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Amended claims in accordance with Rule 137(2) EPC.

(54) **POWER-EFFICIENT MULTI-BEAM ANTENNA**

(57) The present disclosure relates to an antenna device. The antenna device includes a feeding network including a plurality of input ports connectable to sources, a plurality of output ports, and a reversed form of a beamforming network, where a plurality of output ports of the beamforming network are used as the plurality of input ports of the feeding network, and a plurality of input ports of the beamforming network are used as the plurality of outputs of the feeding network. The radiation means is used for generating radio waves based on an output from one of the plurality of output ports of the feeding network. The superstrate is arranged above the radiation means in a main direction of radiation and is adapted to generate one or more directive beams based on the radio waves. In this way, all the available power at the input ports is utilized.

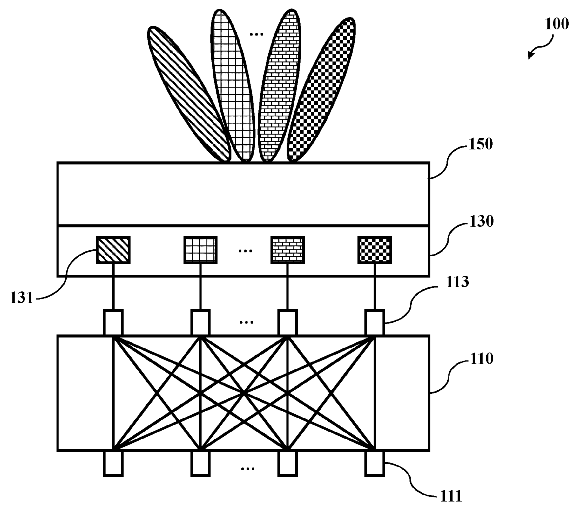

FIG. 1

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Description

TECHNICAL FIELD

[0001] The present disclosure generally relates to the field of communications technology. For instance, the present disclosure provides an antenna device, system, and array.

BACKGROUND

[0002] Multi-beam antennas are widely used in wireless communications to provide higher data rates and more reliability. Multi-beam antennas are designed to produce multiple radiation patterns or beams from a single antenna structure. In some application scenarios, such as the fourth generation (4G) and the fifth generation (5G) mobile network, fixed sets of beams may be used for various purposes, such as channel state information (CSI) beams. Multi-user beams are also widely used in wireless local area networks (WLAN) and other communications networks. Multiple data streams may be communicated through the multi-beam antenna, thus improving the efficiency and capacity of wireless communication systems.

SUMMARY

[0003] Despite the advantages mentioned above, the state-of-the-art multi-beam antennas also come with challenges. For antenna arrays with less than 0.5λ inter-element spacing, a directivity higher than that of a uniformly-fed array (namely, super-directivity) may be achieved by a proper selection of weights for each radiator. However, such feeding normally implies that not all the radiators are fed with the maximum available (or acceptable) power. For active phased arrays, this means under-utilization of a power resource.

[0004] Multi-beam antennas based on feeding networks or lenses may produce directive beams. However, each of the beams generated in this way can only transmit the power incident received at one of the input ports. This is because each input port excites only one beam in one specific direction.

[0005] In view of the above-mentioned problems and disadvantages, the present disclosure aims to improve multi-beam antenna design. An objective may be to provide an energy-efficient multi-beam antenna.

[0006] These and other objectives are achieved by this disclosure, for instance, as described in the independent claims. Advantageous implementations are further described in the dependent claims.

[0007] A first aspect of the present disclosure provides an antenna device comprising a feeding network, a radiation means, and a superstrate.

[0008] The feeding network comprises a plurality of input ports, a plurality of output ports, and a reversed form of a beamforming network. Each input is connectable to a corresponding source. For forming the reversed form of the beamforming network, a plurality of output ports of the beamforming network are used as the plurality of input ports of the feeding network, and a plurality of input ports of the beamforming network are used as the plurality of outputs of the feeding network.

[0009] The radiation means is for generating (or radiating) radio waves based on an output from one of the plurality of output ports of the feeding network.

[0010] The superstrate is arranged above the radiation means in a main direction of radiation and is adapted to generate one or more directive beams based on the radio waves.

[0011] In this way, by using the reversed form of the beamforming network in the feeding network, all available power at the input ports of the feeding network can be utilized through being directed to one of the output ports of the feeding network. Thus, the energy efficiency can be improved. Power requirements on the antenna device can be eased.

[0012] In an implementation form of the first aspect, the feeding network is adapted to direct all available inputs received from the plurality of input ports of the feeding network to one of the pluralities of output ports of the feeding network.

[0013] In an implementation form of the first aspect, the feeding network may be adapted to direct all the available inputs based on a plurality of phase profiles thereof.

[0014] Optionally, a phase profile may be referred to as a pattern of phase difference between the input ports of the feeding network, such that all the available inputs received from the input ports of the feeding network are directed to one particular output port (e.g., to form a beam with a particular phase) of the feeding network. Since the beamforming network is reversed, all available power of the input ports of the feeding network can be directed to one output port of the feeding network.

