers **11** and **12** is 180°, and the reflection phase difference of the second harmonic waves is also 180°. As a result, fluctuations in the transmission characteristics of the fundamental and harmonic frequency ranges of the radio-frequency circuit can be suppressed regardless of load variations. As such, the amplifier circuit **10**C and the radio-frequency circuit are provided in the manner that mitigates fluctuations in transmission characteristics caused by load variations.

[0202] In an example, in the radio-frequency circuit according to the third modification, the harmonic wave corresponds to the second harmonic wave having a frequency twice the fundamental wave.

[0203] With this configuration, the radio-frequency circuit is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and second harmonic frequency ranges of transmit signals.

[0204] In an example, in the radio-frequency circuit according to the third modification, the harmonic wave corresponds to the third harmonic wave having a frequency three times the fundamental wave.

[0205] With this configuration, the radio-frequency circuit is provided in the manner that mitigates fluctuations in the output characteristics of the fundamental and third harmonic frequency ranges of transmit signals.

[0206] In an example, in the radio-frequency circuit according to the third modification, the phase shifter circuit **21**C is configured such that the forward phase of the fundamental wave is −45°. The phase shifter circuit **22**C is configured such that the forward phase of the fundamental wave is +45°. The phase shifter circuit **21**C and the harmonic phase shifter circuit **31**C are configured such that the forward phase of the harmonic wave in the circuit formed by combining the phase shifter circuit **21**C and the harmonic phase shifter circuit **31**C is −45°. The phase shifter circuit **22**C and the harmonic phase shifter circuit **32**C are configured such that the forward phase of the harmonic wave in the circuit formed by combining the phase shifter circuit **22**C and the harmonic phase shifter circuit **32**C is +45°.

[0207] With this configuration, the first signal and the second signal, which are two band-A radio-frequency signals, can be combined in antiphase at the fifth output port. This configuration enables highly efficient power combining of the fundamental wave with respect to load variations. This configuration achieves a **1800** difference between the first reflection phase (−90°) of the fundamental wave of the first signal assuming the fifth output port is observed from the third output port and the second reflection phase (+90°) of the fundamental wave of the second signal assuming the fifth output port is observed from the fourth output port. This configuration achieves a **1800** difference between the third reflection phase of the second harmonic wave of the first signal assuming the fifth output port is observed from the third output port and the fourth reflection phase of the second harmonic wave of the second signal assuming the fifth output port is observed from the fourth output port.

[0208] In an example, in the radio-frequency circuit according to the third modification, the phase shifter circuit **21**C includes the inductor **221** coupled between the third output port and the fourth input port and the capacitor **223** coupled between ground and the path connecting the inductor **221** and the fourth input port, and the phase shifter circuit **22**C includes the capacitor **211** coupled between the fourth output port and the fifth input port and the inductor **213** coupled between ground and the path connecting the capacitor **211** and the fifth input port.

[0209] With this configuration, the phase shifter circuit **21**C is configured as a low pass filter. This configuration achieves a −45° forward phase of the fundamental wave of the band A. The phase shifter circuit **22**C is configured as a high pass filter. This configuration achieves a +45° forward phase of the fundamental wave of the band A.

[0210] In an example, in the radio-frequency circuit according to the third modification, the harmonic phase shifter circuit **31**C includes an LC circuit including the inductor **321** and the capacitor **322** that are coupled in series with each other. The LC circuit is coupled between ground and the path connecting the third output port and the inductor **221**. The harmonic phase shifter circuit **32**C includes the capacitor **311** coupled between ground and the path connecting the fourth output port and the capacitor **211**.

[0211] With this configuration, the harmonic phase shifter circuit **31**C operates as a notch filter with a pass band that corresponds to the fundamental frequency range of the band A. This configuration achieves a 0° forward phase of the fundamental wave of the band A. The harmonic phase shifter circuit **32**C operates as a low pass filter with a pass band that corresponds to the fundamental frequency range. This configuration achieves a 0° forward phase of the fundamental wave.

OTHER EMBODIMENTS

[0212] The radio-frequency circuit according to an embodiment of the present disclosure have been described by using the embodiment and modification, but the radio-frequency circuit according to the present disclosure are not limited to the embodiment and modification. The present disclosure also embraces other embodiments implemented as any combination of the constituent elements of the embodiment and modification, other modifications obtained by making various modifications to the embodiment that occur to those skilled in the art without departing from the scope of the present disclosure, and various hardware devices including the radio-frequency circuit according to the present disclosure.

