A PHASED ARRAY ANTENNA, A MODULAR PHASED ARRAY ANTENNA SYSTEM, AND A METHOD OF MAKING A PHASED ARRAY ANTENNA

TECHNICAL FIELD

The present disclosure relates broadly to a phased array antenna, a modular phased array antenna system, and a method of making a phased array antenna.

BACKGROUND

Satellite Communication (SATCOM) on the move (SOTM) has widespread applications in the land, maritime, and aeronautical environments to provide broadband satellite communication service at any time and place. Compared with lower frequency bands, K/Ka band mobile satellite communication is preferred and has undergone rapid development due to its higher channel capacities for many end users, higher data rate links, and smaller user terminals. In order to maintain established SATCOM links while moving, mobile satellite terminals need to be capable of tracking satellites. Thus, light weight and low profile electronically steerable planar phased array antenna are of major importance for SATCOM on the move applications.

K/Ka band SATCOM on the move services and transponders are based on bi-directional satellite communication links at two different frequency bands: Transmitting (Tx) uplink at Ka-band of 30 GHz (27.5-31.0 GHz) and Receiving (Rx) downlink at K-band of 20 GHz (17.7-21.2 GHz). The antenna requirements for K/Ka-band SOTM user terminal are very challenging. Besides lightweight and low profile for easily mounting on vehicles or airplanes, the phased array antenna needs to operate in dual bands (covering both Tx and Rx) and provide electronically beam scanning over very wide angles. The antenna also needs to be circularly polarized (CP) with high polarization purity to facilitate efficient transmission between transmitter and receiver. Further, it is desirable to have a scalable antenna array architecture to ease its extension to systems of larger dimensions.

Thus, there is a need for a phased array antenna, a modular phased array antenna system, and a method of making a phased array antenna that seeks to address or at least alleviate one of the above problems.

SUMMARY

In accordance with a first aspect of the present disclosure, there is provided a phased array antenna comprising, an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range; wherein the Rx antenna array and Tx antenna array are disposed on a same aperture; wherein the Rx antenna element is separate from the Tx antenna element; and wherein any two immediately adjacent Rx antenna elements and any two immediately adjacent Tx antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction.

The phased array antenna may further comprise one or more Rx core chips, each Rx core chip associated with an Rx subarray of Rx antenna elements; and one or more Rx feeding networks, each Rx feeding network comprising a plurality of Rx feed lines for communicatively coupling the Rx core chip to the Rx antenna elements of the associated Rx subarray; wherein each Rx core chip is positioned substantially at the center of the Rx antenna elements of the associated Rx subarray such that the plurality of Rx feed lines have substantially equal length.

The phased array antenna may further comprise one or more Tx core chips, each Tx core chip associated with a Tx subarray of Tx antenna elements; and one or more Tx feeding networks, each Tx feeding network comprising a plurality of Tx feed lines for communicatively coupling the Tx core chip to the Tx antenna elements of the associated Tx subarray; wherein each Tx core chip is positioned substantially at the center of the Tx antenna elements of the associated Tx subarray such that the plurality of Tx feed lines have substantially equal length.

In the phased array antenna as disclosed herein, the Rx antenna array may comprise an Rx subarray of four Rx antenna elements arranged in a 2 x 2 lattice; the Tx antenna array may comprise a first Tx subarray and a second Tx subarray, each Tx subarray comprising

four Tx antenna elements arranged in a 2 x 2 lattice; and the Rx antenna elements and Tx antenna elements may be arranged in a 4 x 4 lattice.

In the phased array antenna as disclosed herein, the Rx antenna elements of the Rx subarray may be positioned at intersections of the second and fourth rows with the second and fourth columns of the 4 x 4 lattice; the Tx antenna elements of the first Tx subarray may be positioned at intersections of the second and fourth rows with the first and third columns of the 4 x 4 lattice; and the Tx antenna elements of the second Tx subarray may be positioned at intersections of the first and third rows with the second and fourth columns of the 4 x 4 lattice.

In the phased array antenna as disclosed herein, each of the Rx antenna elements and Tx antenna elements may comprise two orthogonal feeding ports.

In the phased array antenna as disclosed herein, the Rx antenna elements of the Rx subarrays may be configured to be excited with identical amplitude and 90° phase difference.

In the phased array antenna as disclosed herein, the Tx antenna elements of the Tx subarrays may be configured to be excited with identical amplitude and 90° phase difference.

In the phased array antenna as disclosed herein, any three neighboring Tx antenna elements of the Tx subarrays may be configured to be excited with identical amplitude and 120° phase difference.

In the phased array antenna as disclosed herein, D may be $0.5\lambda_F$, where λ_F is the wavelength of an electromagnetic wave at the center frequency of the lower of the first and second frequency ranges.

In accordance with a second aspect of the present disclosure, there is provided a phased array antenna comprising, a first antenna array comprising one or more first subarrays of first antenna elements configured to operate via a first frequency range; and a second antenna array comprising one or more second subarrays of second antenna elements configured to operate via a second frequency range different from the first frequency range; wherein the first antenna array and second antenna array are disposed on a same aperture; wherein the first antenna element is separate from the second antenna element; wherein any

two immediately adjacent first antenna elements and any two immediately adjacent second antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction; and wherein the first and second antenna arrays are both Rx or both Tx antenna arrays.