[0015] In an implementation form of the first aspect, the beamforming network may comprise a Butler matrix, or a Blass matrix, or a Nolen matrix, or a Rotman lens, or a Skobelev matrix.

[0016] In an implementation form of the first aspect, the radiation means may comprise radiation sources coupled to the output ports of the feeding network.

[0017] In an implementation form of the first aspect, the radiation sources may comprise a plurality of radiators.

[0018] In an implementation form of the first aspect, each radiator may be a dual-polarized radiator.

[0019] Alternatively, each radiator may be a single-polarized radiator.

[0020] In an implementation form of the first aspect, the superstrate may comprise a metasurface for beamforming.

[0021] In an implementation form of the first aspect, the superstrate may comprise a lens for beamforming. Optionally, the lens comprises a gradient-index (GRIN) dielectric lens.

[0022] A second aspect of the present disclosure provides an antenna system comprising at least one antenna device according to the first aspect or any implementation thereof and a plurality of sources. Each source is coupled to an input port of the feeding network of the at least one antenna device.

[0023] In an implementation form of the second aspect, the plurality of sources may be adapted to provide a plurality of inputs with a plurality of phase profiles to the input ports of the feeding network, such that the plurality of inputs is directed to one of the pluralities of output ports of the feeding network, respectively.

[0024] In an implementation form of the second aspect, the antenna system may be a multiple-input and multiple-output (MIMO) antenna system.

[0025] A third aspect of the present disclosure provides an antenna array comprising two or more antenna devices each according to the first aspect or any implementation thereof. The two or more antenna devices are coupled and arranged in a plane.

BRIEF DESCRIPTION OF DRAWINGS

[0026] The above-described aspects and implementation forms will be explained in the following description in relation to the enclosed drawings, in which:

FIG. 1 shows an example of an antenna device;

FIG. 2 shows an example of a feeding network;

FIG. 3 shows an example of a radiation means and a superstrate; and

FIG. 4 shows an antenna system and an antenna array.

DETAILED DESCRIPTION OF EMBODIMENTS

[0027] FIG. 1 shows an example of an antenna device 100. The antenna device 100 comprises a feeding network 110, radiation means 130, and a superstrate 150.

[0028] The feeding network 110 comprises a plurality of input ports 111, a plurality of output ports 113, and a reversed form of a beamforming network.

[0029] Each input port 111 of the feeding network 110 is connectable to a corresponding source and is adapted to receive an electromagnetic input signal (source signal).

[0030] The beamforming network may be any conventional beamforming network known in the field. For instance, the beamforming network may be a Butler matrix, or a Blass matrix, or a Nolen matrix, or a Rotman lens, or a Skobelev matrix.

[0031] A conventional beamforming network (also referred to as an unreversed beamforming network) comprises a plurality of input ports and output ports. The conventional beamforming network is used to generate multiple directive beams based on one input received from one input port. Conventionally, the energy of the one input signal is distributed among the produced multiple beams. In this disclosure, the usage of the input ports and the output ports of the conventional beamforming network is reversed. That is, the output ports of the beamforming network are used as the input ports 111 of the feeding network 110, and the input ports of the beamforming network are used as the output ports 113 of the feeding network 110. Accordingly, the structure of the beamforming network is reversely placed in the antenna device 100 in the main direction of radiation. In general, the feeding network 110 may be considered as a reversed beamforming network. For instance, the feeding network 110 may be a reversed Butler matrix, or a reversed Blass matrix, or a reversed Nolen matrix, or a reversed Rotman lens, or a reversed Skobelev matrix.

[0032] In other words, the antenna device according to this disclosure comprises a reversed beamforming network, where the conventional input ports of the conventional beamforming network are coupled to the radiation means, and the conventional output ports of the conventional beamforming network are coupled to sources. Source signals are injected into the conventional output ports of the conventional beamforming network, to obtain one output from one of the conventional input ports of the conventional beamforming network, which is contrary to the conventional usage of the conventional beamforming network.

[0033] By reversing the conventional beamforming network, the feeding network 110 can be configured to generate one output from one of its output ports based on a plurality of inputs received from its input ports. Thus, the feeding network 110 can be configured to direct all available power received from the plurality of input ports of the feeding network 110 to one of the pluralities of output ports of the feeding network 110. Each beam generated based on the feeding network 110 can be fed by the total available input power, which is the addition of power incident from all the input ports of the feeding network 110. In this way, the generated beam can feature not only high gain but also high effective isotropic radiated power (EIRP). It is noted that EIRP (dBW) = gain (dBi) + incident power (dBW).

[0034] The radiation means 130 is for generating radiating radio waves based on the output from one of the pluralities of output ports of the feeding network 110. Optionally, the radiation means may comprise radiation sources 131 coupled to the output ports 113 of the feeding network 110.

[0035] The superstrate 150 is arranged above the radiation means 130 in the main direction of radiation and is adapted to generate one or more directive beams based on the radio waves.

