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(54) **ANTENNA DEVICE AND WIRELESS COMMUNICATION APPARATUS**

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(57) **ABSTRACT**

An antenna device includes a ground plane, and an antenna element formed on a first surface of the ground plane, the antenna element including a feed point, a first line extending from the feed point to a first end in a direction away from the first surface, a second line extending along the first surface of the ground plane from the first end of the first line to a second end, and a third line extending along the first surface of the ground plane from the second end of the second line to a third end in a direction different in plan view from an extending direction of the second line.

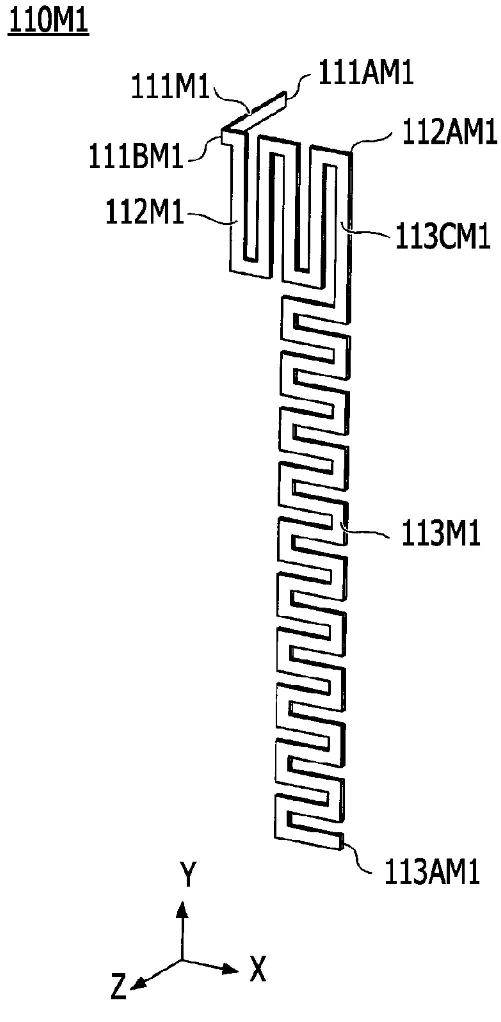


FIG. 1A

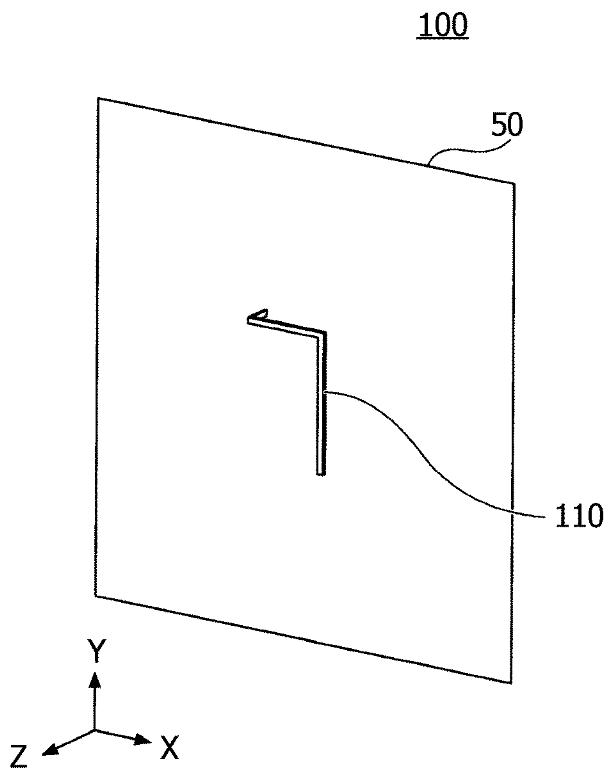


FIG. 1B

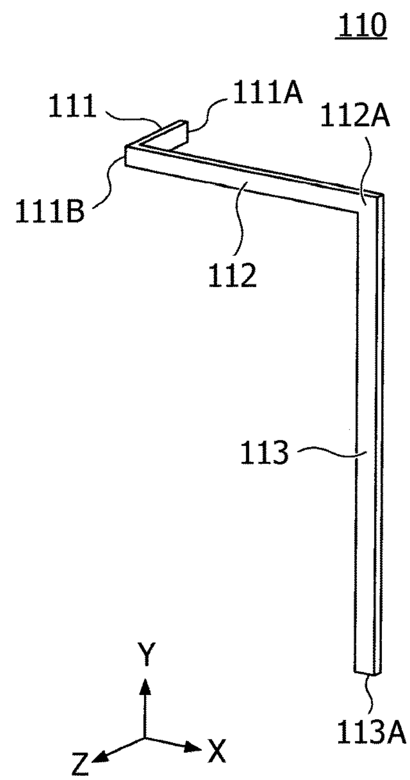


FIG. 1C

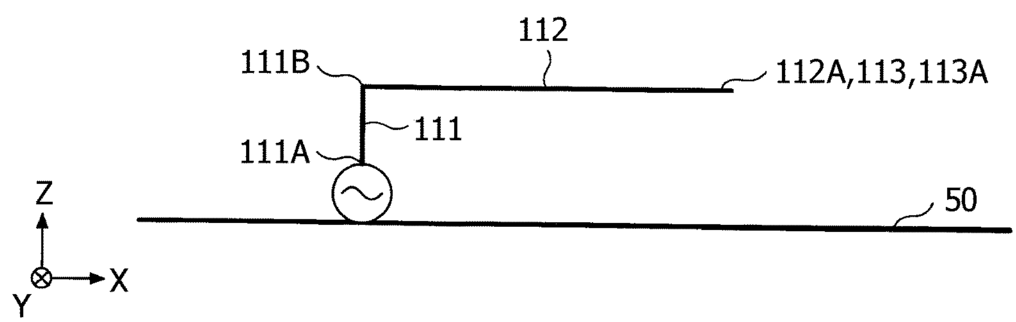


FIG. 2

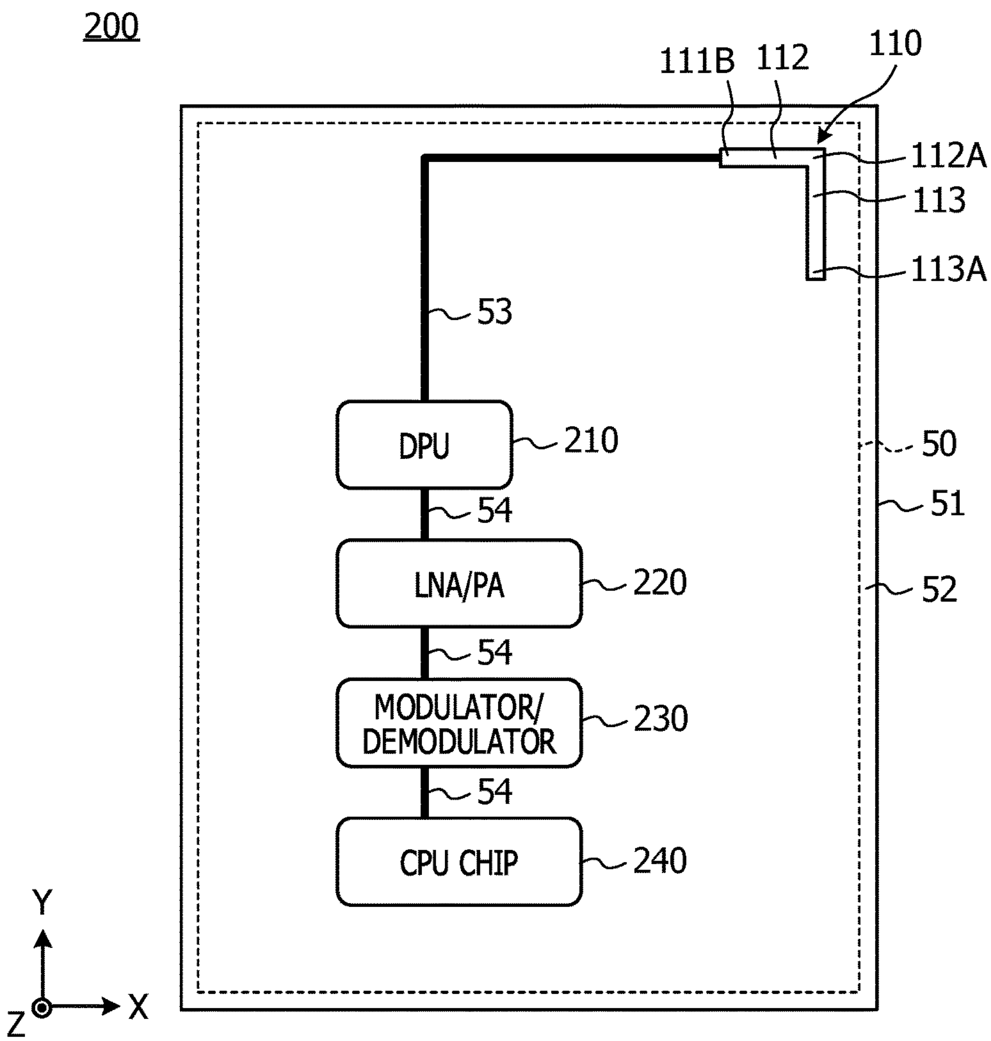

200
111B
112
110
112A
113
113A
53
DPU
210
50
54
51
LNA/PA
220
52
54
MODULATOR/
DEMODULATOR
230
54
CPU CHIP
240
Y
Z
X

FIG. 3A

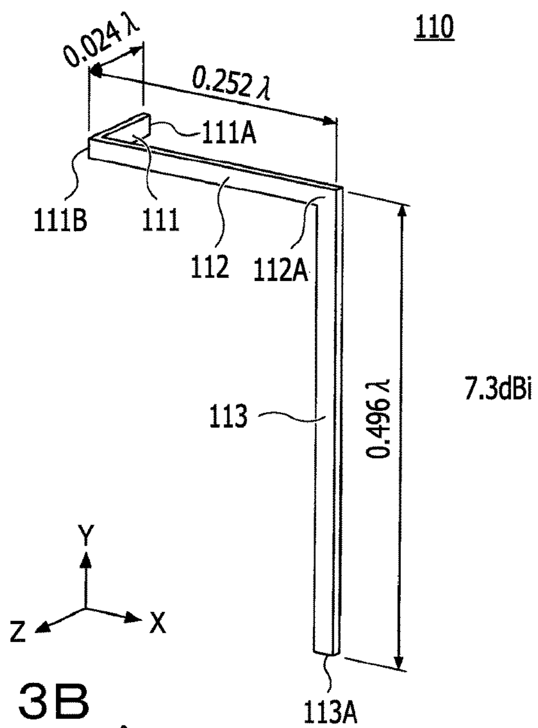


FIG. 3B

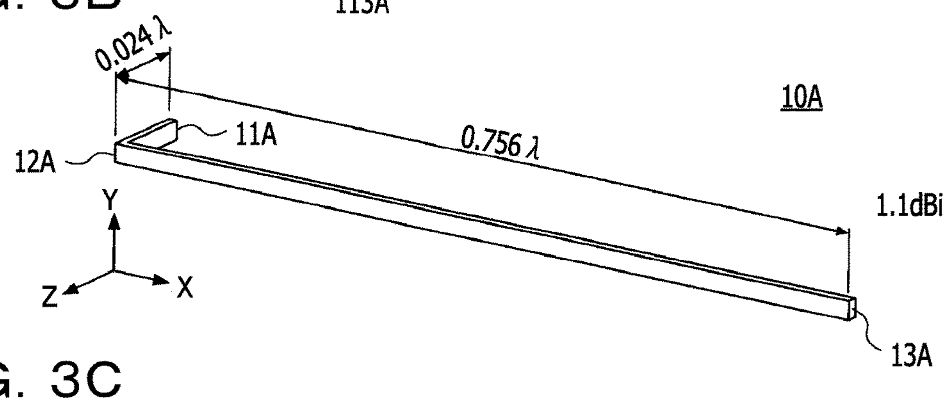


FIG. 3C

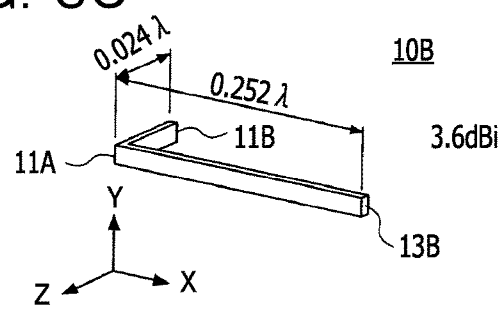


FIG. 4A

+Z DIRECTION: +7.3dBi

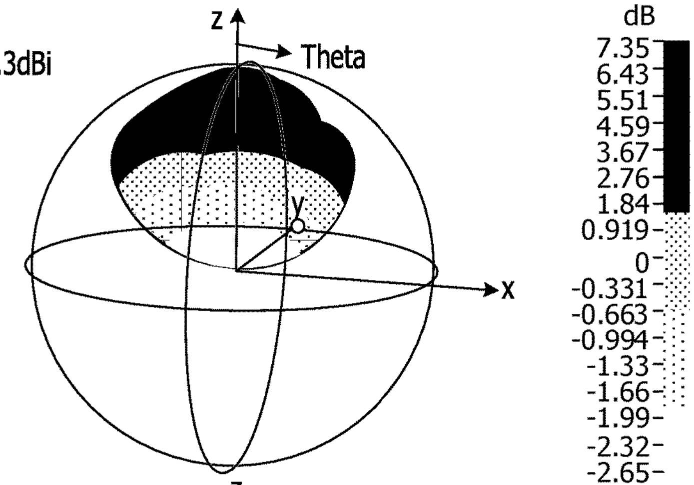


FIG. 4B

+Z DIRECTION: +1.1dBi

