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(54) **AMPLIFIER CIRCUIT**

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(57) **ABSTRACT**

An amplifier circuit **1** includes a power amplifier circuit that includes a power amplifier, a power amplifier circuit that includes a power amplifier in which the phase of a fundamental wave at an output end is delayed by 90 degrees with respect to the power amplifier, and an in-phase combiner circuit that is configured to combine a fundamental wave of a first output signal output from the power amplifier circuit and a fundamental wave of a second output signal output from the power amplifier circuit. The power amplifier circuit is of an inverse class-E type. The power amplifier circuit is of a class-E type.

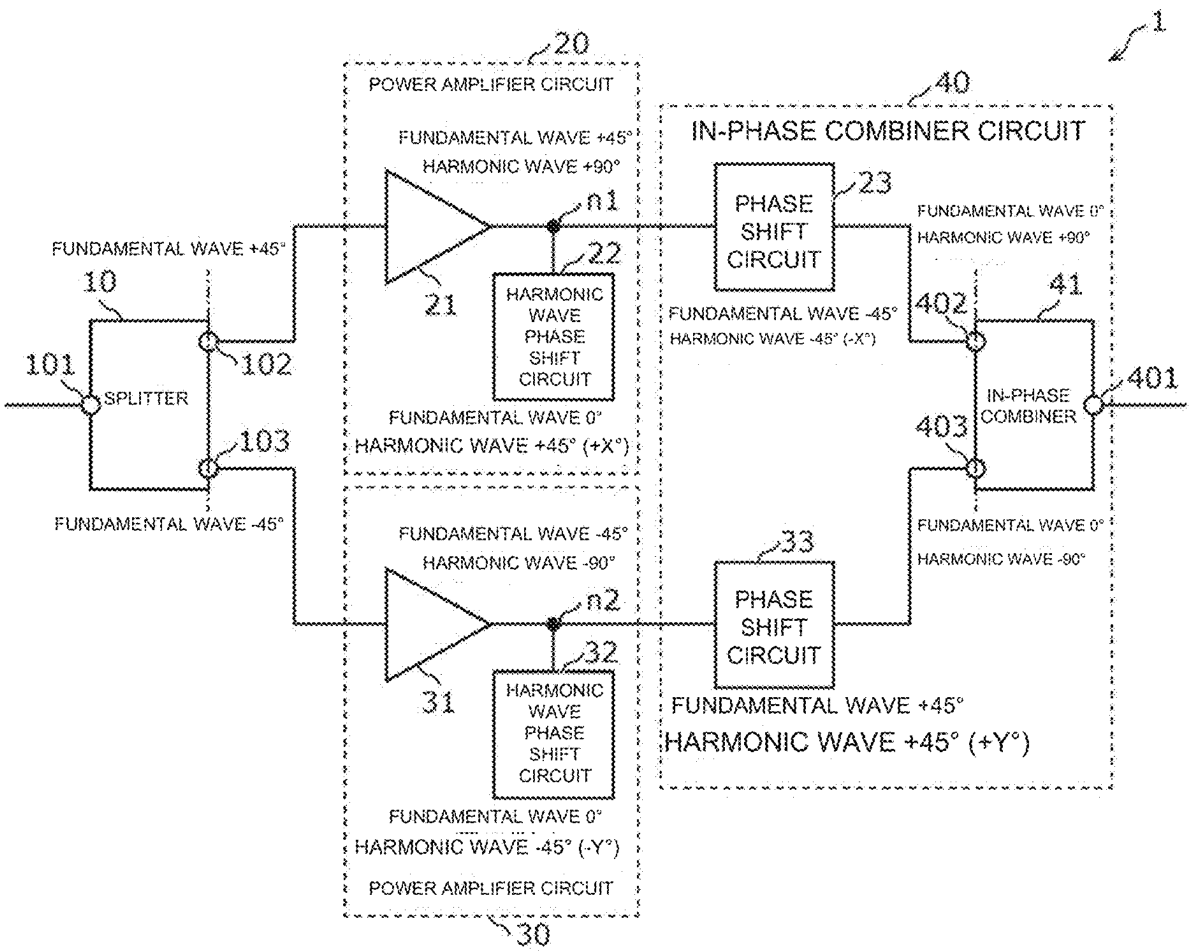


FIG. 1

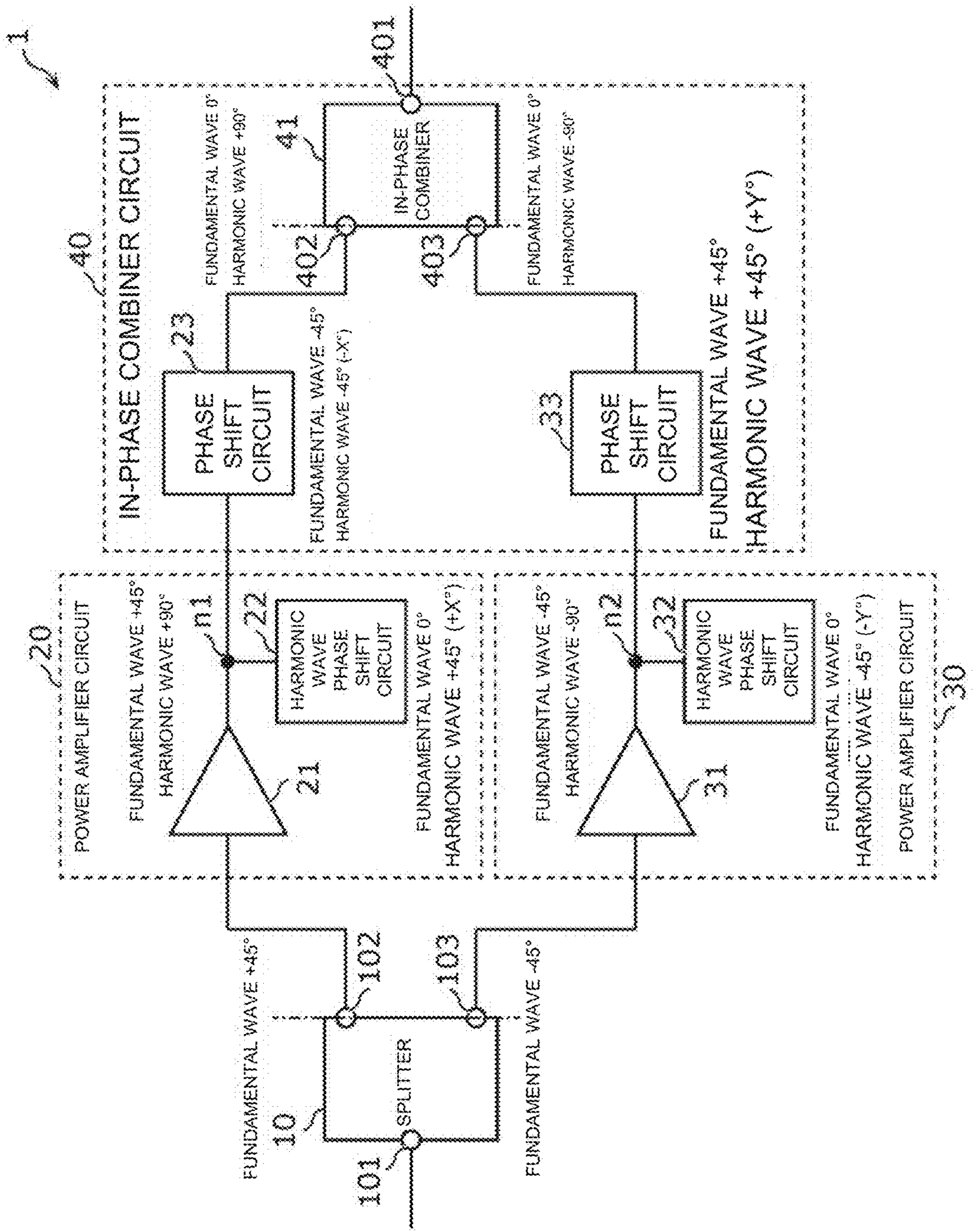

1
10
SPLITTER
101
102
103
FUNDAMENTAL WAVE +45°
FUNDAMENTAL WAVE -45°
20
POWER AMPLIFIER CIRCUIT
21
n1
22
HARMONIC WAVE PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +90°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +45° (+X°)
30
POWER AMPLIFIER CIRCUIT
31
n2
32
HARMONIC WAVE PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -90°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -45° (-Y°)
40
IN-PHASE COMBINER CIRCUIT
23
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -45° (-X°)
33
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +45° (+Y°)
41
IN-PHASE COMBINER
402
403
401
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +90°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -90°

FIG. 2

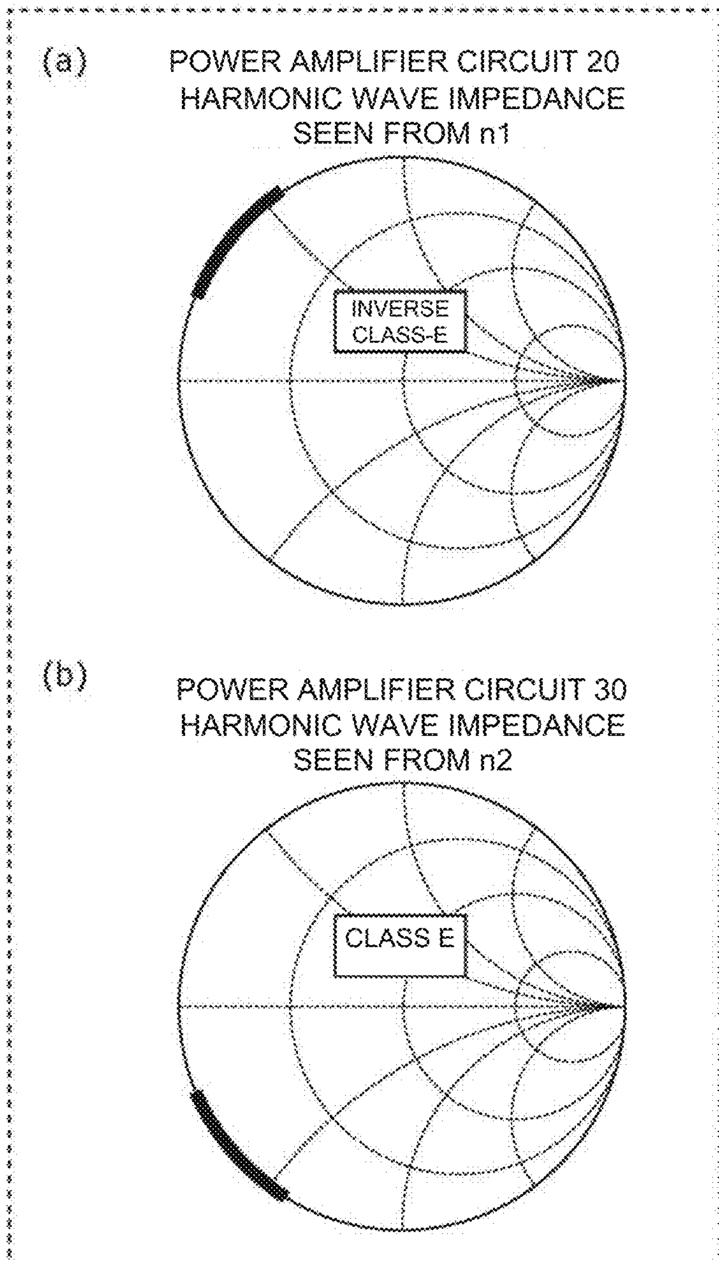
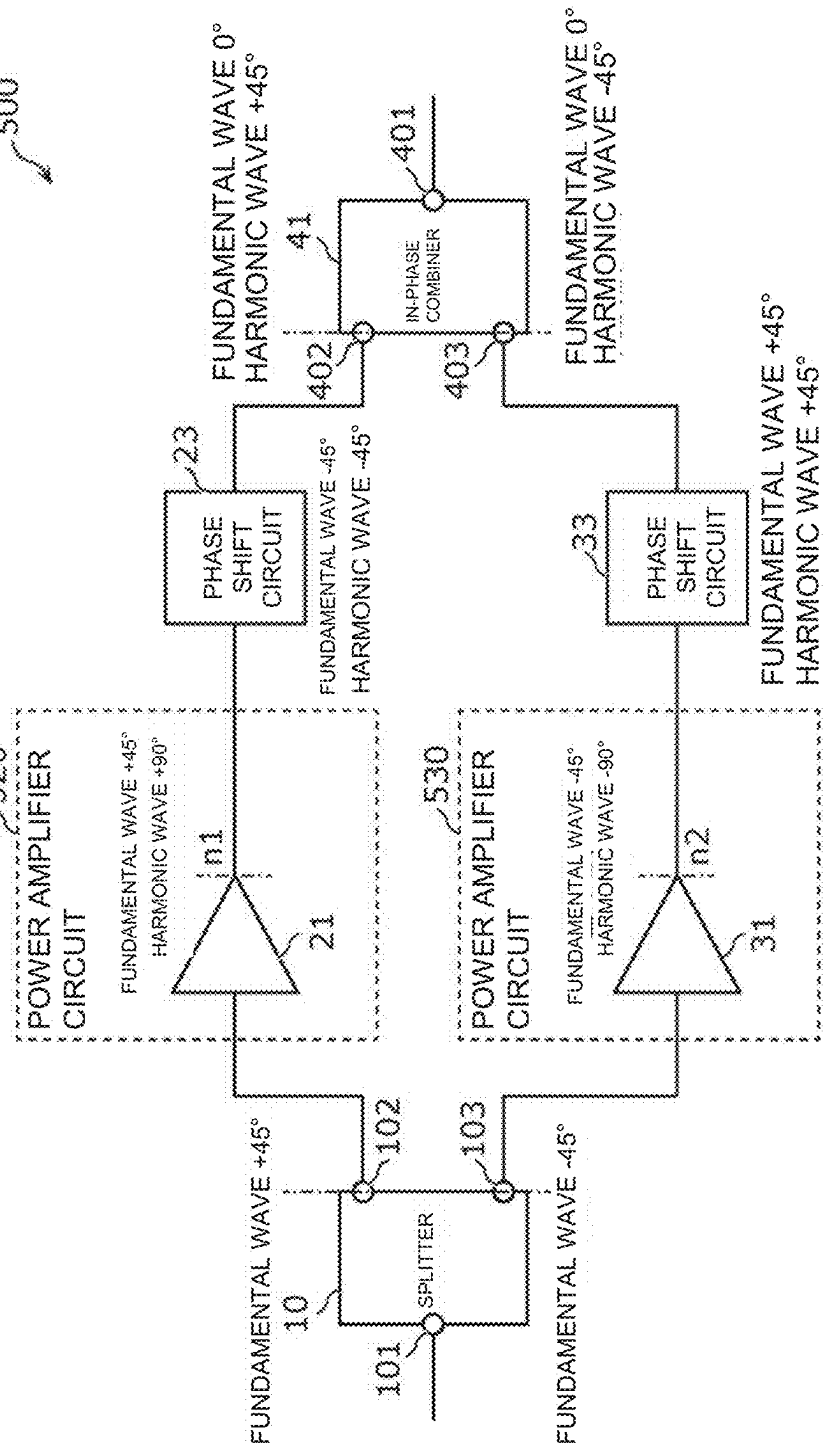

(a)
POWER AMPLIFIER CIRCUIT 20
HARMONIC WAVE IMPEDANCE
SEEN FROM n1
INVERSE
CLASS-E
(b)
POWER AMPLIFIER CIRCUIT 30
HARMONIC WAVE IMPEDANCE
SEEN FROM n2
CLASS E

FIG. 3



500
FUNDAMENTAL WAVE +45°
FUNDAMENTAL WAVE -45°
101
10
SPLITTER
102
103
POWER AMPLIFIER CIRCUIT
520
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +90°
21
n1
POWER AMPLIFIER CIRCUIT
530
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -90°
31
n2
23
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -45°
33
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +45°
402
403
41
IN-PHASE COMBINER
401
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +45°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -45°