[0036] By placing the superstrate 150 on top of the radiation means 130, directive beams can be produced into designed directions of space through the superstrate 150.

[0037] FIG. 2 shows an example of a feeding network 110. In FIG. 1 and FIG. 2, corresponding elements may share the same features and function likewise.

[0038] Based on the antenna device 100 shown in FIG. 1, the beamforming network used in the feeding network 110 may optionally be a Butler matrix, or a Blass matrix, or a Nolen matrix, or a Rotman lens, or a Skobelev matrix. Optionally, the feeding network 110 may be adapted to direct all the available inputs based on a plurality of phase profiles of the available inputs.

[0039] For FIG. 2, the feeding network 110 as a reversed Butler matrix is used as an example. The reversed Butler matrix is adapted to work reciprocally with respect to the conventional usage of a (unreversed) Butler matrix.

[0040] Conventionally, the unreversed Butler matrix is adapted to, depending on the inputs, provide progressive phase outputs with a different progression. An N×N Butler matrix (i.e. N inputs and N outputs), may generate "$(2k-1)\pi/N$" output phase progressions (value is in radians), in which k is an integer in a range of [-N/2 + 1, N/2]. For example, a 4×4 Butler matrix can provide phase differences ($\Delta\phi = \phi_{i+1} - \phi_i$, i = port number) of -45° (progressively among the four output ports), or +135° (progressively among the four output ports), or -135° (progressively among the four output ports), or +45° (progressively among the four output ports), depending on which one of the four inputs is fed. For instance, if the first input is fed, four output signals with a progressive phase difference of -45° may be obtained; if the second input is fed, four output signals with a progressive phase difference of +135° may be obtained. Each of the phase progressions may generate a beam directed in a different steered angle, within a multi-beam antenna.

[0041] Reciprocally, as illustrated in FIG. 2, for the reversed Butler matrix used in the feeding network 110, to obtain an output from one output port of the feeding network 110, input signals with a corresponding phase profile may be provided to the input ports of the feeding network 110. A different phase profile corresponds to a different output port of the feeding network 110. For instance, phase profiles of the input signals provided to the input ports of the feeding network 110 may be based on phase profiles (or referred to as progressive phase differences) of -45°, +135°, -135° or +45°, to obtain an output from the first, the second, the third, the fourth of the output ports of the feeding network 110, respectively. Each output may be a beam with a corresponding phase. For example, a phase profile (or a progressive phase difference) of input signals based on $\Delta\phi$ =-45° corresponds to the first output port (or beam 1). That is, input ports of the feeding network 110 may be fed with input signals with phases of -45°, -90°, -135°, and -180° ($\Delta\phi$ =-45°) to obtain an output at the first output port (beam 1). In this case, all available power received from the four input ports may be directed to one output port (e.g., the first output port) of the feeding network 110, e.g., as a beam 1 labeled in FIG. 2.

[0042] In general, as shown in FIG. 2, to obtain a beam from one (single) output port of the feeding network 110, input signals with a corresponding phase profile may be provided into the input ports of the feeding network 110. For instance, a phase profile of output ports of a conventional beamforming network (which is not reversed, e.g., an unreversed Butler matrix) may be used as a phase profile of input ports of the feeding network 110. It is noted that the phase profile may also be understood as a progressive phase difference among ports, or a phase difference between consecutive ports.

[0043] It is noted that the reversed Butler matrix in FIG. 2 is merely given as an example, any other beamforming network may be reversed and used as the feeding network 110 in this disclosure.

[0044] FIG. 3 shows an example of a radiation means 130 and a superstrate 150. In FIGs. 1-3, corresponding elements may share the same features and function likewise.

[0045] The radiation means 130 may optionally comprise radiation sources 131. The radiation sources 131 are coupled to the output ports of the feeding network 110. Each radiation source is adapted to radiate the output signal from the corresponding output port 113 of the feeding network 110.

[0046] Optionally, as shown in FIG.3, the radiation source may comprise a radiator. The radiator may be single-polarized or dual-polarized.

[0047] Optionally, the radiation source may comprise a horn (e.g., when the feeding network 110 is implemented using waveguide technology).

[0048] Optionally, the radiation source may be an end section of a dielectric-loaded waveguide.

[0049] The superstrate 150 may optionally comprise at least one metasurface for beamforming. Optionally, the metasurface may comprise one or more layers. Each layer comprises a string of elementary cells, which can be dynamically programmed to control the wavefront of an incident wave.

[0050] Additionally or alternatively, the superstrate may comprise at least one lens 151 for beamforming. The at least one lens may comprise a GRIN dielectric lens.

[0051] In general, the superstrate 150 is adapted to produce directive beams and steer the successive beams into successive directions in space. In this way, the directivity of the beam can be increased, and the half-power beam width (HPBW) can be reduced.

[0052] FIG. 4 shows an antenna system 300 and an antenna array 400 that is built based on the antenna device 100. In FIGs. 1-4, corresponding elements may share the same features and function likewise.