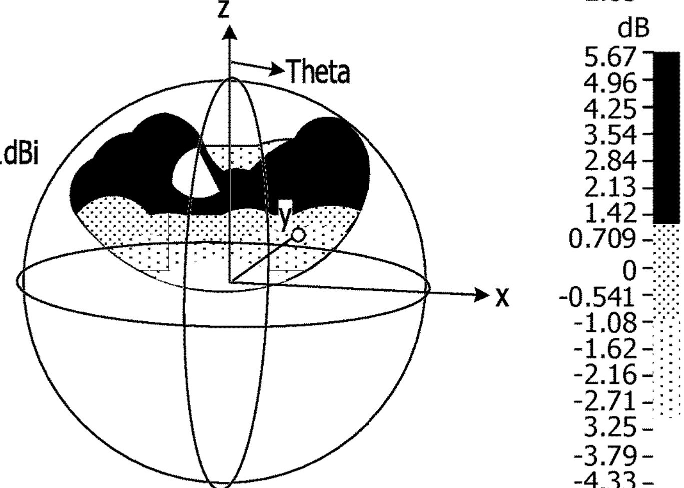


FIG. 4C

+Z DIRECTION: +3.6dBi

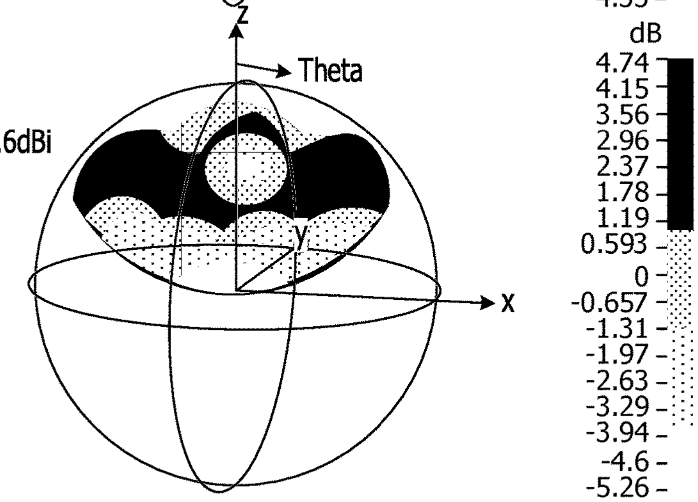


FIG. 5A

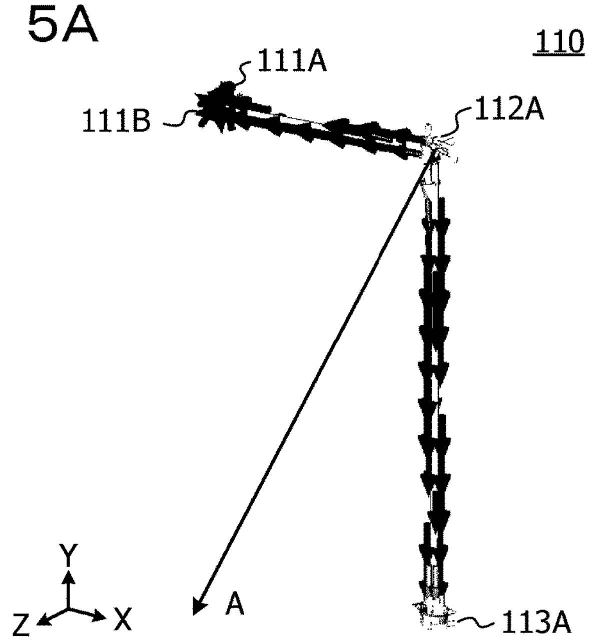


FIG. 5B

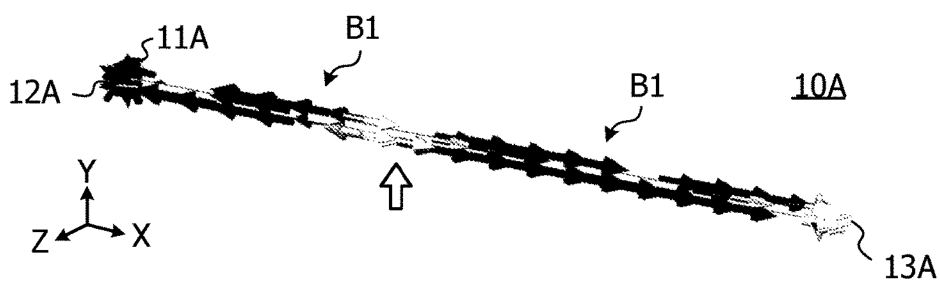


FIG. 5C

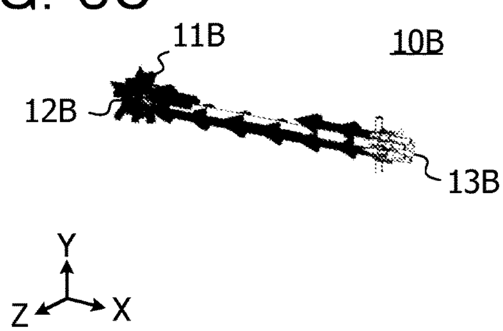


FIG. 6

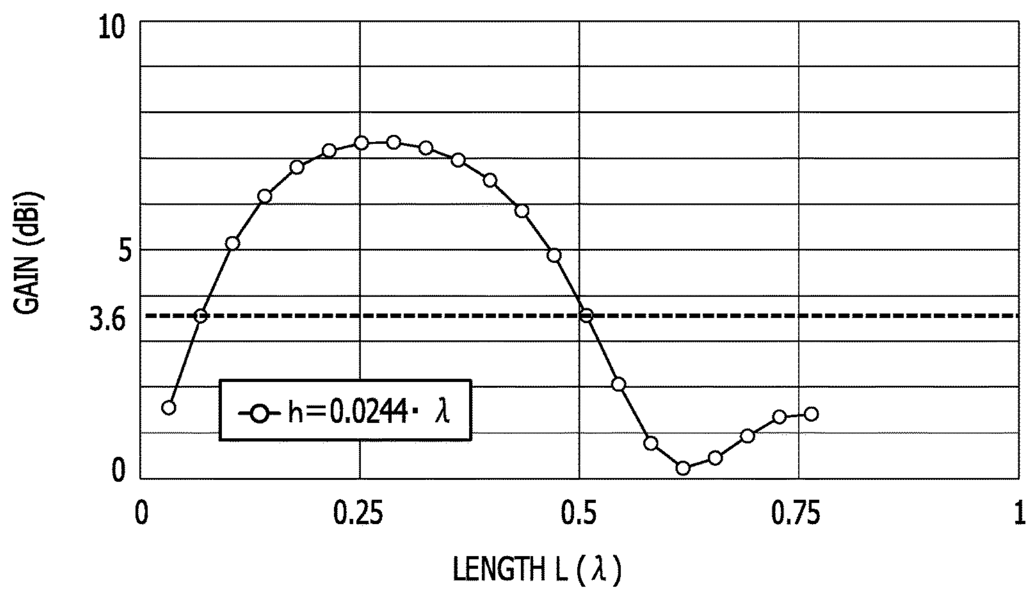


FIG. 7

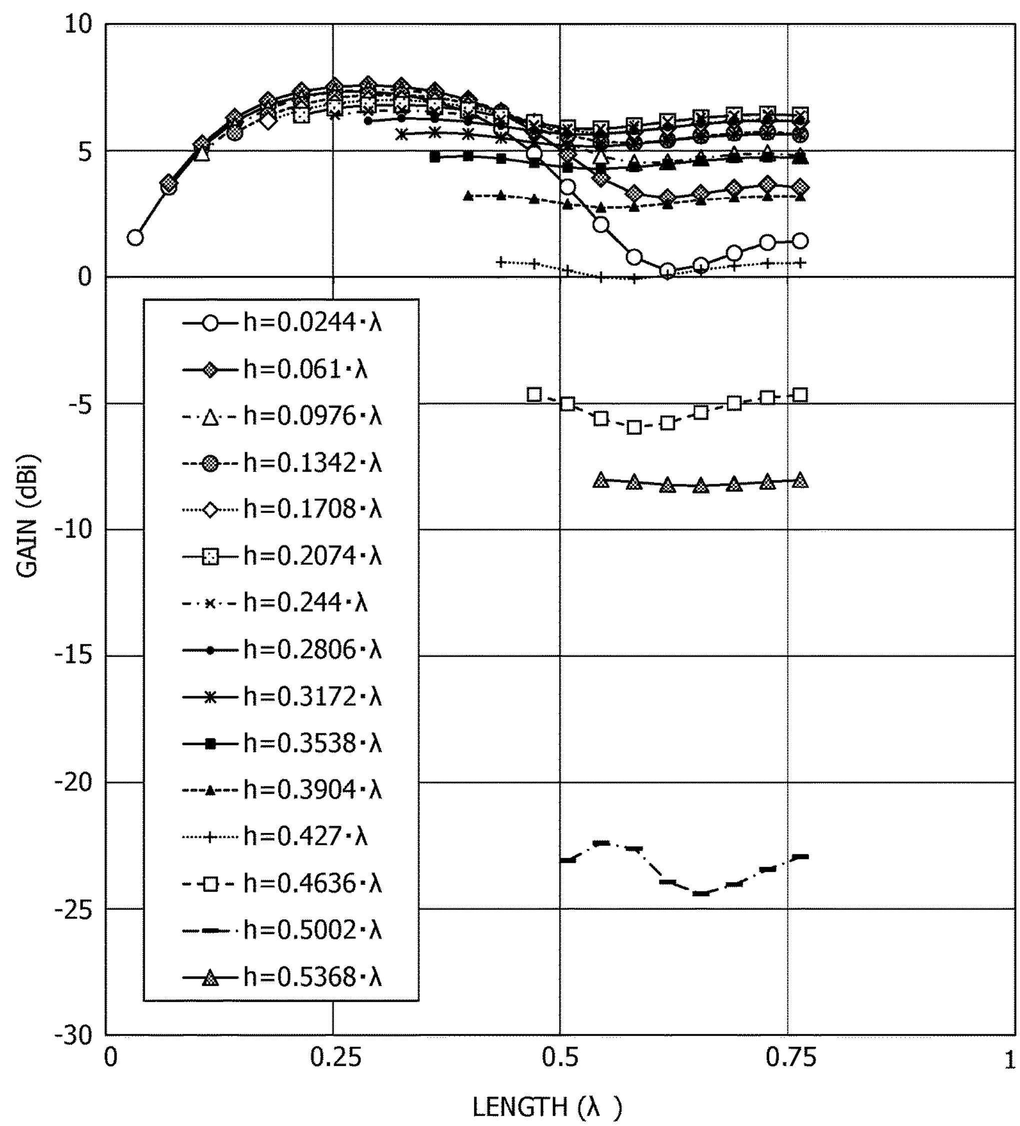

10
5
0
-5
-10
-15
-20
-25
-30
GAIN (dBi)
0
0.25
0.5
0.75
1
LENGTH (λ)
h=0.0244·λ
h=0.061·λ
h=0.0976·λ
h=0.1342·λ
h=0.1708·λ
h=0.2074·λ
h=0.244·λ
h=0.2806·λ
h=0.3172·λ
h=0.3538·λ
h=0.3904·λ
h=0.427·λ
h=0.4636·λ
h=0.5002·λ
h=0.5368·λ

FIG. 8

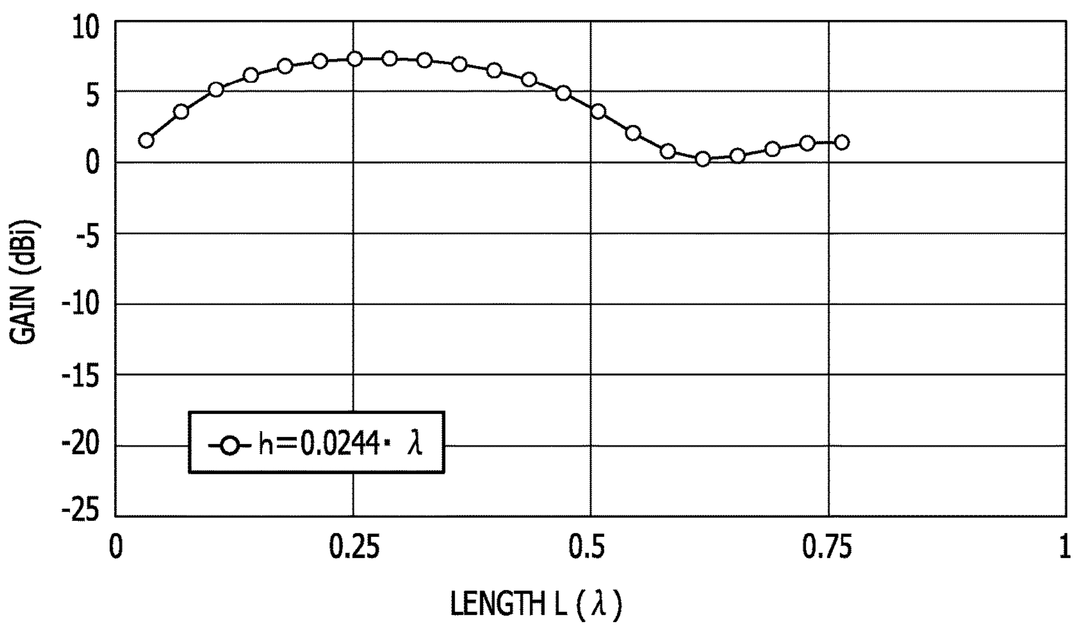
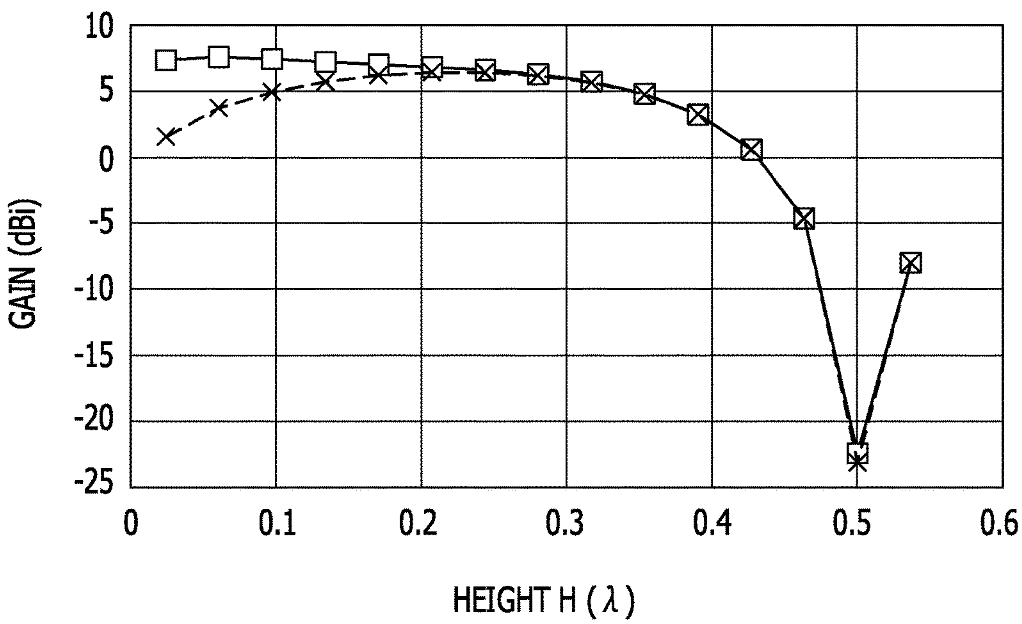