FIG. 4A

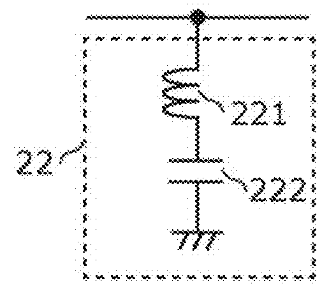


FIG. 4B

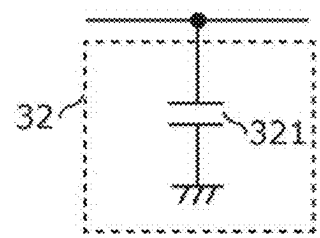


FIG. 4C

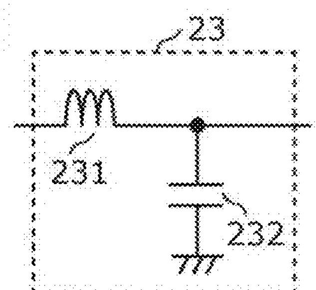


FIG. 4D

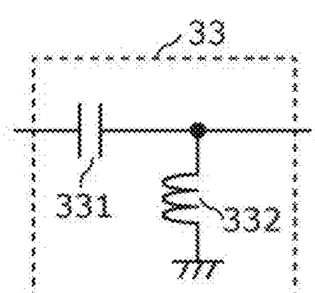


FIG. 5

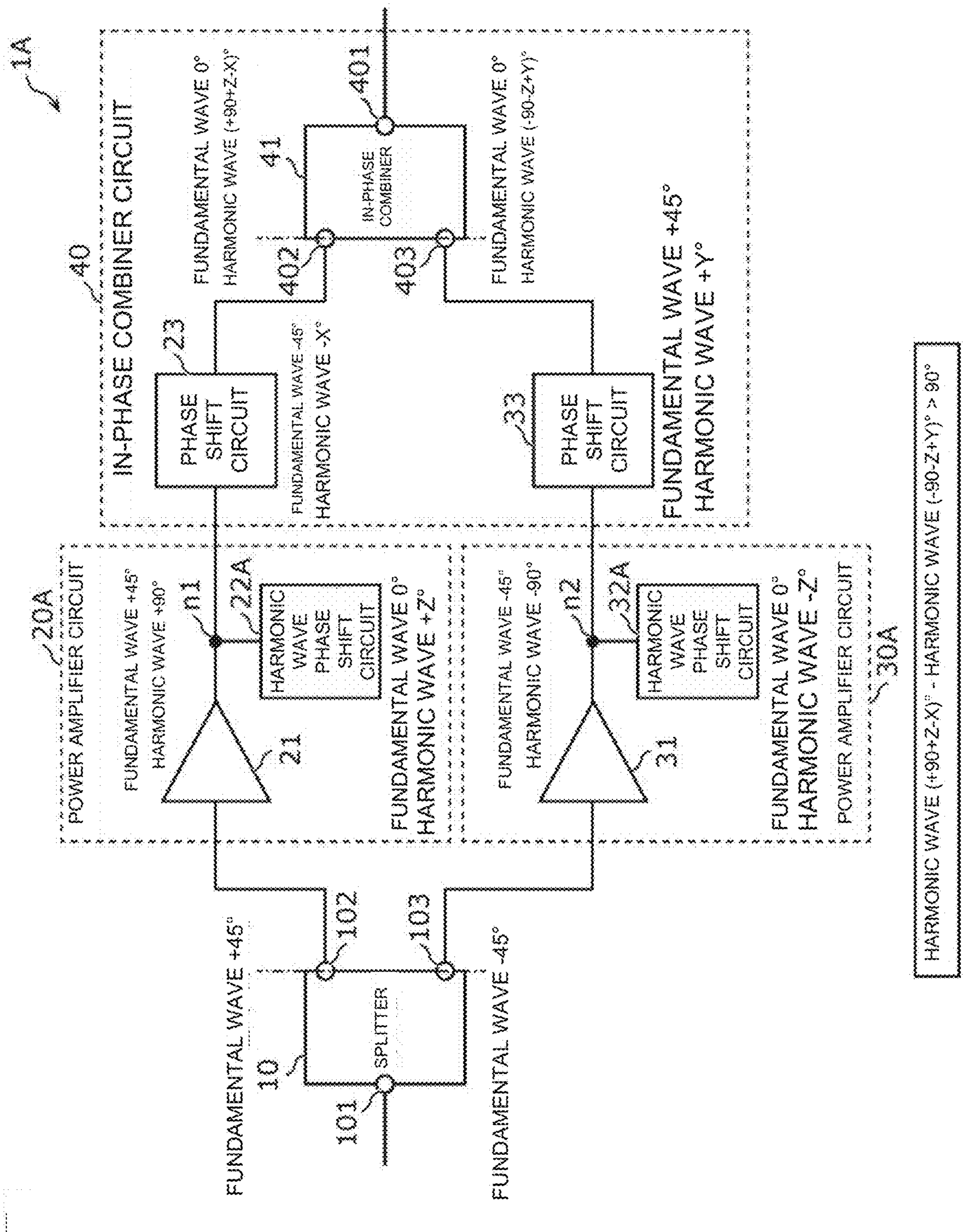
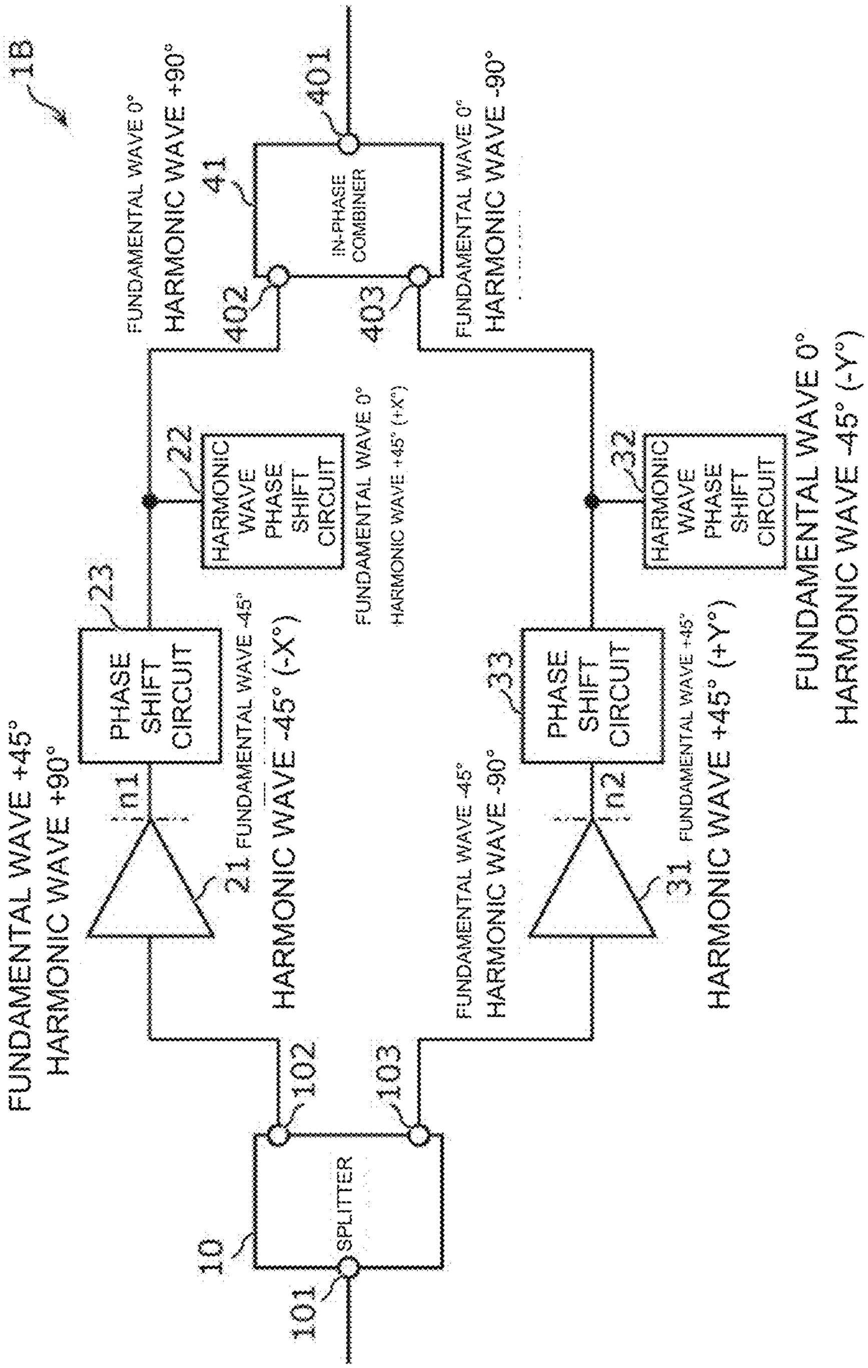

1A
10
SPLITTER
101
102
103
FUNDAMENTAL WAVE +45°
FUNDAMENTAL WAVE -45°
20A
POWER AMPLIFIER CIRCUIT
21
n1
22A
HARMONIC WAVE PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +90°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +Z°
30A
POWER AMPLIFIER CIRCUIT
31
n2
32A
HARMONIC WAVE PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -90°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -Z°
40
IN-PHASE COMBINER CIRCUIT
23
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -X°
33
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +Y°
41
IN-PHASE COMBINER
401
402
403
FUNDAMENTAL WAVE 0°
HARMONIC WAVE (+90+Z-X)°
FUNDAMENTAL WAVE 0°
HARMONIC WAVE (-90-Z+Y)°
HARMONIC WAVE (+90+Z-X)° - HARMONIC WAVE (-90-Z+Y)° > 90°

FIG. 6


1B
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +90°
10
SPLITTER
101
102
103
21
n1
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -45° (-X°)
23
PHASE SHIFT CIRCUIT
22
HARMONIC WAVE PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +45° (+X°)
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +90°
402
41
IN-PHASE COMBINER
401
403
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -90°
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -90°
31
n2
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +45° (+Y°)
33
PHASE SHIFT CIRCUIT
32
HARMONIC WAVE PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -45° (-Y°)

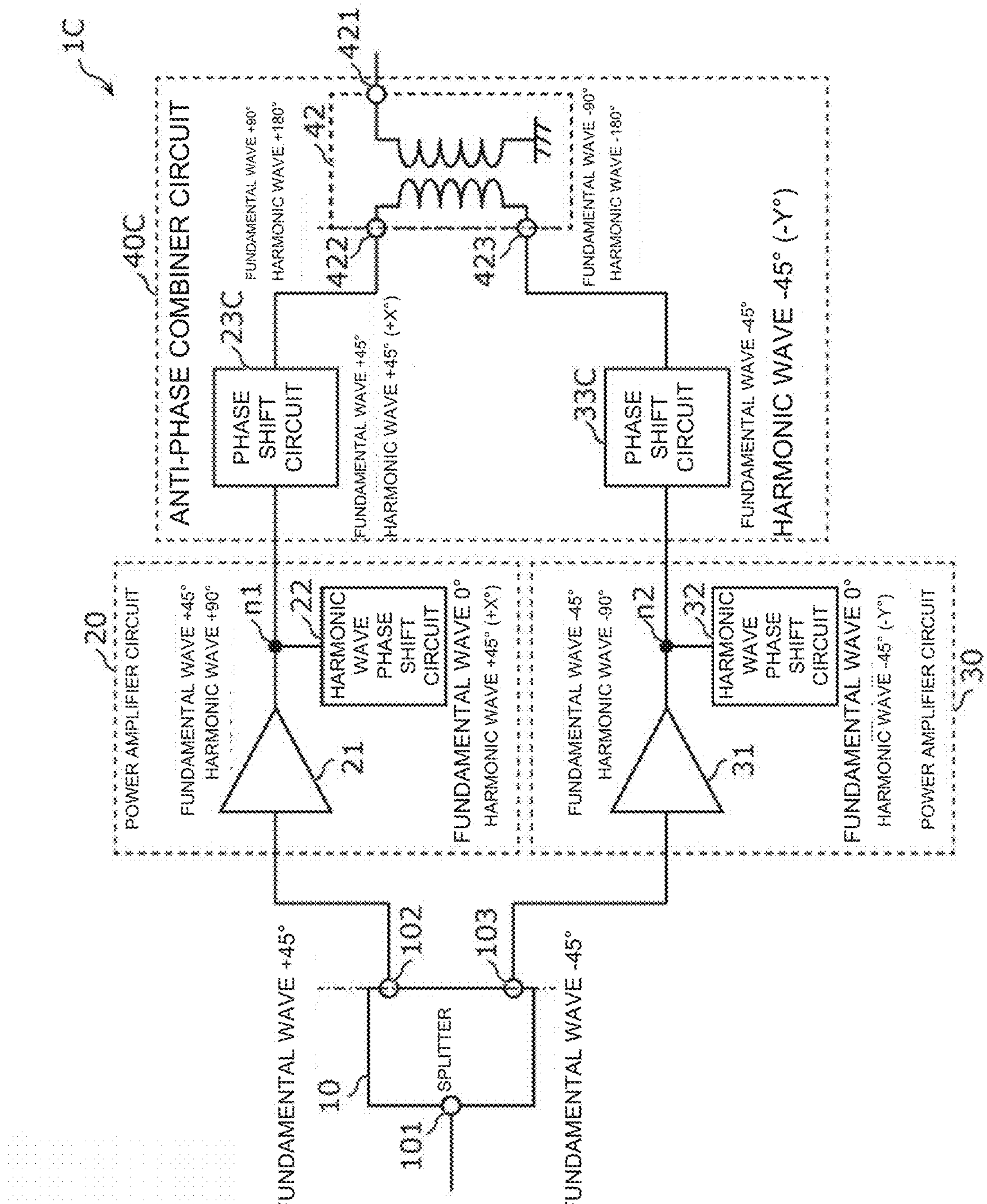
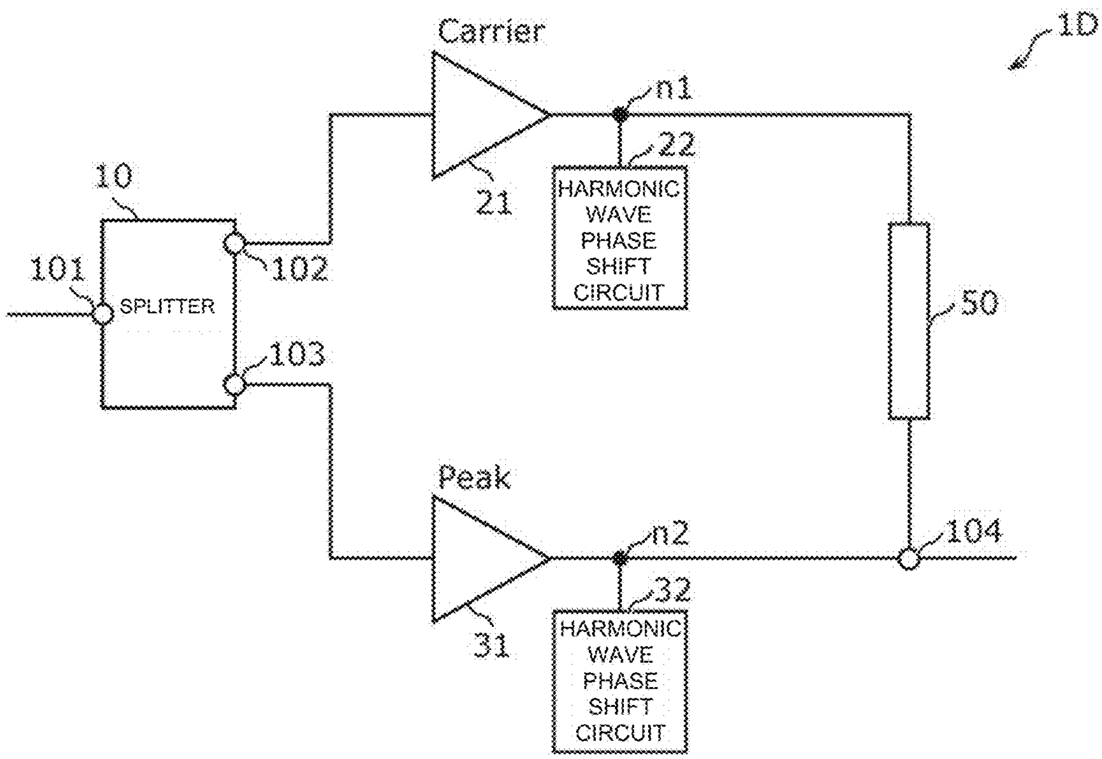

1C
40C
ANTI-PHASE COMBINER CIRCUIT
421
42
422
423
FUNDAMENTAL WAVE +90°
HARMONIC WAVE +180°
FUNDAMENTAL WAVE -90°
HARMONIC WAVE -180°
23C
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +45° (+X°)
33C
PHASE SHIFT CIRCUIT
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -45° (-Y°)
20
POWER AMPLIFIER CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +90°
n1
22
HARMONIC WAVE PHASE SHIFT CIRCUIT
21
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +45° (+X°)
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -90°
n2
32
HARMONIC WAVE PHASE SHIFT CIRCUIT
31
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -45° (-Y°)
POWER AMPLIFIER CIRCUIT
30
FUNDAMENTAL WAVE +45°
102
103
FUNDAMENTAL WAVE -45°
10
SPLITTER
101

FIG. 7

FIG. 8A



Carrier
1D
n1
22
10
21
HARMONIC
WAVE
PHASE
SHIFT
CIRCUIT
101
102
SPLITTER
50
103
Peak
n2
104
32
31
HARMONIC
WAVE
PHASE
SHIFT
CIRCUIT

