

**MULTI-TARGET SPOT BEAMFORMING USING RECONFIGURABLE
INTELLIGENT SURFACE**

CROSS-REFERENCE TO RELATED APPLICATION

- 5 **[0001]** This application claims the benefit of priority of Singapore Patent Application No. 10202400406R filed on 15 February 2024, the content of which being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

- 10 **[0002]** The present invention generally relates to a reconfigurable intelligent surface (RIS) and multi-target spot beamforming using a RIS, and more particularly, relates to a method of controlling a RIS for multi-target spot beamforming, and a RIS controller thereof.

BACKGROUND

- 15 **[0003]** Historically, traditional metasurfaces were designed for a singular function specific to a particular incident electromagnetic wave, leading to limited dynamic functionalities. As a result, achieving variable functionality or operating frequency required redesigning and refabrication, making them less flexible in real-time applications. To overcome such limitations of traditional metasurfaces, the concept of reconfigurable metasurfaces (also known as
20 programmable metasurfaces or a reconfigurable intelligent surface (RIS)) has been disclosed. Reconfigurable metasurfaces offer post-fabrication tunability and have the potential for diverse applications. Different tuning mechanisms have been explored to achieve reconfigurability, such as the use of lumped elements, phase-changing materials, liquid crystals, graphene, vanadium-dioxide, and origami- and kirigami-based structures. Beyond reconfigurability, there
25 has been disclosed programmable metasurfaces that incorporate field-programmable gate arrays (FPGA) to actively manipulate electromagnetic waves and switch between diverse functions in real-time. Programmable metasurfaces have been implemented in various applications, such as imaging, holograms, beam focusing, beam steering, and wireless communication.
- 30 **[0004]** During recent years, the concept of intelligent metasurfaces is introduced, where programmable metasurfaces are equipped with sensing and feedback components to enable self-adaptivity and control their reprogrammable functions without human intervention. This leads to smart control of electromagnetic waves and opens up possibilities for more advanced

applications. With recent advancements in metasurfaces, for example, reconfigurable intelligent surfaces (RISs) are being considered for sixth-generation (6G) wireless communication. RISs integrate numerous reconfigurable elements into a two-dimensional (2D) structure (2D array) and can be applied to various applications, such as smart transportation systems, Internet of Things (IoT), UAV (unmanned aerial vehicle)-based wireless communication, and simultaneous wireless information and power transfer (SWIPT) systems.

[0005] There are several conventional/classical control methods for reconfigurable metasurfaces. These conventional control methods enable dynamic manipulation of electromagnetic waves and offer a higher degree of freedom over incident electromagnetic waves. First of all, lumped elements, such as varactor diodes, have been widely used in reconfigurable metasurfaces. By controlling the bias voltage across the varactor diodes, the effective electromagnetic properties of the reconfigurable metasurface can be tuned. Such a method allows for real-time adjustments of the metasurface response to incident waves and has been employed in various applications, including beam steering, beam focusing, and frequency-selective surfaces. Phase-changing materials, such as vanadium dioxide (VO_2), exhibit a reversible phase transition in response to external stimuli, such as temperature or electrical field. By incorporating such phase-changing materials into the metasurface design, it is possible to dynamically change the effective refractive index, phase, and amplitude of incident waves. This approach enables fast reconfigurability and has been utilized in applications such as beam steering and tunable lenses. Furthermore, liquid crystals are another class of materials used for tunable metasurface designs. By applying an external electric field, the orientation of liquid crystal molecules can be controlled, leading to changes in the effective refractive index of the metasurface. Liquid crystals offer continuous tunability and have been applied in various applications, such as holograms, beam steering, and spatial light modulators. Still further, machine learning techniques have been employed to optimize and control reconfigurable metasurfaces. These machine learning techniques use neural networks and optimization algorithms to adapt the metasurface response based on input signals or environmental conditions. Machine learning-assisted metasurfaces have shown potential in adaptive beamforming and dynamic beam steering applications.

[0006] There exist various wireless communication applications using a RIS. However, there has not been disclosed multi-target spot beamforming using a RIS, or how to achieve multi-target spot beamforming using a RIS. Implementing multi-target spot beamforming using a RIS provides multiple target beam focus positions (or focus points) and thus may

advantageously be utilized for various practical applications, such as but not limited to, short-range wireless communication applications in the range of one meter to hundreds of meters, whereby the RIS may be utilized to produce multiple spot beams at multiple desired locations in a region, such as for avoiding obstacles in the region to enhance or enable wireless communications (e.g., obstruction-free wireless transmission).

[0007] A need therefore exists to enable multi-target spot beamforming using a RIS for enhancing or enabling various practical applications, for example, for producing multiple spot beams at multiple desired locations in a region, such as for avoiding obstacles in the region to minimize or eliminate signal impediments to enhance or enable wireless communications. It is against this background that the present invention has been developed.

SUMMARY

[0008] According to a first aspect of the present invention, there is provided a method of controlling a reconfigurable intelligent surface (RIS) for multi-target spot beamforming at a plurality of target beam focus positions, the RIS comprising a two-dimensional (2D) array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon. The method comprises:

for each of the plurality of target beam focus positions:

determining, for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode orbital angular momentum (OAM) signal transmitter to the unit cell and an object wave from the target beam focus position to the unit cell, the multi-mode OAM signal transmitter being configured to generate and transmit multi-mode OAM waves to irradiate the RIS at a surface thereof; and

for each unit cell of the plurality of the 2D array of unit cells:

determining a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions;

determining a degree of phase shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and

controlling the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.

[0009] According to a second aspect of the present invention, there is provided a RIS controller for controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, the RIS comprising a 2D array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a
5 corresponding degree of phase shift for incident electromagnetic waves irradiated thereon. The RIS controller comprises:

at least one memory; and

at least one processor communicatively coupled to the at least one memory and configured to:

10 for each of the plurality of target beam focus positions:

determine, for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode OAM signal transmitter to the unit cell and an object wave from the target beam focus position to the unit cell, the multi-mode OAM signal transmitter being configured to generate and transmit multi-
15 mode OAM waves to irradiate the RIS at a surface thereof; and

for each unit cell of the plurality of the 2D array of unit cells:

determine a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions;

20 determine a degree of phase shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and

control the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.

[0010] According to a third aspect of the present invention, there is provided a multi-target spot beamforming system comprising:

25 a RIS comprising a 2D array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon;

a multi-mode OAM signal transmitter configured to generate and transmit a multi-mode OAM signal to irradiate the RIS at a surface thereof; and

30 a RIS controller according to the second aspect of the present invention communicatively coupled to the RIS for controlling the RIS for multi-target spot beamforming at a plurality of target beam focus positions.

[0011] According to a fourth aspect of the present invention, there is provided a RIS for controlling a propagation of incident electromagnetic waves irradiated thereon. The RIS comprises:

a 2D array of unit cells, each unit cell comprising:

- 5 a first dielectric substrate having a first side and a second side opposite to the first side;
- a second dielectric substrate having a first side and a second side opposite to the first side;
- a first metallic layer disposed on the first side of the first dielectric substrate, the first metallic layer comprising a first metal microstrip line controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated on the first metal microstrip line to produce intermediate electromagnetic waves;
- 10 a second metallic layer disposed between the first and second dielectric substrates, the second metallic layer comprising a first metal microstrip line connected to the first metal microstrip line of the first metallic layer through a first metal via and is controllable to be any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves received from the first metal microstrip line of the first metallic layer through the first metal via to produce
- 15 output electromagnetic waves; and
- a third metallic layer disposed on the second side of the second dielectric substrate, the third metallic layer comprising a first metal microstrip line connected to the first metal microstrip line of the second metallic layer through a second metal via and configured to radiate the output electromagnetic waves received from the first metal microstrip line of the second metallic layer through the second metal via.
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BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

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FIG. 1 depicts a schematic flow diagram of a method of controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, according to various embodiments of the present invention;

FIG. 2 depicts a schematic block diagram of a RIS controller for controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, according to various embodiments of the present invention;

FIG. 3 depicts a schematic drawing of a multi-target spot beamforming system, according to various embodiments of the present invention;

FIG. 4 depicts a schematic drawing of a RIS, with a schematic exploded view of the unit cell, for controlling a propagation of incident electromagnetic waves irradiated thereon, according to various embodiments of the present invention;

FIG. 5 depicts a method of forming a RIS for controlling a propagation of incident electromagnetic waves, according to various embodiments of the present invention;

FIG. 6 depicts an example implementation of a multi-target wireless multifocal communication (WMC), according to various example embodiments of the present invention;

FIG. 7 depicts a schematic drawing of an example RIS, with a schematic exploded view of the unit cell, for controlling a propagation of incident electromagnetic waves irradiated thereon, according to various example embodiments of the present invention;

FIG. 8 depicts a schematic drawing showing front (or top) and back (or bottom) side views of the example RIS, as well as front, back and right side views of the unit cell thereof, according to various example embodiments of the present invention;

FIG. 9 depicts a table showing four distinct states of the unit cells of the example RIS, according to various example embodiments of the present invention;

FIGs. 10A and 10B show plots of amplitudes and phases full-wave simulation results of the unit cells, according to various example embodiments of the present invention;

FIG. 11 depicts beamforming simulation results for three different example configurations of target beam focus positions using the example RIS, according to various example embodiments of the present invention; and

FIG. 12 depicts a schematic drawing of a multi-target spot-beamforming system configured for multi-target spot beamforming at three target beam focus positions along the normal direction of the RIS, according to various example embodiments of the present invention.

DETAILED DESCRIPTION

[0013] Various embodiments of the present invention provide a method of controlling a reconfigurable intelligent surface (RIS) for multi-target spot beamforming at a plurality of

target beam focus positions, and a RIS controller thereof. In addition, various embodiments of the present invention provide a multi-target spot beamforming system comprising the RIS controller. Furthermore, various embodiments of the present invention provide a RIS for controlling a propagation of incident electromagnetic waves irradiated thereon.

- 5 [0014] As discussed in the background, there exist various wireless communication applications using a RIS. However, there has not been disclosed multi-target spot beamforming using a RIS, or how to achieve multi-target spot beamforming using a RIS. Implementing multi-target spot beamforming using a RIS provides multiple target beam focus positions and thus may advantageously be utilized for various practical applications, such as but not limited to,
- 10 short-range wireless communication applications in the range of one meter to hundreds of meters, whereby the RIS may be utilized to produce multiple spot beams at multiple desired locations in a region, such as for avoiding obstacles in the region to minimize or eliminate signal impediments to enhance or enable wireless communications (e.g., obstruction-free wireless transmission). In this regard, for enabling multi-target spot beamforming using a RIS, various
- 15 embodiments of the present invention provide a method of controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, whereby the RIS comprises a 2D array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon.
- 20 [0015] FIG. 1 depicts a schematic flow diagram of a method 100 of controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions (e.g., focus regions or points), according to various embodiments of the present invention. The RIS comprises a 2D array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident
- 25 electromagnetic waves irradiated thereon. The method 100 comprises: for each of the plurality of target beam focus positions: determining (at 106), for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode OAM signal transmitter to the unit cell and an object wave from the target beam focus position to the unit cell. In this regard, the multi-mode OAM signal transmitter is configured to
- 30 generate and transmit multi-mode OAM waves to irradiate the RIS at a surface thereof. The method 100 further comprises: for each unit cell of the plurality of the 2D array of unit cells: determining (at 108) a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions; determining (at 110) a degree of phase

shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and controlling (at 112) the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.

[0016] Accordingly, the method 100 of controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions advantageously enables multi-target spot beamforming using a RIS. Firstly, the method 100 utilizes a RIS comprising a 2D array of unit cells, whereby each unit cell is controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon. Accordingly, each unit cell is individually
5 controllable (e.g., based on controlling one or more switching elements therein) to be at a selected wave propagation path state for providing a corresponding wave propagation path for the incident electromagnetic waves to propagate in the unit cell to result in a corresponding (e.g., desired) degree of phase shift for the incident electromagnetic waves. The method 100 further combines such a RIS with a multi-mode OAM signal transmitter which generates and
10 transmits multi-mode OAM waves to irradiate the RIS for conversion into multiple spot beams which converge into multiple target beam focus positions by controlling each unit cell of the RIS to be at a respective selected wave propagation path state for providing a corresponding (e.g., desired) degree of phase shift for the incident electromagnetic waves irradiated thereon. Therefore, applying the method 100 for controlling the RIS, multi-target spot beamforming at
15 multiple target beam focus positions can advantageously be achieved, which may be utilized for various practical applications, such as but not limited to, short-range wireless communication applications in the range of one meter to hundreds of meters, whereby the RIS may be utilized to produce multiple spot beams at multiple desired locations in a region using the method 100, such as for avoiding obstacles in the region to minimize or eliminate signal
20 impediments to enhance or enable wireless communications (e.g., obstruction-free wireless transmission). Furthermore, the method 100 advantageously utilizes the unique properties of multi-mode OAM waves (which may also be referred to as OAM beams) by using the multi-mode OAM signal transmitter to generate multi-mode OAM waves at the same location, which are then focused at multiple target beam focus positions, thereby avoiding reliance on signal
25 separation through different spatial positions at the transmitter end. These advantages or technical effects, and/or other advantages or technical effects, will become more apparent to a person skilled in the art as the method 100 of controlling a RIS for multi-target spot
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beamforming, as well as the corresponding RIS controller, is described in more detail according to various embodiments and example embodiments of the present invention.