FIG. 9



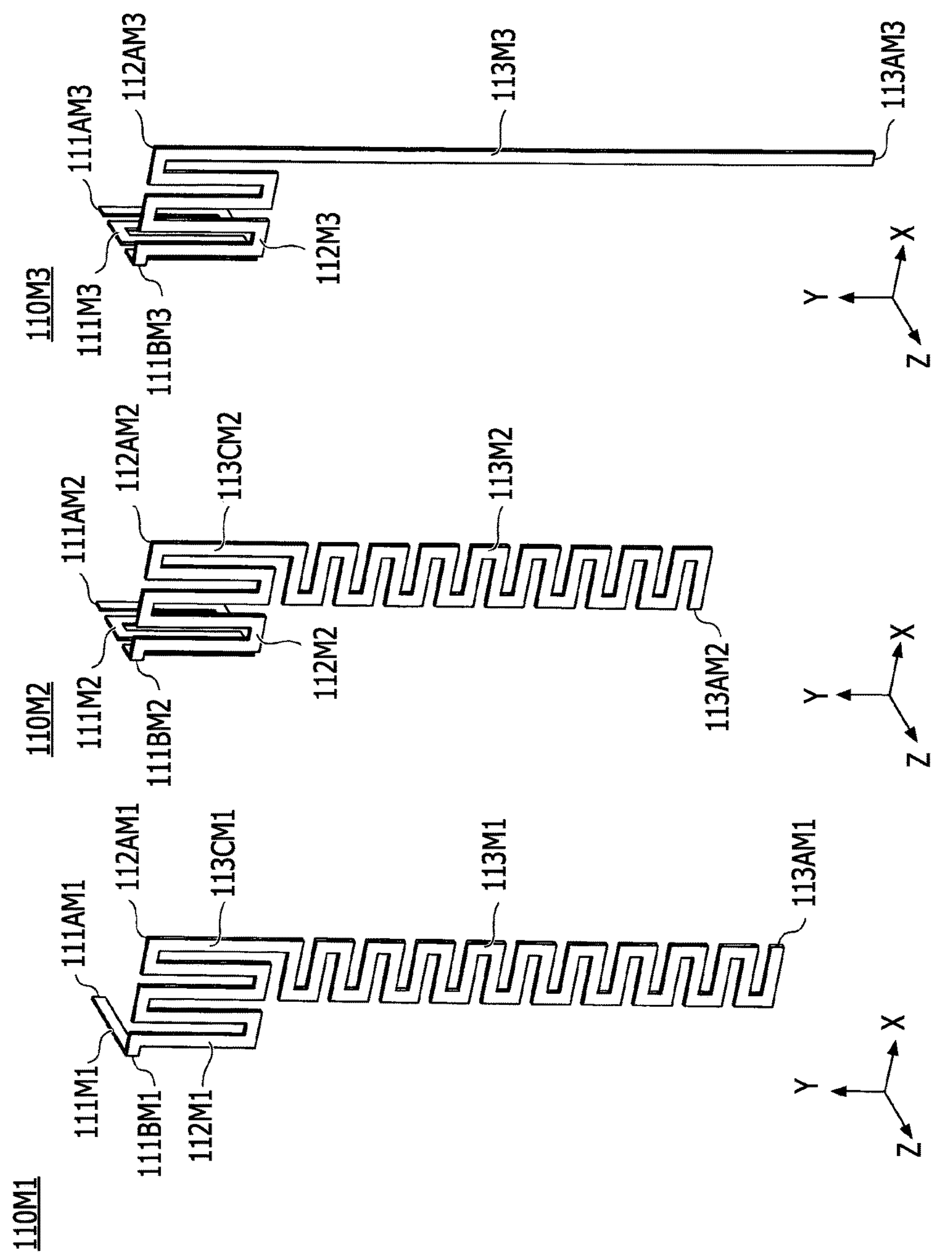


FIG. 10A

FIG. 10B

FIG. 10C

FIG. 11A

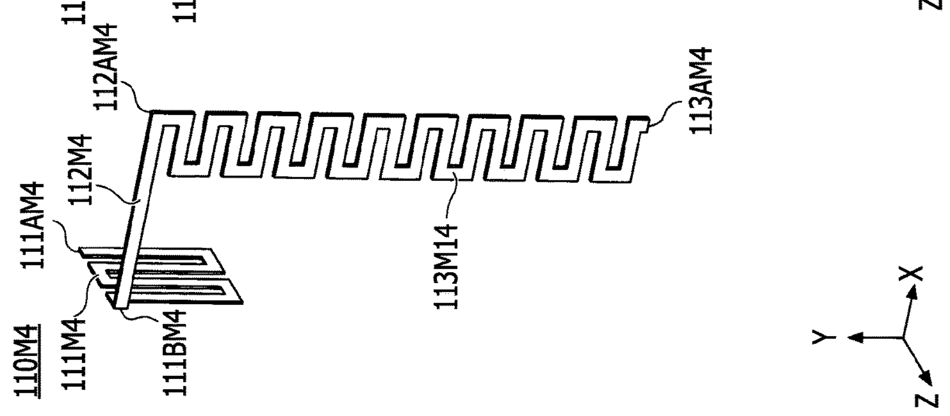


FIG. 11B

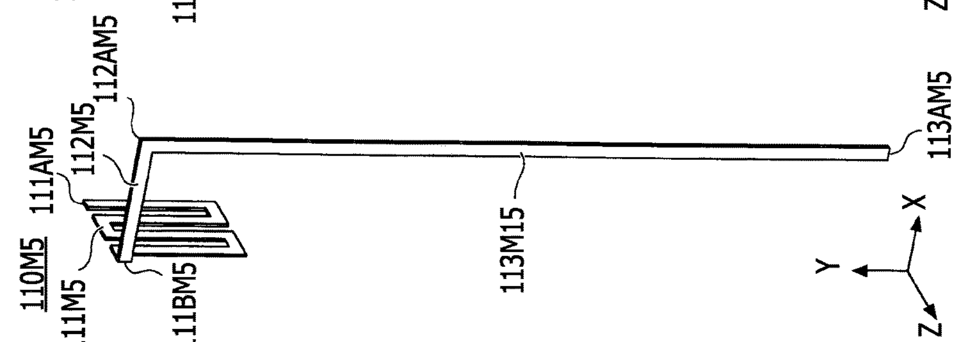


FIG. 11C

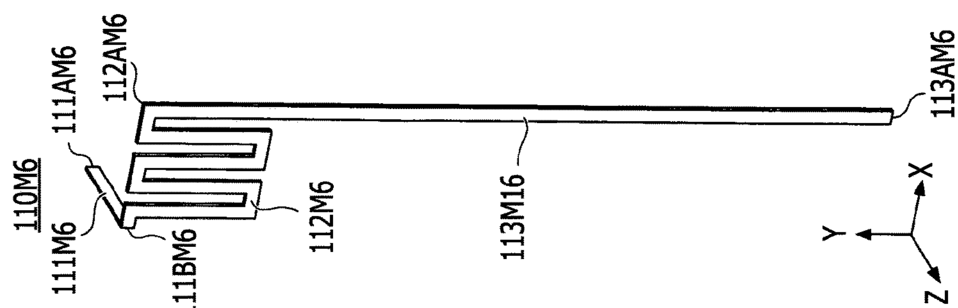
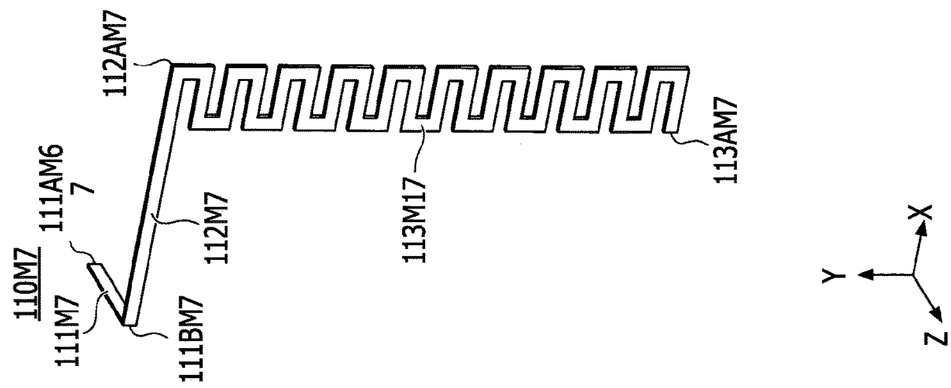


FIG. 11D



ANTENNA DEVICE AND WIRELESS COMMUNICATION APPARATUS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2018-720, filed on Jan. 5, 2018, the entire contents of which are incorporated herein by reference.

FIELD

[0002] The embodiments discussed herein are related to an antenna device and a wireless communication apparatus.