FIG. 8B

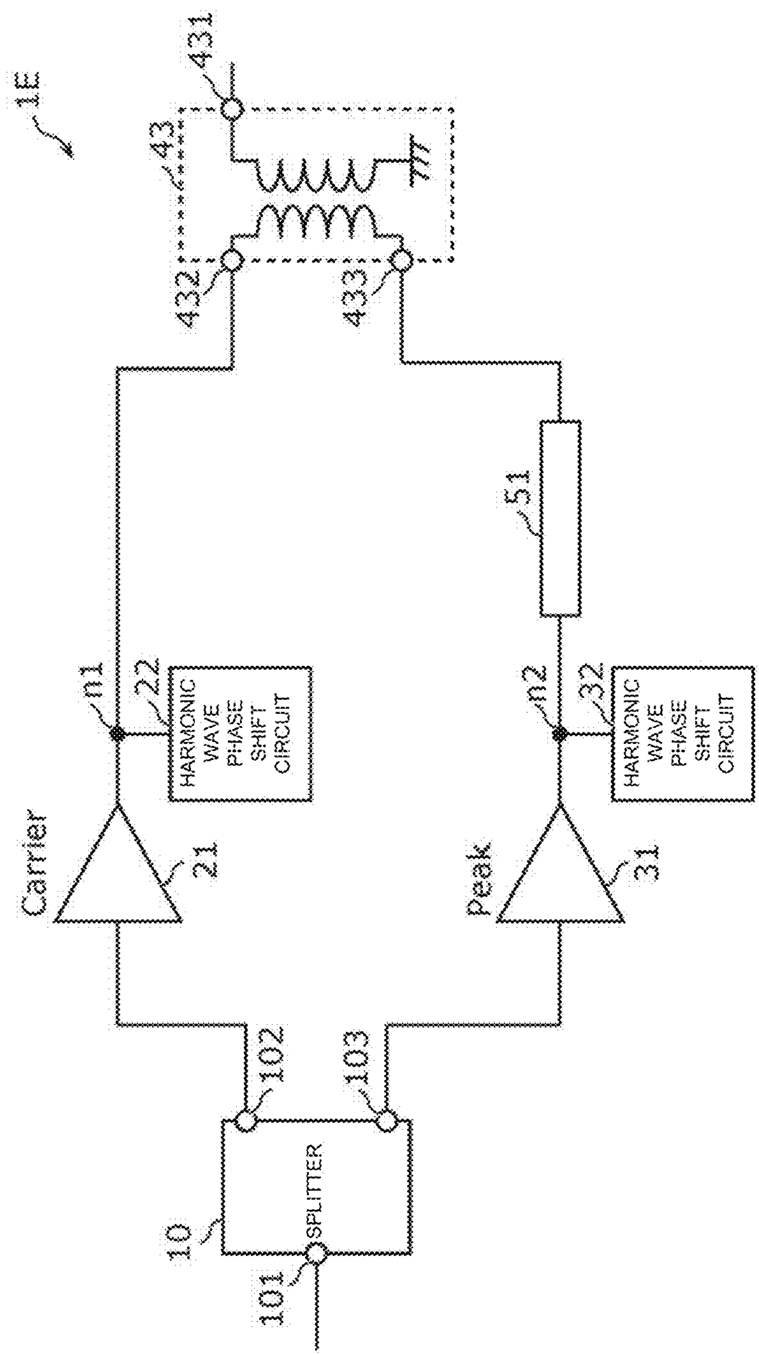
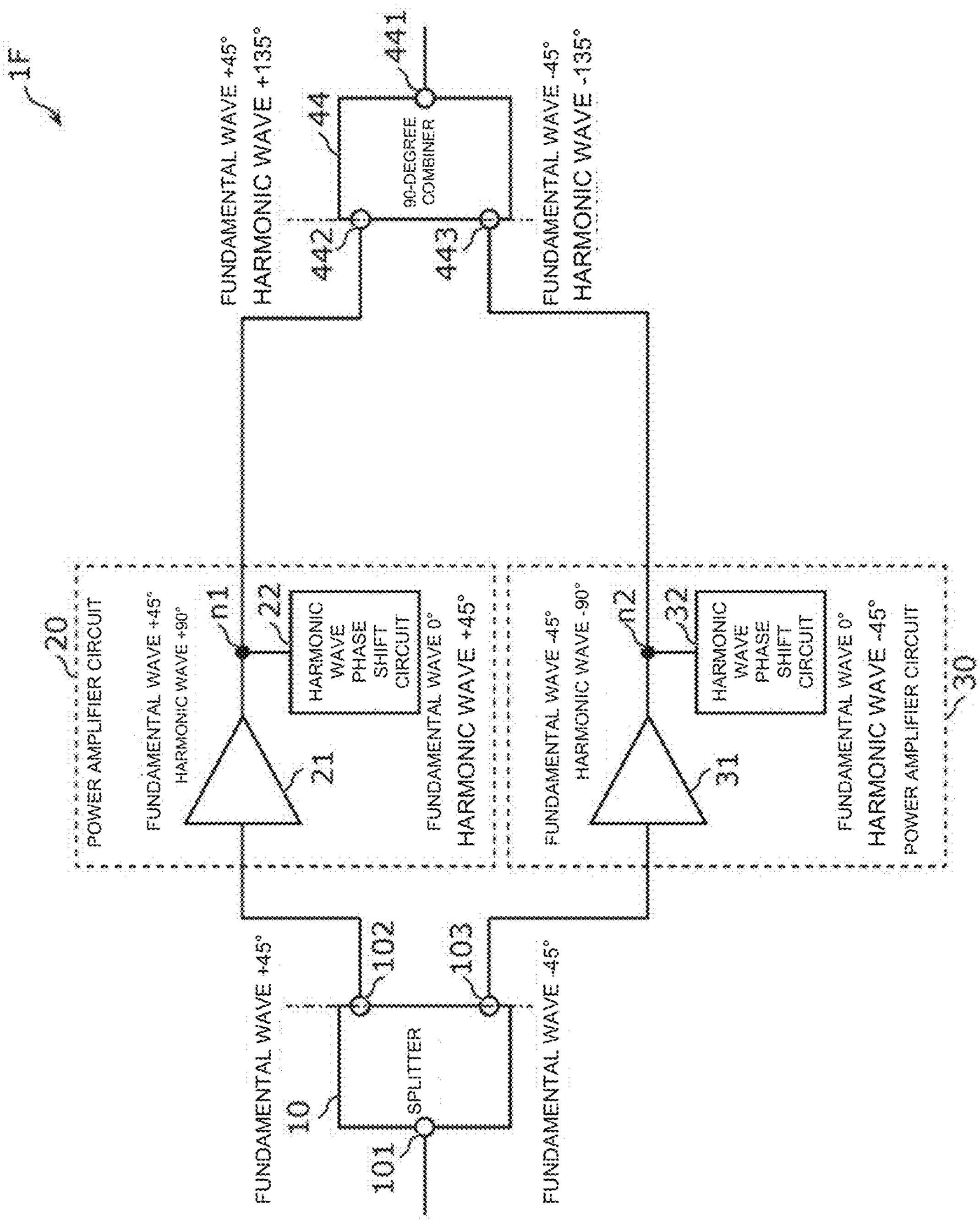

1E
43
431
432
433
51
n1
22
HARMONIC WAVE PHASE SHIFT CIRCUIT
n2
32
HARMONIC WAVE PHASE SHIFT CIRCUIT
Carrier
21
Peak
31
102
103
10
SPLITTER
101

FIG. 9


1F
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +135°
441
44
90-DEGREE COMBINER
442
443
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -135°
20
POWER AMPLIFIER CIRCUIT
FUNDAMENTAL WAVE +45°
HARMONIC WAVE +90°
n1
22
HARMONIC WAVE PHASE SHIFT CIRCUIT
21
FUNDAMENTAL WAVE 0°
HARMONIC WAVE +45°
FUNDAMENTAL WAVE -45°
HARMONIC WAVE -90°
n2
32
HARMONIC WAVE PHASE SHIFT CIRCUIT
31
FUNDAMENTAL WAVE 0°
HARMONIC WAVE -45°
POWER AMPLIFIER CIRCUIT
30
FUNDAMENTAL WAVE +45°
102
103
FUNDAMENTAL WAVE -45°
SPLITTER
10
101
FUNDAMENTAL WAVE

AMPLIFIER CIRCUIT

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to Japanese Patent Application No. JP 2024-020630 filed on Feb. 14, 2024. The entire contents of the above-identified application, including the specification, 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 an amplifier circuit.

2. Description of the Related Art

[0003] In Japanese Unexamined Patent Application Publication No. 63-153904, a power amplifier that includes a first amplifier device and a second amplifier device that form a balanced amplifier and perform a class-F operation, and a filter that is connected between an output end of the first amplifier device and an output end of the second amplifier device and allows second-order harmonic waves to pass therethrough, is disclosed. By canceling second-order harmonic waves at the output end of the first amplifier device and the output end of the second amplifier device, power efficiency of fundamental waves can be improved.

SUMMARY OF THE DISCLOSURE

[0004] However, in the power amplifier disclosed in Japanese Unexamined Patent Application Publication No. 63-153904, due to the class-F operation of the amplifier device, the frequency range of even-order harmonic waves in which load impedance is short-circuited is narrow, and it is thus difficult to accurately cancel second-order harmonic waves over the entire range of a band, for example, defined by 3rd Generation Partnership Project (3GPP (registered trademark)) so that high power efficiency can be ensured.

[0005] The present disclosure has been designed to solve the above-mentioned problem and an object of the present disclosure is to provide an amplifier circuit capable of suppressing harmonic waves accurately.

[0006] In order to achieve the object described above, an amplifier circuit according to an aspect of the present disclosure includes a first power amplifier circuit that includes a first power amplifier; a second power amplifier circuit that includes a second power amplifier in which a phase of a fundamental wave at an output end is delayed by 90 degrees with respect to the first power amplifier; and a combiner circuit that is configured to combine a fundamental wave of a first output signal output from the first power amplifier circuit and a fundamental wave of a second output signal output from the second power amplifier circuit. The first power amplifier circuit is of an inverse class-E type. The second power amplifier circuit is of a class-E type.

[0007] An amplifier circuit according to an aspect of the present disclosure includes a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees with respect to a phase of the first signal; a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end; a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end; a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal obtained by combining in an in-phase manner a first output signal output from the first power amplifier and input through the second input end and a second output signal output from the second power amplifier and input through the third input end; a first phase shift circuit that is connected between the first power amplifier and the combiner and is configured to shift phases of a fundamental wave and a harmonic wave in the first band; a second phase shift circuit that is connected between the second power amplifier and the combiner and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is +90 degrees with respect to the first phase shift circuit; a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave; and a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave. A phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is larger than 90 degrees.

[0008] According to the present disclosure, an amplifier circuit capable of accurately suppressing harmonic waves can be provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a circuit configuration diagram of an amplifier circuit according to an embodiment;

[0010] FIG. **2** includes Smith charts illustrating harmonic wave impedances of a first power amplifier circuit and a second power amplifier circuit in the embodiment;

[0011] FIG. **3** is a circuit configuration diagram of an amplifier circuit according to a comparative example;

[0012] FIG. **4**A is a diagram illustrating an example of the circuit configuration of a first harmonic wave phase shift circuit in the embodiment;

[0013] FIG. **4**B is a diagram illustrating an example of the circuit configuration of a second harmonic wave phase shift circuit in the embodiment;

[0014] FIG. **4**C is a diagram illustrating an example of the circuit configuration of a first phase shift circuit in the embodiment;

[0015] FIG. **4**D is a diagram illustrating an example of the circuit configuration of a second phase shift circuit in the embodiment;

[0016] FIG. **5** is a circuit configuration diagram of an amplifier circuit according to a first modification of the embodiment;

[0017] FIG. **6** is a circuit configuration diagram of an amplifier circuit according to a second modification of the embodiment;

[0018] FIG. **7** is a circuit configuration diagram of an amplifier circuit according to a third modification of the embodiment;

[0019] FIG. **8**A is a circuit configuration diagram of an amplifier circuit according to a fourth modification of the embodiment;

[0020] FIG. **8**B is a circuit configuration diagram of an amplifier circuit according to a fifth modification of the embodiment; and

[0021] FIG. **9** is a circuit configuration diagram of an amplifier circuit according to a sixth modification of the embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0022] Hereinafter, embodiments of the present disclosure will be described in detail with reference to drawings. The embodiments described below each illustrate a comprehensive or specific example. Numerical values, shapes, materials, component elements, arrangements of the component elements, manners in which the component elements are connected, and so on illustrated in the embodiments described below are merely examples and are not intended to limit the present disclosure.

[0023] The drawings are schematic diagrams in which emphasis, omission, or ratio adjustment is performed in an appropriate manner in order that the present disclosure is illustrated. The drawings are not necessarily strictly illustrated and may differ from actual shapes, positional relationships, and ratios. In the drawings, substantially the same configurations are denoted by the same reference signs, and repetitive description may be omitted or simplified.

[0024] Furthermore, in the present disclosure, terms, such as parallel and perpendicular, representing the relationship between elements, terms, such as rectangular, representing the shape of an element, and numerical ranges do not represent only strict meanings but mean inclusion of substantially equivalent ranges, for example, differences on the order of a few percent.

[0025] In a circuit configuration of the present disclosure, "being connected" not only represents being directly connected by a connection terminal and/or a wire conductor but also includes being electrically connected with another circuit element interposed therebetween. "Being connected between A and B" may be understood as being connected to both A and B between A and B.

[0026] Furthermore, in the present disclosure, a "path" represents a transfer line including a wire through which a high frequency signal propagates, an electrode directly connected to the wire, a terminal directly connected to the wire or the electrode, and the like.

[0027] Furthermore, in the present disclosure, "a component A is arranged in series to a path B" may be understood as the state in which both a signal input end and a signal output end of the component A is connected to a wire, an electrode, or a terminal forming the path B.

[0028] In the present disclosure, a "terminal", an "input end", and an "output end" each represent a point at which a conductor inside an element terminates. In the case where the impedance of a conductor between elements is sufficiently low, a terminal is not only construed as a single point but also as an arbitrary point in the conductor between the elements or the entire conductor.

[0029] Furthermore, terms, such as "parallel" and "perpendicular", representing the relationship between elements, terms, such as "rectangular", representing the shape of an element, and numerical ranges do not represent only strict meanings but mean inclusion of substantially equivalent ranges, for example, differences on the order of a few percent.

[0030] A "pass band of a filter" is a part of a frequency spectrum that is transmitted through the filter and is defined as a frequency range in which output power is not attenuated from the maximum output power by 3 dB or more. Thus, a higher frequency end and a lower frequency end of a pass band of a band pass filter are identified as a higher frequency and a lower frequency at two points where output power is attenuated from the maximum output power by 3 dB.

[0031] A "transmission band" represents a frequency band used for transmission in a communication apparatus. A "reception band" represents a frequency band used for reception in the communication apparatus. For example, different frequency bands are used as a transmission band and a reception band in the case of frequency division duplex (FDD), and the same frequency band is used as a transmission band a reception band in the case of time division duplex (TDD). In particular, in the case of FDD, in the case where a communication apparatus is implemented in a user terminal (UE: user equipment) of a cellular network, an uplink band (uplink operation band) is used as a transmission band and a downlink band (downlink operation band) is used as a reception band. In contrast, in the case where a communication apparatus is implemented as a base station (BS) of a cellular network, a downlink band is used as a transmission band and an uplink band is used as a reception band.

[0032] A "pass phase" between two terminals of a high frequency signal is obtained by making a measurement RF probe in contact with the two terminals to measure bandpass characteristics (S**21**) by a network analyzer. Furthermore, a "reflection phase" at a terminal of a high frequency signal is obtained by making a measurement RF probe in contact with the terminal to measure bandpass characteristics (S**11**) by a network analyzer.

[0033] In the present disclosure, numerical values of a pass phase, a reflection phase, and a reflection phase difference do not represent only strict meanings but mean inclusion of substantially equivalent ranges, for example, differences of about 30 percent.

Embodiment

1 Circuit Configuration of Amplifier Circuit **1**

[0034] A circuit configuration of an amplifier circuit **1** will be described. FIG. **1** is a circuit configuration diagram of the amplifier circuit **1** according to an embodiment. As illustrated in the drawing, the amplifier circuit **1** includes a splitter **10**, power amplifier circuits **20** and **30**, and an in-phase combiner circuit **40**.

[0035] The splitter **10** includes an input terminal **101** (first input end), an output terminal **102** (first output end), and an output terminal **103** (second output end). The splitter **10** is configured to split a fundamental wave signal in a transmission band of a first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees (delayed by 90 degrees) relative to a phase of the first signal. In this embodiment, the phase of the first signal is +45 degrees relative to the phase of the fundamental wave signal, and the phase of the second signal is −45 degrees relative to the phase of the fundamental wave signal. The amplifier circuit **1** does not necessarily include the splitter **10**.

[0036] Furthermore, each of the input terminal and the output terminals in this embodiment may be a metal conductor such as a metal electrode or a metal bump or may be a point (node) on a metal wire.

[0037] The power amplifier circuit **20** is an example of a first power amplifier circuit and includes a power amplifier **21**. The power amplifier **21** includes an amplifier transistor. The power amplifier **21** has a fourth input end and a fourth output end. The fourth input end is connected to the output terminal **102**.

[0038] The power amplifier circuit **30** is an example of a second power amplifier circuit and includes a power amplifier **31**. The power amplifier **31** includes an amplifier transistor. The power amplifier **31** includes a fifth input end and a fifth output end. The fifth input end is connected to the output terminal **103**.

[0039] Since the power amplifier **21** amplifies the first signal output from the splitter **10** and the power amplifier **31** amplifies the second signal output from the splitter **10**, the phase of a fundamental wave at the fifth output end of the power amplifier **31** is delayed by 90 degrees with respect to the phase of a fundamental wave at the fourth output end of the power amplifier **21**. In this embodiment, the phase of the fundamental wave at the fourth output end of the power amplifier **21** is +45 degrees relative to the phase of the fundamental wave signal input to the input terminal **101** of the splitter **10**, and the phase of the fundamental wave at the fifth output end of the power amplifier **31** is −45 degrees relative to the phase of the fundamental wave signal.

[0040] Furthermore, since the phase of the fundamental wave at the fifth output end of the power amplifier **31** is delayed by 90 degrees with respect to the phase of the fundamental wave at the fourth output end of the power amplifier **21**, the phase of a second-order harmonic wave at the fifth output end of the power amplifier **31** is delayed by 180 degrees with respect to the phase of a second-order harmonic wave at the fourth output end of the power amplifier **21**. In this embodiment, the phase of the second-order harmonic wave at the fourth output end of the power amplifier **21** is +90 degrees, and the phase of the second-order harmonic wave at the fifth output end of the power amplifier **31** is −90 degrees.

[0041] The power amplifier circuit **20** includes a harmonic wave phase shift circuit **22**, in addition to the power amplifier **21**. The harmonic wave phase shift circuit **22** is an example of a first harmonic wave phase shift circuit. The harmonic wave phase shift circuit **22** is connected to a path connecting the fourth output end of the power amplifier **21** to an in-phase combiner **41** and shifts the phase of a harmonic wave in the first band. The harmonic wave phase shift circuit **22** does not considerably shift the phase of a fundamental wave in the first band. In this embodiment, the pass phase of a second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees.

[0042] The power amplifier circuit **30** includes a harmonic wave phase shift circuit **32**, in addition to the power amplifier **31**. The harmonic wave phase shift circuit **32** is an example of a second harmonic wave phase shift circuit. The harmonic wave phase shift circuit **32** is connected to a path connecting the fifth output end of the power amplifier **31** to the in-phase combiner **41** and shifts the phase of a harmonic wave in the first band. The harmonic wave phase shift circuit **32** does not considerably shift the phase of a fundamental wave in the first band. In this embodiment, the pass phase of a second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees.

[0043] The amplifier transistor included in each of the power amplifiers **21** and **31** 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). In the case where the amplifier transistors mentioned above are bipolar transistors, the fourth input end of the power amplifier **21** and the fifth input end of the power amplifier **31** serve as, for example, base ends of the bipolar transistors and the fourth output end of the power amplifier **21** and the fifth output end of the power amplifier **31** serve as, for example, collector ends of the bipolar transistors. In the case where the amplifier transistors mentioned above are field effect transistors, the fourth input end of the power amplifier **21** and the fifth input end of the power amplifier **31** serve as, for example, gate ends of the field effect transistors and the fourth output end of the power amplifier **21** and the fifth output end of the power amplifier **31** serve as, for example, drain ends of the field effect transistors.