[0017] In various embodiments, for each of the plurality of target beam focus positions, the reference wave (in the above-mentioned determining (at 106), for each unit cell of the plurality of the 2D array of unit cells, the interference pattern at the unit cell between the reference wave and the object wave) is an OAM wave with an OAM mode corresponding to the target beam focus position. Accordingly, in various embodiments, for each of the plurality of target beam focus positions, the multi-mode OAM signal transmitter is configured to generate an OAM wave with a corresponding OAM mode. For example, for two target beam focus positions, the multi-mode OAM signal transmitter is configured to generate multi-mode OAM waves with two OAM modes, for three target beam focus positions, the multi-mode OAM signal transmitter is configured to generate multi-mode OAM waves with three OAM modes, and so on.

[0018] In various embodiments, the interference pattern at the unit cell between the reference wave and the object wave is determined based on an azimuth angle of the unit cell with respect to a center of the RIS serving as an OAM beam reference. In this regard, all OAM beams from the multi-mode OAM signal transmitter point to the center of the RIS board.

[0019] In various embodiments, the above-mentioned determining (at 106), for each unit cell of the plurality of the 2D array of unit cells, the interference pattern at the unit cell between the reference wave and the object wave comprises: determining a first distance between the multi-mode OAM signal transmitter and the unit cell; determining a second distance between the target beam focus position and the unit cell; determining the azimuth angle of the unit cell with respect to the center of the RIS; and determining the interference pattern at the unit cell between the reference wave and the object wave based on the first distance, the second distance and the azimuth angle of the unit cell.

[0020] In various embodiments, the interference pattern at the unit cell between the reference wave and the object wave is determined further based on an amplitude of the reference wave and an amplitude of the object wave.

[0021] In various embodiments, the first distance is determined based on a coordinate of the multi-mode OAM signal transmitter with respect to the center of the RIS and a coordinate of the unit cell with respect to the center of the RIS. In various embodiments, the second distance is determined based on a coordinate of the target beam focus position with respect to the center of the RIS and the coordinate of the unit cell. In various embodiments, the azimuth angle of the unit cell is determined based on the coordinate of the unit cell.

[0022] In various embodiments, the holograph pattern is determined based on a summation of the interference patterns determined at the unit cell for the plurality of target beam focus positions.

5 [0023] In various embodiments, the plurality of target beam focus positions is located at a same side of the RIS as the OAM signal transmitter (thus, the RIS may be a reflective RIS), or the plurality of target beam focus positions is located at an opposite side of the RIS with respect to the OAM signal transmitter (thus, the RIS may be a transmissive RIS).

[0024] In various embodiments, each unit cell is a 2-bit unit cell controllable to be at any selected one of four wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated thereon. In various embodiments, the 10 four wave propagation path states are configured to provide four corresponding degree of phase shifts of about 0 degrees, about 90 degrees, about 180 degrees and about 270 degrees, respectively, for the incident electromagnetic waves irradiated thereon.

[0025] In various embodiments, each unit cell is controllable to be at any selected one of 15 the plurality of wave propagation path states based on controlling a state of a plurality of switching elements of the unit cell for configuring the unit cell to be at any selected one of the plurality of wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated thereon.

[0026] In various embodiments, the above-mentioned controlling the plurality of switching 20 elements of the unit cell for configuring the unit cell to be at any selected one of the plurality of wave propagation path states configures one or more metal microstrip lines of the unit cell to provide a corresponding propagation path for the incident electromagnetic waves irradiated on the unit cell for providing the corresponding degree of phase shift for the incident electromagnetic waves.

25 [0027] FIG. 2 depicts a schematic block diagram of a RIS controller 200 for controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, according to various embodiments of the present invention, corresponding to the method 100 of controlling a RIS for multi-target spot beamforming as described herein according to various embodiments of the present invention. The RIS controller 200 comprises: at least one memory 30 202; and at least one processor 204 communicatively coupled to the at least one memory 202 and configured to: for each of the plurality of target beam focus positions: determine, for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode OAM signal transmitter to the unit cell and an

object wave from the target beam focus position to the unit cell. In this regard, the multi-mode OAM signal transmitter is configured to generate and transmit multi-mode OAM waves to irradiate the RIS at a surface thereof. The at least one processor 204 is further configured to: for each unit cell of the plurality of the 2D array of unit cells: determine a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions; determine a degree of phase shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and control the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.

10 [0028] It will be appreciated by a person skilled in the art that the at least one processor 204 may be configured to perform various functions or operations through set(s) of instructions (e.g., software modules) executable by the at least one processor 204 to perform various functions or operations. Accordingly, as shown in FIG. 2, the RIS controller 200 may comprise: an interference pattern determining module (or an interference pattern determining circuit) 206
15 configured to, for each of the plurality of target beam focus positions: determine, for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode OAM signal transmitter to the unit cell and an object wave from the target beam focus position to the unit cell; a holograph pattern determining module (or a holograph pattern determining circuit) 208 configured to, for each unit cell of the plurality
20 of the 2D array of unit cells, determine a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions; a phase shift determining module (or a phase shift determining circuit) 210 configured to, for each unit cell of the plurality of the 2D array of unit cells, determine a degree of phase shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and a unit cell controlling
25 module (or a unit cell controlling circuit) 212 configured to, for each unit cell of the plurality of the 2D array of unit cells, control the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.

[0029] It will be appreciated by a person skilled in the art that the above-mentioned modules
30 are not necessarily separate modules, and two or more modules may be realized by or implemented as one functional module (e.g., a circuit or a software program) as desired or as appropriate without deviating from the scope of the present invention. For example, two or more of the interference pattern determining module 206, the holograph pattern determining

module 208; the phase shift determining module 210 and the unit cell controlling module 212 may be realized (e.g., compiled together) as one executable software program (e.g., software application or simply referred to as an “app”), which for example may be stored in the at least one memory 202 and executable by the at least one processor 204 to perform the corresponding functions or operations as described herein according to various embodiments of the present invention.

[0030] In various embodiments, the RIS controller 200 for controlling the RIS for multi-target spot beamforming corresponds to the method 100 of controlling a RIS for multi-target spot beamforming as described hereinbefore with reference to FIG. 1, therefore, various operations, functions or steps configured to be performed by the least one processor 204 may correspond to various operations, functions or steps of the method 100 described hereinbefore according to various embodiments, and thus need not be repeated with respect to the RIS controller 200 for clarity and conciseness. In other words, various embodiments described herein in context of methods (e.g., the method 100 of controlling a RIS for multi-target spot beamforming) are analogously valid for the corresponding systems or devices (e.g., the RIS controller 200), and vice versa. For example, in various embodiments, the at least one memory 202 may have stored therein the interference pattern determining module 206, the holograph pattern determining module 208; the phase shift determining module 210 and/or the unit cell controlling module 212, which respectively correspond to various operations, functions or steps of the method 100 of controlling a RIS for multi-target spot beamforming as described hereinbefore according to various embodiments, which are executable by the at least one processor 204 to perform the corresponding operations, functions or steps as described herein.

[0031] A computing system, a controller, a microcontroller or any other system providing a processing capability may be provided according to various embodiments in the present invention. Such a system may be taken to include one or more processors and one or more computer-readable storage mediums. For example, the RIS controller 200 described hereinbefore may include at least one processor 204 and at least one computer-readable storage medium (or memory) 202 which are for example used in various processing carried out therein as described herein. A memory or computer-readable storage medium used in various embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash

memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

[0032] In various embodiments, a “circuit” may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a “circuit” may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g., a microprocessor (e.g., a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A “circuit” may also be a processor executing software, e.g., any kind of computer program, e.g., a computer program using a virtual machine code, e.g., Java. Any other kind of implementation of various functions or operations may also be understood as a “circuit” in accordance with various other embodiments. Similarly, a “module” may be a portion of a system according to various embodiments in the present invention and may encompass a “circuit” as above, or may be understood to be any kind of a logic-implementing entity therefrom.

[0033] Some portions of the present disclosure may be explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm may be, and generally, conceived to be a self-consistent sequence of steps leading to a desired result.

[0034] The present specification also discloses a system (e.g., which may also be embodied as one or more devices or apparatuses), such as the RIS controller 200 (or a RIS controlling system), for performing various operations, functions or steps of various methods described herein. Such a system may be specially constructed for the required purposes or may comprise a general purpose computer system selectively activated or reconfigured by a computer program stored in the computer system. In general, various algorithms that may be presented herein are not limited to being implemented or executed by any particular computer system. Alternatively, the construction of more specialized computer system to perform various operations, functions or steps of various methods described herein may be provided as desired or as appropriate without going beyond the scope of the present invention.

[0035] In addition, the present specification also at least implicitly discloses computer program(s) or software/functional module(s), in that it would be apparent to a person skilled in the art that various operations, functions or steps of various methods described herein may be

put into effect by computer code. The computer program(s) is not intended to be limited to any particular programming language and implementation thereof, and it will be appreciated by a person skilled in the art that a variety of programming languages and coding thereof may be used to implement the computer program(s). Moreover, the computer program(s) is not
5 intended to be limited to any particular control flow as there are a variety of programming languages which can use different control flows. It will be appreciated by a person skilled in the art that a computer program may be stored on any computer-readable storage medium (non-transitory computer-readable storage medium), such as but not limited to, a magnetic disk, an optical disk or a memory chip. For example, a computer program stored on a computer-readable
10 storage medium may be loaded and executed on a computer system to implement various operations, functions or steps of various methods described herein according to various embodiments of the present invention.

[0036] Accordingly, in various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory
15 computer-readable storage medium), comprising instructions (e.g., the interference pattern determining module 206, the holograph pattern determining module 208; the phase shift determining module 210 and/or the unit cell controlling module 212) executable by one or more computer processors to perform the method 100 of controlling a RIS for multi-target spot beamforming as described hereinbefore with reference to FIG. 1 according to various
20 embodiments of the present invention. Accordingly, various computer programs or software modules described herein may be stored in a computer program product receivable by a system therein, such as the RIS controller 200 as shown in FIG. 2, for execution by at least one processor 204 of the RIS controller 200 to perform various operations, functions or steps of various methods described herein according to various embodiments of the present invention.

[0037] It will be appreciated by a person skilled in the art that various modules described herein (e.g., the interference pattern determining module 206, the holograph pattern determining module 208; the phase shift determining module 210 and/or the unit cell controlling module 212) may be software module(s) realized by computer program(s) or set(s)
25 of instructions executable by a computer processor to perform various functions or operations. Various modules described herein (e.g., the interference pattern determining module 206, the holograph pattern determining module 208; the phase shift determining module 210 and/or the unit cell controlling module 212) may also be implemented as hardware module(s) being
30 functional hardware unit(s) designed to perform various functions or operations. More

particularly, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC) or a Field Programmable Gate Array (FPGA).

- 5 For example, in the case of the RIS controller 200 being implemented as a FPGA, the memory 202 (e.g., a non-volatile memory such as a flash memory) may store a configuration file for programming or configuring the FPGA (e.g., corresponding to the processor 204) to perform the method 100 of controlling a RIS for multi-target spot beamforming as described herein according to various embodiments of the present invention. Accordingly, the programmed or
- 10 configured FPGA comprises the interference pattern determining module (as a circuit) 206, the holograph pattern determining module (as a circuit) 208; the phase shift determining module (as a circuit) 210 and the unit cell controlling module (as a circuit) 212 configured to perform the method 100 of controlling a RIS for multi-target spot beamforming as described herein according to various embodiments of the present invention. Numerous other possibilities exist.
- 15 It will also be appreciated by a person skilled in the art that a combination of hardware and software modules may be implemented. Furthermore, various operations, functions or steps of various methods described herein may be performed in parallel rather than sequentially as desired or as appropriate (e.g., as long as it does not render the method(s) inoperable or unsatisfactory for its intended purpose).
- 20 **[0038]** FIG. 3 depicts a schematic diagram of a multi-target spot beamforming system 300 according to various embodiments of the present invention. The multi-target spot beamforming system 300 comprises a RIS 310 comprising a 2D array of unit cells 312, each unit cell 312 being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated
- 25 thereon; a multi-mode OAM signal transmitter 320 configured to generate and transmit multi-mode OAM waves to irradiate the RIS 310 at a surface thereof (e.g., FIG. 3 illustrates two example alternative locations of the multi-mode OAM signal transmitter 320 depending on whether the RIS 310 is a transmissive RIS or a reflective RIS); and the RIS controller 200 as described hereinbefore with reference to FIG. 2 according to various embodiments of the
- 30 present invention communicatively coupled to the RIS 310 for controlling the RIS 310 for multi-target spot beamforming at a plurality of target beam focus positions 330-1, 330-2, 330-3. As shown in FIG. 3, multiple independent signal receivers 340-1, 340-2, 340-3 may be

strategically positioned at the plurality of target beam focus positions 330-1, 330-2, 330-3 for receiving OAM-modulated signals output from the RIS 310.