[0213] For example, in the amplifier circuit, the radio-frequency circuit, and the communication device according to the embodiment and modifications described above, other circuit elements and wire lines may be inserted in the paths connecting the circuit elements and signal paths that are illustrated in the drawings.

[0214] The following describes the features of the radio-frequency circuits explained based on the embodiment. [0215] <1> A radio-frequency circuit comprising: [0216] a first antenna terminal; [0217] a splitter having a first input port, a first output port, and a second output port, the splitter being configured to split a fundamental signal of a transmit band of a first band that is input to the first input port, configured to output from the first output port a first split signal, and configured to output from the second output port a second split signal that has a phase of +90° relative to the first split signal; [0218] a first power amplifier having a second input port and a third output port, the second input port being coupled to the first output port; [0219] a second power amplifier having a third input port and a fourth output port, the third input port being coupled to the second output port; [0220] a combiner circuit having a fourth input port, a fifth input port, and a fifth output port, the combiner circuit being configured to combine in phase a third split signal input from the fourth input port and a fourth split signal input from the fifth input port to generate an output signal and configured to output the output signal from the fifth output port; [0221] a first phase shifter circuit coupled between the third output port and the fourth input port; [0222] a second phase shifter circuit coupled between the fourth output port and the fifth input port; [0223] a first harmonic phase shifter circuit coupled between the third output port and the fourth input port and/or a second harmonic phase shifter circuit coupled between the fourth output port and the fifth input port; and [0224] a first filter coupled between the fifth output port and the first antenna terminal, the first filter having a pass band that includes the transmit band, wherein [0225] the first phase shifter circuit and the second phase shifter circuit are configured such that [0226] a forward phase of a fundamental wave of the transmit band in the second phase shifter circuit in a direction from the fourth output port to the fifth input port is −90° relative to a forward phase of the fundamental wave in the first phase shifter circuit [0227] in a direction from the third output port to the fourth input port, and [0228] the first phase shifter circuit, the second phase shifter circuit, the first harmonic phase shifter circuit, and the second harmonic phase shifter circuit are configured such that [0229] a difference between a first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and a second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°, and [0230] a difference between a third reflection phase of at least one of harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and a fourth reflection phase of the at least one of the harmonic waves assuming the fifth output port is observed from the fourth output port is 180°. [0231] <2> The radio-frequency circuit according to <1>, wherein [0232] the harmonic waves correspond to a second harmonic wave having a frequency twice the fundamental wave. [0233] <3> The radio-frequency circuit according to <1>, wherein [0234] the harmonic waves correspond to a third harmonic wave having a frequency three times the fundamental wave. [0235] <4> The radio-frequency circuit according to any of <1> to <3>, wherein [0236] the first phase shifter circuit is configured such that the forward phase of the fundamental wave is +45°, [0237] the second phase shifter circuit is configured such that the forward phase of the fundamental wave is −45°, [0238] the first phase shifter circuit and the first harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the first phase shifter circuit and the first harmonic phase shifter circuit is +45°, and [0239] the second phase shifter circuit and the second harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the second phase shifter circuit and the second harmonic phase shifter circuit is −45°. [0240] <5> The radio-frequency circuit according to <4>, wherein [0241] the first phase shifter circuit includes [0242] a first capacitor coupled between the third output port and the fourth input port, and [0243] a first inductor coupled between ground and a path connecting the first capacitor and the fourth input port, and [0244] the second phase shifter circuit includes [0245] a second inductor coupled between the fourth output port and the fifth input port, and [0246] a second capacitor coupled between ground and a path connecting the second inductor and the fifth input port. [0247] <6> The radio-frequency circuit according to <5>, comprising the first harmonic phase shifter circuit and the second harmonic phase shifter circuit, wherein [0248] the first harmonic phase shifter circuit includes a third capacitor coupled between ground and a path connecting the third output port and the first capacitor, and [0249] the second harmonic phase shifter circuit includes an LC circuit including a third inductor and a fourth capacitor that are coupled in series with each other, and the LC circuit is coupled between ground and a path connecting the fourth output port and the second inductor. [0250] <7> The radio-frequency circuit according to any of <1> to <6>, further comprising: [0251] a second filter having a pass band that includes a transmit band of a second band, wherein [0252] the combiner circuit includes a switching circuit that has the fourth input port, the fifth input port, the fifth output port, and the sixth output port and that is configured to alternate between connecting the fourth input port and the fifth output port while connecting the fifth input port and the fifth output port and connecting the fourth input port and the sixth output port while connecting the fifth input port and the sixth output port, and [0253] the second filter is coupled to the sixth output port. [0254] <8> The radio-frequency circuit according to <7>, wherein [0255] the switching circuit is included in a semiconductor integrated circuit (IC), [0256] the switching circuit includes [0257] a first switch coupled to the fourth input port and the fifth output port, [0258] a second switch coupled to the fourth input port and the sixth output port, [0259] a third switch coupled to the fifth input port and the fifth output port, and [0260] a fourth switch coupled to the fifth input port and the sixth output port, and [0261] assuming a major surface of the semiconductor IC is viewed in plan view, [0262] the first switch and the third switch are positioned between the fourth input port and the fifth input port, [0263] the fifth output port is positioned between the first switch and the third switch, [0264] the second switch and the fourth switch are positioned between the fourth input port and the fifth input port, and [0265] the sixth output port is positioned between the second switch and the fourth switch. [0266] <9> The radio-frequency circuit according to <7> or <8>, wherein [0267] the switching circuit further includes a monitoring terminal, and [0268] the monitoring terminal is configured to be connected to the fourth input port in a state in which the fourth input port is disconnected from the fifth output port and the sixth output port or to be connected to the fifth input port in a state in which the fifth input port is disconnected from the fifth output port and the sixth output port. [0269] <10> The radio-frequency circuit according to any of <7> to <9>, wherein [0270] at least one of the first phase shifter circuit and the second phase shifter circuit is configured such that a forward phase is changed by alternating between connecting the fourth input port and the fifth input port to the fifth output port and connecting the fourth input port and the fifth input port to the sixth output port. [0271] <11> The radio-frequency circuit according to <10>, wherein [0272] the switching circuit is included in a semiconductor IC, [0273] the first phase shifter circuit includes a first variable circuit having a fifth switch and at least one of an inductor and a capacitor that is coupled to the fifth switch, [0274] the second phase shifter circuit includes a second variable circuit having a sixth switch and at least one of an inductor and a capacitor that is coupled to the sixth switch, [0275] the first variable circuit is coupled to the fourth input port and included in the semiconductor IC, and [0276] the second variable circuit is coupled to the fifth input port and included in the semiconductor IC. [0277] <12> The radio-frequency circuit according to any of <7> to <11>, comprising the first harmonic phase shifter circuit and the second harmonic phase shifter circuit, wherein [0278] at least one of the first harmonic phase shifter circuit and the second harmonic phase shifter circuit is configured such that a forward phase is changed by alternating between connecting the fourth input port and the fifth input port to the fifth output port and connecting the fourth input port and the fifth input port to the sixth output port. [0279] <13> The radio-frequency circuit according to <12>, wherein [0280] the switching circuit is included in a semiconductor IC, [0281] the first harmonic phase shifter circuit includes a third variable circuit having a seventh switch and at least one of an inductor and a capacitor that is coupled to the seventh switch, [0282] the second harmonic phase shifter circuit includes a fourth variable circuit having an eighth switch and at least one of an inductor and a capacitor that is coupled to the eighth switch, and [0283] the third variable circuit and the fourth variable circuit are included in the semiconductor IC. [0284] <14> The radio-frequency circuit according to any of <1> to <13>, further comprising: [0285] a second antenna terminal; [0286] a third power amplifier;