[0044] The in-phase combiner circuit **40** is an example of a combiner circuit and is configured to combine in an in-phase manner a first output signal output from the power amplifier circuit **20** and a second output signal output from the power amplifier circuit **30**. The in-phase combiner circuit **40** includes the in-phase combiner **41** and phase shift circuits **23** and **33**.

[0045] The in-phase combiner **41** is an example of a combiner and includes an input terminal **402** (second input end), an input terminal **403** (third input end), and an output terminal **401** (third output end). The in-phase combiner **41** is configured to output from the output terminal **401** a third output signal generated by combining in an in-phase manner the first output signal from the power amplifier circuit **20** input through the input terminal **402** and the second output signal from the power amplifier circuit **30** input through the input terminal **403**.

[0046] The phase shift circuit **23** is an example of a first phase shift circuit and is connected between the power amplifier circuit **20** and the in-phase combiner **41**. The phase shift circuit **23** is configured to shift phases of a fundamental wave and a harmonic wave in the first band. In this embodiment, the pass phase of the fundamental wave of the phase shift circuit **23** is −45 degrees, and the pass phase of the second-order harmonic wave is −45 degrees.

[0047] The phase shift circuit **33** is an example of a second phase shift circuit. The phase shift circuit **33** is connected between the power amplifier circuit **30** and the in-phase combiner **41** and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that the pass phase of the fundamental wave in the first band is +90 degrees relative to that of the phase shift circuit **23**. In this embodiment, the pass phase of the fundamental wave of the phase shift circuit **33** is +45 degrees, and the pass phase of the second-order harmonic wave is +45 degrees.

[0048] The pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** may be +X degrees (X>0), and the pass phase of the second-order harmonic wave of the phase shift circuit **23** may be −X degrees (X>0). That is, it is simply required that the pass phase of the second-order harmonic wave of a circuit consisting of the harmonic wave phase shift circuit **22** and the phase shift circuit **23** is 0 degrees.

[0049] Furthermore, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** may be −Y degrees (Y>0), and the pass phase of the second-order harmonic wave of the phase shift circuit **33** may be +Y degrees (Y>0). That is, it is simply required that the pass phase of the second-order harmonic wave of a circuit consisting of the harmonic wave phase shift circuit **32** and the phase shift circuit **33** is 0 degrees.

[0050] FIG. **2** includes Smith charts illustrating harmonic wave impedances of the power amplifier circuits **20** and **30** in this embodiment. As illustrated in the drawing, in the amplifier circuit **1** according to this embodiment, since the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees (+X degrees), the impedance of the second-order harmonic wave assuming the in-phase combiner circuit **40** side is seen from a connection point (node n**1**) between the fourth output end of the power amplifier **21** and the harmonic wave phase shift circuit **22** is located in the region of an inductive reactance (inductive impedance). In contrast, since the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees (−Y degrees), the impedance of the second-order harmonic wave assuming the in-phase combiner circuit **40** side is seen from a connection point (node n**2**) between the fifth output end of the power amplifier **31** and the harmonic wave phase shift circuit **32** is located in the region of a capacitive reactance (capacitive impedance).

[0051] That is, in the amplifier circuit **1** according to this embodiment, the power amplifier circuit **20** serves as an inverse class-E amplifier that makes the load impedance inductive with respect to the second-order harmonic wave, and the power amplifier circuit **30** serves as a class-E amplifier that makes the load impedance capacitive with respect to the second-order harmonic wave.

[0052] In other words, there is a phase difference of 90 degrees (or X+Y degrees) between the phase of the impedance with respect to the second-order harmonic wave at the node n**1** of the power amplifier circuit **20** and the phase of the impedance with respect to the second-order harmonic wave at the node n**2** of the power amplifier circuit **30**.

[0053] FIG. **3** is a circuit configuration diagram of an amplifier circuit **500** according to a comparative example. As illustrated in the drawing, the amplifier circuit **500** includes a splitter **10**, power amplifier circuits **520** and **530**, phase shift circuits **23** and **33**, and an in-phase combiner **41**. The amplifier circuit **500** according to the comparative example is different from the amplifier circuit **1** according to this embodiment in the configurations of the power amplifier circuits **520** and **530**. Description of configuration features of the amplifier circuit **500** according to the comparative example that are the same as those of the amplifier circuit **1** according to the embodiment will be omitted, and different configuration features will be mainly described below.

[0054] The power amplifier circuit **520** includes a power amplifier **21**. In this comparative example, the phase of a fundamental wave at the fourth output end (node n**1**) of the power amplifier **21** is +45 degrees relative to the phase of a fundamental wave signal input to the input terminal **101** of the splitter **10**, and the phase of a second-order harmonic wave is +90 degrees.

[0055] The power amplifier circuit **530** includes a power amplifier **31**. In this comparative example, the phase of a fundamental wave at the fifth output end (node n**2**) of the power amplifier **31** is −45 degrees relative to the phase of the fundamental wave signal input to the input terminal **101** of the splitter **10**, and the phase of the second-order harmonic wave is −90 degrees.

[0056] With the configuration of the amplifier circuit **500** according to the comparative example described above, the phase of a fundamental wave of a first output signal at the node n**1** output from the power amplifier **21** is +45 degrees, and the phase of the fundamental wave at the input terminal **402**, after passing through the phase shift circuit **23**, becomes 0 degrees. The phase of a fundamental wave of a second output signal at the node n**2** output from the power amplifier **31** is −45 degrees, and the phase of the fundamental wave at the input terminal **403**, after passing through the phase shift circuit **33**, becomes 0 degrees. Thus, the fundamental wave signals in the first band are combined in an in-phase manner at the in-phase combiner **41** and output as a third output signal from the output terminal **401**. Accordingly, the amplifier circuit **500** operates as a balanced amplifier that is resistant to changes in the load.

[0057] Meanwhile, the phase of a second-order harmonic wave of the first output signal at the node n**1** output from the power amplifier **21** is +90 degrees, and the phase of the second-order harmonic wave at the input terminal **402**, after passing through the phase shift circuit **23**, becomes +45 degrees. Furthermore, the phase of a second-order harmonic wave of the second output signal at the node n**2** output from the power amplifier **31** is −90 degrees, and the phase of the second-order harmonic wave at the input terminal **403**, after passing through the phase shift circuit **33**, becomes −45 degrees. Thus, the second-order harmonic waves in the first band have a phase difference of 90 degrees between the input terminals **402** and **403** of the in-phase combiner **41** and are not suppressed. Accordingly, neither the quality of transmission signals nor power efficiency is improved in the amplifier circuit **500**.

[0058] In contrast, with the configuration of the amplifier circuit **1** according to this embodiment described above, the phase of the fundamental wave of the first output signal at the node n**1** output from the power amplifier **21** is +45 degrees, and the phase of the fundamental wave at the input terminal **402**, after passing through the phase shift circuit **23**, becomes 0 degrees. Furthermore, the phase of the fundamental wave of the second output signal at the node n**2** output from the power amplifier **31** is −45 degrees, and the phase of the fundamental wave at the input terminal **403**, after passing through the phase shift circuit **33**, becomes 0 degrees. Thus, the fundamental wave signals in the first band are combined in an in-phase manner at the in-phase combiner **41** and output as a third output signal from the output terminal **401**. Accordingly, the amplifier circuit **1** operates as a balanced amplifier that is resistant to changes in the load.

[0059] Meanwhile, the phase of a second-order harmonic wave of the first output signal at the node n**1** output from the power amplifier **21** is +135 degrees (or +90+X degrees), and the phase of the second-order harmonic wave at the input terminal **402**, after passing through the phase shift circuit **23**, becomes +90 degrees. Furthermore, the phase of a second-order harmonic wave of a second output signal at the node n**2** output from the power amplifier **31** is −135 degrees (or −90−Y degrees), and the phase of the second-order harmonic wave at the input terminal **403**, after passing through the phase shift circuit **33**, becomes −90 degrees. Thus, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**.

[0060] Furthermore, since each of the power amplifier circuits **20** and **30** in this embodiment is not a class-F amplifier in which the load impedance of even-order harmonic waves is short-circuited and the load impedance of odd-order harmonic waves is open and it is simply required that load impedances of second-order harmonic waves are divided into being inductive and being capacitive, the second-order harmonic waves can be canceled with high accuracy over, for example, the entire range of a wide band defined by 3GPP and a high transmission quality and a high power efficiency can be ensured.

[0061] In the amplifier circuit **1** according to this embodiment, a first phase shift difference (90 degrees or (+X+Y degrees)) obtained by subtracting the pass phase (−45 degrees or (−Y degrees)) of the harmonic wave of the harmonic wave phase shift circuit **32** from the pass phase (+45 degrees or (+X degrees)) of the harmonic wave of the harmonic wave phase shift circuit **22** is equal to a second phase shift difference (90 degrees (or +Y+X degrees)) obtained by subtracting the pass phase (−45 degrees (or −X degrees)) of the harmonic wave of the phase shift circuit **23** from the pass phase (+45 degrees (or +Y degrees)) of the harmonic wave of the phase shift circuit **33**.

[0062] Thus, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**.

[0063] Furthermore, since it is simply required that the second-order harmonic waves in the first band have a phase difference of 180 degrees between the input terminals **402** and **403** of the in-phase combiner **41**, the second-order harmonic waves can be canceled with high accuracy over the entire range of a wide band and a high transmission quality and a high power efficiency can be ensured.

[0064] In the amplifier circuit **1** according to this embodiment, the phase difference obtained by subtracting the phase of the second-order harmonic wave in the first band at the input terminal **403** from the phase of the second-order harmonic wave in the first band at the input terminal **402** should be larger than 90 degrees.

[0065] Thus, compared to the amplifier circuit **500** according to the comparative example, the second-order harmonic waves in the first band can be suppressed. Accordingly, compared to a conventional balanced amplifier in which a harmonic wave phase shift circuit is not additionally provided, the quality of transmission signals and power efficiency can be improved.

[0066] Next, specific circuit configurations of the harmonic wave phase shift circuits **22** and **32** and the phase shift circuits **23** and **33** in this embodiment will be described.

[0067] FIG. **4**A is a diagram illustrating an example of the circuit configuration of the harmonic wave phase shift circuit **22** in this embodiment. As illustrated in the drawing, the harmonic wave phase shift circuit **22** includes, for example, an inductor **221** and a capacitor **222**. The inductor **221** (third inductor) and the capacitor **222** (third capacitor) are connected in series to form an LC circuit, and the LC circuit is connected between a path connecting the fourth output end to an inductor **231** of the phase shift circuit **23** and the ground. The harmonic wave phase shift circuit **22** serves as a notch filter in which a fundamental wave band of the first band serves as a pass band and a second-order harmonic wave band serves as an attenuation band. The pass phase of the fundamental wave is, for example, 0 degrees, and the pass phase of the second-order harmonic wave is, for example, +45 degrees (+X degrees: X>0).

[0068] FIG. **4**B is a diagram illustrating an example of the circuit configuration of the harmonic wave phase shift circuit **32** in this embodiment. As illustrated in the drawing, the harmonic wave phase shift circuit **32** includes, for example, a capacitor **321** (fourth capacitor) that is connected between a path connecting the fifth output end to a capacitor **331** of the phase shift circuit **33** and the ground. The harmonic wave phase shift circuit **32** serves as a low pass filter in which a fundamental wave band of the first band serves as a pass band and a second-order harmonic wave band serves as an attenuation band. The pass phase of the fundamental wave is, for example, 0 degrees, and the pass phase of the second-order harmonic wave is, for example, −45 degrees (−Y degrees: Y>0).

[0069] FIG. **4**C is a diagram illustrating an example of the circuit configuration of the phase shift circuit **23** in this embodiment. As illustrated in the drawing, the phase shift circuit **23** includes, for example, the inductor **231** and a capacitor **232**. The inductor **231** is an example of a first inductor and is connected between the fourth output end and the second input end. The capacitor **232** is an example of a first capacitor and is connected between a path connecting the inductor **231** to the second input end and the ground. The phase shift circuit **23** has a configuration of a low pass filter in which a fundamental wave band and a second-order harmonic wave band of the first band serve as a pass band. The pass phase of the fundamental wave in the first band is, for example, −45 degrees, and the pass phase of the second-order harmonic wave is, for example, −45 degrees (−X degrees).

[0070] FIG. **4**D is a diagram illustrating an example of the circuit configuration of the phase shift circuit **33** in this embodiment. As illustrated in the drawing, the phase shift circuit **33** includes, for example, the capacitor **331** and an inductor **332**. The capacitor **331** is an example of a second capacitor and is connected between the fifth output end and the third input end. The inductor **332** is an example of a second inductor and is connected between a path connecting the capacitor **331** to the third input end and the ground. The phase shift circuit **33** has a configuration of a high pass filter in which a fundamental wave band and a second-order harmonic wave band of the first band serve as a pass band. The pass phase of the fundamental wave in the first band is, for example, +45 degrees, and the pass phase of the second-order harmonic wave is, for example, +45 degrees (+Y degrees).

[0071] The phase shift circuits **23** and **33** and the harmonic wave phase shift circuits **22** and **32** may be included in a single semiconductor IC.

[0072] Accordingly, since the size of the amplifier circuit **1** can be reduced and the length of a signal wire from the power amplifiers **21** and **31** to the in-phase combiner **41** can be reduced, loss in signal transmission in the amplifier circuit **1** can be reduced.

2 Configuration of Amplifier Circuit 1A According to First Modification

[0073] Next, an amplifier circuit **1**A according to a first modification of the embodiment will be described. FIG. **5** is a circuit configuration diagram of the amplifier circuit **1**A according to the first modification of the embodiment. As illustrated in the drawing, the amplifier circuit **1**A includes a splitter **10**, power amplifier circuits **20**A and **30**A, and an in-phase combiner circuit **40**. The amplifier circuit **1**A according to this modification is different from the amplifier circuit **1** according to the embodiment in the configurations of the power amplifier circuits **20**A and **30**A. Description of configuration features of the amplifier circuit **1**A according to this modification that are the same as those of the amplifier circuit **1** according to the embodiment will be omitted, and different configuration features will be mainly described below.

[0074] The power amplifier circuit **20**A is an example of a first power amplifier circuit and includes a power amplifier **21**. The power amplifier **21** has the same configuration as the configuration of the power amplifier **21** in the embodiment. The power amplifier circuit **20**A includes a harmonic wave phase shift circuit **22**A, in addition to the power amplifier **21**. The harmonic wave phase shift circuit **22**A is an example of a first harmonic wave phase shift circuit. The harmonic wave phase shift circuit **22**A is connected to a path connecting the fourth output end of the power amplifier **21** to the in-phase combiner **41** and shifts the phase of a harmonic wave in the first band. The harmonic wave phase shift circuit **22**A does not considerably shift the phase of a fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22**A is +Z degrees (Z>0).

[0075] The power amplifier circuit **30**A is an example of a second power amplifier circuit and includes a power amplifier **31**. The power amplifier **31** has the same configuration as the configuration of the power amplifier **31** in the embodiment. The power amplifier circuit **30**A includes a harmonic wave phase shift circuit **32**A, in addition to the power amplifier **31**. The harmonic wave phase shift circuit **32**A is an example of a second harmonic wave phase shift circuit. The harmonic wave phase shift circuit **32**A is connected to a path connecting the fifth output end of the power amplifier **31** to the in-phase combiner **41** and shifts the phase of a harmonic wave in the first band. The harmonic wave phase shift circuit **32**A does not considerably shift the phase of a fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32**A is −Z degrees (Z>0).

[0076] The phase shift circuit **23** is an example of a first phase shift circuit. The phase shift circuit **23** is connected between the power amplifier circuit **20**A and the in-phase combiner **41** and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band. In this modification, the pass phase of the fundamental wave of the phase shift circuit **23** is −45 degrees, and the pass phase of the second-order harmonic wave is −X degrees (X>0).

[0077] The phase shift circuit **33** is an example of a second phase shift circuit. The phase shift circuit **33** is connected between the power amplifier circuit **30**A and the in-phase combiner **41** and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that the pass phase of the fundamental wave in the first band is +90 degrees relative to that of the phase shift circuit **23**. In this modification, the pass phase of the fundamental wave of the phase shift circuit **33** is +45 degrees, and the pass phase of the second-order harmonic wave is +Y degrees (Y>0).

[0078] With the configuration of the amplifier circuit **1**A according to this modification described above, the phase of a fundamental wave of a first output signal at the node n**1** output from the power amplifier **21** is +45 degrees, and the phase of the fundamental wave at the input terminal **402**, after passing through the phase shift circuit **23**, becomes 0 degrees. Furthermore, the phase of a fundamental wave of a second output signal at the node n**2** output from the power amplifier **31** is −45 degrees, and the phase of the fundamental wave at the input terminal **403**, after passing through the phase shift circuit **33**, becomes 0 degrees. Thus, the fundamental wave signals in the first band are combined in an in-phase manner at the in-phase combiner **41** and output as a third output signal from the output terminal **401**. Accordingly, the amplifier circuit **1**A operates as a balanced amplifier that is resistant to changes in the load.

[0079] In contrast, the phase of a second-order harmonic wave of the first output signal at the node n**1** output from the power amplifier **21** is +90+Z degrees, and the phase of the second-order harmonic wave at the input terminal **402**, after passing through the phase shift circuit **23**, becomes +90+Z-X degrees. Furthermore, the phase of a second-order harmonic wave of the second output signal at the node n**2** output from the power amplifier **31** is −90−Z degrees, and the phase of the second-order harmonic wave at the input terminal **403**, after passing through the phase shift circuit **33**, becomes −90−Z+Y degrees. Thus, the second-order harmonic waves in the first band have a phase difference of (+90+Z−X)−(−90−Z+Y)=180+2Z−X−Y between the input terminals **402** and **403** of the in-phase combiner **41**. This phase difference is larger than 90 degrees.

[0080] Thus, compared to the amplifier circuit **500** according to the comparative example, the second-order harmonic waves in the first band can be suppressed. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved compared to a conventional balanced amplifier in which a harmonic wave phase shift circuit is not additionally provided.