[0039] In various embodiments, each unit cell 312 is not limited to any particular or specific design or configuration as long as it is controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves (OAM electromagnetic waves) irradiated thereon, as described herein according to various embodiments of the present invention. In other words, any RIS is within the scope of the present invention as long as it comprises a 2D array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon.

[0040] In various embodiments, there is provided a RIS 410 for controlling a propagation of incident electromagnetic waves irradiated thereon. In this regard, the concept of reconfigurable intelligent surface (or reconfigurable metasurfaces) has been disclosed. Reconfigurable metasurfaces offer post-fabrication tunability and have the potential for diverse applications. Different tuning mechanisms have been explored to achieve reconfigurability, such as the use of lumped elements, phase-changing materials, liquid crystals, graphene, vanadium-dioxide, and origami- and kirigami-based structures. For example, in the case of lumped elements, such as varactor diodes, by controlling the bias voltage across the varactor diodes, the effective electromagnetic properties of the reconfigurable metasurface can be tuned. Moreover, for example, previous studies have achieved 2-bit phase-shifting unit cells by extracting the equivalent circuit of each unit cell and then incorporating PIN diodes at specific positions. In such conventional 2-bit phase-shifting unit cells, the switching of these PIN diodes adjusts the capacitance values in the equivalent circuit, thereby altering the resonant frequency of the entire unit cell to achieve the desired phase shift of the incident electromagnetic waves. Accordingly, conventional design or approach fundamentally relies on the equivalent circuit of the unit cell for achieving the desired phase shift of the incident electromagnetic waves. However, various embodiments note that such a conventional design or approach suffers from various technical problems, including a very complex and time-consuming design process. In particular, when switching a PIN diode, the equivalent circuit of the entire unit cell would change, especially when distributed capacitance is present, making the RF structure design very complex. For example, typically, professional RF researchers would need to spend a significant amount of time and effort fine-tuning the equivalent circuit of the entire unit cell part by part

iteratively, thereby posing significant challenges (e.g., with respect to cost and time) for practical applications of such conventional RISs in wireless communication systems, which hinder the commercialization of such conventional RISs in RF devices in wireless communication networks. In this regard, various embodiments of the present invention provide

5 a RIS 410 for controlling a propagation of incident electromagnetic waves that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional RISs, and more particularly, that has an effective and efficient design/architecture, such as effective in controlling the degree of phase shift of incident electromagnetic waves while enabling an efficient/practical design process (e.g., significantly reducing design complexity and time, and

10 thus fabrication costs), thereby improving practical applications of the RIS in wireless communication systems.

[0041] FIG. 4 depicts a schematic drawing of a RIS 410, with a schematic exploded view of the unit cell 412, for controlling a propagation of incident electromagnetic waves irradiated thereon, according to various embodiments of the present invention. The RIS 410 comprises: a

15 2D array of unit cells 412, each unit cell 412 comprising: a first dielectric substrate 420 having a first side and a second side opposite to the first side; a second dielectric substrate 430 having a first side and a second side opposite to the first side; a first metallic layer disposed on the first side of the first dielectric substrate 420, the first metallic layer comprising a first metal microstrip line 442 controllable to be at any selected one of a plurality of wave propagation

20 path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated on the first metal microstrip line 442 to produce intermediate electromagnetic waves; a second metallic layer disposed between the first and second dielectric substrates 420, 430, the second metallic layer comprising a first metal microstrip line 462 connected to the first metal microstrip line 442 of the first metallic layer through a first metal via 470 and is

25 controllable to be any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves received from the first metal microstrip line 442 of the first metallic layer through the first metal via 470 to produce output electromagnetic waves; and a third metallic layer disposed on the second side of the second dielectric substrate 430, the third metallic layer comprising a first metal microstrip

30 line 482 connected to the first metal microstrip line 462 of the second metallic layer through a second metal via 472 and configured to radiate the output electromagnetic waves received from the first metal microstrip line 482 of the second metallic layer through the second metal via 472.

[0042] The RIS 410 for controlling a propagation of incident electromagnetic waves according to various embodiments of the present invention advantageously has an effective and efficient design/architecture, including being effective in controlling the degree of phase shift of incident electromagnetic waves while enabling an efficient/practical design process. In particular, in contrast to conventional design or approach which fundamentally relies on fine-tuning the equivalent circuit of the unit cell part by part for altering the resonant frequency of the unit cell in an attempt to achieve the desired phase shift of the incident electromagnetic waves, the RIS 410 adopts a fundamentally different design or approach which controls the degree of phase shift of electromagnetic waves using a metal microstrip line configured for the electromagnetic waves received to propagate therein (along the metal microstrip line) as traveling waves. Based on such a technical design or approach, a metal microstrip line may be configured with a particular length to provide a corresponding propagation delay of the traveling waves (electromagnetic waves) to consequently result in a corresponding (e.g., desired or required) degree of phase shift of the electromagnetic waves. Such a particular length of the metal microstrip line may thus also be referred to as a delay line length. The metal microstrip line may further be controllable (e.g., based on controlling one or more switching elements connected thereto) to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for electromagnetic waves. For example, the metal microstrip line may be configured with a particular length such that it provides a first degree of phase shift for the electromagnetic waves when at a first wave propagation path state and provides a second degree of phase shift for the electromagnetic waves when at a second wave propagation path state. In various embodiments, the metal microstrip line may also be configured together with one or more other metal microstrip lines to, when connected with each other, have a particular length to provide a corresponding propagation delay of the electromagnetic wave to consequently result in a corresponding degree of phase shift of the electromagnetic waves. Similarly, the metal microstrip line, together with the one or more other metal microstrip lines, may further be controllable (e.g., based on controlling one or more switching elements connected thereto) to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for electromagnetic waves. Accordingly, different degree of phase shifts of electromagnetic waves traveling along a metal microstrip line can advantageously be achieved by controlling/adjusting the wave propagation path state of the metal microstrip line amongst different wave propagation path states corresponding to the different degree of phase shifts, respectively.

[0043] Accordingly, based on such a technical design or approach according to various embodiments of the present invention, the unit cell design process is significantly simplified since the desired degree of phase shift of electromagnetic waves can be achieved by configuring the metal microstrip line with a particular length to provide a corresponding propagation delay of the electromagnetic waves, and such a particular length (delay line length) can be easily or simply determined based the wavelength of the electromagnetic waves. Therefore, the very complex and time-consuming design process associated with fine-tuning the equivalent circuit of the unit cell part by part according to conventional design process is avoided. Accordingly, the RIS 410 for controlling a propagation of incident electromagnetic waves according to various embodiments of the present invention advantageously has an effective and efficient design/architecture, such as effective in controlling the degree of phase shift of incident electromagnetic waves while enabling an efficient/practical design process (e.g., significantly reducing design complexity and time, and thus fabrication costs), thereby improving practical applications of the RIS 410 in wireless communication systems. These advantages or technical effects, and/or other advantages or technical effects, will become more apparent to a person skilled in the art as the RIS 410 for controlling a propagation of incident electromagnetic waves is described in more detail according to various embodiments and example embodiments of the present invention.

[0044] In various embodiments, the first metal microstrip line 442 of the first metallic layer is connected to one or more switching elements (not shown in FIG. 4) at the first metallic layer. In this regard, the first metal microstrip line 442 is controllable to be at any selected one of the plurality of wave propagation path states based on controlling a state of the one or more switching elements connected thereto for configuring the first metal microstrip line 442 to be at any selected one of the plurality of wave propagating path states for providing a corresponding degree of phase shift for the incident electromagnetic waves to produce the intermediate electromagnetic waves. In various embodiments, the first metal microstrip line 462 of the second metallic layer is connected to one or more switching elements (not shown in FIG. 4) at the second metallic layer. In this regard, the first metal microstrip line 462 is controllable to be at any selected one of the plurality of wave propagation path states based on controlling a state of the one or more switching elements connected thereto for configuring the first metal microstrip line 462 to be at any selected one of the plurality of wave propagating path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves to produce the output electromagnetic waves.

[0045] In various embodiments, the one or more switching elements at the first metallic layer comprises a first switching element and a second switching element. In this regard, the first metal microstrip line 442 of the first metallic layer is controllable to be at a first or second wave propagation path state based on controlling a state of the first and second switching elements connected thereto for configuring the first metal microstrip line 442 to be at the first or second wave propagating path state for providing a first degree or second degree of phase shift, respectively, for the incident electromagnetic waves to produce the intermediate electromagnetic waves. In various embodiments, the one or more switching elements at the second metallic layer comprises a third switching element and a fourth switching element, and the first metal microstrip line 462 of the second metallic layer is controllable to be at a first or second wave propagation path state based on controlling a state of the third and fourth switching elements connected thereto for configuring the first metal microstrip line 462 to be at the first or second wave propagating path state for providing a first degree or second degree of phase shift, respectively, for the intermediate electromagnetic waves to produce the output electromagnetic waves.

[0046] In various embodiments, the first degree and second degree of phase shifts provided by the first metal microstrip line 442 of the first metallic layer are about 0 degrees and about 180 degrees of phase shifts, respectively. In various embodiments, the first degree and second degree of phase shifts provided by the first metal microstrip line 462 of the second metallic layer are about 0 degrees and about 90 degrees of phase shifts, respectively.

[0047] In various embodiments, the first metal microstrip line 442 of the first metallic layer comprises a first portion, a second portion and a third portion (not illustrated in FIG. 4). In this regard, the first and second portions is spaced apart by a first gap therebetween and the second and third portions being spaced apart by a second gap therebetween. The first switching element is arranged at the first gap between the first and second portions for providing a switchable connection between the first and second portions. In this regard, the first switching element is controllable to be at one of a conducting state and a non-conducting state. The second switching element is arranged at the second gap between the second and third portions for providing a switchable connection between the second and third portions. In this regard, the second switching element is controllable to be at one of a conducting state and a non-conducting state.

[0048] In various embodiments, the first metal microstrip line 442 of the first metallic layer is configured to provide about 0 degrees of phase shift of the incident electromagnetic waves irradiated thereon based on the state of the first and second switching elements being at the

conducting state and the non-conducting state, respectively. The first metal microstrip line 442 of the first metallic layer is configured to provide about 180 degrees of phase shift of the incident electromagnetic waves irradiated thereon based on the state of the first and second switching elements being at the non-conducting state and the conducting state, respectively.

5 [0049] In various embodiments, the first and second switching elements are each a PIN diode and are arranged at the first and second gaps to have opposite polarity.

[0050] In various embodiments, the first metal via 470 is connected to the first metal microstrip line 442 of the first metallic layer at the second portion thereof. Furthermore, the first metal via 470 is connected to the first metal microstrip line 462 of the second metallic layer
10 at a first end portion thereof.

[0051] In various embodiments, the second metal via 472 is connected to the first metal microstrip line 462 of the second metallic layer at a second end portion thereof. Furthermore, the first and second end portions is at opposite ends of the first metal microstrip line 462 of the second metallic layer.

15 [0052] In various embodiments, the second metallic layer further comprises a second metal microstrip line arranged to be spaced apart from the first metal microstrip line 462 of the second metallic layer by a gap therebetween. In this regard, the third and fourth switching elements are arranged at the gap between the first and second metal microstrip lines of the second metallic layer for providing a switchable connection therebetween. In this regard, the third and fourth
20 switching elements each is controllable to be at one of a conducting state and a non-conducting state.

[0053] In various embodiments, the first metal microstrip line 462 of the second metallic layer is configured to provide about 0 degrees of phase shift of the intermediate electromagnetic waves received based on the state of the third and fourth switching elements both being at the
25 non-conducting state. In various embodiments, the first metal microstrip line 462, together with the second metal microstrip line, of the second metallic layer is configured to provide about 90 degrees of phase shift of the intermediate electromagnetic waves received based on the state of the third and fourth switching elements both being at the conducting state.

[0054] In various embodiments, the third and fourth switching elements are each a PIN
30 diode and are arranged at the gap in parallel and to have the same polarity. Furthermore, the third and fourth switching elements are arranged at the gap so as to be spaced apart by an appropriate distance.