[0053] The antenna system 300 comprises at least one antenna device 100 and a plurality of sources 200. The plurality of sources 200 may be referred to as a switching network 200. Each source is coupled to a corresponding input port of a feeding network of an antenna device 100, respectively.

[0054] For instance, each source 200 may be an electromagnetic source, or a microwave source, or the like.

[0055] The switching network 200 may be adapted to provide a plurality of inputs with a plurality of phase profiles to the input ports of the feeding network of the antenna device, such that all available input powers can be directed to one of the pluralities of output ports of the feeding network 110 (through the reversed beamforming network).

[0056] For instance, the switching network 200 may comprise RF phase shifter(s) to produce signals with a corresponding progressive phase difference. For instance, the switching network 200 may be configured to use a phase profile of output ports of a conventional beamforming network (which is not reversed, e.g., an unreversed Butler matrix) as a phase profile of input ports of the feeding network 110.

[0057] Optionally, when two or more antenna devices 100 are coupled and arranged in a plane, an antenna array 400 may be formed, which may be used to achieve an even higher gain (directivity) than a single antenna device 100.

[0058] In summation, this disclosure provides a solution for antenna design that allows to generate high directivity beams in a multi-beam antenna whilst also using all the available power, by jointly feeding the input ports. The feeding network 110 is used to concentrate all the input power coming from all the input ports, into a single output port. The superstrate is used to concentrate all that power into a beam radiated towards a specific direction in space. By modifying the phase progression at the input ports of the feeding network 110, the power can be directed to different output ports subsequently. In this way, the antenna device can produce directive beams in different directions in space.

[0059] An application scenario of this disclosure is for MIMO communication. A multi-beam antenna structure may be built based on the antenna device/system/array introduced in this disclosure. In this way, higher power directed to user equipment may be achieved. Further, highly independent communication channels may be achieved. Overall, the system throughput can be enhanced.

[0060] It is further noted that the antenna device 100 introduced in this disclosure may be reciprocally used as a receiving antenna device.

[0061] The present invention has been described in conjunction with various embodiments as examples as well as implementations. However, other variations can be understood and effected by those persons skilled in the art and practicing the claimed invention, from the studies of the drawings, this disclosure and the independent claims. In the claims as well as in the description the word "comprising" does not exclude other elements or steps and the indefinite article "a" or "an" does not exclude a plurality. A single element or other unit may fulfill the functions of several entities or items recited in the claims. The mere fact that certain measures are recited in the mutual different dependent claims does not indicate that a combination of these measures cannot be used in an advantageous implementation.

Claims

1. An antenna device (100) comprising:

a feeding network (110) comprising a plurality of input ports (111) each connectable to a source, a plurality of output ports (113), and a reversed form of a beamforming network, wherein for forming the reversed form of the beamforming network, a plurality of output ports of the beamforming network are used as the plurality of input ports (111) of the feeding network (110), and a plurality of input ports of the beamforming network are used as the plurality of outputs (113) of the feeding network (110);

radiation means (130) for generating radio waves based on an output from one of the plurality of output ports (113) of the feeding network (110); and

a superstrate (150) arranged above the radiation means (130) in a main direction of radiation, wherein the superstrate (150) is adapted to generate one or more directive beams based on the radio waves.

2. The antenna device (100) according to claim 1, wherein the feeding network (110) is adapted to direct all available inputs received from the plurality of input ports (111) of the feeding network (110) to one of the pluralities of output ports (113) of the feeding network (110).

3. The antenna device (100) according to claim 2, wherein the feeding network (110) is adapted to direct all the available inputs based on a plurality of phase profiles thereof.

4. The antenna device (100) according to any one of claims 1 to 3, wherein the beamforming network comprises a Butler matrix, or a Blass matrix, or a Nolen matrix, or a Rotman lens, or a Skobelev matrix.

5. The antenna device (100) according to any one of claims 1 to 4, wherein the radiation means (130) comprises radiation sources, wherein the radiation sources are coupled to the output ports (113) of the feeding network (110).

6. The antenna device (100) according to claim 5, wherein the radiation sources comprise a plurality of radiators.

7. The antenna device (100) according to claim 6, wherein each radiator is a dual-polarized radiator.

8. The antenna device (100) according to any one of claims 1 to 7, wherein the superstrate (150) comprises a metasurface for beamforming.

9. The antenna device (100) according to any one of claims 1 to 8, wherein the superstrate (150) comprises a lens for beamforming.

10. The antenna device (100) according to claim 9, wherein the lens comprises a gradient-index, GRIN, dielectric lens.

11. An antenna system (300) comprising at least one antenna device (100) according to any one of claims 1 to 10 and a plurality of sources (200), wherein each source is coupled to an input port of the feeding network (110) of the at least one antenna device (100).

12. The antenna system (300) according to claim 11, wherein the plurality of sources (200) are adapted to provide a plurality of inputs with a plurality of phase profiles to the input ports (111) of the feeding network (110), such that the plurality of inputs are directed to one of the plurality of output ports (113) of the feeding network (110).