3 Configuration of Amplifier Circuit 1B According to Second Modification

[0081] Next, an amplifier circuit **1**B according to a second modification of the embodiment will be described. FIG. **6** is a circuit configuration diagram of the amplifier circuit **1**B according to the second modification of the embodiment. As illustrated in the drawing, the amplifier circuit **1**B includes a splitter **10**, power amplifiers **21** and **31**, harmonic wave phase shift circuits **22** and **32**, phase shift circuits **23** and **33**, and an in-phase combiner **41**. The amplifier circuit **1**B according to this modification is different from the amplifier circuit **1** according to the embodiment in the connection arrangement of the harmonic wave phase shift circuits and the phase shift circuits. Description of configuration features of the amplifier circuit **1**B according to this modification that are the same as those of the amplifier circuit **1** according to the embodiment will be omitted, and different configuration features will be mainly described below.

[0082] The phase shift circuit **23** is an example of a first phase shift circuit. The phase shift circuit **23** is connected between the power amplifier **21** and the in-phase combiner **41** and is configured to shift phases of a fundamental wave and a harmonic wave in the first band. In this modification, the pass phase of the fundamental wave of the phase shift circuit **23** is −45 degrees, and the pass phase of the second-order harmonic wave is −45 degrees (or −X degrees: X>0).

[0083] The phase shift circuit **33** is an example of a second phase shift circuit. The phase shift circuit **33** is connected between the power amplifier **31** and the in-phase combiner **41** and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that the pass phase of the fundamental wave in the first band is +90 degrees relative to that of the phase shift circuit **23**. In this modification, the pass phase of the fundamental wave of the phase shift circuit **33** is +45 degrees, and the pass phase of the second-order harmonic wave is +45 degrees (or +Y degrees: Y>0).

[0084] The harmonic wave phase shift circuit **22** is an example of a first harmonic wave phase shift circuit. The harmonic wave phase shift circuit **22** is connected to a path connecting the phase shift circuit **23** to the in-phase combiner **41** and shifts the phase of the harmonic wave in the first band. The harmonic wave phase shift circuit **22** does not considerably shift the phase of the fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees (or +X degrees: X>0).

[0085] The harmonic wave phase shift circuit **32** is an example of a second harmonic wave phase shift circuit. The harmonic wave phase shift circuit **32** is connected to a path connecting the phase shift circuit **33** to the in-phase combiner **41** and shifts the phase of the harmonic wave in the first band. The harmonic wave phase shift circuit **32** does not considerably shift the phase of the fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees (or −Y: Y>0).

[0086] With the configuration of the amplifier circuit **1**B according to this modification described above, the phase of a fundamental wave of a first output signal at the fourth output end (node n**1**) of the power amplifier **21** is +45 degrees, and the phase of the fundamental wave at the input terminal **402**, after passing through the phase shift circuit **23** and the harmonic wave phase shift circuit **22**, becomes 0 degrees. Furthermore, the phase of a fundamental wave of a second output signal at the fifth output end (node n**2**) of the power amplifier **31** is −45 degrees, and the phase of the fundamental wave at the input terminal **403**, after passing through the phase shift circuit **33** and the harmonic wave phase shift circuit **32**, becomes 0 degrees. Thus, the fundamental wave signals in the first band are combined in an in-phase manner at the in-phase combiner **41** and output as a third output signal from the output terminal **401**. Accordingly, the amplifier circuit **1**B operates as a balanced amplifier that is resistant to changes in the load.

[0087] In contrast, the phase of a second-order harmonic wave of the first output signal at the node n**1** output from the power amplifier **21** is +90 degrees, and the phase of the second-order harmonic wave at the input terminal **402**, after passing through the phase shift circuit **23** and the harmonic wave phase shift circuit **22**, becomes +90 degrees. Furthermore, the phase of a second-order harmonic wave of the second output signal at the node n**2** output from the power amplifier **31** is −90 degrees, and the phase of the second-order harmonic wave at the input terminal **403**, after passing through the phase shift circuit **33** and the harmonic wave phase shift circuit **32**, becomes −90 degrees. Thus, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**B.

[0088] In the amplifier circuit **1**B according to this modification, the power amplifier **21**, the phase shift circuit **23**, and the harmonic wave phase shift circuit **22** are connected in this order. Thus, the impedance of the second-order harmonic wave assuming the in-phase combiner **41** side is seen from the fourth output end (node n**1**) of the power amplifier **21** is not inductive, and the power amplifier **21** does not serve as an inverse class-E amplifier. Furthermore, since the power amplifier **31**, the phase shift circuit **33**, and the harmonic wave phase shift circuit **32** are connected in this order, the impedance of the second-order harmonic wave assuming the in-phase combiner **41** side is seen from the fifth output end (node n**2**) of the power amplifier **31** is not capacitive, and the power amplifier **31** does not serve as a class-E amplifier.

4 Configuration of Amplifier Circuit 1C According to Third Modification

[0089] Next, an amplifier circuit **1**C according to a third modification of the embodiment will be described. FIG. **7** is a circuit configuration diagram of the amplifier circuit **1**C according to the third modification of the embodiment. As illustrated in the drawing, the amplifier circuit **1**C includes a splitter **10**, power amplifier circuits **20** and **30**, and an anti-phase combiner circuit **40**C. The amplifier circuit **1**C according to this modification is different from the amplifier circuit **1** according to the embodiment in the configuration of a combiner circuit. Description of configuration features of the amplifier circuit **1**C according to this modification that are the same as those of the amplifier circuit **1** according to the embodiment will be omitted, and different configuration features will be mainly described below.

[0090] The anti-phase combiner circuit **40**C is an example of a combiner circuit and is configured to combine in an anti-phase manner a first output signal output from the power amplifier circuit **20** and a second output signal output from the power amplifier circuit **30**. The anti-phase combiner circuit **40**C includes a transformer **42** and phase shift circuits **23**C and **33**C.

[0091] The transformer **42** includes an input terminal **422** (second input end), which is one end of a primary side coil, an input terminal **423** (third input end), which is the other end of the primary side coil, and an output terminal **421** (third output end), which is one end of a secondary side coil that is electromagnetically coupled to the primary side coil. The other end of the secondary side coil is connected to the ground. With the configuration described above, the transformer **42** is configured to output from the output terminal **421** a third output signal generated by combining in an anti-phase manner the first output signal from the power amplifier circuit **20** input through the input terminal **422** and the second output signal from the power amplifier circuit **30** input through the input terminal **423**.

[0092] The phase shift circuit **23**C is an example of a first phase shift circuit. The phase shift circuit **23**C is connected between the power amplifier circuit **20** and the transformer **42** and is configured to shift phases of a fundamental wave and a harmonic wave in the first band. In this modification, the pass phase of the fundamental wave of the phase shift circuit **23**C is +45 degrees, and the pass phase of the second-order harmonic wave is +45 degrees.

[0093] The phase shift circuit **33**C is an example of a second phase shift circuit. The phase shift circuit **33**C is connected between the power amplifier circuit **30** and the transformer **42** and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that the pass phase of the fundamental wave in the first band is −90 degrees relative to that of the phase shift circuit **23**C. In this modification, the pass phase of the fundamental wave of the phase shift circuit **33**C is −45 degrees, and the pass phase of the second-order harmonic wave is −45 degrees.

[0094] The pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** may be +X degrees (X>0), and the pass phase of the second-order harmonic wave of the phase shift circuit **23**C may be +X degrees (X>0).

[0095] Furthermore, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** may be −Y degrees (Y>0), and the pass phase of the second-order harmonic wave of the phase shift circuit **33**C may be −Y degrees (Y>0).

[0096] In the amplifier circuit **1**C according this modification, since the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees (+X degrees), the impedance of the second-order harmonic wave assuming the anti-phase combiner circuit **40**C side is seen from the connection point (node n**1**) between the fourth output end of the power amplifier **21** and the harmonic wave phase shift circuit **22** is located in the region of an inductive reactance (inductive impedance). In contrast, since the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees (−Y degrees), the impedance of the second-order harmonic wave assuming the anti-phase combiner circuit **40**C side is seen from the connection point (node n**2**) between the fifth output end of the power amplifier **31** and the harmonic wave phase shift circuit **32** is located in the region of a capacitive reactance (capacitive impedance).

[0097] That is, in the amplifier circuit **1**C according to this modification, the power amplifier circuit **20** serves as an inverse class-E amplifier that makes the load impedance inductive with respect to the second-order harmonic wave, and the power amplifier circuit **30** serves as a class-E amplifier that makes the load impedance capacitive with respect to the second-order harmonic wave.

[0098] In other words, there is a phase difference of 90 degrees (or X+Y degrees) between the phase of the impedance with respect to the second-order harmonic wave at the node n**1** of the power amplifier circuit **20** and the phase of the impedance with respect to the second-order harmonic wave at the node n**2** of the power amplifier circuit **30**.

[0099] With the configuration of the amplifier circuit **1**C according to this modification described above, the phase of the fundamental wave of the first output signal at the node n**1** output from the power amplifier **21** is +45 degrees, and the phase of the fundamental wave at the input terminal **422**, after passing through the phase shift circuit **23**C, becomes +90 degrees. Furthermore, the phase of the fundamental wave of the second output signal at the node n**2** output from the power amplifier **31** is −45 degrees, and the phase of the fundamental wave at the input terminal **423**, after passing through the phase shift circuit **33**C, becomes −90 degrees. Thus, the fundamental wave signals in the first band are combined in an anti-phase manner at the transformer **42** and output as the third output signal from the output terminal **421**. Accordingly, the amplifier circuit **1**C operates as a balanced amplifier that is resistant to changes in the load.

[0100] In contrast, the phase of the second-order harmonic wave of the first output signal at the node n**1** output from the power amplifier **21** is +135 degrees (or +90+X degrees), and the phase of the second-order harmonic wave at the input terminal **422**, after passing through the phase shift circuit **23**C, becomes +180 degrees. Furthermore, the phase of the second-order harmonic wave of the second output signal at the node n**2** output from the power amplifier **31** is −135 degrees (or −90−Y degrees), and the phase of the second-order harmonic wave at the input terminal **423**, after passing through the phase shift circuit **33**C, becomes −180 degrees. Thus, the second-order harmonic waves in the first band have a phase difference of 360 degrees (in-phase relationship) between the input terminals **422** and **423** of the transformer **42** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**C.

[0101] Furthermore, since each of the power amplifier circuits **20** and **30** in this modification is not a class-F amplifier in which the load impedance of even-order harmonic waves is short-circuited and the load impedance of odd-order harmonic waves is open and it is simply required that load impedances of second-order harmonic waves are divided into being inductive and being capacitive, the second-order harmonic waves can be canceled with high accuracy over, for example, the entire range of a wide band defined by 3GPP and a high transmission quality and a high power efficiency can be ensured.

[0102] In the amplifier circuit **1**C according to this modification, a first phase shift difference (90 degrees or (+X+Y degrees)) obtained by subtracting the pass phase (−45 degrees or (−Y degrees)) of the harmonic wave of the harmonic wave phase shift circuit **32** from the pass phase (+45 degrees or (+X degrees)) of the harmonic wave of the harmonic wave phase shift circuit **22** is equal to a second phase shift difference (90 degrees (or +Y+X degrees)) obtained by subtracting the pass phase (−45 degrees (or −Y degrees)) of the harmonic wave of the phase shift circuit **33**C from the pass phase (+45 degrees (or +X degrees)) of the harmonic wave of the phase shift circuit **23**C.

[0103] Accordingly, the second-order harmonic waves in the first band become in the in-phase relationship between the input terminals **422** and **423** of the transformer **42** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**C.

[0104] Furthermore, it is simply required that the second-order harmonic waves in the first band have a phase difference of 0 degrees (±360×m: m is a natural number) between the input terminals **422** and **423** of the transformer **42**. Therefore, the second-order harmonic waves can be canceled with high accuracy over the entire range of a wide band, and a high transmission quality and a high power efficiency can be ensured.

[0105] In the amplifier circuit **1**C according to this modification, the phase difference obtained by subtracting the phase of the second-order harmonic wave in the first band at the input terminal **423** from the phase of the second-order harmonic wave in the first band at the input terminal **422** should be smaller than 90 degrees.

[0106] Accordingly, since the second-order harmonic waves in the first band are suppressed, the quality of transmission signals and power efficiency can be improved compared to a conventional balanced amplifier of an anti-phase combining type in which a harmonic wave phase shift circuit is not additionally provided.

5 Configuration of Amplifier Circuit 1D According to Fourth Modification

[0107] Next, an amplifier circuit **1**D according to a fourth modification of the embodiment will be described. FIG. **8**A is a circuit configuration diagram of the amplifier circuit **1**D according to the fourth modification of the embodiment. As illustrated in the drawing, the amplifier circuit **1**D includes a splitter **10**, power amplifiers **21** and **31**, harmonic wave phase shift circuits **22** and **32**, and a phase shift line **50**. The amplifier circuit **1**D according to this modification is different in that the amplifier circuit **1**D also operates as a Doherty amplifier. Description of configuration features of the amplifier circuit **1**D according to this modification that are the same as those of the amplifier circuit **1** according to the embodiment will be omitted, and different configuration features will be mainly described below.

[0108] The splitter **10** includes an input terminal **101** (first input end), an output terminal **102** (first output end), and an output terminal **103** (second output end). The splitter **10** is configured to split a fundamental wave signal in a transmission band of a first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees (delayed by 90 degrees) relative to a phase of the first signal.

[0109] The power amplifier **21** is an example of a carrier amplifier and includes an amplifier transistor. The power amplifier **21** has a third input end and a fourth output end, and the third input end is connected to the output terminal **102** of the splitter **10**.

[0110] The power amplifier **31** is an example of a peak amplifier and includes an amplifier transistor. The power amplifier **31** has a fourth input end and a fifth output end, and the fourth input end is connected to the output terminal **103** of the splitter **10**.

[0111] The amplifier transistor in each of the power amplifiers **21** and **31** is, for example, a bipolar transistor such as an HBT or a field-effect transistor such as a MOSFET.

[0112] The power amplifier **21** amplifies a transmission signal in the first band input to the third input end thereof. The power amplifier **21** is, for example, a class-A (or class-AB) amplifier circuit that is capable of performing an amplifying operation for all the power levels of signals input to the power amplifier **21**. In particular, the power amplifier **21** is capable of performing a highly efficient amplifying operation in a low output region and a medium output region.

[0113] The power amplifier **31** amplifies a transmission signal in the first band input to the fourth input end thereof. The power amplifier **31** is, for example, a class-C amplifier circuit that is capable of performing an amplifying operation in a region where the power level of signals input to the power amplifier **31** is high. A bias current smaller than a bias current applied to the amplifier transistor included in the power amplifier **21** may be applied to the amplifier transistor included in the power amplifier **31**. Accordingly, as the power level of a signal input to the power amplifier **31** increases, the output impedance decreases. Thus, the power amplifier **31** is capable of performing a low-distortion amplifying operation in a high output region.

[0114] Since the power amplifier **21** amplifies the first signal output from the splitter **10** and the power amplifier **31** amplifies the second signal output from the splitter **10**, the phase of a fundamental wave at the fifth output end of the power amplifier **31** is delayed by 90 degrees with respect to the phase of a fundamental wave at the fourth output end of the power amplifier **21**.

[0115] The phase shift line **50** has a second input end and a third output end. The second input end is connected to the fourth output end, and the third output end is connected to the fifth output end with the output terminal **104** interposed therebetween. The phase shift line **50** is configured to delay a fundamental wave of a first output signal from the power amplifier **21** input through the second input end by 90 degrees. Due to the arrangement of the phase shift line **50**, the phase of the fundamental wave of the first output signal output from the power amplifier **21** and the phase of a fundamental wave of a second output signal output from the power amplifier **31** are made to match. Accordingly, the fundamental wave of the first output signal and the fundamental wave of the second output signal are combined in an in-phase manner (current combining) at the output terminal **104**. The phase shift line **50** and the output terminal **104** form a combiner circuit.

[0116] The harmonic wave phase shift circuit **22** is an example of a first harmonic wave phase shift circuit. The harmonic wave phase shift circuit **22** is connected to a path connecting the fourth output end of the power amplifier **21** to the second input end of the phase shift line **50** and shifts the phase of a harmonic wave in the first band. The harmonic wave phase shift circuit **22** does not considerably shift the phase of a fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees.

[0117] The harmonic wave phase shift circuit **32** is an example of a second harmonic wave phase shift circuit. The harmonic wave phase shift circuit **32** is connected to a path connecting the fifth output end of the power amplifier **31** to the output terminal **104** and shifts the phase of the harmonic wave in the first band. The harmonic wave phase shift circuit **32** does not considerably shift the phase of the fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees.

[0118] The pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** may be +X degrees (X>0), and the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** may be −Y degrees (Y>0).

[0119] The power amplifier **21** and the harmonic wave phase shift circuit **22** form a first power amplifier circuit, and the power amplifier **31** and the harmonic wave phase shift circuit **32** form a second power amplifier circuit.

[0120] With the configuration of the amplifier circuit **1**D described above, the output impedance of the power amplifier **21** at the time assuming a small signal is input is higher than that at the time assuming a large signal is input. That is, assuming a small signal is input, the power amplifier **31** enters an OFF state, and the output impedance of the power amplifier **21** increases. Thus, the amplifier circuit **1**D can operate with high efficiency.

[0121] In contrast, assuming a large signal is input, operation of the power amplifiers **21** and **31** allows a large power signal to be output and a decrease in the output impedance of the power amplifier **31** allows signal distortion to be suppressed.

[0122] Furthermore, since the phase of the fundamental wave at the fifth output end of the power amplifier **31** is delayed by 90 degrees with respect to the phase of the fundamental wave at the fourth output end of the power amplifier **21**, the phase of the second-order harmonic wave at the fifth output end of the power amplifier **31** is delayed by 180 degrees with respect to the phase of the second-order harmonic wave at the fourth output end of the power amplifier **21**. In this modification, the phase of the second-order harmonic wave at the fourth output end of the power amplifier **21** is +90 degrees, and the phase of the second-order harmonic wave at the fifth output end of the power amplifier **31** is −90 degrees.