- [0055] In various embodiments, the first metallic layer further comprises a second metal microstrip line arranged to be parallel to and spaced apart from the first metal microstrip line 442 of the first metallic layer. In this regard, the first and second metal microstrip lines of the first metallic layer being configured to have different lengths for enhancing a response bandwidth of the first metallic layer. Similarly, the third metallic layer further comprises a second metal microstrip line arranged to be parallel to and spaced apart from the first metal microstrip line 482 of the third metallic layer. In this regard, the first and second metal microstrip lines of the third metallic layer being configured to have different lengths for enhancing a response bandwidth of the third metallic layer.
- 10 [0056] In various embodiments, the RIS 410 further comprises: a third dielectric substrate having a first side and a second side opposite to the first side. In this regard, the third dielectric substrate is disposed between the first and second dielectric substrates 420, 430; and a fourth metallic layer disposed between the first and third dielectric substrates. The fourth metallic layer is configured as a ground layer.
- 15 [0057] In various embodiments, the second metallic layer is disposed between the second and third dielectric substrates, and the first metal microstrip line 462 of the second metallic layer comprises a center portion connected to the fourth metallic layer through a third metal via for grounding the center portion.
- [0058] In various embodiments, each unit cell is a 2-bit phase-shifting unit cell controllable to be at any selected one of four wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated thereon.
- 20 [0059] In various embodiments, the four wave propagation path states are configured to provide four corresponding degree of phase shifts of about 0 degrees, about 90 degrees, about 180 degrees and about 270 degrees, respectively, for the incident electromagnetic waves
- 25 irradiated thereon.
- [0060] In various embodiments, the incident electromagnetic waves are multi-mode OAM waves.
- [0061] In various embodiments, the RIS 410 is configured as a transmissive RIS.
- [0062] FIG. 5 depicts a method 500 of forming the RIS 410 for controlling a propagation of incident electromagnetic waves, according to various embodiments of the present invention. The method 500 comprises forming a 2D array of unit cells 412. In this regard, forming the 2D array of unit cells 412 comprises, for each unit cell 412: providing or forming (at 502) a first dielectric substrate 420 having a first side and a second side opposite to the first side; providing
- 30

or forming (at 504) a second dielectric substrate 430 having a first side and a second side opposite to the first side; forming or disposing (at 506) a first metallic layer on the first side of the first dielectric substrate 420, the first metallic layer comprising a first metal microstrip line 442 controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated on the first metal microstrip line 442 to produce intermediate electromagnetic waves; forming or disposing (at 508) a second metallic layer between the first and second dielectric substrates 420, 430, the second metallic layer comprising a first metal microstrip line 462 connected to the first metal microstrip line 442 of the first metallic layer through a first metal via 470 and is controllable to be any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves received from the first metal microstrip line 442 of the first metallic layer through the first metal via 470 to produce output electromagnetic waves; and forming or disposing (at 510) a third metallic layer on the second side of the second dielectric substrate 430, the third metallic layer comprising a first metal microstrip line 482 connected to the first metal microstrip line 462 of the second metallic layer through a second metal via 472 and configured to radiate the output electromagnetic waves received from the first metal microstrip line 462 of the second metallic layer through the second metal via 472.

[0063] In various embodiments, the method 500 is for forming or fabricating the RIS 410 as described herein with reference to FIG. 4 according to various embodiments of the present invention, therefore, various steps or operations of the method 500 may correspond to forming, providing or configuring various components, parts or portions of the RIS 410 as described herein according to various embodiments, and thus such corresponding steps or operations need not be described or repeated with respect to the method 500 for clarity or conciseness. In other words, various embodiments described herein in the context of the RIS 410 are analogously valid for the method 500 of forming the RIS 410 (e.g., for forming the RIS 410 having various components, parts, portions and/or configurations as described hereinbefore according to various embodiments), and vice versa. It will also be appreciated by a person skilled in the art that the method 500 of forming the RIS 410 is not limited to any particular order of operations/steps, which may be performed or ordered as desired or as appropriate based on the fabrication technique employed.

[0064] In various embodiments, the method 100 of controlling a RIS for multi-target spot beamforming is applied to control the RIS 410 as described herein according to various embodiments of the present invention.

5 [0065] In various embodiments, the RIS controller 200 for controlling a RIS for multi-target spot beamforming is applied to control the RIS 410 as described herein according to various embodiments of the present invention.

[0066] In various embodiments, the RIS of the multi-target spot beamforming system 300 is the RIS 410 as described herein according to various embodiments of the present invention.

10 [0067] It will be appreciated by a person skilled in the art that the terminology used herein is for the purpose of describing various embodiments only and is not intended to be limiting of the present invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components,
15 but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0068] Any reference to an element or a feature herein using a designation such as “first”, “second” and so forth does not limit the quantity or order of such elements or features, unless stated or the context requires otherwise. For example, such designations may be used herein as
20 a convenient way of distinguishing between two or more elements or instances of an element. Thus, a reference to first and second elements does not necessarily mean that only two elements can be employed, or that the first element must precede the second element, unless stated or the context requires otherwise. In addition, a phrase referring to “at least one of” a list of items refers to any single item therein or any combination of two or more items therein.

25 [0069] In order that the present invention may be readily understood and put into practical effect, various example embodiments of the present invention will be described hereinafter by way of examples only and not limitations. It will be appreciated by a person skilled in the art that the present invention may, however, be embodied in various different forms or configurations and should not be construed as limited to the example embodiments set forth
30 hereinafter. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present invention to those skilled in the art.

[0070] According to various example embodiments, OAM-enhanced multi-target spot-beamforming using a RIS is provided. Accordingly, various example embodiments of the present invention lie in the domain of RIS systems, and more specifically, pertains to a system that is reconfigurable and controlled based on OAM technology. The advancements and innovations in the field of RIS and OAM have enabled numerous technological leaps, particularly in the sector of wave manipulation and wireless communications. Yet, there remains a significant scope for improvement and application. Various example embodiments seek to further the field of RIS by leveraging a RIS holograph phase compensation method or algorithm to convert multi-mode OAM waves (which may also be referred to as OAM beams) to multiple focus points (multiple target beam focus positions) in short-range wireless communication scenarios, such as in the range of one meter to hundreds of meters, thereby reducing mutual interference between different communication nodes and enhancing the stability of the wireless communication system. In particular, for enabling multi-target spot beamforming using a RIS, various example embodiments of the present invention provide a method of controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, as well as a RIS controller thereof. In addition, various example embodiments of the present invention provide a multi-target spot beamforming system comprising the RIS controller. Furthermore, various example embodiments of the present invention provide a RIS for controlling a propagation of incident electromagnetic waves that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional RISs, and more particularly, that has an effective and efficient design/architecture, such as effective in controlling the degree of phase shift of incident electromagnetic waves while enabling an efficient/practical design process (e.g., significantly reducing design complexity and time, and thus fabrication costs), thereby improving practical applications of the RIS in wireless communication systems, such as a multi-target wireless multifocal communication (WMC) system.

[0071] As an example practical application, various example embodiments provide a multi-target wireless multifocal communication system that can be seamlessly integrated into a variety of vehicular platforms. The wireless multifocal communication system is able to provide robust, high-speed data transmission, demonstrating sufficient adaptability to meet the evolving needs of the automotive industry. Therefore, as an example practical application, various example embodiments provide a flexible and effective technical solution for in-vehicle communication, thereby reducing the overall complexity and cost associated with traditional wired networks for in-vehicle communication.

[0072] In addition, various example embodiments revolve around harnessing the power of RIS and OAM technologies together for addressing the issue of spectrum scarcity commonly associated with traditional wireless communication systems. The OAM-based beam steering process enables space division multifocal transmission through a multi-bit quantified RIS, thus
5 facilitating the efficient reuse of frequency band resources. For example, by incorporating these technologies into the vehicular platforms, various example embodiments seek to significantly enhance the efficiency and reliability of in-vehicle wireless communications. For example, the OAM-based vehicle-integrated multi-target spot beamforming system according to various example embodiments demonstrates the viability of non-obstructed multifocal
10 communications within a vehicular setting. In various example embodiments, a RIS holography-based phase compensation method is applied to convert multi-mode OAM beams to multiple focus points in short-range wireless communication scenarios, such as in-vehicle wireless communications.

[0073] Accordingly, various example embodiments of the present invention
15 advantageously provide a unique and effective approach towards the development of a highly efficient short-range wireless communication system. By leveraging cutting-edge OAM and RIS technology, various example embodiments seek to revolutionize short-range communication networks, such as in-vehicle communication networks, by replacing the existing wired system with a more adaptable and cost-effective wireless system. Therefore, the
20 OAM-enhanced RIS multi-target spot beamforming system (e.g., OAM-enhanced RIS vehicle-integrated multi-target spot beamforming system) according to various example embodiments of the present invention, significantly enhances short-range wireless communications, such as in-vehicle communications.

[0074] FIG. 6 depicts an example implementation of a multi-target wireless multifocal
25 communication 600, according to various example embodiments of the present invention, corresponding to the multi-target spot-beamforming system 300 as described hereinbefore with reference to FIG. 3 according to various embodiments of the present invention. For illustration purpose only and without limitation, the wireless multifocal communication system 600 is shown in FIG. 6 implemented for in-vehicle wireless communications. However, it will be
30 appreciated by a person skilled in the art that the present invention is not limited to such a specific wireless communication practical application and may be implemented in other types of wireless communication practical applications as desired or as appropriate, especially in relation to short-range wireless communications such as in the range of one meter to hundreds

of meters, such as indoor wireless communications within a building. Accordingly, the wireless multifocal communication system 600 may advantageously be provided to enable space division non-obstructed wireless data transmission in a region, such as a confined region within a vehicle.

5 [0075] As shown in FIG. 6, the wireless multifocal communication system 600 comprises: a RIS 610 comprising a 2D array of unit cells 612; a multi-mode OAM signal transmitter 620 configured to generate and transmit multi-mode OAM waves to irradiate the RIS 610 at a surface thereof; and a RIS controller 602 communicatively coupled to the RIS 610 for controlling the RIS 610 for multi-target spot beamforming at a plurality of target beam focus
10 positions 630-1, 630-2, 630-3. Each unit cell 612 is controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves (multi-mode OAM waves from the multi-mode OAM signal transmitter 620) irradiated thereon. In various example embodiments, as shown in FIG. 6, the RIS 610 may be deployed or arranged along a roof of a vehicle for converting the multi-mode
15 OAM waves irradiated on the RIS 610 into multiple spot beams for output from the RIS 610 which converge to multiple target beam focus positions 630-1, 630-2, 630-3. As shown in FIG. 6, in various example embodiments, the RIS 610 may be configured either as a transmissive RIS or a reflective RIS. In the case of the RIS 610 being configured as a reflective RIS, the target beam focus positions 630-1, 630-2, 630-3 is thus located at the same side of the RIS 610
20 as the OAM signal transmitter 620 (e.g., the OAM signal transmitter 620 may be located inside the vehicle as illustrated in FIG. 6). In the case of the RIS 610 being configured as a reflective RIS 620, the target beam focus positions 630-1, 630-2, 630-3 is thus located at an opposite side of the RIS 610 with respect to the OAM signal transmitter 620 (e.g., the OAM signal transmitter 620 may be located on a base station as illustrated in FIG. 6). As shown in FIG. 6, multiple
25 independent signal receivers 640-1, 640-2, 640-3 may be strategically positioned within various spatial locations in a region, such as inside a vehicle. These signal receivers 640-1, 640-2, 640-3 may thus serve as endpoints for the wireless multifocal communication system 600, capturing and processing the OAM-modulated signals output from the RIS 610.

[0076] Accordingly, the multi-mode OAM signal transmitter 620 is employed to generate and transmit multi-mode OAM waves for enabling multifocal communications. In this regard,
30 different OAM modes carry distinct baseband modulated information. The RIS 610 may be an easily deployable RIS circuit board, which is designed to be versatile and adaptable, thus allowing for seamless integration into various wireless communication scenarios. The RIS 610

enables the manipulation of electromagnetic waves and is configured to manipulate or convert the multi-mode OAM waves irradiated thereon for multifocal communications. The RIS controller 602 is configured to control the RIS 610 to achieve the multifocal communications. In particular, the RIS controller 602 is configured to control the RIS 610 to convert the multi-mode OAM waves irradiated on the RIS 610 into multiple spot beams for output from the RIS 610 which converge to multiple target beam focus positions 630-1, 630-2, 630-3. Accordingly, the RIS controller 602 facilitates the precise control and adjustments or reconfiguration of the RIS 610 to optimize the propagation of the multi-mode OAM signals. Accordingly, the RIS holograph phase compensation method or algorithm described herein according to various example embodiments of the present invention for multi-target spot beamforming at multiple target beam focus positions (e.g., focus regions) may be stored or implemented in the RIS controller 602. As an illustrative example and without limitation, the RIS controller 602 may be implemented using Field-Programmable Gate Array (FPGA) technology, that is, implemented as an FPGA. In such a case, a RIS holograph phase compensation algorithm may be programmed into an FPGA to configure the FPGA to perform the RIS holograph phase compensation method to control the RIS 610 for multi-target spot beamforming.