BACKGROUND

[0003] There has been an antenna device configured to be used at or in proximity to a user body. The antenna device has an antenna structure including a first conducting element, the antenna structure being configured so that a current is induced in at least the first conducting element during operation. The first conducting element extends over a length of between 1/16 of a wavelength and a full wavelength in a direction substantially orthogonal to the surface of the user body when the antenna device is formed in an intended operational position. With the antenna device mentioned above, the electromagnetic field propagates primarily in a direction along the surface of the user.

[0004] With the existing antenna device, the electromagnetic field (electrical field) propagates primarily in a direction along a surface of the user. The direction along the surface of the user is a direction parallel to a ground plane of the antenna device.

[0005] That is, the existing antenna device, whose directivity is set such that the electrical field is distributed along a direction in which the ground plane spreads out, does not have a large directivity in a direction vertically away from the ground plane. Therefore, the existing antenna device is incapable of yielding a communication distance in a direction vertical to the ground plane.

[0006] The following is a reference document.

[Document 1] Japanese National Publication of International Patent Application No. 2013-541913.

SUMMARY

[0007] According to an aspect of the embodiments, an antenna device includes a ground plane, and an antenna element formed on a first surface of the ground plane, the antenna element including a feed point, a first line extending from the feed point to a first end in a direction away from the first surface, a second line extending along the first surface of the ground plane from the first end of the first line to a second end, and a third line extending along the first surface of the ground plane from the second end of the second line to a third end in a direction different in plan view from an extending direction of the second line, wherein a length from the feed point to the third end of the third line of the antenna element is a length corresponding to three-quarters of an electrical length of a wavelength at a resonant frequency of the antenna element, and wherein a vector of a resonant current flowing in the second line and a vector of a resonant current flowing in the third line at the resonant frequency reinforce each other.

[0008] The object and advantages of the invention will be realized and attained by means of the elements and combinations particularly pointed out in the claims.

[0009] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are not restrictive of the invention.

BRIEF DESCRIPTION OF DRAWINGS

[0010] FIGS. **1**A to **1**C are diagrams illustrating an antenna device according to an embodiment;

[0011] FIG. **2** is a diagram illustrating a wireless communication apparatus including an antenna device according to an embodiment;

[0012] FIGS. **3**A to **3**C are diagrams illustrating an antenna element according to an embodiment and antenna elements for comparison;

[0013] FIGS. **4**A to **4**C are diagrams illustrating radiation patterns of an antenna element according to an embodiment and antenna elements for comparison;

[0014] FIGS. **5**A to **5**C are diagrams illustrating current distributions of an antenna element according to an embodiment and antenna elements for comparison;

[0015] FIG. **6** is a diagram illustrating gain characteristics relative to a length in a simulation model of an antenna device according to an embodiment;

[0016] FIG. **7** is a diagram illustrating gain characteristics relative to a height and a length in a simulation model of an antenna device according to an embodiment;

[0017] FIG. **8** is a diagram illustrating gain characteristics relative to a length for a height of 0.0244λ;

[0018] FIG. **9** is a diagram illustrating the relationship between a height and a gain of an antenna element according to an embodiment;

[0019] FIGS. **10**A to **10**C are diagrams respectively illustrating antenna elements of modifications of an embodiment; and

[0020] FIGS. **11**A to **11**D are diagrams respectively illustrating antenna elements of modifications of an embodiment.

DESCRIPTION OF EMBODIMENTS

[0021] Hereinafter, an embodiment to which an antenna device and a wireless communication apparatus of the present disclosure are applied will be described.

Embodiment

[0022] FIGS. **1**A to **1**C are diagrams illustrating an antenna device **100** according to an embodiment. FIGS. **1**A and **1**B illustrate a simulation model of the antenna device **100**, and FIG. **1**C illustrates an equivalent circuit of the antenna device **100**. Hereinafter, description will be given by using the XYZ coordinates in common and "in plan view" refers to "in XY plane view".

[0023] As illustrated in FIGS. **1**A and **1**B, the antenna device **100** includes a ground plane **50** and an antenna element **110**. The antenna device **100** may be, for example, included in a wireless communication apparatus that performs wireless communication, such as a smartphone terminal device, a tablet computer, or a game machine, or may be mounted on any object or the like so that a network of Internet of Things (IoT) is constructed. The object or the like may be something that is fixed and does not move, such as a wall of a building or the like, or may be something that moves.

[0024] The ground plane **50** is a metal layer or a metal plate maintained at a ground potential or a reference potential and may be considered as a ground layer or a ground plate. The ground plane **50** is arranged parallel to the XY plane.

[0025] The ground plane **50** may be, for example, a metal layer, a metal plate, or the like included in the wireless communication apparatus mentioned above, or may be a metal layer, a metal plate, or the like mounted on a dedicated substrate, housing, or the like. Such a metal layer, a metal plate, or the like may be something included in a circuit board according to a standard, such as, for example, frame retardant type 4 (FR4).

[0026] Of the two surfaces of the ground plane **50**, the surface on the positive Z-axis direction side thereof on which the antenna element **110** is disposed is an example of a first surface. In the simulation model, the ground plane **50** is a ground layer infinitely spreads out.

[0027] As illustrated in FIG. **1**A, the antenna element **110** is disposed to overlap the ground plane **50** in plan view. As illustrated in FIG. **1**B, the antenna element **110** includes a feed point **111**A, a line **111**, a bent portion **111**B, a line **112**, a bent portion **112**A, a line **113**, and an end portion **113**A.

[0028] The antenna element **110** is made of metal and is, for example, implemented by a metal layer of copper foil or the like. The antenna element **110** has a shape in which the antenna element **110** is bent at the bent portion **111**B and at the bent portion **112**A.

[0029] The antenna element **110** is a monopole antenna element in which the length from the feed point **111**A to the end portion **113**A, that is, the whole length of the antenna element **110**, is set to a length corresponding to three-quarters ($3\lambda/4$) of the wavelength (electrical length λ) at a resonant frequency f. The resonant frequency is, by way of example, 2.44 GHz. The electrical length λ is the wavelength of an electromagnetic wave that propagates through the antenna element **110**.

[0030] The feed point **111**A is disposed proximate to the ground plane **50**. For example, the feed point **111**A is disposed at a position that is a predetermined short distance away from the surface on the positive Z-axis direction side of the ground plane **50**. The predetermined short distance is, for example, about the thickness of an insulating layer of a substrate disposed between the feed point **111**A and the ground plane **50**, and is, by way of example, 1 mm. The feed point **111**A is coupled via a microstrip line, the core wire of a coaxial cable, or the like to a feeding circuit, such that feeding is performed.

[0031] The line **111** includes the feed point **111**A and extends in the positive Z-axis direction from the feed point **111**A to the bent portion **111**B. The length of the line **111** is set to a length less than or equal to three-tenths (0.3λ) of the wavelength (electrical length λ) at the resonant frequency f. The line **111** is an example of a first line.

[0032] The bent portion **111**B is a portion at which the line **111** extending in the positive Z-axis direction is bent to the positive X-axis direction. The bent portion **111**B is an end opposite the feed point **111**A of the line **111** and is an example of a first end. The bent portion **111**B is a portion for joining the line **111** and the line **112** and may be considered as a joint portion.

[0033] This portion, which is referred to as the bent portion **111**B herein, is not limited to having a form in which the line **111** and the line **112** are implemented by bending a metal layer, but may have a form in which different lines **111** and **112** are joined by the bent portion **111**B. The bent portion **111**B may be handled as a joint portion.

[0034] The line **112** extends in the X-axis direction from the bent portion **111**B to a bent portion **112**A. The line **112** is an example of a second line. The line **112** is disposed at a position of a certain height relative to the ground plane **50** between the bent portion **111**B and the bent portion **112**A.

[0035] The bent portion **112**A is a portion at which the line **112** extending in the positive X-axis direction is bent to the negative Y-axis direction. The bent portion **112**A is also an end opposite the bent portion **111**B of the line **112** and is an example of a second end. In addition, the bent portion **112**A is a portion for joining the line **112** and the line **113** and may be considered as a joint portion.

[0036] This portion, which is referred to as the bent portion **112**A herein, is not limited to having a form in which the line **112** and the line **113** are implemented by bending a metal layer, but may have a form in which different lines **112** and **113** are joined by the bent portion **112**A.

[0037] The line **113** includes the end portion **113**A and extends in the Y-axis direction from the bent portion **112**A to the end portion **113**A. The line **113** is an example of a third line. The line **113** is disposed at a position of a certain height relative to the ground plane **50** between the bent portion **112**A and the end portion **113**A.

[0038] The end portion **113**A is an end on the negative Y-axis direction side of the line **113** and is an end opposite the feed point **111**A of the antenna element **110**. The end portion **113**A is an open end and is an example of a third end.

[0039] In the antenna element **110** in such a manner, as described above, the length from the feed point **111**A to the end portion **113**A, that is, the whole length of the antenna element **110**, is set to a length corresponding to three-quarters ($3\lambda/4$) of the wavelength (electrical length λ) at the resonant frequency f.

[0040] The bent portion **112**A is formed at a position that enables the vector of a resonant current flowing in the line **112** at the resonant frequency f and the vector of a resonant current flowing in the line **113** at the resonant frequency f to reinforce each other.

[0041] Mutual reinforcement of the vector of the resonant current flowing in the line **112** and the vector of the resonant current flowing in the line **113** refers to the fact that the scalar magnitude of a resultant vector obtained by combining the vectors of the resonant currents flowing in the lines **112** and **113** that extend in different directions is greater than the scalar magnitude of either of the two vectors of the resonant currents flowing in the lines **112** and **113**.