13. The antenna system (300) according to claim 11 or 12, wherein the antenna system is a multiple-input and multiple-output, MIMO, antenna system.

14. An antenna array (400) comprising two or more antenna devices (100) each according to any one of claims 1 to 10, wherein the two or more antenna devices (100) are coupled and arranged in a plane.

Amended claims in accordance with Rule 137(2) EPC.

1. An antenna device (100) comprising:

a feeding network (110) comprising a plurality of input ports (111) each connectable to a source, a plurality of output ports (113), and a reversed form of a beamforming network, wherein for forming the reversed form of the beamforming network, a plurality of output ports of the beamforming network are used as the plurality of input ports (111) of the feeding network (110), and a plurality of input ports of the beamforming network are used as the plurality of outputs (113) of the feeding network (110);
radiation means (130) for generating radio waves based on an output from one of the plurality of output ports (113) of the feeding network (110); and
a superstrate (150) arranged above the radiation means (130) in a main direction of radiation, wherein the superstrate (150) is adapted to generate one or more directive beams based on the radio waves, wherein the feeding network (110) is adapted to direct all available inputs received from the plurality of input ports (111) of the feeding network (110) to one of the pluralities of output ports (113) of the feeding network (110), and the superstrate (150) comprises a metasurface for beamforming.

2. The antenna device (100) according to claim 1, wherein the feeding network (110) is adapted to direct all the available inputs based on a plurality of phase profiles thereof.

3. The antenna device (100) according to any one of claims 1 to 2, wherein the beamforming network comprises a Butler matrix, or a Blass matrix, or a Nolen matrix, or a Rotman lens, or a Skobelev matrix.

4. The antenna device (100) according to any one of claims 1 to 3, wherein the radiation means (130) comprises radiation sources, wherein the radiation sources are coupled to the output ports (113) of the feeding network (110).

5. The antenna device (100) according to claim 4, wherein the radiation sources comprise a plurality of radiators.

6. The antenna device (100) according to claim 5, wherein each radiator is a dual-polarized radiator.

7. The antenna device (100) according to any one of claims 1 to 6, wherein the superstrate (150) comprises a lens for beamforming.

8. The antenna device (100) according to claim 7, wherein the lens comprises a gradient-index, GRIN, dielectric lens.

9. An antenna system (300) comprising at least one antenna device (100) according to any one of claims 1 to 8 and a plurality of sources (200), wherein each source is coupled to an input port of the feeding network (110) of the at least one antenna device (100).

10. The antenna system (300) according to claim 9, wherein the plurality of sources (200) are adapted to provide a plurality of inputs with a plurality of phase profiles to the input ports (111) of the feeding network (110), such that the plurality of inputs are directed to one of the plurality of output ports (113) of the feeding network (110).

11. The antenna system (300) according to claim 9 or 10, wherein the antenna system is a multiple-input and multiple-output, MIMO, antenna system.

12. An antenna array (400) comprising two or more antenna devices (100) each according to any one of claims 1 to 8, wherein the two or more antenna devices (100) are coupled and arranged in a plane.