[0077] Accordingly, the multi-mode OAM signal transmitter 620, the RIS 610, the RIS controller 602 and the signal receivers 640-1, 640-2, 640-3 work in unison to enable the multi-target wireless multifocal communications system, offering enhanced communication capabilities within confined spaces, such as the interior of a vehicle. Accordingly, for example, the wireless multifocal communication system 600 can revolutionize vehicular communication networks, replacing existing vehicular wired communication networks with a significantly more efficient vehicular wireless communication system. In doing so, in-vehicle communication can be significantly simplified or streamlined, thereby reducing installation, maintenance, and upgrade costs.

[0078] An example RIS for controlling a propagation of an incident electromagnetic wave irradiated thereon, will now be described in further detail according to various example embodiments of the present invention. In particular, as an illustrative example, a 2-bit phase-quantified (i.e., four phase-shifting states for providing four different degree of phase shifts) transmissive RIS with a 2D array of 2-bit phase-shifting transmissive unit cells configured to provide four possible (or candidate) degree of phase shifts will be described according to various example embodiments of the present invention. It will be appreciated by a person skilled in the art that the RIS 610 is not limited to being configured as a transmissive RIS (i.e.,

may alternatively be configured as a reflective RIS) and is not limited to having a 2-bit phase-shifting unit cell design (i.e., may be configured to be any number of bits (i.e., provide any number of phase-shifting states, e.g., 3-bit or 4-bit phase-shifting unit cell design) as desired or as appropriate, such as based on the desired or required number of degree of phase shifts.

- 5 [0079] From a radio frequency (RF) hardware perspective, previous studies have achieved 2-bit phase-shifting RIS unit cells by extracting the equivalent circuit of each unit cell and then incorporating PIN diodes at specific positions. In such conventional 2-bit phase-shifting unit cells, the switching of these PIN diodes adjusts the capacitance values in the equivalent circuit, thereby altering the resonant frequency of the entire unit cell to achieve the desired phase shift
- 10 of the incident electromagnetic waves. Accordingly, conventional design or approach fundamentally relies on fine-tuning the equivalent circuit of the unit cell part by part for altering the resonant frequency of the unit cell in an attempt to achieve the desired phase shift of the incident electromagnetic waves. However, such a conventional design or approach suffers from various technical problems, including a very complex and time-consuming design process. In
- 15 particular, when switching a PIN diode, the equivalent circuit of the entire unit cell would change, especially when distributed capacitance is present, making the RF structure design very complex. For example, typically, professional RF researchers would need to spend a significant amount of time and effort fine-tuning the equivalent circuit of the entire unit cell part by part iteratively, thereby posing significant challenges (e.g., with respect to cost and time) for
- 20 practical applications of such conventional RISs in wireless communication systems, which hinder the commercialization of such conventional RISs in RF devices in wireless communication networks.

- [0080] In contrast, a fundamentally different RIS design philosophy is adopted according to various example embodiments of the present invention. In particular, each RIS unit cell is
- 25 configured to capture incident electromagnetic waves to propagate therein as traveling waves. In this regard, the unit cell is configured to control the degree of phase shift of electromagnetic waves using one or more metal microstrip lines configured for the electromagnetic waves received to propagate therein as traveling waves. Based on such a technical design or approach, a metal microstrip line may be configured with a particular length to provide a corresponding
- 30 propagation delay of the traveling waves (electromagnetic waves) to consequently result in a corresponding (e.g., desired or required) degree of phase shift of the electromagnetic waves. Therefore, the length of the metal microstrip line (which may also be referred to as the delay path length) may be determined or configured accordingly to provide a corresponding degree

of phase shift, whereby the longer the length of the microstrip line, the greater the propagation delay, and consequently, the larger the phase shift of the electromagnetic waves. The metal microstrip line may further be controllable (e.g., based on controlling one or more switching elements connected thereto (e.g., PIN diodes)) to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for electromagnetic waves. For example, the metal microstrip line may be configured with a particular length such that it provides a first degree of phase shift for the electromagnetic waves when at a first wave propagation path state and provides a second degree of phase shift for the electromagnetic waves when at a second wave propagation path state. The metal microstrip line may also be configured together with one or more other metal microstrip lines to, when connected with each other, have a particular length to provide a corresponding propagation delay of the electromagnetic waves to consequently result in a corresponding degree of phase shift of the electromagnetic waves. Similarly, the metal microstrip line, together with the one or more other metal microstrip lines, may further be controllable (e.g., based on controlling one or more switching elements connected thereto) to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for electromagnetic waves. Accordingly, different degree of phase shifts of electromagnetic waves traveling along a metal microstrip line can advantageously be achieved by controlling/adjusting the wave propagation path state of the metal microstrip line amongst different wave propagation path states (i.e., amongst different propagation paths) corresponding to the different degree of phase shifts, respectively.

[0081] Compared to traditional methods, the RIS RF part design according to various example embodiments of the present invention provide a number of technical advantages. For example, the unit cell design process is significantly simpler, for example, since it does not require attention to the equivalent capacitance and inductance of the unit cell as required in traditional methods. In contrast, the required length (delay line length) of the metal microstrip line for achieving a desired degree of phase shift of the electromagnetic waves can be directly and accurately determined or calculated based on the wavelength of the electromagnetic waves for configuring the metal microstrip line (or the corresponding metallic layer). In addition, influence between different phase-shifting states (or wave propagation path states) of the unit cell is avoided or minimized, because, in the unit cell design according to various example embodiments of the present invention, different degree of phase shifts advantageously correspond to different delay line paths (different wave propagation paths). For example, as

illustrated in the example unit cell configuration/architecture shown in FIGs. 7 to 9 (to be described in detail later below), different delay line paths (different wave propagation paths) for corresponding different degree of phase shifts, respectively, are independent of each other. Accordingly, the RIS according to various example embodiments of the present invention
5 advantageously offers a simple, reliable and effective solution for improving practical application of the RIS in the wireless communication system, and more particularly, short-range wireless communication systems.

[0082] FIG. 7 depicts a schematic drawing of the example RIS 710, with a schematic exploded view of the unit cell 712, for controlling a propagation of incident electromagnetic waves irradiated thereon, according to various example embodiments of the present invention.
10 FIG. 8 depicts a schematic drawing showing front (or top) and back (or bottom) side views of the RIS 700, as well as front, back and right side views of the unit cell 712 thereof, according to various example embodiments of the present invention. The unit cell 712 is configured as a multi-bit phase-shifting unit cell (which may also be referred to as a multi-bit phase-quantified reconfigurable element) for manipulating or controlling the phase of incoming electromagnetic waves. As described hereinbefore, as an illustrative example according to various example
15 embodiments, the example RIS 710 is configured as a 2-bit phase-quantified transmissive RIS, and thus, each unit cell 712 is configured as a 2-bit phase-shifting transmissive unit cell.

[0083] The RIS 710 comprises a 2D array of unit cells 712. Each unit cell 712 comprises:
20 a first dielectric substrate 720 having a first side and a second side opposite to the first side; a second dielectric substrate 730 having a first side and a second side opposite to the first side; a first metallic layer 740 disposed on the first side of the first dielectric substrate 720, the first metallic layer 740 comprising a first metal microstrip line 742 controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase
25 shift for the incident electromagnetic waves irradiated on the first metal microstrip line 742 to produce intermediate electromagnetic waves; a second metallic layer 760 disposed between the first and second dielectric substrates 720, 730, the second metallic layer 760 comprising a first metal microstrip line 762 connected to the first metal microstrip line 742 of the first metallic layer 762 through a first metal via 770 and is controllable to be any selected one of a plurality
30 of wave propagation path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves received from the first metal microstrip line 742 of the first metallic layer 740 through the first metal via 770 to produce output electromagnetic waves; and a third metallic layer 780 disposed on the second side of the second dielectric substrate 730, the

third metallic layer 780 comprising a first metal microstrip line 782 connected to the first metal microstrip line 762 of the second metallic layer 760 through a second metal via 772 and configured to radiate the output electromagnetic waves received from the first metal microstrip line 782 of the second metallic layer 760 through the second metal via 772.

- 5 [0084] In various example embodiments, the first metal microstrip line 742 of the first metallic layer 740 is connected to a first switching element 752 and a second switching element 754 at the first metallic layer 740. In this regard, the first metal microstrip line 742 is controllable to be at any selected one of a first wave propagation path state and a second wave propagation path state based on controlling a state of the first and second switching elements
- 10 752, 754 connected thereto for configuring the first metal microstrip line 742 to be at any selected one of the first and second wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves to produce the intermediate electromagnetic waves. In various example embodiments, the first metal microstrip line 762 of the second metallic layer 760 is connected to a third switching element 756 and a fourth
- 15 switching element 758 at the second metallic layer 760. In this regard, the first metal microstrip line 762 is controllable to be at any selected one of a first wave propagation path state and a second wave propagation path state based on controlling a state of the third and fourth switching elements 756, 758 connected thereto for configuring the first metal microstrip line 762 to be at any selected one of the first and second wave propagation path states for providing a
- 20 corresponding degree of phase shift for the intermediate electromagnetic waves to produce the output electromagnetic waves.

- [0085] In various example embodiments, the first degree and second degree of phase shifts provided by the first metal microstrip line 742 of the first metallic layer 740 are about 0 degrees and about 180 degrees of phase shifts, respectively. In various example embodiments, the first
- 25 degree and second degree of phase shifts provided by the first metal microstrip line 762 of the second metallic layer 760 are about 0 degrees and about 90 degrees of phase shifts, respectively.

- [0086] In various example embodiments, as shown in FIG. 7, the first metal microstrip line 742 of the first metallic layer 740 comprises a first portion, a second portion and a third portion. In this regard, the first and second portions is spaced apart by a first gap therebetween and the
- 30 second and third portions being spaced apart by a second gap therebetween. The first switching element 752 is arranged at the first gap between the first and second portions for providing a switchable connection between the first and second portions. In this regard, the first switching element is controllable to be at one of a conducting state and a non-conducting state. The second

switching element 754 is arranged at the second gap between the second and third portions for providing a switchable connection between the second and third portions. In this regard, the second switching element 754 is controllable to be at one of a conducting state and a non-conducting state.

- 5 [0087] In various example embodiments, the first metal microstrip line 742 of the first metallic layer 740 is configured to provide about 0 degrees of phase shift of the incident electromagnetic waves irradiated thereon based on the state of the first and second switching elements 752, 754 being at the conducting state and the non-conducting state, respectively. For example, when a positive or forward voltage is applied to the first switching element 752 (but
10 not to the second switching element 754), the first switching element 752 is at the conducting state and current passes through from the first portion to the second portion in a direction from the first portion to the second portion (corresponding to the first wave propagation path state of the first metal microstrip line 742). Accordingly, in this manner, the first metal microstrip line 742 is controlled and configured to be at the first wave propagation path state for providing
15 about 0 degrees of phase shift of the incident electromagnetic waves for the incident electromagnetic waves to produce the intermediate electromagnetic waves. Furthermore, the first metal microstrip line 742 of the first metallic layer 740 is configured to provide about 180 degrees of phase shift of the incident electromagnetic waves irradiated thereon based on the state of the first and second switching elements 752, 754 being at the non-conducting state and
20 the conducting state, respectively. For example, when a positive or forward voltage is applied to the second switching element 754 (but not to the first switching element 752), the second switching element 754 is at the conducting state and current passes through from the third portion to the second portion in a direction from the third portion to the second portion (corresponding to the second wave propagation path state of the first metal microstrip line 742),
25 which is exactly opposite to that when a positive or forward voltage is applied to the first switching element 752. Accordingly, in this manner, the first metal microstrip line 742 is controlled and configured to be at the second wave propagation path state for providing about 180 degrees of phase shift of the incident electromagnetic waves for the incident electromagnetic waves to produce the intermediate electromagnetic waves. Accordingly, in
30 various example embodiments, with the first, second and third portions and the first and second switching elements arranged in the manner as described above, the first metal microstrip line 742 is configured to be controllable to be at any selected one of the first and second propagation

path states based on controlling a state of the first and second switching elements 752, 754 for providing about 0 or 180 degrees of phase shift in an effective and efficient manner.

[0088] In various example embodiments, the first and second switching elements 752, 754 are each a PIN diode and are arranged at the first and second gaps to have opposite polarity (for
5 configuring the wave propagation paths of the first and second wave propagation path state of the first metal microstrip line 742 to be in opposite directions).

[0089] In various example embodiments, the first metal via 770 is connected to the first metal microstrip line 742 of the first metallic layer 740 at the second portion thereof. Furthermore, the first metal via 770 is connected to the first metal microstrip line 762 of the
10 second metallic layer 760 at a first end portion thereof.

[0090] In various example embodiments, the second metal via 772 is connected to the first metal microstrip line 762 of the second metallic layer at a second end portion thereof. Furthermore, the first and second end portions is at opposite ends of the first metal microstrip line 762 of the second metallic layer.

[0091] In various example embodiments, the second metallic layer 760 further comprises a second metal microstrip line 764 arranged to be spaced apart from the first metal microstrip line 762 of the second metallic layer 760 by a gap therebetween. In this regard, the third and fourth switching elements 756, 758 are arranged at the gap between the first and second metal microstrip lines 762, 764 of the second metallic layer for providing a switchable connection
15 therebetween. In this regard, the third and fourth switching elements 756, 758 each is controllable to be at one of a conducting state and a non-conducting state.