In accordance with a third aspect of the present disclosure, there is provided a modular phased array antenna system comprising a plurality of unit modules, each unit module comprising a phased array antenna as disclosed herein.

The modular phased array antenna system may comprise N by N unit modules arranged in a square lattice configuration, wherein N is an integer of at least 2.

In the modular phased array antenna system as disclosed herein, when N is 2, the unit modules may be configured to be sequentially excited with a 90° phase difference.

The modular phased array antenna system may comprise four groups of unit modules, each group having a plurality of unit modules arranged in a square lattice configuration; wherein each group of unit modules is configured to share a same phase of excitation; and wherein the four groups of unit modules are configured to be sequentially excited with a 90° phase difference.

In accordance with a fourth aspect of the present disclosure, there is provided a method of making a phased array antenna, the method comprising, forming an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and forming a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range; wherein the Rx antenna array and Tx antenna array are disposed on a same aperture; wherein the Rx antenna element is separated from the Tx antenna element; and wherein any two adjacent Rx antenna elements and any two adjacent Tx antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction.

The method may further comprise providing one or more Rx core chips, each Rx core chip associated with an Rx subarray of Rx antenna elements; and forming one or more Rx feeding networks, each Rx feeding network comprising a plurality of Rx feed lines for communicatively coupling the Rx core chip to the Rx antenna elements of the associated Rx

subarray; wherein each Rx core chip is positioned substantially at the center of the Rx antenna elements of the associated Rx subarray such that the plurality of Rx feed lines have substantially equal length.

The method may further comprise providing one or more Tx core chips, each Tx core chip associated with a Tx subarray of Tx antenna elements; and forming one or more Tx feeding networks, each Tx feeding network comprising a plurality of Tx feed lines for communicatively coupling the Tx core chip to the Tx antenna elements of the associated Tx subarray; wherein each Tx core chip is positioned substantially at the center of the Tx antenna elements of the associated Tx subarray such that the plurality of Tx feed lines have substantially equal length.

The method may comprise forming an Rx subarray of four Rx antenna elements arranged in a 2 x 2 lattice; and forming a first Tx subarray and a second Tx subarray, each Tx subarray comprising four Tx antenna elements arranged in a 2 x 2 lattice; wherein the Rx antenna elements and Tx antenna elements may be arranged in a 4 x 4 lattice.

The method may further comprise positioning the Rx antenna elements of the Rx subarray at intersections of the second and fourth rows with the second and fourth columns of the 4 x 4 lattice; positioning the Tx antenna elements of the first Tx subarray at intersections of the second and fourth rows with the first and third columns of the 4 x 4 lattice; and positioning the Tx antenna elements of the second Tx subarray at intersections of the first and third rows with the second and fourth columns of the 4 x 4 lattice.

The method may further comprise providing two orthogonal feeding ports for each of the Rx antenna elements and Tx antenna elements.

In accordance with a fifth aspect of the present disclosure, there is provided a method of making a phased array antenna, the method comprising, forming a first antenna array comprising one or more first subarrays of first antenna elements configured to operate via a first frequency range; and forming a second antenna array comprising one or more second subarrays of second antenna elements configured to operate via a second frequency range different from the first frequency range; wherein the first antenna array and second antenna array are disposed on a same aperture; wherein the first antenna element is separate from the second antenna element; wherein any two immediately adjacent first antenna elements

and any two immediately adjacent second antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction; and wherein the first and second antenna arrays are both Rx or both Tx antenna arrays.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the 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:

FIG. 1 is a schematic block diagram of a phased array antenna in an example embodiment.

FIG. 2A is a schematic diagram of a phased array antenna in an example embodiment.

FIG. 2B is another schematic diagram of the phased array antenna in the example embodiment.

FIG. 3A is a schematic diagram showing a first possible array lattice for a Tx array of a first phased array antenna in an example embodiment.

FIG. 3B is a schematic diagram showing a second possible array lattice for an Rx array of the first phased array antenna in the example embodiment.

FIG. 4A is a schematic diagram showing a first possible array lattice for a Tx array of a second phased array antenna in an example embodiment.

FIG. 4B is a schematic diagram showing a second possible array lattice for an Rx array of the second phased array antenna in the example embodiment.

FIG. 5A is a schematic diagram illustrating different modular array antenna configurations in an example embodiment.

FIG. 5B is a schematic diagram of the different modular array antenna configurations demonstrating multi-level sequentially rotated excitation for enhancing circular polarization (CP) performance in the example embodiment.

FIG. 6 is a schematic flowchart for illustrating a method of making a phased array antenna in an example embodiment.

FIG. 7 is a schematic diagram showing simulation set-ups of an array antenna in an example embodiment.

FIG. 8A to FIG. 8I are plots of simulated patterns of the Tx array at 30 GHz with beam scanning along x-axis (ϕ=0°) in the example embodiment.