[0123] With the configuration of the amplifier circuit **1**D according to this modification described above, the phase of the second-order harmonic wave of the first output signal at the connection point (node n**1**) between the fourth output end of the power amplifier **21** and the harmonic wave phase shift circuit **22** is +135 degrees (or +90+X degrees) and the phase of the second-order harmonic wave at the output terminal **104**, after passing through the phase shift line **50**, becomes +45 (or X degrees). Furthermore, the phase of the second-order harmonic wave of the second output signal at the node n**2** output from the power amplifier **31** is −135 degrees (or −90−Y degrees), and the phase of the second-order harmonic wave at the output terminal **104** is −135 degrees (or −90−Y degrees). Accordingly, the second-order harmonic wave of the first output signal and the second-order harmonic wave of the second output signal have a phase difference of 180 degrees (anti-phase relationship) at the output terminal **104** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**D.

[0124] Furthermore, in the amplifier circuit **1**D according to this modification, the first power amplifier circuit serves as an inverse class-E amplifier that makes the load impedance inductive with respect to the second-order harmonic wave and the second power amplifier circuit serves as a class-E amplifier that makes the load impedance capacitive with respect to the second-order harmonic wave.

[0125] Accordingly, the second-order harmonic waves can be canceled with high accuracy over, for example, the entire range of a wide band defined by 3GPP, and a high transmission quality and a high power efficiency can be ensured.

[0126] In the amplifier circuit **1**D according to this modification, the phase difference obtained by subtracting the phase of the second-order harmonic wave of the second output signal at the output terminal **104** from the phase of the second-order harmonic wave of the first output signal at the output terminal **104** should be larger than 90 degrees.

[0127] Accordingly, since the second-order harmonic waves in the first band are suppressed, the quality of transmission signals and power efficiency can be improved compared to a conventional Doherty amplifier in which a harmonic wave phase shift circuit is not additionally provided.

6 Configuration of Amplifier Circuit 1E According to Fifth Modification

[0128] Next, an amplifier circuit **1**E according to a fifth modification of the embodiment will be described. FIG. **8**B is a circuit configuration diagram of the amplifier circuit **1**E according to the fifth modification of the embodiment. As illustrated in the drawing, the amplifier circuit **1**E includes a splitter **10**, power amplifiers **21** and **31**, harmonic wave phase shift circuits **22** and **32**, a phase shift line **51**, and a transformer **43**. The amplifier circuit **1**E according to this modification is different from the amplifier circuit **1**D according to the fourth modification in the configuration of signal combining. Description of configuration features of the amplifier circuit **1**E according to this modification that are the same as those of the amplifier circuit **1**D according to the fourth modification will be omitted, and different configuration features will be mainly described below.

[0129] The transformer **43** includes an input terminal **432** (third input end), which is one end of a primary side coil, an input terminal **433** (fourth input end), which is the other end of the primary side coil, and an output terminal **431** (fourth output end), which is one end of a secondary side coil that is electromagnetically coupled to the primary side coil. The other end of the secondary side coil is connected to the ground. With the configuration described above, the transformer **43** is configured to output from the output terminal **431** a third output signal generated by combining in an anti-phase manner a first output signal from the power amplifier circuit **20** input through the input terminal **432** and a second output signal from the power amplifier circuit **30** input through the input terminal **433**.

[0130] The phase shift line **51** has a second input end and a third output end and is configured to delay a fundamental wave of the second output signal from the power amplifier **31** input through the second input end by 90 degrees. Due to the arrangement of the phase shift line **51**, the phase of a fundamental wave of the first output signal output from the power amplifier **21** and the phase of a fundamental wave of the second output signal output from the power amplifier **31** become opposite. Accordingly, the fundamental wave of the first output signal and the fundamental wave of the second output signal are combined in an anti-phase manner (voltage combining) at the transformer **43**. The phase shift line **51** and the transformer **43** form a combiner circuit.

[0131] The power amplifier **21** is an example of a carrier amplifier and includes an amplifier transistor. The power amplifier **21** has a fifth input end and a fifth output end, the fifth input end is connected to the output terminal **102** of the splitter **10**, and the fifth output end is connected to the input terminal **432**.

[0132] The power amplifier **31** is an example of a peak amplifier and includes an amplifier transistor. The power amplifier **31** has a sixth input end and a sixth output end. The sixth input end is connected to the output terminal **103** of the splitter **10**, and the sixth output end is connected to the second input end. Furthermore, the third output end is connected to the input terminal **433**.

[0133] The power amplifier **21** amplifies a transmission signal in the first band input to the fifth input end thereof. The power amplifier **21** is, for example, a class-A (or class-AB) amplifier circuit that is capable of performing an amplifying operation for all the power levels of signals input to the power amplifier **21**. In particular, the power amplifier **21** is capable of performing a highly efficient amplifying operation in a low output region and a medium output region.

[0134] The power amplifier **31** amplifies a transmission signal in the first band input to the sixth input end thereof. The power amplifier **31** is, for example, a class-C amplifier circuit that is capable of performing an amplifying operation in a region where the power level of signals input to the power amplifier **31** is high. A bias current smaller than a bias current applied to the amplifier transistor included in the power amplifier **21** may be applied to the amplifier transistor included in the power amplifier **31**. Accordingly, as the power level of a signal input to the power amplifier **31** increases, the output impedance decreases. Thus, the power amplifier **31** is capable of performing a low-distortion amplifying operation in a high output region.

[0135] Since the power amplifier **21** amplifies a first signal output from the splitter **10** and the power amplifier **31** amplifies a second signal output from the splitter **10**, the phase of the fundamental wave at the sixth output end of the power amplifier **31** is delayed by 90 degrees with respect to the phase of the fundamental wave at the fifth output end of the power amplifier **21**.

[0136] The harmonic wave phase shift circuit **22** is an example of a first harmonic wave phase shift circuit. The harmonic wave phase shift circuit **22** is connected to a path connecting the fifth output end to the input terminal **432** and shifts the phase of a harmonic wave in the first band. The harmonic wave phase shift circuit **22** does not considerably shift the phase of the fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees.

[0137] The harmonic wave phase shift circuit **32** is an example of a second harmonic wave phase shift circuit. The harmonic wave phase shift circuit **32** is connected to a path connecting the sixth output end to the second input end and shifts the phase of the harmonic wave in the first band. The harmonic wave phase shift circuit **32** does not considerably shift the phase of the fundamental wave in the first band. In this modification, the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees.

[0138] The pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** may be +X degrees (X>0), and the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** may be −Y degrees (Y>0).

[0139] The power amplifier **21** and the harmonic wave phase shift circuit **22** form a first power amplifier circuit, and the power amplifier **31** and the harmonic wave phase shift circuit **32** form a second power amplifier circuit.

[0140] With the configuration of the amplifier circuit **1**E described above, the output impedance of the power amplifier **21** at the time assuming a small signal is input is higher than that at the time assuming a large signal is input. That is, assuming a small signal is input, the power amplifier **31** enters an OFF state, and the output impedance of the power amplifier **21** increases. Thus, the amplifier circuit **1**E can operate with high efficiency.

[0141] In contrast, assuming a large signal is input, operation of the power amplifiers **21** and **31** allows a large power signal to be output and a decrease in the output impedance of the power amplifier **31** allows signal distortion to be suppressed.

[0142] Furthermore, since the phase of the fundamental wave at the sixth output end of the power amplifier **31** is delayed by 90 degrees with respect to the phase of the fundamental wave at the fifth output end of the power amplifier **21**, the phase of the second-order harmonic wave at the sixth output end of the power amplifier **31** is delayed by 180 degrees with respect to the phase of the second-order harmonic wave at the fifth output end of the power amplifier **21**. In this modification, the phase of the second-order harmonic wave at the fifth output end is +90 degrees, and the phase of the second-order harmonic wave at the sixth output end is −90 degrees.

[0143] With the configuration of the amplifier circuit **1**E according to this modification described above, the phase of the second-order harmonic wave of the first output signal at the connection point (node n**1**) between the fifth output end of the power amplifier **21** and the harmonic wave phase shift circuit **22** is +135 degrees (or +90+X degrees), and the phase of the second-order harmonic wave at the input terminal **432** is +135 degrees (or +90+X degrees). Furthermore, the phase of the second-order harmonic wave of the second output signal at the connection point (node n**2**) between the sixth output end of the power amplifier **31** and the harmonic wave phase shift circuit **32** is −135 degrees (or −90−Y degrees), and the phase of the second-order harmonic wave at the input terminal **433**, after passing through the phase shift line **51**, becomes −225 degrees (or −135−Y degrees). Thus, the second-order harmonic wave of the first output signal and the second-order harmonic wave of the second output signal have a phase difference of 360 degrees (in-phase relationship) between the input terminals **432** and **433** of the transformer **43** and are canceled. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**E.

[0144] Furthermore, in the amplifier circuit **1**E according to this modification, the first power amplifier circuit serves as an inverse class-E amplifier that makes the load impedance inductive with respect to the second-order harmonic wave, and the second power amplifier circuit serves as a class-E amplifier that makes the load impedance capacitive with respect to the second-order harmonic wave.

[0145] Accordingly, the second-order harmonic waves can be canceled with high accuracy over, for example, the entire range of a wide band defined by 3GPP, and a high transmission quality and a high power efficiency can be ensured.

[0146] In the amplifier circuit **1**E according to this modification, the phase difference obtained by subtracting the phase of the second-order harmonic wave of the second output signal at the input terminal **433** from the phase of the second-order harmonic wave of the first output signal at the input terminal **432** should be smaller than 90 degrees.

[0147] Accordingly, since the second-order harmonic waves in the first band are suppressed, the quality of transmission signals and power efficiency can be improved compared to a conventional Doherty amplifier in which a harmonic wave phase shift circuit is not additionally provided.

7 Configuration of Amplifier Circuit 1F According to Sixth Modification

[0148] Next, an amplifier circuit **1**F according to a sixth modification of the embodiment will be described. FIG. **9** is a circuit configuration diagram of the amplifier circuit **1**F according to the sixth modification of the embodiment. As illustrated in the drawing, the amplifier circuit **1**F includes a splitter **10**, power amplifier circuits **20** and **30**, and a 90-degree combiner **44**. The amplifier circuit **1**F according to this modification is different from the amplifier circuit **1** according to the embodiment in the configuration of a combiner circuit. Description of configuration features of the amplifier circuit **1**F according to this modification that are the same as those of the amplifier circuit **1** according to the embodiment will be omitted, and different configuration features will be mainly described below.

[0149] The combiner circuit in this modification includes the 90-degree combiner **44** but includes no phase shift circuit. The 90-degree combiner **44** includes an input terminal **442** (second input end), an input terminal **443** (third input end), and an output terminal **441** (third output end) and is configured to output from the output terminal **441** a third output signal generated by combining a first output signal input through the input terminal **442** and a signal obtained by shifting the phase of a second output signal input through the input terminal **443** to become +90 degrees with respect to the phase of the first output signal.

[0150] With the amplifier circuit **1**F according to this modification, since the pass phase of a second-order harmonic wave of the harmonic wave phase shift circuit **22** is +45 degrees, the impedance of the second-order harmonic wave assuming the 90-degree combiner **44** side is seen from the connection point (node n**1**) between the fourth output end of the power amplifier **21** and the harmonic wave phase shift circuit **22** is located in the region of an inductive reactance (inductive impedance). In contrast, since the pass phase of a second-order harmonic wave of the harmonic wave phase shift circuit **32** is −45 degrees, the impedance of the second-order harmonic wave assuming the 90-degree combiner **44** side is seen from the connection point (node n**2**) between the fifth output end of the power amplifier **31** and the harmonic wave phase shift circuit **32** is located in the region of a capacitive reactance (capacitive impedance).

[0151] That is, in the amplifier circuit **1**F according to this modification, the power amplifier circuit **20** serves as an inverse class-E amplifier that makes the load impedance inductive with respect to the second-order harmonic wave, and the power amplifier circuit **30** serves as a class-E amplifier that makes the load impedance capacitive with respect to the second-order harmonic wave.

[0152] In other words, the phase of the impedance with respect to the second-order harmonic wave at the node n**1** of the power amplifier circuit **20** and the phase of the impedance with respect to the second-order harmonic wave at the node n**2** of the power amplifier circuit **30** have a phase difference of 90 degrees.

[0153] With the configuration of the amplifier circuit **1**F according to this modification described above, the phase of a fundamental wave of the first output signal at the node n**1** output from the power amplifier **21** is +45 degrees and the phase of the fundamental wave at the input terminal **442** is +45 degrees. Furthermore, the phase of a fundamental wave of the second output signal at the node n**2** output from the power amplifier **31** is −45 degrees, and the phase of the fundamental wave at the input terminal **443** is −45 degrees. Thus, the fundamental wave signals in the first band are combined in an in-phase manner at the 90-degree combiner **44** and output as the third output signal from the output terminal **441**. Accordingly, the amplifier circuit **1**F operates as a balanced amplifier that is resistant to changes in the load.

[0154] In contrast, the phase of the second-order harmonic wave of the first output signal at the node n**1** output from the power amplifier **21** is +135 degrees, and the phase of the second-order harmonic wave at the input terminal **442** is +135 degrees. Furthermore, the phase of the second-order harmonic wave of the second output signal at the node n**2** output from the power amplifier **31** is −135 degrees, and the phase of the second-order harmonic wave at the input terminal **443** is −135 degrees. Thus, the second-order harmonic waves in the first band have a phase difference of 270 degrees between the input terminals **442** and **443**, and the phase difference becomes 180 degrees at the 90-degree combiner **44** and is canceled out. Therefore, since the second-order harmonic waves are suppressed, the quality of transmission signals and power efficiency can be improved in the amplifier circuit **1**F.

[0155] Furthermore, since each of the power amplifier circuits **20** and **30** in this modification is not a class-F amplifier in which the load impedance of even-order harmonic waves is short-circuited and the load impedance of odd-order harmonic waves is open and it is simply required that load impedances of second-order harmonic waves are divided into being inductive and being capacitive, the second-order harmonic waves can be canceled with high accuracy over, for example, the entire range of a wide band defined by 3GPP and a high transmission quality and a high power efficiency can be ensured.

8 Effects and Others

[0156] As described above, the amplifier circuit **1** according to this embodiment (the amplifier circuit **1**A according to the first modification and the amplifier circuit **1**D according to the fourth modification) includes the power amplifier circuit **20** (**20**A) that includes the power amplifier **21**, the power amplifier circuit **30** (**30**A) that includes the power amplifier **31** in which the phase of a fundamental wave at an output end thereof is delayed by 90 degrees with respect to the power amplifier **21**, and the in-phase combiner circuit **40** (phase shift line **50**) that is configured to combine a fundamental wave of a first output signal output from the power amplifier circuit **20** (**20**A) and a fundamental wave of a second output signal output from the power amplifier circuit **30** (**30**A). The power amplifier circuit **20** (**20**A) is of an inverse class-E type, and the power amplifier circuit **30** (**30**A) is of a class-E type.

[0157] Accordingly, since the power amplifier circuits **20** (**20**A) and **30** (**30**A) are not class-F amplifiers in which the load impedance of even-order harmonic waves is short-circuited and the load impedance of odd-order harmonic waves is open but are an inverse class-E amplifier and a class-E amplifier, respectively, in which load impedances of second-order harmonic waves are divided into being inductive and being capacitive, the second-order harmonic waves can be canceled with high accuracy over, for example, the entire range of a wide band defined by 3GPP. Thus, the amplifier circuit can function as a balanced amplifier that is resistant to changes in the load, and a high transmission quality and a high power efficiency can be ensured.

[0158] Furthermore, for example, the amplifier circuit **1** (**1**A) further includes the splitter **10** that includes the input terminal **101** and the output terminals **102** and **103** and is configured to split a fundamental wave signal in a transmission band of the first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees with respect to a phase of the first signal. The in-phase combiner circuit **40** includes the in-phase combiner **41** that includes the input terminals **402** and **403** and the output terminal **401** and is configured to output from the output terminal **401** a third output signal generated by combining in an in-phase manner the first output signal from the power amplifier circuit **20** (**20**A) input through the input terminal **402** and the second output signal from the power amplifier circuit **30** (**30**A) input through the input terminal **403**, the phase shift circuit **23** that is connected between the power amplifier circuit **20** (**20**A) and the in-phase combiner **41** and is configured to shift phases of a fundamental wave and a second-order harmonic wave in the first band, and the phase shift circuit **33** that is connected between the power amplifier circuit **30** (**30**A) and the in-phase combiner **41** and is configured to shift the phases of the fundamental wave and a second-order harmonic wave in the first band in such a manner that the pass phase of the fundamental wave is +90 degrees with respect to the phase shift circuit **23**. The power amplifier circuit **20** (**20**A) includes the power amplifier **21** that has the fourth input end and the fourth output end, the fourth input end being connected to the output terminal **102**, and the harmonic wave phase shift circuit **22** that is connected to a path connecting the fourth output end to the input terminal **402** and is configured to shift the phase of the second-order harmonic wave. The power amplifier circuit **30** (**30**A) includes the power amplifier **31** that has the fifth input end and the fifth output end, the fifth input end being connected to the output terminal **103**, and the harmonic wave phase shift circuit **32** that is connected to a path connecting the fifth output end to the input terminal **403** and is configured to shift the phase of the second-order harmonic wave. A phase shift difference obtained by subtracting the phase of the second-order harmonic wave at the input terminal **403** from the phase of the second-order harmonic wave at the input terminal **402** is larger than 90 degrees.

[0159] Accordingly, compared to a conventional balanced amplifier of an in-phase combining type in which a harmonic wave phase shift circuit is not additionally provided, the second-order harmonic waves in the first band can be suppressed over a wide range. Therefore, the quality of transmission signals and power efficiency can be improved.

[0160] Furthermore, for example, in the amplifier circuit **1**, a first phase shift difference obtained by subtracting the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** from the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is equal to a second phase shift difference obtained by subtracting the pass phase of the second-order harmonic wave of the phase shift circuit **23** from the pass phase of the second-order harmonic wave of the phase shift circuit **33**.

[0161] Accordingly, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Thus, the amplifier circuit **1** in which the quality of transmission signals and power efficiency are improved can be provided.