[0092] In various example embodiments, the first metal microstrip line 762 of the second metallic layer 760 is configured to provide about 0 degrees of phase shift of the intermediate electromagnetic waves received based on the state of the third and fourth switching elements
25 756, 758 both being at the non-conducting state. For example, the first metal microstrip line 762 is set to $\frac{1}{4}$ traveling wave length. In this regard, when no voltage is applied to the third and fourth switching elements 756, 758, they are at the non-conducting state and the first and second metal microstrip lines 762, 764 are thus not connected, which configures or results in the first metal microstrip line 762 to only allow odd mode transmission of current, which corresponds
30 to no additional phase shift, thus providing 0 degrees of phase shift. Accordingly, in this manner, the first metal microstrip line 762 is controlled and configured to be at the first wave propagation path state for providing about 0 degrees of phase shift of the intermediate electromagnetic waves received to produce the output electromagnetic waves.

- [0093] In various embodiments, the first metal microstrip line 762, together with the second metal microstrip line 764, of the second metallic layer 760 is configured to provide about 90 degrees of phase shift of the intermediate electromagnetic waves received based on the state of the third and fourth switching elements 756, 758 both being at the conducting state. For example, the first and second metal microstrip lines 762, 764 are set to $\frac{1}{4}$ traveling wave length. In this regard, when a positive voltage is applied to the third and fourth switching element 756, 758, they are at the conducting state and the third and fourth switching elements 756, 758 are thus connected in parallel to form a transmission network, which configure or result in the first and second metal microstrip line 762, 764 to only allow even mode transmission of current, which correspond to providing 90 degrees of phase shift relative to the above-mentioned odd mode transmission of current. Accordingly, in this manner, the first metal microstrip line 742 is controlled and configured to be at the second wave propagation path state for providing about 180 degrees of phase shift of the incident electromagnetic waves for the incident electromagnetic waves to produce the intermediate electromagnetic waves. Accordingly, in various example embodiments, with the first, second and third portions and the first and second switching elements arranged in the manner as described above, the first metal microstrip line 742 is configured to be controllable to be at any selected one of the first and second propagation path states based on controlling a state of the third and fourth switching elements 756, 758 for providing about 0 or 90 degrees of phase shift in an effective and efficient manner.
- [0094] In various example embodiments, the third and fourth switching elements 756, 758 are each a PIN diode and are arranged at the gap in parallel and to have the same polarity.
- [0095] In various example embodiments, the first metallic layer 740 further comprises a second metal microstrip line 744 arranged to be parallel to and spaced apart from the first metal microstrip line 742 of the first metallic layer 740. In this regard, the first and second metal microstrip lines 742, 744 of the first metallic layer 740 is configured to have different lengths for enhancing a response bandwidth of the first metallic layer. Similarly, the third metallic layer 780 further comprises a second metal microstrip line 784 arranged to be parallel to and spaced apart from the first metal microstrip line 782 of the third metallic layer 780. In this regard, the first and second metal microstrip lines 782, 784 of the third metallic layer 780 is configured to have different lengths for enhancing a response bandwidth of the third metallic layer 780. It will be appreciated by a person skilled in the art that the different lengths for enhancing the response bandwidth may be determined based on an optimization process or algorithm to obtain optimal lengths. For example, the first and second metal microstrip lines 782, 784 may be

further configured with respect to an empirical relief to provide good impedance matching. The gap in the first and second metal microstrip lines 782 may be provided to construct a distributed capacitor and the second metal microstrip line 784 may provide distributed inductance and capacitance characteristics.

5 [0096] In various example embodiments, the RIS 410 further comprises: a third dielectric substrate 790 having a first side and a second side opposite to the first side. In this regard, the third dielectric substrate 790 is disposed between the first and second dielectric substrates 720, 730; and a fourth metallic layer 792 disposed between the first and third dielectric substrates 720, 790. The fourth metallic layer 792 is configured as a ground layer.

10 [0097] In various example embodiments, the second metallic layer 760 is disposed between the second and third dielectric substrates 730, 790, and the first metal microstrip line 762 of the second metallic layer 760 comprises a center portion connected to the fourth metallic layer 792 through a third metal via 774 for grounding the center portion. In various example embodiments, an end portion of the second metal microstrip line 764 of the second metallic
15 layer 760 is connected to a fourth metal via 776 for receiving control voltage signals for the third and fourth switching elements 756, 758.

[0098] Accordingly, in various example embodiments, each unit cell 712 is a 2-bit phase-shifting unit cell controllable to be at any selected one of four wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves
20 irradiated thereon. In various example embodiments, the four wave propagation path states are configured to provide four corresponding degree of phase shifts of about 0 degrees, about 90 degrees, about 180 degrees and about 270 degrees, respectively, for the incident electromagnetic waves irradiated thereon. It will be appreciated by a person skilled in the art that dimensions and shapes of components of the unit cell 712 may be determined based on an
25 optimization process or algorithm to obtain optimal dimensions.

[0099] Therefore, in various example embodiments, the unit cell 712 may comprise four metallic layers 740, 760, 780, 792 and three dielectric substrate layers 720, 730, 790, resulting in a meticulously crafted structure designed to manipulate the phase of incoming electromagnetic waves. For example, the uppermost or first metallic layer 740 may comprise
30 the first and second metal microstrip lines 742, 744 in the form of two rectangular patches which are made from copper. For example, the first metal microstrip line 742 (the long strip) may measure about 15.2 mm in length and about 2.7 mm in width, and the second metal microstrip line 744 (the short strip) may measure about 7.4 mm in length and about 1.8 mm in

width. In various example embodiments, the first and second metal microstrip lines 742, 744 capture the incident electromagnetic waves, serving as the initial point of interaction between the electromagnetic waves and the transmissive RIS board 710. At a middle or central portion of the first metal microstrip line 742, two slots are provided, each holding a respective switching element (e.g., PIN diode) 752, 754 with opposite polarity from each other for bridging the
5 respective slot. By controlling the state of these two switching elements 752, 754, as described hereinbefore, the first metal microstrip line 742 is capable of achieving either 0-degree or 180-degree of phase shift of the interacted waves. The first and second metal microstrip lines 742, 744 may be mounted atop two dielectric substrates 720, 790, which for example may be made
10 from Taconic TLX-8, measuring about 1.5 mm (h_1) and about 1.0 mm (h_2) in thickness, respectively. These dielectric substrates 720, 790 provide structural support and ensure optimal wave transmission characteristics. Positioned between these two dielectric substrates 720, 790 is the ground layer 792, which may be made of copper and have a thickness of about 0.035mm. The ground layer 792 is utilized to isolate signal coupling. The first metal microstrip line 742
15 of the uppermost metallic layer 740 connects to the first metal microstrip line 762 of the second metallic layer 760 configured as a 90-degree delay network located on the back side of the dielectric substrate 790 through a metal via 770.

[00100] The second metallic layer 760 is configured as a 90-degree delay network which for example may operate at 10 GHz. Two switching elements (e.g., PIN diodes) 756, 758 are
20 installed on two bridges, respectively, and they synchronize their switching under the control of bias voltage. The two bridges are arranged to be parallel to each other such that when the two PIN diodes 756, 758 are at the conducting state, the first and second metallic layers 762, 764 form a transmission network so that the electromagnetic waves of even mode can pass through the transmission network, resulting in the 90 degrees of phase shift. For example, when
25 the two PIN diodes 756, 758 are at the open-circuit state, the two PIN diodes' connections are at the maximum voltage and the current therethrough is minimum, which is suitable for odd mode signal to pass through (voltage values at the two PIN diodes 756, 758 are opposite). On the other hand, when the two PIN diodes 756, 758 are at the short-circuit state, the two PIN diodes' connections are at the maximum current and the voltage thereat is minimum, which is
30 suitable for even mode through (voltage values at the two PIN diodes 756, 758 are the same). Therefore, by adjusting/controlling the on-off state of the two PIN diodes 756, 758, the electromagnetic waves can be subjected to either 0-degree or 90-degree of phase shift.

[00101] The signal from the second metallic layer 760 may then be coupled to a strip-shaped radiating structure 780 through a microstrip line 782 and a metal via 772, which enables the energy to radiate into the free space behind the RIS 710. The strip-shaped radiating structure 780 is separated from the 90-degree delay network (the second metallic layer 760) by a dielectric substrate 730, which for example may have a thickness h_3 of 1.5 mm for the purpose of impedance matching. Accordingly, in various example embodiments, the front and back radiating structures 740, 780 each comprises two rectangular strips of different lengths, which expands the overall response bandwidth of the RIS board 710.

[00102] In various example embodiments, each PIN diode 752, 754, 756, 758 is individually controlled by distinct control lines. These control lines feature an inductor that isolates AC radio frequency signals, preventing potential interference with the DC control circuit. In addition, each control line may include an LED for visual representation of the patch's current state. In various example embodiments, the center portion of the first metal microstrip line 762 of the second metallic layer 760 is grounded through a metal via 774, for example, such as the control voltage of the PIN diodes 756, 758 form a loop, completing the current circuit. For example, the unit cell 712 may be configured to operate at 10 GHz and is capable of four distinct states (wave propagation path states), as shown in FIG. 9. By altering the state of the respective PIN diode 752, 754, 756, 758, the phase of an incident electromagnetic wave can be modified with the constant amplitude.

[00103] FIGs. 10A and 10B show plots of amplitudes and phases full-wave simulation results of the multi-bit phase-quantified RIS 710 according to various example embodiments of the present invention. It can be seen from FIG. 10A that the amplitude attenuation can be kept stable and controlled at about 1dB when changing different phase states. Similarly, FIG. 10B shows that the difference between different phase states is around 90 degrees, which meets the requirement of 2-bit uniform phase quantization. The plots shown in FIGs. 10A and 10B intend to show the distribution of different lines, showing roughly uniform amplitude attenuation, while the phase changes of different states are uniform, close to 90 degrees. Accordingly, the RIS 710 is capable of signal transmission. For example, the energy transmission loss of the RIS 710 is less than 1 dB (e.g., other transmission RIS designs have over 2-3 dB in transmission loss). Moreover, each unit cell 712 of the RIS 710 has an independent 2-bit phase modulation capability, ensuring minimal amplitude alteration. This enhancement significantly boosts the RIS's control over spatial electromagnetic waves, providing technical support for the multifocal energy convergence in confined spaces, such as within a vehicle.

[00104] A method of controlling a RIS for multi-target spot beamforming (e.g., corresponding to the method 100 of controlling a RIS for multi-target spot beamforming as described hereinbefore according to various embodiments of the present invention) will now be described according to various example embodiments of the present invention, which may also
5 be referred to as a holograph phase compensation method. As explained hereinbefore and shown in FIGs. 3 and 6, the RIS may be configured either as a transmissive RIS (e.g., RIS 710) or a reflective RIS. In this regard, the method may be applied to control any RIS, including either transmissive RIS (e.g., RIS 710) or reflective RIS) for multi-target spot beamforming, as long as it comprises a 2D array of unit cells, each unit cell being controllable to be at any
10 selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon.

[00105] The RIS is able to flexibly steer incident and outgoing beams by changing the distribution of the reflection coefficients on the whole board. In various example embodiments, to ensure that the power of the outgoing signal is not compromised, the RIS is modeled as a
15 phase-shifting-only surface, which does not block incident waves, thereby maintaining high efficiency of the transmission signals. Various example embodiments provide a holograph phase compensation method for controlling a RIS for multi-target spot beamforming. Based on this holography approach, the compensation of the RIS may be regarded as a hologram formed at the RIS location by mutual interference between a reference wave (an OAM wave with an
20 OAM mode corresponding to the target beam focus position) generated by the multi-mode OAM signal transmitter and an object wave generated by a signal receiver located at a target beam focus position. In this regard, by irradiating the RIS with the reference wave, the corresponding object wave can be efficiently reconstructed, thus efficiently establishing a one-to-one mapping communication link from the different OAM modes to the RIS and then to the
25 multiple signal receivers located at multiple target beam focus positions, respectively.

[00106] For better understanding and illustration purpose, the method of controlling a RIS will be described with reference to components shown in the multi-target wireless multifocal communication 600 in FIG. 6 and the coordinate systems shown in FIG. 3. According to various example embodiments, the method of controlling a RIS 610 comprises: for each of the plurality
30 of target beam focus positions 630-1, 630-2, 630-3: determining, for each unit cell 612 of the plurality of the 2D array of unit cells, an interference pattern at the unit cell 612 between a reference wave from a multi-mode OAM signal transmitter 620 to the unit cell 612 and an object wave from the target beam focus position 630-1, 630-2, 630-3 to the unit cell 612. The

multi-mode OAM signal transmitter 620 is configured to generate and transmit multi-mode OAM waves to irradiate the RIS 610 at a surface thereof. The method further comprises: for each unit cell 612 of the plurality of the 2D array of unit cells: determining a holograph pattern based on the interference patterns determined at the unit cell 612 for the plurality of target beam focus positions 630-1, 630-2, 630-3; determining a degree of phase shift for the unit cell 612 to provide based on the holograph pattern determined for the unit cell 612; and controlling the unit cell 612 to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell 612 to provide.