and [0287] a third filter coupled between the second antenna terminal and an output port of the third power amplifier, the third filter having a pass band that includes the transmit band of the first band. [0288] <15> A radio-frequency circuit comprising: [0289] a first antenna terminal; [0290] a splitter having a first input port, a first output port, and a second output port, the splitter being configured to split a fundamental signal of a transmit band of a first band that is input to the first input port, configured to output from the first output port a first split signal, and configured to output from the second output port a second split signal that has a phase of +90° relative to the first split signal; [0291] a first power amplifier having a second input port and a third output port, the second input port being coupled to the first output port; [0292] a second power amplifier having a third input port and a fourth output port, the third input port being coupled to the second output port; [0293] a combiner circuit having a fourth input port, a fifth input port, and a fifth output port, the combiner circuit being configured to combine in antiphase a third split signal input from the fourth input port and a fourth split signal input from the fifth input port to generate an output signal and configured to output the output signal from the fifth output port; [0294] a first phase shifter circuit coupled between the third output port and the fourth input port; [0295] a second phase shifter circuit coupled between the fourth output port and the fifth input port; [0296] a first harmonic phase shifter circuit coupled between the third output port and the fourth input port and/or a second harmonic phase shifter circuit coupled between the fourth output port and the fifth input port; and [0297] a first transmit filter coupled between the fifth output port and the first antenna terminal, the first transmit filter having a pass band that includes the transmit band, wherein [0298] the first phase shifter circuit and the second phase shifter circuit are configured such that [0299] a forward phase of a fundamental wave of the transmit band in the second phase shifter circuit in a direction from the fourth output port to the fifth input port is −90° relative to a forward phase of the fundamental wave in the first phase shifter circuit in a direction from the third output port to the fourth input port, and [0300] the first phase shifter circuit, the second phase shifter circuit, the first harmonic phase shifter circuit, and the second harmonic phase shifter circuit are configured such that [0301] a difference between a first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and a second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°, and [0302] a difference between a third reflection phase of at least one of harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and a fourth reflection phase of the at least one of the harmonic waves assuming the fifth output port is observed from the fourth output port is 180°. [0303] <16> The radio-frequency circuit according to <15>, wherein [0304] the harmonic waves correspond to a second harmonic wave having a frequency twice the fundamental wave. [0305] <17> The radio-frequency circuit according to <15>, wherein [0306] the harmonic waves correspond to a third harmonic wave having a frequency three times the fundamental wave. [0307] <18> The radio-frequency circuit according to any of <15> to <17>, wherein [0308] the first phase shifter circuit is configured such that the forward phase of the fundamental wave is −45°, [0309] the second phase shifter circuit is configured such that the forward phase of the fundamental wave is +45°, [0310] the first phase shifter circuit and the first harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the first phase shifter circuit and the first harmonic phase shifter circuit is −45°, and [0311] the second phase shifter circuit and the second harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the second phase shifter circuit and the second harmonic phase shifter circuit is +45°. [0312] <19> The radio-frequency circuit according to <18>, wherein [0313] the first phase shifter circuit includes [0314] a first inductor coupled between the third output port and the fourth input port, and [0315] a first capacitor coupled between ground and a path connecting the first inductor and the fourth input port, and [0316] the second phase shifter circuit includes [0317] a second capacitor coupled between the fourth output port and the fifth input port, and [0318] a second