[0162] Furthermore, for example, in the amplifier circuit **1**, the phase shift circuit **23** is configured in such a manner that the pass phases of the fundamental wave and the second-order harmonic wave are −45 degrees, the phase shift circuit **33** is configured in such a manner that the pass phases of the fundamental wave and the second-order harmonic wave are +45 degrees, the harmonic wave phase shift circuit **22** is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and the harmonic wave phase shift circuit **32** is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0163] Accordingly, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Thus, the amplifier circuit **1** in which the quality of transmission signals and power efficiency are improved can be provided.

[0164] Furthermore, for example, in the amplifier circuit **1**, the phase shift circuit **23** is configured in such a manner that the pass phase of the fundamental wave is −45 degrees and the pass phase of the harmonic wave is −X degrees (X>0), the phase shift circuit **33** is configured in such a manner that the pass phase of the fundamental wave is +45 degrees and the pass phase of the harmonic wave is +Y degrees (Y>0), the harmonic wave phase shift circuit **22** is configured in such a manner that the pass phase of the harmonic wave is +X degrees (X>0), and the harmonic wave phase shift circuit **32** is configured in such a manner that the pass phase of the harmonic wave is −Y degrees (Y>0).

[0165] Accordingly, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Thus, the amplifier circuit **1** in which the quality of transmission signals and power efficiency are improved can be provided.

[0166] Furthermore, for example, the amplifier circuit **1**D according to the fourth modification further includes the splitter **10** that includes the input terminal **101** and the output terminals **102** and **103** and is configured to split a fundamental wave signal in a transmission band of the first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees with respect to a phase of the first signal. The combiner circuit includes the phase shift line **50** that has the second input end and the third output end and is configured to delay the fundamental wave of the first output signal from the first power amplifier circuit input through the second input end by 90 degrees. The first power amplifier circuit includes a carrier amplifier (power amplifier **21**) that has the third input end and the fourth output end, the third input end being connected to the output terminal **102**, the fourth output end being connected to the second input end, and the harmonic wave phase shift circuit **22** that is connected to a path connecting the fourth output end to the second input end and is configured to shift a phase of a second-order harmonic wave in the first band. The second power amplifier circuit includes a peak amplifier (power amplifier **31**) that has the fourth input end and the fifth output end, the fourth input end being connected to the output terminal **103**, the fifth output end being connected to the third output end, and the harmonic wave phase shift circuit **32** that is connected to a path connecting the fifth output end to the third output end and is configured to shift the phase of the second-order harmonic wave. A phase shift difference obtained by subtracting the phase of the second-order harmonic wave from the fifth output end input to the third output end from the phase of the second-order harmonic wave from the fourth output end input to the third output end is larger than 90 degrees.

[0167] Accordingly, compared to a conventional Doherty amplifier in which a harmonic wave phase shift circuit is not additionally provided, the second-order harmonic waves in the first band can be suppressed with high accuracy, and the quality of transmission signals and power efficiency can be improved.

[0168] Furthermore, for example, the amplifier circuit **1**E according to the fifth modification further includes the splitter **10** that includes the input terminal **101** and the output terminals **102** and **103** and is configured to split a fundamental wave signal in a transmission band of the first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees with respect to a phase of the first signal. The combiner circuit includes the phase shift line **51** that has the second input end and the third output end and is configured to delay the fundamental wave of the second output signal input through the second input end by 90 degrees, and the transformer **43** that has the input terminals **432** and **433** and the output terminal **431** and is configured to output from the output terminal **431** a third output signal generated by combining in an anti-phase manner the first output signal input through the input terminal **432** and the second output signal input through the input terminal **433**. The first power amplifier circuit includes a carrier amplifier (power amplifier **21**) that has the fifth input end and the fifth output end, the fifth input end being connected to the output terminal **102**, the fifth output end being connected to the input terminal **432**, and the harmonic wave phase shift circuit **22** that is connected to a path connecting the fifth output end to the input terminal **432** and is configured to shift a phase of a second-order harmonic wave in the first band. The second power amplifier circuit includes a peak amplifier (power amplifier **31**) that has the sixth input end and the sixth output end, the sixth input end being connected to the output terminal **103**, the sixth output end being connected to the second input end, and the harmonic wave phase shift circuit **32** that is connected to a path connecting the sixth output end to the second input end and is configured to shift the phase of the second-order harmonic wave. A phase shift difference obtained by subtracting the phase of the second-order harmonic wave at the fourth input end from the phase of the second-order harmonic wave at the third input end is smaller than 90 degrees.

[0169] Accordingly, compared to a conventional Doherty amplifier in which a harmonic wave phase shift circuit is not additionally provided, the second-order harmonic waves in the first band can be suppressed with high accuracy, and the quality of transmission signals and power efficiency can be improved.

[0170] Furthermore, for example, the amplifier circuit **1**C further includes the splitter **10** that includes the input terminal **101** and the output terminals **102** and **103** and is configured to split a fundamental wave signal in a transmission band of the first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees with respect to a phase of the first signal. The anti-phase combiner circuit **40**C includes the transformer **42** that has the input terminals **422** and **423** and the output terminal **421** and is configured to output from the output terminal **421** a third output signal generated by combining in an anti-phase manner a first output signal input through the input terminal **422** and a second output signal input through the input terminal **423**, the phase shift circuit **23**C that is connected between the power amplifier circuit **20** and the transformer **42** and is configured to shift phases of the fundamental wave and a second-order harmonic wave in the first band, and the phase shift circuit **33**C that is connected between the power amplifier circuit **30** and the transformer **42** and is configured to shift the phases of the fundamental wave and the second-order harmonic wave in the first band in such a manner that the pass phase of the fundamental wave is −90 degrees with respect to the phase shift circuit **23**C. The power amplifier circuit **20** includes the power amplifier **21** that has the fourth input end and the fourth output end, the fourth input end being connected to the output terminal **102**, and the harmonic wave phase shift circuit **22** that is connected to a path connecting the fourth output end to the transformer **42** and is configured to shift the phase of the second-order harmonic wave. The power amplifier circuit **30** includes the power amplifier **31** that has the fifth input end and the fifth output end, the fifth input end being connected to the output terminal **103**, and the harmonic wave phase shift circuit **32** that is connected to a path connecting the fifth output end to the transformer **42** and is configured to shift the phase of the second-order harmonic wave. A phase shift difference obtained by subtracting the phase of the second-order harmonic wave at the input terminal **423** from the phase of the second-order harmonic wave at the input terminal **422** is smaller than 90 degrees.

[0171] Accordingly, compared to a conventional balanced amplifier of an anti-phase combining type in which a harmonic wave phase shift circuit is not additionally provided, the second-order harmonic waves in the first band can be suppressed over a wide range. Therefore, the quality of transmission signals and power efficiency can be improved.

[0172] Furthermore, for example, in the amplifier circuit **1**C, a first phase shift difference obtained by subtracting the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** from the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is equal to a second phase shift difference obtained by subtracting the pass phase of the second-order harmonic wave of the phase shift circuit **33**C from the pass phase of the second-order harmonic wave of the phase shift circuit **23**C.

[0173] Accordingly, the second-order harmonic waves in the first band have an in-phase relationship between the input terminals **422** and **423** of the transformer **42** and are canceled. Thus, the amplifier circuit **1**C in which the quality of transmission signals and power efficiency are improved can be provided.

[0174] Furthermore, for example, in the amplifier circuit **1**C, the phase shift circuit **23**C is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees, the phase shift circuit **33**C is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees, the harmonic wave phase shift circuit **22** is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and the harmonic wave phase shift circuit **32** is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0175] Accordingly, the second-order harmonic waves in the first band have an in-phase relationship between the input terminals **422** and **423** of the transformer **42** and are canceled. Thus, the amplifier circuit **1**C in which the quality of transmission signals and power efficiency are improved can be provided.

[0176] Furthermore, for example, the amplifier circuit **1**F according to the sixth modification further includes the splitter **10** that includes the input terminal **101** and the output terminals **102** and **103** and is configured to split a fundamental wave signal in a transmission band of the first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees with respect to a phase of the first signal. The combiner circuit includes the 90-degree combiner **44** that includes the input terminal **442** (second input end), the input terminal **443** (third input end), and the output terminal **441** (third output end) and is configured to output from the output terminal **441** a third output signal generated by combining a first output signal input through the input terminal **442** and a signal obtained by shifting a phase of a second output signal input through the input terminal **443** to be +90 degrees with respect to a phase of the first output signal. The power amplifier circuit **20** includes the power amplifier **21** that has the fourth input end and the fourth output end, the fourth input end being connected to the output terminal **102**, and the harmonic wave phase shift circuit **22** that is connected to a path connecting the fourth output end to the input terminal **442** and is configured to shift a phase of a second-order harmonic wave in the first band. The power amplifier circuit **30** includes the power amplifier **31** that has the fifth input end and the fifth output end, the fifth input end being connected to the output terminal **103**, and the harmonic wave phase shift circuit **32** that is connected to a path connecting the fifth output end to the input terminal **443** and is configured to shift the phase of the second-order harmonic wave. A phase shift difference obtained by subtracting the phase of the second-order harmonic wave at the input terminal **443** from the phase of the second-order harmonic wave at the input terminal **442** is 90 degrees.

[0177] Accordingly, compared to a conventional balanced amplifier of a 90-degree combining type in which a harmonic wave phase shift circuit is not additionally provided, the second-order harmonic waves in the first band can be suppressed over a wide range. Therefore, the quality of transmission signals and power efficiency can be improved.

[0178] Furthermore, for example, in the amplifier circuit **1**F, the harmonic wave phase shift circuit **22** is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and the harmonic wave phase shift circuit **32** is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0179] Accordingly, the second-order harmonic waves in the first band have a phase difference of 270 degrees between the input terminals **442** and **443** of the 90-degree combiner **44**, become anti-phase at the 90-degree combiner **44**, and are canceled. Thus, the amplifier circuit **1**F in which the quality of transmission signals and power efficiency are improved can be provided.

[0180] Furthermore, the amplifier circuit **1** according to this embodiment (the amplifier circuit **1**A according to the first modification and the amplifier circuit **1**C according to the second modification) includes the splitter **10** that includes the input terminal **101** and the output terminals **102** and **103** and is configured to split a fundamental wave signal in a transmission band of the first band input to the input terminal **101**, output from the output terminal **102** a first signal, and output from the output terminal **103** a second signal whose phase is −90 degrees with respect to a phase of the first signal, the power amplifier **21** that has the fourth input end and the fourth output end, the fourth input end being connected to the output terminal **102**, the power amplifier **31** that has the fifth input end and the fifth output end, the fifth input end being connected to the output terminal **103**, the in-phase combiner **41** that has the input terminals **402** and **403** and the output terminal **401** and is configured to output from the output terminal **401** a third output signal obtained by combining in an in-phase manner a first output signal output from the power amplifier **21** and input through the input terminal **402** and a second output signal output from the power amplifier **31** and input through the input terminal **403**, the phase shift circuit **23** that is connected between the power amplifier **21** and the in-phase combiner **41** and is configured to shift phases of a fundamental wave and a second-order harmonic wave in the first band, the phase shift circuit **33** that is connected between the power amplifier **31** and the in-phase combiner **41** and is configured to shift the phases of the fundamental wave and the second-order harmonic wave in the first band in such a manner that the pass phase of the fundamental wave is +90 degrees with respect to the phase shift circuit **23**, the harmonic wave phase shift circuit **22** (**22**A) that is connected to a path connecting the fourth output end and the input terminal **402** and is configured to shift the phase of the second-order harmonic wave, and the harmonic wave phase shift circuit **32** (**32**A) that is connected to a path connecting the fifth output end to the input terminal **403** and is configured to shift the phase of the second-order harmonic wave. A phase shift difference obtained by subtracting the phase of the second-order harmonic wave at the input terminal **403** from the phase of the second-order harmonic wave at the input terminal **402** is larger than 90 degrees.

[0181] Accordingly, compared to a conventional balanced amplifier of an in-phase combining type in which a harmonic wave phase shift circuit is not additionally provided, the second-order harmonic waves in the first band can be suppressed with high accuracy. Thus, the amplifier circuit can function as a balanced amplifier that is resistant to changes in the load, and the quality of transmission signals and power efficiency can be improved.

[0182] Furthermore, for example, in the amplifier circuit **1**B, a first phase shift difference obtained by subtracting the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **32** from the pass phase of the second-order harmonic wave of the harmonic wave phase shift circuit **22** is equal to a second phase shift difference obtained by subtracting the pass phase of the second-order harmonic wave of the phase shift circuit **23** from the pass phase of the second-order harmonic wave of the phase shift circuit **33**.

[0183] Accordingly, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Thus, the amplifier circuit **1**B in which the quality of transmission signals and power efficiency are improved can be provided.

[0184] Furthermore, for example, in the amplifier circuit **1**B, the phase shift circuit **23** is configured in such a manner that the pass phases of the fundamental wave and the second-order harmonic wave are −45 degrees, the phase shift circuit **33** is configured in such a manner that the pass phases of the fundamental wave and the second-order harmonic wave are +45 degrees, the harmonic wave phase shift circuit **22** is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and the harmonic wave phase shift circuit **32** is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0185] Accordingly, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Thus, the amplifier circuit **1**B in which the quality of transmission signals and power efficiency are improved can be provided.

[0186] Furthermore, for example, in the amplifier circuit **1**B, the phase shift circuit **23** is configured in such a manner that the pass phase of the fundamental wave is −45 degrees and the pass phase of the harmonic wave is −X degrees (X>0), the phase shift circuit **33** is configured in such a manner that the pass phase of the fundamental wave is +45 degrees and the pass phase of the harmonic wave is +Y degrees (Y>0), the harmonic wave phase shift circuit **22** is configured in such a manner that the pass phase of the harmonic wave is +X degrees (X>0), and the harmonic wave phase shift circuit **32** is configured in such a manner that the pass phase of the harmonic wave is −Y degrees (Y>0).

[0187] Accordingly, the second-order harmonic waves in the first band have a phase difference of 180 degrees (anti-phase relationship) between the input terminals **402** and **403** of the in-phase combiner **41** and are canceled. Thus, the amplifier circuit **1**B in which the quality of transmission signals and power efficiency are improved can be provided.

[0188] Furthermore, for example, in the amplifier circuit **1** (**1**A and **1**B), the phase shift circuit **23** includes the inductor **231** that is connected between the fourth output end and the input terminal **402** and the capacitor **232** that is connected between a path connecting the inductor **231** to the input terminal **402** and the ground, and the phase shift circuit **33** includes the capacitor **331** that is connected between the fifth output end and the input terminal **403** and the inductor **332** that is connected between a path connecting the capacitor **331** to the input terminal **403** and the ground.

[0189] Accordingly, the phase shift circuit **23** can configure a low pass filter in which a fundamental wave band and a second-order harmonic wave band of the first band serve as a pass band, the pass phase of the fundamental wave in the first band can be −45 degrees, and the pass phase of the second-order harmonic wave can be −45 degrees (−X degrees: X>0). Furthermore, the phase shift circuit **33** can configure a high pass filter in which the fundamental wave band and the second-order harmonic wave band of the first band serve as a pass band, the pass phase of the fundamental wave in the first band can be +45 degrees, and the pass phase of the second-order harmonic wave can be +45 degrees (+Y degrees: Y>0).

[0190] Furthermore, for example, in the amplifier circuit **1** (**1**A and **1**B), the harmonic wave phase shift circuit **22** (**22**A) includes an LC circuit including the inductor **221** and the capacitor **222** that are connected in series. The LC circuit is connected between a path connecting the fourth output end to the inductor **231** and the ground. The harmonic wave phase shift circuit **32** (**32**A) includes the capacitor **321** that is connected between a path connecting the fifth output end to the capacitor **331** and the ground.

[0191] Accordingly, the harmonic wave phase shift circuit **22** (**22**A) can configure a notch filter in which the fundamental wave band of the first band serves as a pass band and the second-order harmonic wave band serves as an attenuation band, the pass phase of the fundamental wave can be 0 degrees, and the pass phase of the second-order harmonic wave can be +45 degrees (+X degrees: X>0). Furthermore, the harmonic wave phase shift circuit **32** (**32**A) can configure a low pass filter in which the fundamental wave band of the first band serves as a pass band and the second-order harmonic wave serves as an attenuation band, the pass phase of the fundamental wave can be 0 degrees, and the pass phase of the second-order harmonic wave can be −45 degrees (−Y degrees: Y>0).

[0192] Furthermore, for example, in the amplifier circuit **1** (**1**A and **1**B), the phase shift circuits **23** and **33** and the harmonic wave phase shift circuits **22** (**22**A) and **32** (**32**A) are included in a single semiconductor IC.

[0193] Accordingly, since the size of the amplifier circuit **1** (**1**A and **1**B) can be reduced and the length of a signal wire from the power amplifiers **21** and **31** to the in-phase combiner **41** can be reduced, signal transfer loss in the amplifier circuit **1** (**1**A and **1**B) can be reduced.

Other Embodiments

[0194] Amplifier circuits according to embodiments of the present disclosure have been described above as an embodiment and modifications. However, amplifier circuits according to the present disclosure are not limited to the embodiments and modifications described above. Other embodiments implemented by combining component elements in the embodiments and modifications described above, modifications obtained by making various modifications conceivable by those skilled in the art to the embodiments and modifications described above without departing from the spirit of the present disclosure, and various types of equipment including an amplifier circuit described above are also included in the present disclosure.

[0195] For example, in the amplifier circuits according to the embodiments and modifications described above, second-order harmonic waves are used as harmonic waves. However, harmonic waves at third or higher order may be used.

[0196] For example, in the amplifier circuits according to the embodiments and the modifications described above, other circuit elements, wires, or the like may be inserted between paths connecting circuit elements and signal paths disclosed in the drawings.

[0197] Features of amplifier circuits described above based on embodiments described above will be described below.

[0198] <1> An amplifier circuit comprising:

[0199] a first power amplifier circuit that includes a first power amplifier;

[0200] a second power amplifier circuit that includes a second power amplifier in which a phase of a fundamental wave at an output end is delayed by 90 degrees with respect to the first power amplifier; and

[0201] a combiner circuit that is configured to combine a fundamental wave of a first output signal output from the first power amplifier circuit and a fundamental wave of a second output signal output from the second power amplifier circuit,

[0202] wherein the first power amplifier circuit is of an inverse class-E type, and

[0203] wherein the second power amplifier circuit is of a class-E type.