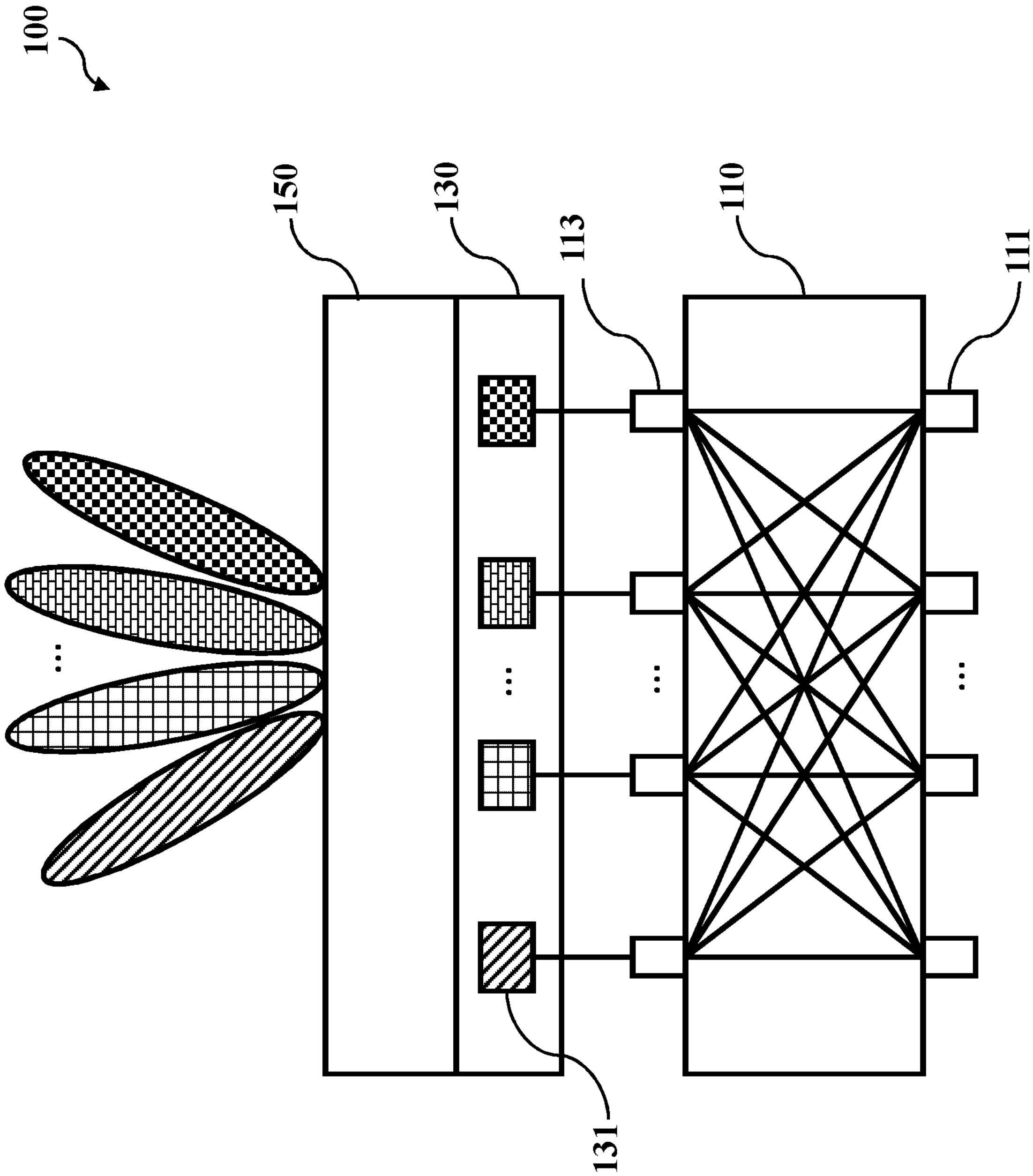

FIG. 1

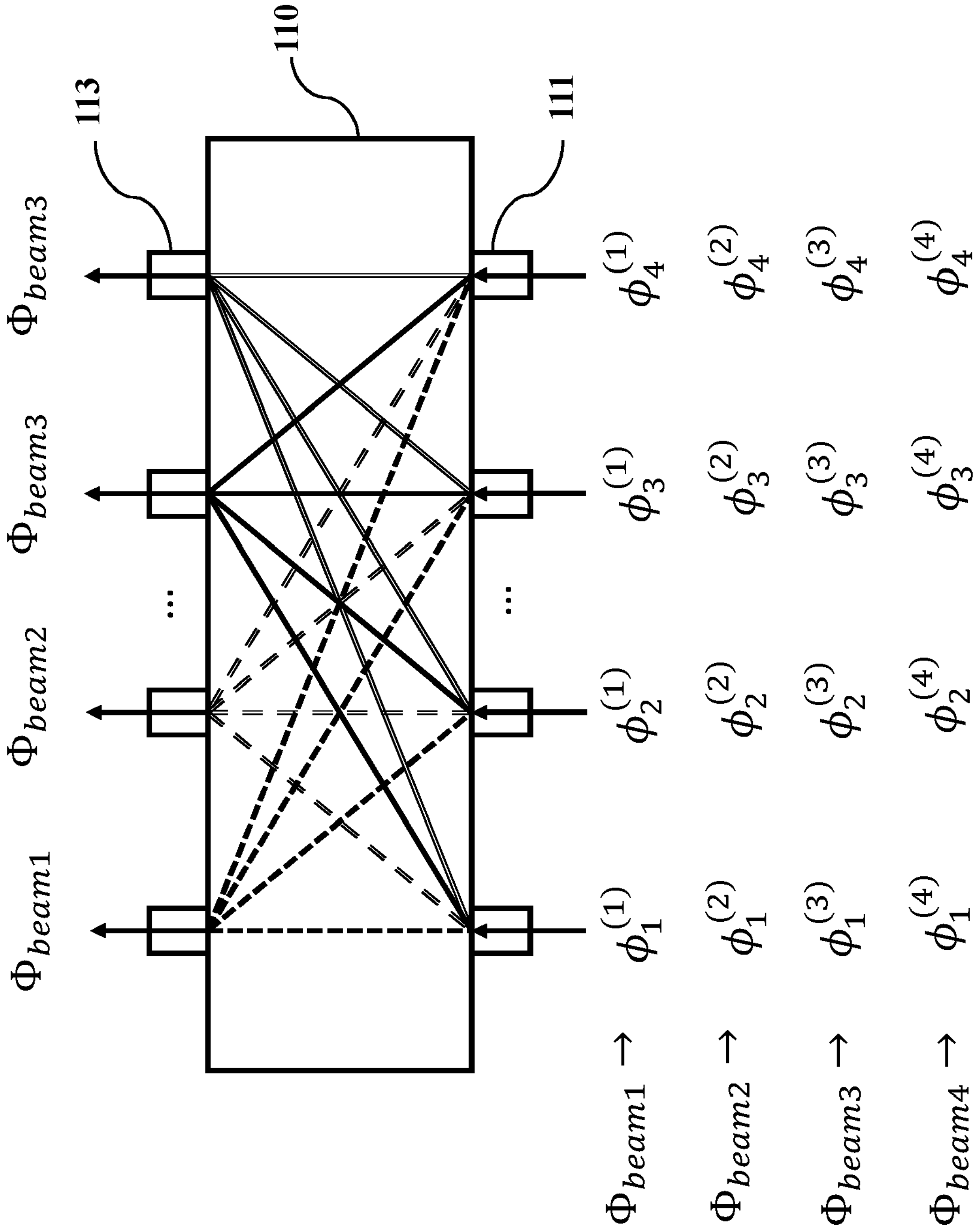
110
111
113
Φ_{beam1}
Φ_{beam2}
Φ_{beam3}
Φ_{beam3}
$\Phi_{beam1} \rightarrow$ $\phi_1^{(1)}$ $\phi_2^{(1)}$ $\phi_3^{(1)}$ $\phi_4^{(1)}$
$\Phi_{beam2} \rightarrow$ $\phi_1^{(2)}$ $\phi_2^{(2)}$ $\phi_3^{(2)}$ $\phi_4^{(2)}$
$\Phi_{beam3} \rightarrow$ $\phi_1^{(3)}$ $\phi_2^{(3)}$ $\phi_3^{(3)}$ $\phi_4^{(3)}$
$\Phi_{beam4} \rightarrow$ $\phi_1^{(4)}$ $\phi_2^{(4)}$ $\phi_3^{(4)}$ $\phi_4^{(4)}$