inductor coupled between ground and a path connecting the second capacitor and the fifth input port. [0319] <20> The radio-frequency circuit according to <19>, comprising the first harmonic phase shifter circuit and the second harmonic phase shifter circuit, wherein [0320] the first harmonic phase shifter circuit includes an LC circuit including a third inductor and a third capacitor that are coupled in series with each other, and the LC circuit is coupled between ground and a path connecting the third output port and the first inductor, and [0321] the second harmonic phase shifter circuit includes a fourth capacitor coupled between ground and a path connecting the fourth output port and the second capacitor.
[0322] The present disclosure can be used as an amplifier circuit, a radio-frequency circuit, or a communication device provided at the front-end, in a wide variety of communication hardware, such as mobile phones.

Claims

1. A radio-frequency circuit comprising: a first antenna terminal; a splitter having a first input port, a first output port, and a second output port, the splitter being configured to split a fundamental signal of a transmit band of a first band that is input to the first input port, configured to output from the first output port a first split signal, and configured to output from the second output port a second split signal that has a phase of +90° relative to the first split signal; a first power amplifier having a second input port and a third output port, the second input port being coupled to the first output port; a second power amplifier having a third input port and a fourth output port, the third input port being coupled to the second output port; a combiner circuit having a fourth input port, a fifth input port, and a fifth output port, the combiner circuit being configured to combine in phase a third split signal input from the fourth input port and a fourth split signal input from the fifth input port to generate an output signal and configured to output the output signal from the fifth output port; a first phase shifter circuit coupled between the third output port and the fourth input port; a second phase shifter circuit coupled between the fourth output port and the fifth input port; a first harmonic phase shifter circuit coupled between the third output port and the fourth input port and/or a second harmonic phase shifter circuit coupled between the fourth output port and the fifth input port; and a first filter coupled between the fifth output port and the first antenna terminal, the first filter having a pass band that includes the transmit band, wherein the first phase shifter circuit and the second phase shifter circuit are configured such that a forward phase of a fundamental wave of the transmit band in the second phase shifter circuit in a direction from the fourth output port to the fifth input port is −90° relative to a forward phase of the fundamental wave in the first phase shifter circuit in a direction from the third output port to the fourth input port, and the first phase shifter circuit, the second phase shifter circuit, the first harmonic phase shifter circuit, and the second harmonic phase shifter circuit are configured such that a difference between a first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and a second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°, and a difference between a third reflection phase of at least one of harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and a fourth reflection phase of the at least one of the harmonic waves assuming the fifth output port is observed from the fourth output port is 180°.
2. The radio-frequency circuit according to claim 1, wherein the harmonic waves correspond to a second harmonic wave having a frequency twice the fundamental wave.
3. The radio-frequency circuit according to claim 1, wherein the harmonic waves correspond to a third harmonic wave having a frequency three times the fundamental wave.
4. The radio-frequency circuit according to claim 1, wherein the first phase shifter circuit is configured such that the forward phase of the fundamental wave is +45°, the second phase shifter circuit is configured such that the forward phase of the fundamental wave is −45°, the first phase