[0204] <2> The amplifier circuit according to <1>, further comprising:

[0205] a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees with respect to a phase of the first signal,

[0206] wherein the combiner circuit includes

[0207] a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal generated by combining in an in-phase manner the first output signal input through the second input end and the second output signal input through the third input end,

[0208] a first phase shift circuit that is connected between the first power amplifier circuit and the combiner and is configured to shift phases of a fundamental wave and a harmonic wave in the first band, and

[0209] a second phase shift circuit that is connected between the second power amplifier circuit and the combiner and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is +90 degrees with respect to the first phase shift circuit,

[0210] wherein the first power amplifier circuit includes

[0211] a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end, and

[0212] a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave,

[0213] wherein the second power amplifier circuit includes

[0214] a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end, and

[0215] a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave, and

[0216] wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is larger than 90 degrees.

[0217] <3> The amplifier circuit according to <2>, wherein a first phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second harmonic wave phase shift circuit from a pass phase of the harmonic wave of the first harmonic wave phase shift circuit is equal to a second phase shift difference obtained by subtracting a pass phase of the harmonic wave of the first phase shift circuit from a pass phase of the harmonic wave of the second phase shift circuit.

[0218] <4> The amplifier circuit according to <3>,

[0219] wherein the first phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees,

[0220] wherein the second phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees,

[0221] wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

[0222] wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0223] <5> The amplifier circuit according to <3>,

[0224] wherein the first phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is −45 degrees and the pass phase of the harmonic wave is −X degrees (X>0),

[0225] wherein the second phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is +45 degrees and the pass phase of the harmonic wave is +Y degrees (Y>0),

[0226] wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +X degrees (X>0), and

[0227] wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −Y degrees (Y>0).

[0228] <6> The amplifier circuit according to <1>, further comprising:

[0229] a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,

[0230] wherein the combiner circuit includes

[0231] a phase shift line that has a second input end and a third output end and is configured to delay the fundamental wave of the first output signal input through the second input end by 90 degrees,

[0232] wherein the first power amplifier circuit includes

[0233] a carrier amplifier that has a third input end and a fourth output end, the third input end being connected to the first output end, the fourth output end being connected to the second input end, and

[0234] a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift a phase of a harmonic wave in the first band,

[0235] wherein the second power amplifier circuit includes

[0236] a peak amplifier that has a fourth input end and a fifth output end, the fourth input end being connected to the second output end, the fifth output end being connected to the third output end, and

[0237] a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third output end and is configured to shift the phase of the harmonic wave, and

[0238] wherein a phase shift difference obtained by subtracting the phase of the harmonic wave from the fifth output end input to the third output end from the phase of the harmonic wave from the fourth output end input to the third output end is larger than 90 degrees.

[0239] <7> The amplifier circuit according to <1>, further comprising:

[0240] a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,

[0241] wherein the combiner circuit includes

[0242] a phase shift line that has a second input end and a third output end and is configured to delay the fundamental wave of the second output signal input through the second input end by 90 degrees, and

[0243] a transformer that has a third input end, a fourth input end, and a fourth output end and is configured to output from the fourth output end a third output signal generated by combining in an anti-phase manner the first output signal input through the third input end and the second output signal input through the fourth input end,

[0244] wherein the first power amplifier circuit includes

[0245] a carrier amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the first output end, the fifth output end being connected to the third input end, and

[0246] a first harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift a phase of a harmonic wave in the first band,

[0247] wherein the second power amplifier circuit includes

[0248] a peak amplifier that has a sixth input end and a sixth output end, the sixth input end being connected to the second output end, the sixth output end being connected to the second input end, and

[0249] a second harmonic wave phase shift circuit that is connected to a path connecting the sixth output end to the second input end and is configured to shift the phase of the harmonic wave, and

[0250] wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the fourth input end from the phase of the harmonic wave at the third input end is smaller than 90 degrees.

[0251] <8> The amplifier circuit according to <1>, further comprising:

[0252] a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,

[0253] wherein the combiner circuit includes

[0254] a transformer that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal generated by combining in an anti-phase manner the first output signal input through the second input end and the second output signal input through the third input end,

[0255] a first phase shift circuit that is connected between the first power amplifier circuit and the transformer and is configured to shift phases of a fundamental wave and a harmonic wave in the first band, and

[0256] a second phase shift circuit that is connected between the second power amplifier circuit and the transformer and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is −90 degrees relative to the first phase shift circuit,

[0257] wherein the first power amplifier circuit includes

[0258] a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end, and

[0259] a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave,

[0260] wherein the second power amplifier circuit includes

[0261] a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end, and

[0262] a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave, and

[0263] wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is smaller than 90 degrees.

[0264] <9> The amplifier circuit according to <8>, wherein a first phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second harmonic wave phase shift circuit from a pass phase of the harmonic wave of the first harmonic wave phase shift circuit is equal to a second phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second phase shift circuit from a pass phase of the harmonic wave of the first phase shift circuit.

[0265] <10> The amplifier circuit according to <9>,

[0266] wherein the first phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees,

[0267] wherein the second phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees,

[0268] wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

[0269] wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0270] <11> The amplifier circuit according to <1>, further comprising:

[0271] a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,

[0272] wherein the combiner circuit includes

[0273] a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal generated by combining the first output signal input through the second input end and a signal obtained by shifting a phase of the second output signal input through the third input end to be +90 degrees with respect to a phase of the first output signal,

[0274] wherein the first power amplifier circuit includes a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end, and

[0275] a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift a phase of a harmonic wave in the first band,

[0276] wherein the second power amplifier circuit includes

[0277] a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end, and

[0278] a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave, and

[0279] wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the second input end from the phase of the harmonic wave at the third input end is 90 degrees.

[0280] <12> The amplifier circuit according to <11>,

[0281] wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

[0282] wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0283] <13> An amplifier circuit comprising:

[0284] a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees with respect to a phase of the first signal;

[0285] a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end;

[0286] a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end;

[0287] a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal obtained by combining in an in-phase manner a first output signal output from the first power amplifier and input through the second input end and a second output signal output from the second power amplifier and input through the third input end;

[0288] a first phase shift circuit that is connected between the first power amplifier and the combiner and is configured to shift phases of a fundamental wave and a harmonic wave in the first band;

[0289] a second phase shift circuit that is connected between the second power amplifier and the combiner and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is +90 degrees with respect to the first phase shift circuit;

[0290] a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave; and

[0291] a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave,

[0292] wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is larger than 90 degrees.

[0293] <14> The amplifier circuit according to <13>, wherein a first phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second harmonic wave phase shift circuit from a pass phase of the harmonic wave of the first harmonic wave phase shift circuit is equal to a second phase shift difference obtained by subtracting a pass phase of the harmonic wave of the first phase shift circuit from a pass phase of the harmonic wave of the second phase shift circuit.

[0294] <15> The amplifier circuit according to <14>,

[0295] wherein the first phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees,

[0296] wherein the second phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees,

[0297] wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

[0298] wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

[0299] <16> The amplifier circuit according to <14>,

[0300] wherein the first phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is −45 degrees and the pass phase of the harmonic wave is −X degrees (X>0),

[0301] wherein the second phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is +45 degrees and the pass phase of the harmonic wave is +Y degrees (Y>0),

[0302] wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +X degrees (X>0), and

[0303] wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −Y degrees (Y>0).

[0304] <17> The amplifier circuit according to any one of <13> to <16>,

[0305] wherein the first phase shift circuit includes

[0306] a first inductor that is connected between the fourth output end and the second input end, and

[0307] a first capacitor that is connected between a path connecting the first inductor to the second input end and a ground, and

[0308] wherein the second phase shift circuit includes

[0309] a second capacitor that is connected between the fifth output end and the third input end, and

[0310] a second inductor that is connected between a path connecting the second capacitor to the third input end and the ground.

[0311] <18> The amplifier circuit according to <17>,

[0312] wherein the first harmonic wave phase shift circuit includes

[0313] an LC circuit that includes a third inductor and a third capacitor that are connected in series,

[0314] wherein the LC circuit is connected between a path connecting the fourth output end to the first inductor and the ground, and

[0315] wherein the second harmonic wave phase shift circuit includes

[0316] a fourth capacitor that is connected between a path connecting the fifth output end to the second capacitor and the ground.

[0317] <19> The amplifier circuit according to any one of <13> to <18>, wherein the first phase shift circuit, the second phase shift circuit, the first harmonic wave phase shift circuit, and the second harmonic wave phase shift circuit are included in a single semiconductor IC.

[0318] The present disclosure can be widely used as an amplifier circuit arranged in a front end part in a communication apparatus such as a mobile phone.

What is claimed is:

1. An amplifier circuit comprising:

a first power amplifier circuit that includes a first power amplifier;

a second power amplifier circuit that includes a second power amplifier in which a phase of a fundamental wave at an output end is delayed by 90 degrees with respect to the first power amplifier; and

a combiner circuit that is configured to combine a fundamental wave of a first output signal output from the first power amplifier circuit and a fundamental wave of a second output signal output from the second power amplifier circuit,

wherein the first power amplifier circuit is of an inverse class-E type, and

wherein the second power amplifier circuit is of a class-E type.

2. The amplifier circuit according to claim **1**, further comprising:

a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees with respect to a phase of the first signal,

wherein the combiner circuit includes

a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal generated by combining in an in-phase manner the first output signal input through the second input end and the second output signal input through the third input end,

a first phase shift circuit that is connected between the first power amplifier circuit and the combiner and is configured to shift phases of a fundamental wave and a harmonic wave in the first band, and

a second phase shift circuit that is connected between the second power amplifier circuit and the combiner and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is +90 degrees with respect to the first phase shift circuit,

wherein the first power amplifier circuit includes

a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end, and

a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave,

wherein the second power amplifier circuit includes

a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end, and

a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave, and

wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is larger than 90 degrees.

3. The amplifier circuit according to claim **2**, wherein a first phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second harmonic wave phase shift circuit from a pass phase of the harmonic wave of the first harmonic wave phase shift circuit is equal to a second phase shift difference obtained by subtracting a pass phase of the harmonic wave of the first phase shift circuit from a pass phase of the harmonic wave of the second phase shift circuit.

4. The amplifier circuit according to claim 3,
wherein the first phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees,
wherein the second phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees,
wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and
wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

5. The amplifier circuit according to claim 3,
wherein the first phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is −45 degrees and the pass phase of the harmonic wave is −X degrees (X>0),
wherein the second phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is +45 degrees and the pass phase of the harmonic wave is +Y degrees (Y>0),
wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +X degrees (X>0), and
wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −Y degrees (Y>0).

6. The amplifier circuit according to claim 1, further comprising:
a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,
wherein the combiner circuit includes
a phase shift line that has a second input end and a third output end and is configured to delay the fundamental wave of the first output signal input through the second input end by 90 degrees,
wherein the first power amplifier circuit includes
a carrier amplifier that has a third input end and a fourth output end, the third input end being connected to the first output end, the fourth output end being connected to the second input end, and
a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift a phase of a harmonic wave in the first band,
wherein the second power amplifier circuit includes
a peak amplifier that has a fourth input end and a fifth output end, the fourth input end being connected to the second output end, the fifth output end being connected to the third output end, and
a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third output end and is configured to shift the phase of the harmonic wave, and
wherein a phase shift difference obtained by subtracting the phase of the harmonic wave from the fifth output end input to the third output end from the phase of the harmonic wave from the fourth output end input to the third output end is larger than 90 degrees.

7. The amplifier circuit according to claim 1, further comprising:
a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,
wherein the combiner circuit includes
a phase shift line that has a second input end and a third output end and is configured to delay the fundamental wave of the second output signal input through the second input end by 90 degrees, and
a transformer that has a third input end, a fourth input end, and a fourth output end and is configured to output from the fourth output end a third output signal generated by combining in an anti-phase manner the first output signal input through the third input end and the second output signal input through the fourth input end,
wherein the first power amplifier circuit includes
a carrier amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the first output end, the fifth output end being connected to the third input end, and
a first harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift a phase of a harmonic wave in the first band,
wherein the second power amplifier circuit includes
a peak amplifier that has a sixth input end and a sixth output end, the sixth input end being connected to the second output end, the sixth output end being connected to the second input end, and
a second harmonic wave phase shift circuit that is connected to a path connecting the sixth output end to the second input end and is configured to shift the phase of the harmonic wave, and
wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the fourth input end from the phase of the harmonic wave at the third input end is smaller than 90 degrees.

8. The amplifier circuit according to claim 1, further comprising:
a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,
wherein the combiner circuit includes
a transformer that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal generated by combining in an anti-phase manner the first output signal input through the second input end and the second output signal input through the third input end,
a first phase shift circuit that is connected between the first power amplifier circuit and the transformer and is

configured to shift phases of a fundamental wave and a harmonic wave in the first band, and

a second phase shift circuit that is connected between the second power amplifier circuit and the transformer and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is −90 degrees relative to the first phase shift circuit,

wherein the first power amplifier circuit includes

a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end, and

a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave,

wherein the second power amplifier circuit includes

a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end, and

a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave, and

wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is smaller than 90 degrees.

9. The amplifier circuit according to claim **8**, wherein a first phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second harmonic wave phase shift circuit from a pass phase of the harmonic wave of the first harmonic wave phase shift circuit is equal to a second phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second phase shift circuit from a pass phase of the harmonic wave of the first phase shift circuit.

10. The amplifier circuit according to claim **9**,

wherein the first phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees,

wherein the second phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees,

wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

11. The amplifier circuit according to claim **1**, further comprising:

a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees relative to a phase of the first signal,

wherein the combiner circuit includes

a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal generated by combining the first output signal input through the second input end and a signal obtained by shifting a phase of the second output signal input through the third input end to be +90 degrees with respect to a phase of the first output signal,

wherein the first power amplifier circuit includes

a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end, and

a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift a phase of a harmonic wave in the first band,

wherein the second power amplifier circuit includes

a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end, and

a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave, and

wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the second input end from the phase of the harmonic wave at the third input end is 90 degrees.

12. The amplifier circuit according to claim **11**,

wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

13. An amplifier circuit comprising:

a splitter that has a first input end, a first output end, and a second output end and is configured to split a fundamental wave signal in a transmission band of a first band input to the first input end, output from the first output end a first signal, and output from the second output end a second signal whose phase is −90 degrees with respect to a phase of the first signal;

a first power amplifier that has a fourth input end and a fourth output end, the fourth input end being connected to the first output end;

a second power amplifier that has a fifth input end and a fifth output end, the fifth input end being connected to the second output end;

a combiner that has a second input end, a third input end, and a third output end and is configured to output from the third output end a third output signal obtained by combining in an in-phase manner a first output signal output from the first power amplifier and input through the second input end and a second output signal output from the second power amplifier and input through the third input end;

a first phase shift circuit that is connected between the first power amplifier and the combiner and is configured to shift phases of a fundamental wave and a harmonic wave in the first band;

a second phase shift circuit that is connected between the second power amplifier and the combiner and is configured to shift the phases of the fundamental wave and the harmonic wave in the first band in such a manner that a pass phase of the fundamental wave is +90 degrees with respect to the first phase shift circuit;

a first harmonic wave phase shift circuit that is connected to a path connecting the fourth output end to the second input end and is configured to shift the phase of the harmonic wave; and

a second harmonic wave phase shift circuit that is connected to a path connecting the fifth output end to the third input end and is configured to shift the phase of the harmonic wave,

wherein a phase shift difference obtained by subtracting the phase of the harmonic wave at the third input end from the phase of the harmonic wave at the second input end is larger than 90 degrees.

14. The amplifier circuit according to claim **13**, wherein a first phase shift difference obtained by subtracting a pass phase of the harmonic wave of the second harmonic wave phase shift circuit from a pass phase of the harmonic wave of the first harmonic wave phase shift circuit is equal to a second phase shift difference obtained by subtracting a pass phase of the harmonic wave of the first phase shift circuit from a pass phase of the harmonic wave of the second phase shift circuit.

15. The amplifier circuit according to claim **14**,

wherein the first phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are −45 degrees,

wherein the second phase shift circuit is configured in such a manner that the pass phases of the fundamental wave and the harmonic wave are +45 degrees,

wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +45 degrees, and

wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −45 degrees.

16. The amplifier circuit according to claim **14**,

wherein the first phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is −45 degrees and the pass phase of the harmonic wave is −X degrees (X>0),

wherein the second phase shift circuit is configured in such a manner that the pass phase of the fundamental wave is +45 degrees and the pass phase of the harmonic wave is +Y degrees (Y>0),

wherein the first harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is +X degrees (X>0), and

wherein the second harmonic wave phase shift circuit is configured in such a manner that the pass phase of the harmonic wave is −Y degrees (Y>0).

17. The amplifier circuit according to claim **16**,

wherein the first phase shift circuit includes

a first inductor that is connected between the fourth output end and the second input end, and

a first capacitor that is connected between a path connecting the first inductor to the second input end and a ground, and

wherein the second phase shift circuit includes a second capacitor that is connected between the fifth output end and the third input end, and

a second inductor that is connected between a path connecting the second capacitor to the third input end and the ground.

18. The amplifier circuit according to claim **17**,

wherein the first harmonic wave phase shift circuit includes

an LC circuit that includes a third inductor and a third capacitor that are connected in series,

wherein the LC circuit is connected between a path connecting the fourth output end to the first inductor and the ground, and

wherein the second harmonic wave phase shift circuit includes

a fourth capacitor that is connected between a path connecting the fifth output end to the second capacitor and the ground.

19. The amplifier circuit according to claim **16**, wherein the first phase shift circuit, the second phase shift circuit, the first harmonic wave phase shift circuit, and the second harmonic wave phase shift circuit are included in a single semiconductor IC.

20. The amplifier circuit according to claim **13**, wherein the first phase shift circuit, the second phase shift circuit, the first harmonic wave phase shift circuit, and the second harmonic wave phase shift circuit are included in a single semiconductor IC.

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