[0042] The bent portion **112**A is more preferably disposed at a position corresponding to a node of a resonant current that occurs in the antenna element **110** at a resonant frequency. If the node of the resonant current is positioned at the bent portion **112**A, the two vectors of resonant currents flowing in the lines **112** and **113** have a relationship in which these vectors effectively reinforce each other. The position corresponding to the node is not limited to one point of the node of the resonant current but covers positions in front of and behind the node, and is a position at which the two vectors of resonant currents flowing in the lines **112** and **113** have a relationship in which these vectors reinforce each other.

[0043] The length from the feed point **111**A through the bent portion **111**B to the bent portion **112**A is set to a length corresponding to the length (0.0698λ to 0.5070λ) that is 0.0698 times to 0.5070 times the wavelength (electrical length λ) at the resonant frequency f. The reason why this length is set to such a length will be described below.

[0044] As described above, the length of the line **111** is set to a length corresponding to the length that is three-tenth (0.3λ) or less of the wavelength (electrical length λ) at the resonant frequency f. The reason why the length is set to such a length will be described below.

[0045] By way of example, a form in which the length of the line **111** (the length from the feed point **111**A to the bent portion **111**B) is 0.024λ and the length from the feed point **111**A through the bent portion **111**B to the bent portion **112**A is 0.276λ will be described.

[0046] In this case, the length of the line **112** (the length from the bent portion **111**B to the bent portion **112**A) is 0.252λ and the length of the line **113** (the length from the bent portion **112**A to the end portion **113**A) is 0.496λ.

[0047] The reason why the lengths are set to such values will be described below. The length corresponding to three-quarters (3λ/4) of the wavelength (electrical length λ) at the resonant frequency f is not limited exactly to 3λ/4 but is meant to include a length slightly shifted from 3λ/4 in consideration of the permittivities and the like of the neighboring components.

[0048] The length corresponding to the length less than or equal to three-tenth (0.3λ) of the wavelength (electrical length λ) is not limited exactly to 0.3λ but is meant to include a length less than or equal to a length slightly shifted from 0.3λ in consideration of the permittivities and the like of the neighboring components.

[0049] The length corresponding to a length (0.0698λ to 0.5070λ) that is 0.0698 times to 0.5070 times the wavelength (electrical length λ) at the resonant frequency f is not limited exactly to a range of 0.0698λ to 0.5070λ but is meant to include a length included in a range slightly shifted from the range of 0.0698λ to 0.5070λ in consideration of the permittivities and the like of the neighboring components.

[0050] The equivalent circuit of the antenna element **110** in such a manner is, as illustrated in FIG. **1**C, a circuit extending from the feed point **111**A to the bent portion **112**A on the XZ plane. The line **113** extends from the bent portion **112**A to the end portion **113**A in the negative Y-axis direction.

[0051] FIG. **2** is a diagram illustrating a configuration of a wireless communication apparatus **200** including the antenna device **100**. FIG. **2** illustrates a configuration of the wireless communication apparatus **200** as viewed in plan. The wireless communication apparatus **200** illustrated in FIG. **2** is, by way of example, included in a smartphone terminal device.

[0052] The wireless communication apparatus **200** includes a substrate **51**, an antenna element **110**, a duplexer (DUP) **210**, a low noise amplifier (LNA)/power amplifier (PA) **220**, a modulator/demodulator **230**, and a central processing unit (CPU) chip **240**.

[0053] The substrate **51**, which is, by way of example, an FR4 standard circuit board, includes the ground plane **50**, an insulating layer **52**, a microstrip line **53**, and wiring **54**. The ground plane **50** is disposed on the surface on the negative Z-axis direction side of the insulating layer **52**, and the microstrip line **53** and the wiring **54** are disposed on the surface on the positive Z-axis direction side of the insulating layer **52**. On the surface on the positive Z-axis direction side of the insulating layer **52**, the DUP **210**, the LNA/PA **220**, the modulator/demodulator **230**, and the CPU chip **240** are also mounted.

[0054] The ground plane **50** is rectangular in plan view and is disposed over the substantial entirety of the insulating layer **52** that is also rectangular in plan view. The antenna element **110** is disposed on the negative Z-axis direction side of the insulating layer **52** so as to be positioned at the corner on the positive X-axis direction side and on the positive Y-axis direction side of the ground plane **50** in plan view.

[0055] The microstrip line **53** has a characteristic impedance (for example, 50Ω) that matches the impedance of the antenna element **110**, and transmits a signal under low-loss and low-reflection conditions between the antenna element **110** and the DUP **210**. Although the form of performing feeding via the microstrip line **53** is described herein by way of example, any of the transmission paths having a characteristic impedance that matches that of the antenna element **110** may be used other than the microstrip line **53**.

[0056] The antenna element **110** has a height due to the line **111** (refer to FIG. **1**B), and therefore an insulator having a height equal to the height due to the line **111** is disposed on the surface on the positive Z-axis direction side of the insulating layer **52**, such that the antenna element **110** is held by the insulator. The antenna device **100** is constructed of the antenna element **110** and the ground plane **50**.

[0057] Instead of such a configuration, a configuration in which the antenna element **110** is held by a member mounted on the positive Z-axis direction side of the insulating layer **52** may be employed. Such a member is, for example, a housing or the like of a wireless communication apparatus including the antenna device **100**.

[0058] The DUP **210**, the LNA/PA **220**, the modulator/demodulator **230**, and the CPU chip **240** are coupled via the wiring **54**.

[0059] The DUP **210**, which is coupled via the microstrip line **53** and a via (not illustrated) to the antenna element **110**, switches between transmission and reception functions. The DUP **210** has filter capabilities, and therefore when the antenna element **110** receives signals of a plurality of frequencies, the DUP **210** is able to separate the signals of the respective frequencies inside of itself.

[0060] The LNA/PA **220** amplifies the power of both transmission waves and received waves. The modulator/demodulator **230** modulates transmission waves and demodulates received waves. The CPU chip **240** has the function of a communication processor that performs communication processing of the wireless communication apparatus **200** and the function of an application processor that executes application programs. The CPU chip **240** includes an inner memory for storing data to be transmitted, data that has been received, and the like. The LNA/PA **220**, the modulator/demodulator **230**, and the CPU chip **240** are an example of a feeding circuit.

[0061] The microstrip line **53** and the wiring **54** are formed, for example, by patterning copper foil on the surface of the insulating layer **52**. Although not illustrated in

FIG. **2**, a matching circuit for adjusting the impedance characteristic is formed between the antenna device **100** and the DUP **210**.

[0062] FIGS. **3**A to **3**C are diagrams illustrating the antenna element **110** according to the embodiment and antenna elements **10**A and **10**B for comparison. FIGS. **3**A to **3**C also illustrate gains in the vertical direction determined by electromagnetic field simulation. The vertical direction is the positive Z-axis direction and is a direction vertical to the ground plane **50**. The vertical direction may be handled as the front direction of the antenna device **100**.

[0063] Although the ground plane **50** is not illustrated in FIGS. **3**A to **3**C, electromagnetic field simulation is performed assuming that the ground plane **50** is present in the cases of FIGS. **3**A to **3**C, as in the case of FIG. **1**A.

[0064] The antenna element **110** according to the embodiment illustrated in FIG. **3**A is the same as illustrated in FIG. **1**B such that the lengths of the lines **111**, **112**, and **113** are 0.024λ, 0.252λ, and 0.496λ, respectively.

[0065] The antenna element **10**A for comparison illustrated in FIG. **3**B has a configuration in which the line **113** of the antenna element **110** extends straightly without being bent relative to the line **112**. For example, the antenna element **10**A extends in the positive Z-axis direction from a feed point **11**A and is bent at a bent portion **12**A into the positive X-axis direction to extend to an end portion **13**A. The antenna element **10**A, which is an antenna element for a modified type of a monopole antenna, is reversed L-shaped and has a length of 3λ/4.

[0066] The length from the feed point **11**A to the bent portion **12**A is 0.024λ, which is the same as the length of the line **111** of the antenna element **110**. That is, the height of the antenna element **10**A relative to the ground plane **50** is equal to the height of the antenna element **110** relative to the ground plane **50**. The length from the bent portion **12**A to the end portion **13**A is 0.756λ, and the length from the feed point **11**A to the end portion **13**A is a length corresponding to three-quarters (3λ/4) of the wavelength (electrical length λ) at the resonant frequency f.

[0067] The antenna element **10**B for comparison illustrated in FIG. **3**C is an element having a length obtained by reducing the length of the antenna element **10**A illustrated in FIG. **3**B to a quarter (λ/4) of the wavelength (electrical length λ) at the resonant frequency f. For example, the antenna element **10**B extends in the positive Z-axis direction from a feed point **11**B and is bent at a bent portion **12**B into the positive X-axis direction to extend to an end portion **13**B. The antenna element **10**B is a reversed L-shaped monopole antenna.

[0068] The length from the feed point **11**B to the bent portion **12**B is 0.024λ, which is the same as the length of the line **111** of the antenna element **110**. That is, the height of the antenna element **10**B relative to the ground plane **50** is equal to the height of the antenna element **110** relative to the ground plane **50**. The length from the bent portion **12**B to the end portion **13**B is 0.252λ.

[0069] As indicated in FIG. **3**A, the gain in the vertical direction of the antenna element **110** is 7.3 dBi; as indicated in FIG. **3**B, the gain in the vertical direction of the antenna element **10**A is 1.1 dBi; and, as indicated in FIG. **3**C, the gain in the vertical direction of the antenna element **10**B is 3.6 dBi.