shifter circuit and the first harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the first phase shifter circuit and the first harmonic phase shifter circuit is +45°, and the second phase shifter circuit and the second harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the second phase shifter circuit and the second harmonic phase shifter circuit is −45°.

5. The radio-frequency circuit according to claim 4, wherein the first phase shifter circuit includes a first capacitor coupled between the third output port and the fourth input port, and a first inductor coupled between ground and a path connecting the first capacitor and the fourth input port, and the second phase shifter circuit includes a second inductor coupled between the fourth output port and the fifth input port, and a second capacitor coupled between ground and a path connecting the second inductor and the fifth input port.

6. The radio-frequency circuit according to claim 5, comprising the first harmonic phase shifter circuit and the second harmonic phase shifter circuit, wherein the first harmonic phase shifter circuit includes a third capacitor coupled between ground and a path connecting the third output port and the first capacitor, and the second harmonic phase shifter circuit includes an LC circuit including a third inductor and a fourth capacitor that are coupled in series with each other, and the LC circuit is coupled between ground and a path connecting the fourth output port and the second inductor.

7. The radio-frequency circuit according to claim 6, further comprising: a second filter having a pass band that includes a transmit band of a second band, wherein the combiner circuit includes a switching circuit that has the fourth input port, the fifth input port, the fifth output port, and the sixth output port and that is configured to alternate between connecting the fourth input port and the fifth output port while connecting the fifth input port and the fifth output port and connecting the fourth input port and the sixth output port while connecting the fifth input port and the sixth output port, and the second filter is coupled to the sixth output port.

8. The radio-frequency circuit according to claim 7, wherein the switching circuit is included in a semiconductor integrated circuit (IC), the switching circuit includes a first switch coupled to the fourth input port and the fifth output port, a second switch coupled to the fourth input port and the sixth output port, a third switch coupled to the fifth input port and the fifth output port, and a fourth switch coupled to the fifth input port and the sixth output port, and assuming a major surface of the semiconductor IC is viewed in plan view, the first switch and the third switch are positioned between the fourth input port and the fifth input port, the fifth output port is positioned between the first switch and the third switch, the second switch and the fourth switch are positioned between the fourth input port and the fifth input port, and the sixth output port is positioned between the second switch and the fourth switch.

9. The radio-frequency circuit according to claim 7, wherein the switching circuit further includes a monitoring terminal, and the monitoring terminal is configured to be connected to the fourth input port in a state in which the fourth input port is disconnected from the fifth output port and the sixth output port or to be connected to the fifth input port in a state in which the fifth input port is disconnected from the fifth output port and the sixth output port.

10. The radio-frequency circuit according to claim 7, wherein at least one of the first phase shifter circuit and the second phase shifter circuit is configured such that a forward phase is changed by alternating between connecting the fourth input port and the fifth input port to the fifth output port and connecting the fourth input port and the fifth input port to the sixth output port.

11. The radio-frequency circuit according to claim 10, wherein the switching circuit is included in a semiconductor IC, the first phase shifter circuit includes a first variable circuit having a fifth switch and at least one of an inductor and a capacitor that is coupled to the fifth switch, the second phase shifter circuit includes a second variable circuit having a sixth switch and at least one of an inductor and a capacitor that is coupled to the sixth switch, the first variable circuit is coupled to the fourth input port and included in the semiconductor IC, and the second variable circuit is coupled to the fifth input port and included in the semiconductor IC.

12. The radio-frequency circuit according to claim 7, comprising the first harmonic phase shifter circuit and the second harmonic phase shifter circuit, wherein at least one of the first harmonic phase shifter circuit and the second harmonic phase shifter circuit is configured such that a forward phase is changed by alternating between connecting the fourth input port and the fifth input port to the fifth output port and connecting the fourth input port and the fifth input port to the sixth output port.