[00107] In various example embodiments, for each of the plurality of target beam focus positions 630-1, 630-2, 630-3, the reference wave (in the above-mentioned determining, for each unit cell 612 of the plurality of the 2D array of unit cells, the interference pattern at the unit cell 612 between the reference wave and the object wave) is an OAM wave with an OAM mode corresponding to the target beam focus position. Accordingly, in various example embodiments, for each of the plurality of target beam focus positions 630-1, 630-2, 630-3, the multi-mode OAM signal transmitter 620 is configured to generate an OAM wave with a corresponding OAM mode. For example, for the three target beam focus positions 630-1, 630-2, 630-3 shown in FIG. 6, the multi-mode OAM signal transmitter is configured to generate multi-mode OAM waves with three OAM modes.

[00108] In various example embodiments, the interference pattern at the unit cell between the reference wave and the object wave is determined based on an azimuth angle $\phi_{m,n}$ of the unit cell 612 with respect to a center of the RIS 610 serving as an OAM beam reference.

[00109] In various example embodiments, the above-mentioned determining, for each unit cell 612 of the plurality of the 2D array of unit cells, the interference pattern at the unit cell 612 between the reference wave and the object wave comprises: determining a first distance $d_{o,m,n}$ between the multi-mode OAM signal transmitter 620 and the unit cell 612; determining a second distance $d_{u,m,n}$ between the target beam focus position 630-1, 630-2, 630-3 and the unit cell 612; determining the azimuth angle $\phi_{m,n}$ of the unit cell 612 with respect to the center of the RIS 610; and determining the interference pattern $T_{m,n}$ at the unit cell 612 between the reference wave and the object wave based on the first distance $d_{o,m,n}$, the second distance $d_{u,m,n}$ and the azimuth angle $\phi_{m,n}$ of the unit cell 612.

[00110] In various example embodiments, the interference pattern at the unit cell 612 between the reference wave and the object wave is determined further based on an amplitude A_l of the reference wave and an amplitude A_u of the object wave.

- [00111] In various example embodiments, the first distance $d_{o,m,n}$ is determined based on a coordinate $\vec{v}_o = [x_o, y_o, z_o]$ of the multi-mode OAM signal transmitter 620 with respect to the center of the RIS 610 and a coordinate $\vec{v}_{m,n} = [x_{m,n}, y_{m,n}, z_{m,n}]$ of the unit cell 612 with respect to the center of the RIS 610. In various example embodiments, the second distance $d_{u,m,n}$ is
- 5 determined based on a coordinate $\vec{v}_u = [x_u, y_u, z_u]$ of the target beam focus position (which may correspond to a coordinate of a user) with respect to the center of the RIS 610 and the coordinate $\vec{v}_{m,n}$ of the unit cell 612. In various example embodiments, the azimuth angle $\phi_{m,n}$ of the unit cell 612 is determined based on the coordinate $\vec{v}_{m,n}$ of the unit cell 612.
- [00112] In various example embodiments, the holograph pattern is determined based on a
- 10 summation of the interference patterns $T_{m,n}$ determined at the unit cell 612 for the plurality of target beam focus positions 630-1, 630-2, 630-3.
- [00113] As an illustrative example, an example algorithm (Algorithm I) according to the method of controlling a RIS for multi-target spot beamforming (which may be referred to as a holograph phase compensation algorithm) is provided below.

15

Algorithm I: Determining the holograph phase compensation of each unit cell 612 on the RIS 610

Input: Setup basic parameters, e.g., coordinate of the OAM generator 620 $\vec{v}_o = [x_o, y_o, z_o]$, coordinates of each RIS unit cell 612 $\vec{v}_{m,n} = [x_{m,n}, y_{m,n}, z_{m,n}]$, and coordinates of each user (corresponding to the coordinates of each target beam focus positions 630-1, 630-2, 630-3) $\vec{v}_u = [x_u, y_u, z_u]$, where $M \times N$ denotes the total number of the unit cells 612 in the RIS 610, l denotes the OAM mode (or OAM mode number), U denotes the total number of target beam focus positions 630-1, 630-2, 630-3, which equals to the number of users.

Output: the whole unit-cell phase-quantized distribution pattern on the RIS 610 can be obtained as follows:

- 1: for: $u = 1, 2, \dots, U$; (i.e., calculate for each user (which corresponds to each target beam focus position));
 - 2: for: $m = 1, 2, \dots, M$; (i.e., calculate for the unit cells 612 of each row of the RIS 610 in turn);
 - 3: for: $n = 1, 2, \dots, N$; (i.e., calculate for the unit cells 612 of each column of the RIS 610 in turn);
 - 4: Calculate the distance $d_{o,m,n}^l = |\vec{v}_o - \vec{v}_{m,n}|$, for each unit cell 612, which determines the distance between the OAM generator 620 and each unit cell 612 on the RIS 610;
 - 5: Calculate the distance $d_{u,m,n} = |\vec{v}_u - \vec{v}_{m,n}| - z_{m,n}$, for each unit cell 612, which determines the distance (transmission difference) between each target beam focus position 630-1, 630-2, 630-3 and each unit cell 612 on the RIS 610;
 - 6: Calculate $\phi_{m,n} = \arctan(y_{m,n}/x_{m,n})$, which determines the azimuth angle of the unit cell 612 with respect to a center of the RIS 610;
-

7: Calculate the interference pattern for each focus point (i.e., for each target beam focus positions 630-1, 630-2, 630-3), e.g., $T_{m,n}^{l=u} = A_l \times \exp(ikd_{o,m,n}^l + il\phi_{m,n}) \times A_u \times \exp(ikd_{u,m,n})$, which determines the interference pattern between the reference wave (the OAM wave with the OAM mode l corresponding to the target beam focus position u (i.e., for $l=u$)) generated by the OAM generator 620 and the object wave generated from each target beam focus position u (e.g., from each user u), where A_l denotes the amplitude of the reference wave with the OAM mode l , A_u denotes the amplitude of the object wave and $il\phi_{m,n}$ corresponds to the OAM phase compensation;

8: Calculate the holograph pattern on each unit cell 612 based on the interference patterns obtained in Step 7 for the plurality of target beam focus positions 630-1, 630-2, 630-3, i.e.,

$$T_{m,n} = \sum_{u=1}^U T_{m,n}^{l=u};$$

9: Calculate the phase compensation on each unit cell 612 based on the holograph pattern determined, i.e., $I_{m,n}^{\text{Phase}} = \text{angle}(T_{m,n})$;

10: end for

11: end for

12: end for

13: Make the phase quantization according to FIG. 9, and obtain the phase-quantized unit-cell pattern on the whole RIS board 610.

[00114] Accordingly, as illustrated in FIG. 6, the holograph phase compensation algorithm is able to convert multiple OAM beams with different OAM modes from the OAM generator 620 into spot beams and converge them using the RIS 610 (either a transmissive RIS or a reflective RIS) toward the target beam focus positions 630-1, 630-2, 630-3 (e.g., corresponding to receiver positions). In particular, the OAM generator 620 is employed at the transmitter end which is capable of generating multi-mode OAM beams at the same location. Applying the holograph phase compensation algorithm to control the RIS 610, these multi-mode OAM beams can advantageously be focused on different receiving locations. Unlike traditional methods or algorithms that rely on signal separation through different spatial positions at the transmitter end and do not exploit the unique properties of multi-mode OAM beams, the holograph phase compensation method according to various example embodiments overcomes such deficiencies associated with traditional methods. In particular, the holograph phase compensation method achieves multi-mode transmission from a signal point, enabling multi-focal, low-interference reception.

[00115] FIG. 11 shows beamforming simulation results for three different configurations of target beam focus positions using the transmissive RIS 710 according to various example embodiments of the present invention. Through full-wave simulation, when two different modes of OAM beams traverse the RIS 710, the holograph phase compensation algorithm adjusts the distribution of the entire RIS array to convert the OAM mode beams with different

OAM modes received on one side of the RIS 710 into spot beams and converge them to different spatial positions on the opposite side of the RIS 710. As illustrative examples, the convergence or focus points (or regions) can be arranged along the normal direction of the RIS (see top image of FIG. 11), symmetrically positioned on either side of the normal (see middle image of FIG. 11), or at any two distinct spatial locations (see bottom image of FIG. 11). As an example illustration, FIG. 12 shows a schematic drawing of a multi-target spot-beamforming system (or a multi-target wireless multifocal communication system) comprising the above-mentioned RIS 610; the above-mentioned multi-mode OAM signal transmitter 620 configured to generate and transmit multi-mode OAM waves to irradiate the RIS 610 at a surface thereof; and the above-mentioned RIS controller 602 (not shown in FIG. 12) configured for controlling the RIS 610 for multi-target spot beamforming at three target beam focus positions (or focus points) 1130-1, 1130-2, 1130-3 along the normal direction of the RIS 610.

[00116] While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method of controlling a reconfigurable intelligent surface (RIS) for multi-target spot beamforming at a plurality of target beam focus positions, the RIS comprising a two-dimensional (2D) array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon, the method comprising:
 - for each of the plurality of target beam focus positions:
 - determining, for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode orbital angular momentum (OAM) signal transmitter to the unit cell and an object wave from the target beam focus position to the unit cell, the multi-mode OAM signal transmitter being configured to generate and transmit multi-mode OAM waves to irradiate the RIS at a surface thereof; and
 - for each unit cell of the plurality of the 2D array of unit cells:
 - determining a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions;
 - determining a degree of phase shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and
 - controlling the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.
2. The method according to claim 1, wherein for each of the plurality of target beam focus positions, the reference wave is an OAM wave with an OAM mode corresponding to the target beam focus position.
3. The method according to claim 1 or 2, wherein the interference pattern at the unit cell between the reference wave and the object wave is determined based on an azimuth angle of the unit cell with respect to a center of the RIS serving as an OAM beam reference.
4. The method according to claim 3, wherein said determining, for each unit cell of the plurality of the 2D array of unit cells, the interference pattern at the unit cell between the reference wave and the object wave comprises:

determining a first distance between the multi-mode OAM signal transmitter and the unit cell;

determining a second distance between the target beam focus position and the unit cell;

determining the azimuth angle of the unit cell with respect to the center of the RIS; and

5 determining the interference pattern at the unit cell between the reference wave and the object wave based on the first distance, the second distance and the azimuth angle of the unit cell.

5. The method according to claim 4, wherein the interference pattern at the unit cell
10 between the reference wave and the object wave is determined further based on an amplitude of the reference wave and an amplitude of the object wave.

6. The method according to claim 4 or 5, wherein
the first distance is determined based on a coordinate of the multi-mode OAM signal
15 transmitter with respect to the center of the RIS and a coordinate of the unit cell with respect to the center of the RIS,

the second distance is determined based on a coordinate of the target beam focus position with respect to the center of the RIS and the coordinate of the unit cell, and

the azimuth angle of the unit cell is determined based on the coordinate of the unit cell.
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7. The method according to any one of claims 1 to 6, wherein the holograph pattern is determined based on a summation of the interference patterns determined at the unit cell for the plurality of target beam focus positions.

25 8. The method according to any one of claims 1 to 7, wherein the plurality of target beam focus positions is located at a same side of the RIS as the OAM signal transmitter, or the plurality of target beam focus positions is located at an opposite side of the RIS with respect to the OAM signal transmitter.

30 9. The method according to any one of claims 1 to 8, wherein each unit cell is a 2-bit unit cell controllable to be at any selected one of four wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated thereon.

10. The method according to claim 9, wherein the four wave propagation path states are configured to provide four corresponding degree of phase shifts of about 0 degrees, about 90 degrees, about 180 degrees and about 270 degrees, respectively, for the incident electromagnetic waves irradiated thereon.

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11. The method according to any one of claims 1 to 10, wherein each unit cell is controllable to be at any selected one of the plurality of wave propagation path states based on controlling a state of a plurality of switching elements of the unit cell for configuring the unit cell to be at any selected one of the plurality of wave propagation path states for providing a corresponding

10 degree of phase shift for the incident electromagnetic waves irradiated thereon.

12. The method according to claim 11, wherein said controlling the plurality of switching elements of the unit cell for configuring the unit cell to be at any selected one of the plurality of wave propagation path states configures one or more metal microstrip lines of the unit cell

15 to provide a corresponding propagation path for the incident electromagnetic waves irradiated on the unit cell for providing the corresponding degree of phase shift for the incident electromagnetic waves.