[0070] From the above, the gain in the vertical direction of the antenna element **110** is about double the gain in the vertical direction of the reversed L-shaped antenna element **10**B having a length of λ/4. In contrast, the gain in the vertical direction of the antenna element **10**A that is reversed L-shaped and has a length of 3λ/4 is about one-seventh of the gain in the vertical direction of the antenna element **110** and is about one-third of the gain in the vertical direction of the antenna element **10**B.

[0071] FIGS. **4**A to **4**C are diagrams illustrating radiation patterns of the antenna elements **110**, **10**A, and **10**B. The XYZ coordinates in FIGS. **4**A to **4**C are equal to the XYZ coordinates illustrated in FIGS. **1**A to **3**C. In FIGS. **4**A to **4**C, the antenna elements **110**, **10**A, and **10**B are each disposed at the origin of the XYZ coordinates.

[0072] As illustrated in FIG. **4**A, the radiation pattern of the antenna element **110** is oriented in the vertical direction (positive Z-axis direction), and a large gain of +7.3 dBi is obtained.

[0073] As illustrated in FIG. **4**B, the radiation pattern of the antenna element **10**A has a large depression in the vertical direction (positive Z-axis direction) and has a gain of +1.1 dB, which is a very small value.

[0074] As illustrated in FIG. **4**C, the radiation pattern of the antenna element **10**B is oriented in the vertical direction (positive Z-axis direction) and the gain thereof is about half (+3.6 dBi) the gain of the antenna element **110**.

[0075] FIGS. **5**A to **5**C are diagrams illustrating current distributions of the antenna elements **110**, **10**A, and **10**B. The current distributions indicated by arrows in FIGS. **5**A to **5**C are obtained by electromagnetic field simulation. The arrow direction indicates a direction in which a resonant current flows at some instance, and the current distribution illustrated in grayscale indicates that the darker the color of an arrow, the higher the current density whereas the lighter the color of an arrow, the lower the current density.

[0076] As illustrated in FIG. **5**A, for the current distribution of the antenna element **110**, it is recognized that the current density is highest at the feed portion **111**A and at an intermediate portion between the bent portion **112**A and the end portion **113**A and is lowest at the bent portion **112**A and at the end portion **113**A.

[0077] Since the antenna element **110** has a length of 3λ/4, antinodes of the resonant current are at the feed point **111**A and at an intermediate portion between the bent portion **112**A and the end portion **113**A and nodes of the resonant current are at the bent portion **112**A and at the end portion **113**A.

[0078] As illustrated in FIG. **5**B, since the antenna element **10**A has a length of 3λ/4, in the current distribution, nodes of the resonant current are at a position λ/4 away from the feed point **11**A and at the end portion **13**A and antinodes of the resonant current are at the feed point **11**A and at a position λ/2 away from the feed point **11**A.

[0079] As illustrated in FIG. **5**C, since the antenna element **10**B has a length of λ/4, in the current distribution, a node of the resonant current is at the end portion **13**B and an antinode of the resonant current is at the feed point **11**B.

[0080] From the current distributions of the antenna elements **110**, **10**A, and **10**B as described above, respective gains thereof will be discussed. The antenna element **10**B is an exemplary quarter-wavelength (λ/4) monopole antenna, and the gain of the antenna element **10**B may be used as a determination criterion.

[0081] For the antenna element **10**A, it is considered that resonant currents oriented opposite to each other, which are indicated by arrows B1 and B2, occur on both sides of the node and thereby the radiation is cancelled out. It is also considered that the cancellation of radiation causes the gain to be lower than the gain of the antenna element **10**B.

[0082] In the antenna element **110**, the bent portion **112**A is a node of the resonant current, and a resonant current from the bent portion **112**A toward the bent portion **111**B and a resonant current from the bent portion **112**A toward the end portion **113**A differ in direction.

[0083] The reason why, in the antenna element **110** in such a configuration, a gain greater than the gain in the antenna element **10**B is obtained is as follows. A resultant vector (vector indicated by an arrow A) obtained by combining the vector of the resonant current from the bent portion **112**A toward the bent portion **111**B and the vector of the resonant current from the bent portion **112**A toward the end portion **113**A is greater than the vector of the resonant current of the antenna element **10**B, so that a gain about double the gain of the antenna element **10**B is obtained. The vector of the resonant current of the antenna element **10**B is a current vector obtained midway between the end portion **13**B and the bent portion **12**B.

[0084] FIG. **6** is a diagram illustrating the gain in a simulation model of the antenna device **100** when a length L from the feed point **111**A to the bent portion **112**A is varied. The gain is a gain in the vertical direction (positive Z-axis direction). The length L is represented by a normalized value obtained by division by the wavelength (electrical length λ) at the resonant frequency f.

[0085] The length of the line **111** is fixed to 0.024λ and the length of the antenna element **110** is substantially fixed at 3λ/4. The length of the antenna element **110** is not fixed at 3λ/4 but is substantially fixed at 3λ/4 because as the length L varies, the length of the antenna element **110** may vary to some extent due to impedance adjustment or the like.

[0086] When the length L is varied from 0.024λ to about 0.76λ, the gain is about 7.3 dBi at the length L of about 0.25λ. Assuming that the gain (3.6 dBi) of the antenna element **10**B is a determination criterion, the gain is 3.6 dBi or more with the length L within a range of 0.0698λ to 0.5070λ.

[0087] Therefore, it has been found that setting the length L to be within a range of 0.0698λ to 0.5070λ yields a gain greater than or equal to the gain of the antenna element **10**B having a length of a quarter wavelength (λ/4). With the length L of 0.024λ, there is formed an antenna element in a configuration in which the line **112** is not formed and the line **113** is directly joined to the line **111**.

[0088] FIG. **7** is a diagram illustrating relationships between the length L and the gain in a simulation model of the antenna device **100** when the height h from the feed point **111**A to the bent portion **111**B is changed. The gain is a gain in the vertical direction (positive Z-axis direction). The length L, as in FIG. **6**, is a length from the feed point **111**A to the bent portion **112**A and is represented by a normalized value obtained by division by the wave length (electrical length λ) at the resonant frequency f. The length of the antenna element **110** is substantially fixed at 3λ/4. Substantially fixing the length of the antenna element **110** at 3λ/4 has a meaning similar to that described with reference to FIG. **6**.

[0089] The characteristics illustrated in FIG. **7** are obtained by varying the length L from 0.024λ to about 0.76λ and varying the height h. The height h is set to 0.0244λ, 0.061λ, 0.0976λ, 0.1342λ, 0.1708λ, 0.2074λ, 0.244λ, 0.2806λ, 0.3172λ, 0.3538λ, 0.3904λ, 0.427λ, 0.4636λ, 0.5002λ, and 0.5368λ.

[0090] FIG. **8** is a diagram illustrating the characteristics with the height h of 0.0244λ, which are selected from the characteristics illustrated in FIG. **7**.

[0091] As illustrated in FIG. **7**, for the height h of 0.5002λ, the gain has low values of about −23 dBi to about −24 dBi. This is considered because a node of a resonant current is positioned about 0.25λ away from the feed point **111**A and therefore the node of the resonant current is at an intermediate portion of the line **111**, cancelling out the radiation. It is considered that, for the heights h of 0.4636λ and 0.5386λ, similar phenomena occur, resulting in gains of about −5 dBi and about −8 dBi, respectively.

[0092] It is also considered that, for the height h of 0.427λ, the radiation is cancelled out by resonant currents in opposite directions flowing in the line **111**, such that the gain is about 0 dBi.

[0093] For the heights h of 0.3172λ, 0.3538λ, and 0.3904λ, the gain is about 5 dBi to about 5.5 dBi, about 4.5 dBi to about 5 dBi, and about 3 dBi, respectively.

[0094] For the heights h of 0.0244λ, 0.061λ, 0.976λ, 0.1342λ, 0.1708λ, 0.2074λ, 0.244λ, and 0.2806λ, it has been found that a high gain of about 7 dBi or more is obtained when the length L is in the neighborhood of about 0.3λ.

[0095] As illustrated in FIG. **8**, for the height h of 0.0244λ, when the length L is varied, the gain varies within a range of about 2 dBi to 7.3 dBi, and the length L to yield the greatest gain (7.3 dBi) is about 0.25λ.

[0096] FIG. **9** is a diagram illustrating a relationship between the height h and the gain in the antenna element **110**. The gain indicated by an X-shaped marker in FIG. **9** is the greatest gain obtained by varying the length L for each of the cases where the height h is 0.0244λ, where the height h is 0.061λ, where the height h is 0.976λ, where the height h is 0.1342λ, where the height h is 0.1708λ, where the height h is 0.2074λ, where the height h is 0.244λ, where the height h is 0.2806λ, where the height h is 0.3172λ, where the height h is 0.3538λ, where the height h is 0.3904λ, where the height h is 0.427λ, where the height h is 0.4636λ, where the height h is 0.5002λ, and where the height h is 0.5368λ. That is, the greatest gain obtained when the height h is 0.0244λ is a value obtained when the length L is about 0.25λ, and the greatest gain obtained when the height h is 0.5368λ is a value obtained when the length L is about 0.54λ.

[0097] In FIG. **9**, for comparison, the gain characteristics obtained when, in the antenna element **10**A (refer to FIG. **5**B), the height h (the length from the feed point **11**A to the bent portion **12**A) is varied are indicated by square markers. With reference to FIG. **9**, it has been found that when the height h is less than or equal to 0.3λ, the gain of the antenna element **110** is 0.1 dBi or more greater than the gain of the antenna element **10**A.