13. The radio-frequency circuit according to claim 12, wherein the switching circuit is included in a semiconductor IC, the first harmonic phase shifter circuit includes a third variable circuit having a seventh switch and at least one of an inductor and a capacitor that is coupled to the seventh switch, the second harmonic phase shifter circuit includes a fourth variable circuit having an eighth switch and at least one of an inductor and a capacitor that is coupled to the eighth switch, and the third variable circuit and the fourth variable circuit are included in the semiconductor IC.

14. The radio-frequency circuit according claim 6, further comprising: a second antenna terminal; a third power amplifier; and a third filter coupled between the second antenna terminal and an output port of the third power amplifier, the third filter having a pass band that includes the transmit band of the first band.

15. A radio-frequency circuit comprising: a first antenna terminal; a splitter having a first input port, a first output port, and a second output port, the splitter being configured to split a fundamental signal of a transmit band of a first band that is input to the first input port, configured to output from the first output port a first split signal, and configured to output from the second output port a second split signal that has a phase of +90° relative to the first split signal; a first power amplifier having a second input port and a third output port, the second input port being coupled to the first output port; a second power amplifier having a third input port and a fourth output port, the third input port being coupled to the second output port; a combiner circuit having a fourth input port, a fifth input port, and a fifth output port, the combiner circuit being configured to combine in antiphase a third split signal input from the fourth input port and a fourth split signal input from the fifth input port to generate an output signal and configured to output the output signal from the fifth output port; a first phase shifter circuit coupled between the third output port and the fourth input port; a second phase shifter circuit coupled between the fourth output port and the fifth input port; a first harmonic phase shifter circuit coupled between the third output port and the fourth input port and/or a second harmonic phase shifter circuit coupled between the fourth output port and the fifth input port; and a first transmit filter coupled between the fifth output port and the first antenna terminal, the first transmit filter having a pass band that includes the transmit band, wherein the first phase shifter circuit and the second phase shifter circuit are configured such that a forward phase of a fundamental wave of the transmit band in the second phase shifter circuit in a direction from the fourth output port to the fifth input port is −90° relative to a forward phase of the fundamental wave in the first phase shifter circuit in a direction from the third output port to the fourth input port, and the first phase shifter circuit, the second phase shifter circuit, the first harmonic phase shifter circuit, and the second harmonic phase shifter circuit are configured such that a difference between a first reflection phase of the fundamental wave assuming the fifth output port is observed from the third output port and a second reflection phase of the fundamental wave assuming the fifth output port is observed from the fourth output port is 180°, and a difference between a third reflection phase of at least one of harmonic waves of the transmit band assuming the fifth output port is observed from the third output port and a fourth reflection phase of the at least one of the harmonic waves assuming the fifth output port is observed from the fourth output port is 180°.

16. The radio-frequency circuit according to claim 15, wherein the harmonic waves correspond to a second harmonic wave having a frequency twice the fundamental wave.

17. The radio-frequency circuit according to claim 15, wherein the harmonic waves correspond to a third harmonic wave having a frequency three times the fundamental wave.
18. The radio-frequency circuit according to claim 17, wherein the first phase shifter circuit is configured such that the forward phase of the fundamental wave is −45°, the second phase shifter circuit is configured such that the forward phase of the fundamental wave is +45°, the first phase shifter circuit and the first harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the first phase shifter circuit and the first harmonic phase shifter circuit is −45°, and the second phase shifter circuit and the second harmonic phase shifter circuit are configured such that the forward phase of the harmonic waves in a circuit formed by combining the second phase shifter circuit and the second harmonic phase shifter circuit is +45°.
19. The radio-frequency circuit according to claim 18, wherein the first phase shifter circuit includes a first inductor coupled between the third output port and the fourth input port, and a first capacitor coupled between ground and a path connecting the first inductor and the fourth input port, and the second phase shifter circuit includes a second capacitor coupled between the fourth output port and the fifth input port, and a second inductor coupled between ground and a path connecting the second capacitor and the fifth input port.
20. The radio-frequency circuit according to claim 19, comprising the first harmonic phase shifter circuit and the second harmonic phase shifter circuit, wherein the first harmonic phase shifter circuit includes an LC circuit including a third inductor and a third capacitor that are coupled in series with each other, and the LC circuit is coupled between ground and a path connecting the third output port and the first inductor, and the second harmonic phase shifter circuit includes a fourth capacitor coupled between ground and a path connecting the fourth output port and the second capacitor.