FIG. 2

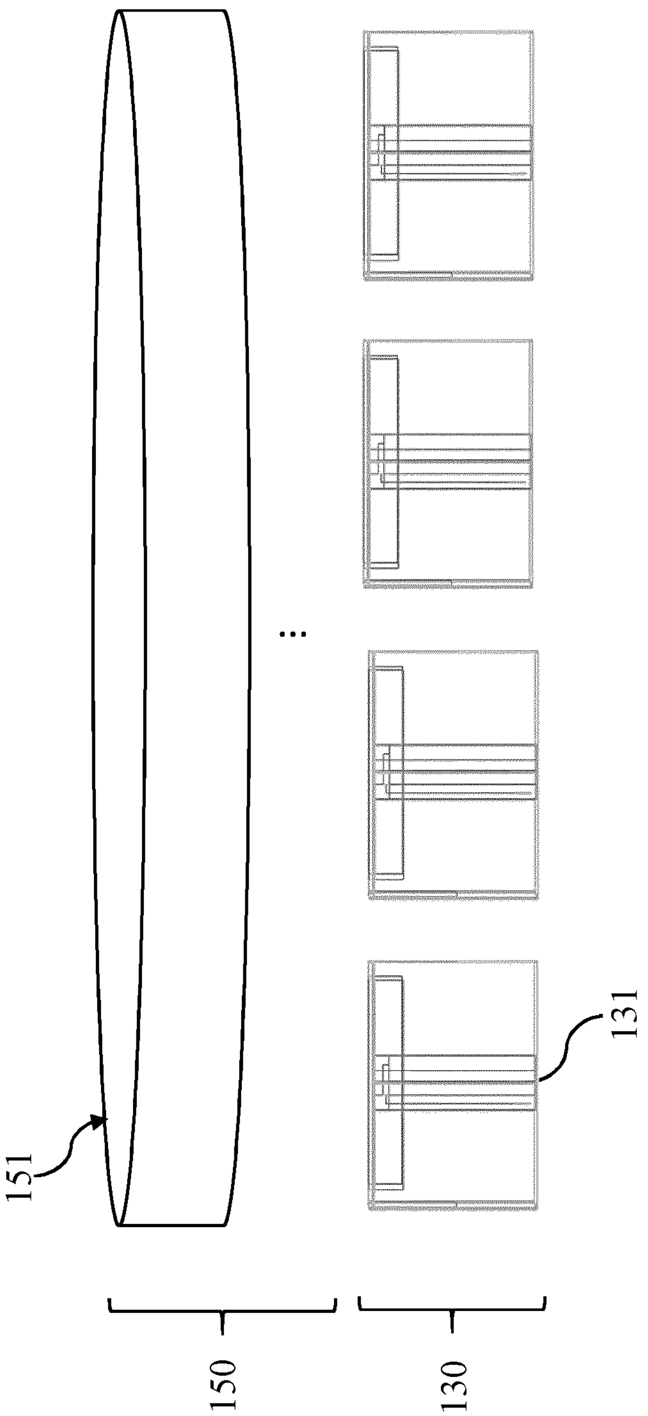

FIG. 3

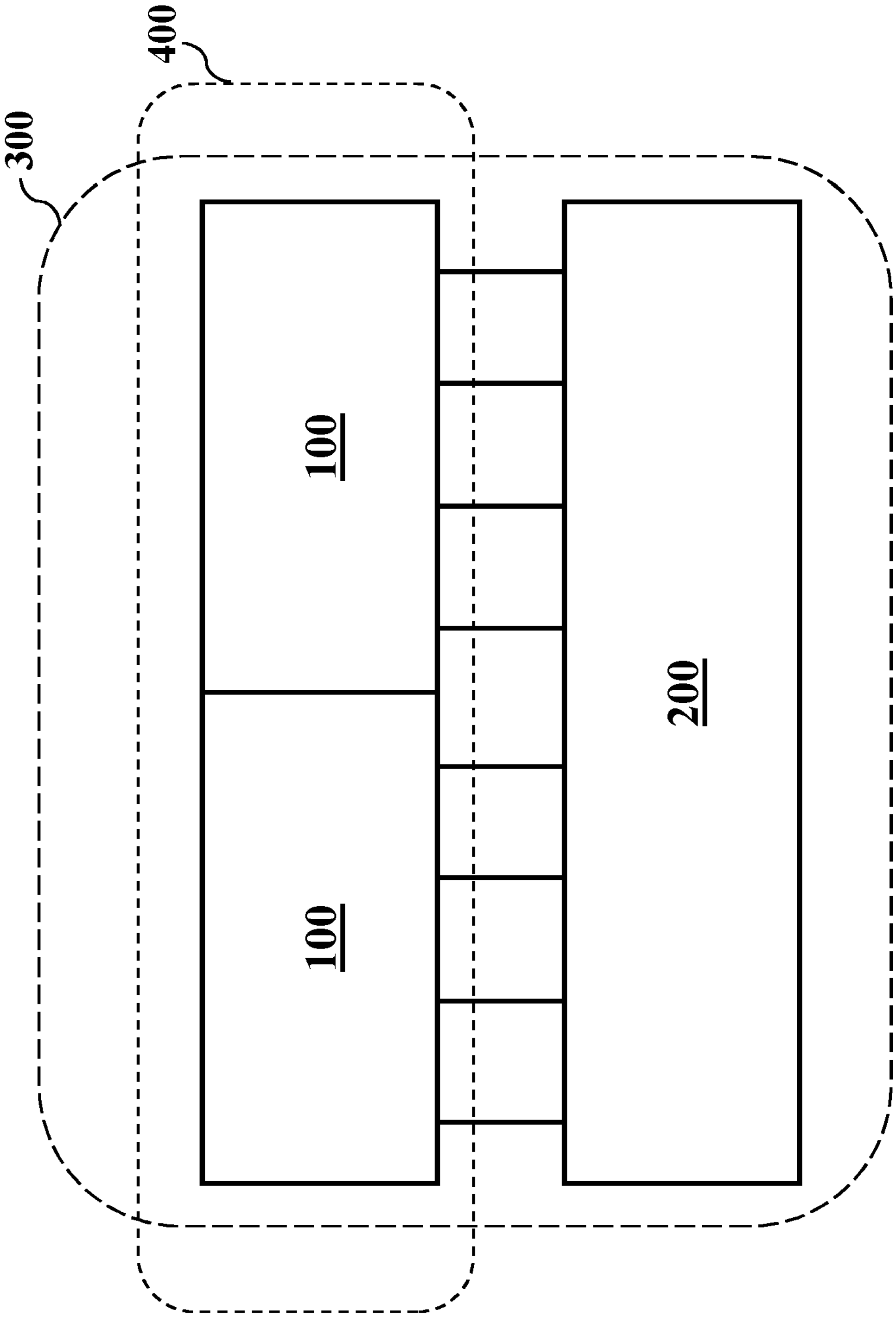

FIG. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 23 21 2525

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	DUTTA RANJIT KUMAR ET AL: "A Two-Stage Beamforming Antenna Using Butler Matrix and Reconfigurable Frequency Selective Surface for Wide Angle Beam Tilting", IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, IEEE, PISCATAWAY, NJ, US, vol. 22, no. 10, 14 June 2023 (2023-06-14), pages 2342-2346, XP011950651, ISSN: 1536-1225, DOI: 10.1109/LAWP.2023.3286819 [retrieved on 2023-06-15]	1-8	INV. H01Q3/40 H01Q15/08 H01Q19/06 H01Q21/06 H01Q21/28 H01Q25/00
A	* the whole document *	9-14	
X	US 5 115 248 A (ROEDERER ANTOINE [NL]) 19 May 1992 (1992-05-19)	1-7,9-14	
A	* column 4 - column 11; figures 3-27B *	8	
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A	* column 2 - column 6; figures 2, 3 *	8	

TECHNICAL FIELDS SEARCHED (IPC)

H01Q

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	12 April 2024	Keyrouz, Shady

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO.

EP 23 21 2525

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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12-04-2024

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