[0098] As described above, according to the embodiment, the bent portion **112**A of the antenna element **110** whose whole length is three-quarters of the wavelength (electrical length λ) at the resonant frequency f is disposed at a position at which the vector of a current flowing in the line **112** and the vector of a current flowing in the line **113** have a relationship in which the vectors reinforce each other. Therefore, the antenna device **100** having a high gain may be formed.

[0099] Accordingly, the antenna device **100**, which has a sufficient communication distance in a direction vertical to the ground plane, and the wireless communication apparatus **200** may be provided.

[0100] For example, since the bent portion **112**A is at a position corresponding to a node of the resonant current, a resultant vector obtained by combining the vector of a current flowing in the line **112** and the vector of a current flowing in the line **113** is greater than the vector of the resonant current in the antenna element **10**B (refer to FIG. **3**C) for comparison whose whole length is λ/4. Thus, the antenna device **100** having a high gain may be provided.

[0101] In addition, by setting the length from the feed point **111**A to the bent portion **112**A to a length corresponding to the length that is 0.0698 times to 0.5070 times the electrical length λ, a gain greater than or equal to the gain of the antenna element **10**B for comparison (refer to FIG. **3**C) whose whole length is λ/4 may be obtained.

[0102] In addition, by setting the length from the feed point **111**A to the bent portion **111**B (the height h relative to the ground plane **50**) to be less than or equal to 0.3λ, the antenna device **100** having a gain that is 0.1 dBi or more greater than the reverse L-shaped antenna element **10**A (refer to FIG. **3**B) whose whole length is three-quarters of the electrical length λ may be provided.

[0103] In the above, the form of the antenna element **110** in which the line **113** is bent at right angles to the line **112**, in plan view, has been described; however, the angle of the line **113** relative to the line **112**, in plan view, may not be vertical. The angle of the line **113** relative to the line **112**, in plan view, may be an angle at which a resultant vector that allows the vector of a current flowing in the line **112** and the vector of a current flowing in the line **113** to reinforce each other is obtained and at which the resultant vector greater than the vector of the resonant current in the antenna element **10**B (refer to FIG. **3**C) is obtained.

[0104] In addition, although the form in which the lines **111**, **112**, and **113** are linear has been described above, the lines **111**, **112**, and **113** may be shaped in ways other than so as to be linear. FIGS. **10**A to **10**C and FIGS. **11**A to **11**D are diagrams illustrating antenna elements **110M1** to **110M7** according to modifications of the embodiment.

[0105] The antenna elements **110M1** to **110M7** are antenna elements in which the shape of at least one of the lines **111**, **112**, and **113** of the antenna element **110** is deformed into a meander shape. The conditions such as the lengths of the lines **111**, **112**, and **113** are similar to the conditions for the antenna element **110** described with reference to FIG. **1** to FIG. **9**, and therefore the shapes and the like of the lines of the antenna elements **110M1** to **110M7** will be described here.

[0106] The antenna element **110M1** illustrated in FIG. **10**A includes lines **111M1**, **112M1**, and **113M1**. The line **111M1** extends linearly from a feed point **111**AM**1** to a bent portion **111**BM**1**, the line **112M1** extends in a meander shape from the bent portion **111**BM**1** to a bent portion **112**AM**1**, and the line **113M1** extends from the bent portion **112**AM**1** toward an end portion **113**AM**1** such that, after passing through a linear portion **113**CM**1**, the line **113M1** extends in a meander shape.

[0107] The antenna element **110M2** illustrated in FIG. **10**B includes lines **111M2**, **112M2**, and **113M2**. The line **111M2** extends in a meander shape from a feed point **111**AM**2** to a bent portion **111**BM**2**, the line **112M2** extends in a meander shape from the bent portion **111**BM**2** to a bent portion **112**AM**2**, and the line **113M2** extends from the bent portion **112**AM**2** toward an end portion **113**AM**2** such that, after passing through a linear portion **113**CM**2**, the line **113M2** extends in a meander shape.

[0108] The antenna element **110M3** illustrated in FIG. **10**C includes lines **111M3**, **112M3**, and **113M3**. The line **111M3** extends in a meander shape from a feed point **111**AM**3** to a bent portion **111**BM**3**, the line **112M3** extends in a meander shape from the bent portion **111**BM**3** to a bent portion **112**AM**3**, and the line **113M3** extends linearly from the bent portion **112**AM**3** toward an end portion **113**AM**3**.

[0109] The antenna element **110M4** illustrated in FIG. **11**A includes lines **111M4**, **112M4**, and **113M4**. The line **111M4** extends in a meander shape from a feed point **111**AM**4** to a bent portion **111**BM**4**, the line **112M4** extends linearly from the bent portion **111**BM**4** to a bent portion **112**AM**4**, and the line **113M4** extends in a meander shape from the bent portion **112**AM**4** toward an end portion **113**AM**4**.

[0110] The antenna element **110M5** illustrated in FIG. **11**B includes lines **111M5**, **112M5**, and **113M5**. The line **111M5** extends in a meander shape from a feed point **111**AM**5** to a bent portion **111**BM**5**, the line **112M5** extends linearly from the bent portion **111**BM**5** to a bent portion **112**AM**5**, and the line **113M5** extends linearly from the bent portion **112**AM**5** toward an end portion **113**AM**5**.

[0111] The antenna element **110M6** illustrated in FIG. **11**C includes lines **111M6**, **112M6**, and **113M6**. The line **111M6** extends linearly from a feed point **111**AM**6** to a bent portion **111**BM**6**, the line **112M6** extends in a meander shape from the bent portion **111**BM**6** to a bent portion **112**AM**6**, and the line **113M6** extends linearly from the bent portion **112**AM**6** toward an end portion **113**AM**6**.

[0112] The antenna element **110M7** illustrated in FIG. **11**D includes lines **111M7**, **112M7**, and **113M7**. The line **111M7** extends linearly from a feed point **111**AM**7** to a bent portion **111**BM**7**, the line **112M7** extends linearly from the bent portion **111**BM**7** to a bent portion **112**AM**7**, and the line **113M7** extends in a meander shape from the bent portion **112**AM**7** toward an end portion **113**AM**7**.

[0113] In the antenna elements **110M1** to **110M7** as described above, the vectors (in the X-axis direction) of resonant currents flowing in the lines **112M1** to **112M7** and the vectors (in the Y-axis direction) of resonant currents flowing in the lines **113M1** to **113M7** reinforce each other, and therefore antenna devices having high gains may be provided, as in the case using the antenna element **110** described with reference to FIG. **1**A to FIG. **9**.

[0114] All examples and conditional language provided herein are intended for the pedagogical purposes of aiding the reader in understanding the invention and the concepts contributed by the inventor to further the art, and are not to be construed as limitations to such specifically recited examples and conditions, nor does the organization of such examples in the specification relate to a showing of the superiority and inferiority of the invention. Although one or more embodiments of the present invention have been described in detail, it should be understood that the various changes, substitutions, and alterations could be made hereto without departing from the spirit and scope of the invention.

What is claimed is:

1. An antenna device comprising:

a ground plane; and

an antenna element formed on a first surface of the ground plane, the antenna element including

a feed point,

a first line extending from the feed point to a first end in a direction away from the first surface,

a second line extending along the first surface of the ground plane from the first end of the first line to a second end, and

a third line extending along the first surface of the ground plane from the second end of the second line to a third end in a direction different in plan view from an extending direction of the second line,

wherein a length from the feed point to the third end of the third line of the antenna element is a length corresponding to three-quarters of an electrical length of a wavelength at a resonant frequency of the antenna element, and

wherein a vector of a resonant current flowing in the second line and a vector of a resonant current flowing in the third line at the resonant frequency reinforce each other.

2. The antenna device according to claim **1**, wherein

the second end is a position corresponding to a node of a resonant current flowing in the antenna element at the resonant frequency.

3. The antenna device according to claim **1**, wherein

a position of the second end is a position corresponding to a length of 0.0698 times to 0.5070 times the electrical length of the wavelength at the resonant frequency.

4. The antenna device according to claim **1**, wherein

a length from the feed point to the first end of the first line is a length corresponding to a length less than or equal to three-tenths of the electrical length of the wavelength at the resonant frequency.

5. The antenna device according to claim **1**, wherein

a scalar magnitude of a resultant vector obtained by combining the vector of the resonant current flowing in the second line and the vector of the resonant current flowing in the third line at the resonant frequency is greater than a scalar magnitude of a vector of a resonant current flowing at the resonant frequency in a monopole antenna extending from the feed point.

6. The antenna device according to claim **1**, wherein

the first line, the second line, or the third line has a meander shape.

7. The antenna device according to claim **1**, wherein

the first line extends vertically from the first surface.

8. The antenna device according to claim **1**, wherein

a height of the second line and a height of the third line relative to the first surface are equal.

9. The antenna device according to claim **1**, wherein

an angle of an extending direction of the third line in plan view relative to an extending direction of the second line is a right angle.

10. The antenna device according to claim **1**, wherein

the feed point is disposed proximate to the first surface.

11. A wireless communication apparatus comprising:

an antenna device; and

a feeding circuit that feeds the antenna device, the antenna device including

a ground plane, and

an antenna element formed on a first surface of the ground plane,

the antenna element including

a feed point,

a first line extending from the feed point to a first end in a direction away from the first surface,

a second line extending along the first surface of the ground plane from the first end of the first line to a second end, and

a third line extending along the first surface of the ground plane from the second end of the second line to a third end in a direction different in plan view from an extending direction of the second line,

wherein a length from the feed point to the third end of the third line of the antenna element is a length corresponding to three-quarters of an electrical length of a wavelength at a resonant frequency of the antenna element, and

wherein a vector of a resonant current flowing in the second line and a vector of a resonant current flowing in the third line at the resonant frequency reinforce each other.

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