13. A reconfigurable intelligent surface (RIS) controller for controlling a RIS for multi-target spot beamforming at a plurality of target beam focus positions, the RIS comprising a two-dimensional (2D) array of unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon, the RIS controller comprising:

at least one memory; and

25 at least one processor communicatively coupled to the at least one memory and configured to:

for each of the plurality of target beam focus positions:

determine, for each unit cell of the plurality of the 2D array of unit cells, an interference pattern at the unit cell between a reference wave from a multi-mode orbital angular momentum (OAM) signal transmitter to the unit cell and an object wave from the target beam

30 focus position to the unit cell, the multi-mode OAM signal transmitter being configured to generate and transmit multi-mode OAM waves to irradiate the RIS at a surface thereof; and

for each unit cell of the plurality of the 2D array of unit cells:

determine a holograph pattern based on the interference patterns determined at the unit cell for the plurality of target beam focus positions;

determine a degree of phase shift for the unit cell to provide based on the holograph pattern determined for the unit cell; and

5 control the unit cell to be at a selected one of the plurality of wave propagation path states corresponding to the degree of phase shift determined for the unit cell to provide.

14. The RIS according to claim 13, wherein for each of the plurality of target beam focus positions, the reference wave is an OAM wave with an OAM mode corresponding to the target
10 beam focus position.

15. The RIS controller according to claim 13 or 14, wherein the interference pattern at the unit cell between the reference wave and the object wave is determined based on an azimuth angle of the unit cell with respect to a center of the RIS serving as an OAM beam reference.
15

16. The RIS controller according to claim 15, wherein said determine, for each unit cell of the plurality of the 2D array of unit cells, the interference pattern at the unit cell between the reference wave and the object wave comprises:

determining a first distance between the multi-mode OAM signal transmitter and the
20 unit cell;

determining a second distance between the target beam focus position and the unit cell;

determining the azimuth angle of the unit cell with respect to the center of the RIS; and

determining the interference pattern at the unit cell between the reference wave and the object wave based on the first distance, the second distance and the azimuth angle of the unit
25 cell.

17. The RIS controller according to claim 16, wherein the interference pattern at the unit cell between the reference wave and the object wave is determined further based on an amplitude of the reference wave and an amplitude of the object wave.
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18. The RIS controller according to claim 16 or 17, wherein

the first distance is determined based on a coordinate of the multi-mode OAM signal transmitter with respect to the center of the RIS and a coordinate of the unit cell with respect to the center of the RIS,

- 5 the second distance is determined based on a coordinate of the target beam focus position with respect to the center of the RIS and the coordinate of the unit cell, and
the azimuth angle of the unit cell is determined based on the coordinate of the unit cell.

19. The RIS controller according to any one of claims 13 to 18, wherein the holograph
10 pattern is determined based on a summation of the interference patterns determined at the unit cell for the plurality of target beam focus positions.

20. The RIS controller according to any one of claims 13 to 19, wherein the plurality of
target beam focus positions is located at a same side of the RIS as the OAM signal transmitter,
or the plurality of target beam focus positions is located at an opposite side of the RIS with
15 respect to the OAM signal transmitter.

21. The RIS controller according to any one of claims 13 to 20, wherein each unit cell is a
2-bit unit cell controllable to be at any selected one of four wave propagation path states for
providing a corresponding degree of phase shift for the incident electromagnetic waves
20 irradiated thereon.

22. The RIS controller according to claim 21, wherein the four wave propagation path states
are configured to provide four corresponding degree of phase shifts of about 0 degrees, about
90 degrees, about 180 degrees and about 270 degrees, respectively, for the incident
25 electromagnetic waves irradiated thereon.

23. The RIS controller according to any one of claims 13 to 22, wherein each unit cell is
controllable to be at any selected one of the plurality of wave propagation path states based on
controlling a state of a plurality of switching elements of the unit cell for configuring the unit
30 cell to be at any selected one of the plurality of wave propagation path states for providing a
corresponding degree of phase shift for the incident electromagnetic waves irradiated thereon.

24. The RIS controller according to claim 23, wherein said controlling the plurality of switching elements of the unit cell for configuring the unit cell to be at any selected one of the plurality of wave propagation path states configures one or more metal microstrip lines of the unit cell to provide a corresponding propagation path for the incident electromagnetic waves
5 irradiated on the unit cell for providing the corresponding degree of phase shift for the incident electromagnetic waves.

25. A multi-target spot beamforming system comprising:
a reconfigurable intelligent surface (RIS) comprising a two-dimensional (2D) array of
10 unit cells, each unit cell being controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for incident electromagnetic waves irradiated thereon;
a multi-mode orbital angular momentum (OAM) signal transmitter configured to generate and transmit a multi-mode OAM signal to irradiate the RIS at a surface thereof; and
15 a RIS controller according to any one of claims 13 to 24 communicatively coupled to the RIS for controlling the RIS for multi-target spot beamforming at a plurality of target beam focus positions.

26. A reconfigurable intelligent surface (RIS) for controlling a propagation of incident
20 electromagnetic waves irradiated thereon, the RIS comprising:
a two-dimensional (2D) array of unit cells, each unit cell comprising:
a first dielectric substrate having a first side and a second side opposite to the first side;
a second dielectric substrate having a first side and a second side opposite to the
25 first side;
a first metallic layer disposed on the first side of the first dielectric substrate, the first metallic layer comprising a first metal microstrip line controllable to be at any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves irradiated on the first metal microstrip line to
30 produce intermediate electromagnetic waves;
a second metallic layer disposed between the first and second dielectric substrates, the second metallic layer comprising a first metal microstrip line connected to the first metal microstrip line of the first metallic layer through a first metal via and is controllable

to be any selected one of a plurality of wave propagation path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves received from the first metal microstrip line of the first metallic layer through the first metal via to produce output electromagnetic waves; and

- 5 a third metallic layer disposed on the second side of the second dielectric substrate, the third metallic layer comprising a first metal microstrip line connected to the first metal microstrip line of the second metallic layer through a second metal via and configured to radiate the output electromagnetic waves received from the first metal microstrip line of the second metallic layer through the second metal via.

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27. The RIS according to claim 26, wherein

- the first metal microstrip line of the first metallic layer is connected to one or more switching elements at the first metallic layer, the first metal microstrip line being controllable to be at any selected one of the plurality of wave propagation path states based on controlling a state of the one or more switching elements connected thereto for configuring the first metal microstrip line to be at any selected one of the plurality of wave propagating path states for providing a corresponding degree of phase shift for the incident electromagnetic waves to produce the intermediate electromagnetic waves, and

- the first metal microstrip line of the second metallic layer is connected to one or more switching elements at the second metallic layer, the first metal microstrip line being controllable to be at any selected one of the plurality of wave propagation path states based on controlling a state of the one or more switching elements connected thereto for configuring the first metal microstrip line to be at any selected one of the plurality of wave propagating path states for providing a corresponding degree of phase shift for the intermediate electromagnetic waves to produce the output electromagnetic waves.

28. The RIS according to claim 27, wherein

- the one or more switching elements at the first metallic layer comprises a first switching element and a second switching element, and the first metal microstrip line of the first metallic layer is controllable to be at a first or second wave propagation path state based on controlling a state of the first and second switching elements connected thereto for configuring the first metal microstrip line to be at the first or second wave propagating path state for providing a

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first degree or second degree of phase shift, respectively, for the incident electromagnetic waves to produce the intermediate electromagnetic waves, and

the one or more switching elements at the second metallic layer comprises a third switching element and a fourth switching element, and the first metal microstrip line of the second metallic layer is controllable to be at a first or second wave propagation path state based on controlling a state of the third and fourth switching elements connected thereto for configuring the first metal microstrip line to be at the first or second wave propagating path state for providing a first degree or second degree of phase shift, respectively, for the intermediate electromagnetic waves to produce the output electromagnetic waves.

10

29. The RIS according to claim 28, wherein

the first degree and second degree of phase shifts provided by the first metal microstrip line of the first metallic layer are about 0 degrees and about 180 degrees of phase shifts, respectively, and

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the first degree and second degree of phase shifts provided by the first metal microstrip line of the second metallic layer are about 0 degrees and about 90 degrees of phase shifts, respectively.

30. The RIS according to claim 28 or 29, wherein

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the first metal microstrip line of the first metallic layer comprises a first portion, a second portion and a third portion, the first and second portions being spaced apart by a first gap therebetween and the second and third portions being spaced apart by a second gap therebetween,

the first switching element is arranged at the first gap between the first and second portions for providing a switchable connection between the first and second portions, the first switching element being controllable to be at one of a conducting state and a non-conducting state, and

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the second switching element is arranged at the second gap between the second and third portions for providing a switchable connection between the second and third portions, the second switching element being controllable to be at one of a conducting state and a non-conducting state.

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31. The RIS according to claim 30, wherein

the first metal microstrip line of the first metallic layer is configured to provide about 0 degrees of phase shift of the incident electromagnetic waves irradiated thereon based on the state of the first and second switching elements being at the conducting state and the non-conducting state, respectively, and

5 the first metal microstrip line of the first metallic layer is configured to provide about 180 degrees of phase shift of the incident electromagnetic waves irradiated thereon based on the state of the first and second switching elements being at the non-conducting state and the conducting state, respectively.

10 32. The RIS according to claim 30 or 31, wherein the first and second switching elements are each a PIN diode and are arranged at the first and second gaps to have opposite polarity.

33. The RIS according to any one of claims 30 to 32, wherein
the first metal via is connected to the first metal microstrip line of the first metallic layer
15 at the second portion thereof, and
the first metal via is connected to the first metal microstrip line of the second metallic layer at a first end portion thereof.

34. The RIS according to claim 33, wherein
20 the second metal via is connected to the first metal microstrip line of the second metallic layer at a second end portion thereof, the first and second end portions being at opposite ends of the first metal microstrip line of the second metallic layer.

35. The RIS according to any one of claims 28 to 34, wherein
25 the second metallic layer further comprises a second metal microstrip line arranged to be spaced apart from the first metal microstrip line of the second metallic layer by a gap therebetween, and

the third and fourth switching elements are arranged at the gap between the first and second metal microstrip lines of the second metallic layer for providing a switchable connection
30 therebetween, the third and fourth switching elements each being controllable to be at one of a conducting state and a non-conducting state.

36. The RIS according to claim 35, wherein

the first metal microstrip line of the second metallic layer is configured to provide about 0 degrees of phase shift of the intermediate electromagnetic waves received based on the state of the third and fourth switching elements both being at the non-conducting state, and

5 the first metal microstrip line, together with the second metal microstrip line, of the second metallic layer is configured to provide about 90 degrees of phase shift of the intermediate electromagnetic waves received based on the state of the third and fourth switching elements both being at the conducting state.

37. The RIS according to claim 35 or 36, wherein the third and fourth switching elements
10 are each a PIN diode and are arranged at the gap in parallel and to have the same polarity.

38. The RIS according to any one of claims 26 to 37, wherein
the first metallic layer further comprises a second metal microstrip line arranged to be parallel to and spaced apart from the first metal microstrip line of the first metallic layer, the
15 first and second metal microstrip lines of the first metallic layer being configured to have different lengths for enhancing a response bandwidth of the first metallic layer, and

the third metallic layer further comprises a second metal microstrip line arranged to be parallel to and spaced apart from the first metal microstrip line of the third metallic layer, the first and second metal microstrip lines of the third metallic layer being configured to have
20 different lengths for enhancing a response bandwidth of the third metallic layer.

39. The RIS according to any one of claims 26 to 38, further comprising:
a third dielectric substrate having a first side and a second side opposite to the first side, the third dielectric substrate being disposed between the first and second dielectric substrates;
25 and
a fourth metallic layer disposed between the first and third dielectric substrates, the fourth metallic layer being configured as a ground layer.

40. The RIS according to claim 39, wherein
30 the second metallic layer is disposed between the second and third dielectric substrates, and
the first metal microstrip line of the second metallic layer comprises a center portion connected to the fourth metallic layer through a third metal via for grounding the center portion.

41. The RIS according to any one of claims 26 to 40, wherein each unit cell is a 2-bit phase-shifting unit cell controllable to be at any selected one of four wave propagation path states for providing a corresponding degree of phase shift for the incident electromagnetic waves
5 irradiated thereon.

42. The RIS according to claim 41, wherein the four wave propagation path states are configured to provide four corresponding degree of phase shifts of about 0 degrees, about 90 degrees, about 180 degrees and about 270 degrees, respectively, for the incident
10 electromagnetic waves irradiated thereon.

43. The RIS according to any one of claims 26 to 42, wherein the incident electromagnetic waves are multi-mode OAM waves.

15 44. The RIS according to any one of claims 26 to 43, wherein the RIS is configured as a transmissive RIS.

45. The method according to any one of claims 1 to 12 for controlling the RIS according to any one of claims 26 to 44 for multi-target spot beamforming at the plurality of target beam
20 focus positions.

46. The RIS controller according to any one of claims 13 to 24 for controlling the RIS according to any one of claims 26 to 44 for multi-target spot beamforming at the plurality of target beam focus positions.
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47. The multi-target spot beamforming system according to claim 25, wherein the RIS is the RIS according to any one of claims 26 to 44.
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