FIG. 9A to FIG. 9I are plots of simulated patterns of the Tx array at 30 GHz with beam scanning along diagonal line (ϕ=45°) in the example embodiment.

FIG. 10A to FIG. 10I are plots of simulated patterns of the Tx array at 30 GHz with beam scanning along y-axis (ϕ=90°) in the example embodiment.

FIG. 11A to FIG. 11I are plots of simulated patterns of the Rx array at 20 GHz with beam scanning along x-axis (ϕ=0°) in the example embodiment.

FIG. 12A to FIG. 12I are plots of simulated patterns of the Rx array at 20 GHz with beam scanning along diagonal line (ϕ=45°) in the example embodiment.

FIG. 13A to FIG. 13I are plots of simulated patterns of the Rx array at 20 GHz with beam scanning along y-axis (ϕ=90°) in the example embodiment.

FIG. 14 is a schematic drawing of a computer system suitable for implementing an example embodiment.

DETAILED DESCRIPTION

Example, non-limiting embodiments may provide a phased array antenna, a modular phased array antenna system, and a method of making a phased array antenna. In various embodiments, the abbreviation "Rx" may denote the terms "receiver" or "receiving", and the abbreviation "Tx" may denote the terms "transmitter" or "transmitting".

FIG. 1 is a schematic block diagram of a phased array antenna 100 in an example embodiment. The phased array antenna 100 comprises an Rx antenna array 102 comprising one or more Rx subarrays, e.g., 104A, 104B of Rx antenna elements, e.g., 106A – 106H, configured to operate / receive via a first frequency range / band. The phased array antenna 100 further comprises a Tx antenna array 108 comprising one or more Tx subarrays, e.g., 110A 110B, of Tx antenna elements, e.g., 112A – 112H, configured to operate / transmit via a second frequency range / band. The Rx antenna array 102 and Tx antenna array 108 are disposed on a same aperture 114. The Rx antenna elements 106A – 106H are separated from the Tx antenna elements 112A – 112H. Any two immediately adjacent Rx antenna elements, e.g., 106A–106H, and any two immediately adjacent Tx antenna elements, e.g., 112A-112H, are separated by a distance D along a first direction and a second direction perpendicular to the first direction. The distance D is determined by the resonant frequency of the antenna element at the lower of the first and second frequency bands, e.g. the Rx antenna element 106A.

In the example embodiment, each Rx subarray, e.g., 104A, comprises a plurality of Rx antenna elements, e.g., 106A – 106D. For example, the Rx subarray 104A comprises four Rx antenna elements 106A, 106B, 106C, and 106D. The Rx subarray 104B comprises four Rx antenna elements 106E, 106F, 106G, and 106H. In the example embodiment, each Tx subarray, e.g., 110A, comprises a plurality of Tx antenna elements, e.g., 112A – 112D. For example, the Tx subarray 110A comprises four Tx antenna elements 112A, 112B, 112C, and 112D. The Tx subarray 110B comprises four Tx antenna elements 112E, 112F, 112G, and 112H.

In the example embodiment, the term "separate" as used herein means that the Rx antenna element and the Tx antenna element are not integrated with each other. The term "separate" as used herein also means that the Rx antenna element and the Tx antenna element do not occupy the same position on a lattice or substantially overlap each other when

disposed on the same aperture. For example, the Rx antenna element and the Tx antenna element may not occupy the same position on a common / same lattice.

In the example embodiment, any two immediately adjacent Rx antenna elements, e.g., 106A-106H, and any two immediately adjacent Tx antenna elements, e.g., 112A-112H, are separated by a distance D along a first direction and a second direction perpendicular to the first direction, along a plane / surface of the aperture 114. The first direction is substantially parallel to the X-axis or horizontal axis. The second direction is substantially parallel to the Y-axis or vertical axis. The Rx antenna elements, e.g., 106A-106H, and Tx antenna elements, e.g., 112A-112H, may be arranged in a lattice configuration. Two immediately adjacent Rx antenna elements along the same row, e.g., 106A and 106B, or along the same column, e.g., 106A and 106C, of the lattice may be separated by the distance D. Two immediately adjacent Tx antenna elements along the same row, e.g., 112A and 112B, or along the same column, e.g., 112A and 112C, of the lattice may be separated by the distance D.

In the example embodiment, the phased array antenna 100 may comprise one or more Rx core chips. Each Rx core chip may be associated with an Rx subarray of Rx antenna elements. The phased array antenna 100 may further comprise one or more Rx feeding networks. Each Rx feeding network may comprise a plurality of Rx feed lines for communicatively coupling the Rx core chip to the Rx antenna elements of the associated Rx subarray. Each Rx core chip may be positioned substantially at the center of the Rx antenna elements of the associated Rx subarray such that the plurality of Rx feed lines have substantially equal length. The substantially equal length of the plurality of Rx feed lines may allow the Rx antenna elements to be excited with substantially identical feeding paths. For example, an Rx core chip may be associated with the Rx subarray 104A with Rx antenna elements 106A, 106B, 106C, and 106D. Another Rx feeding network comprising a plurality of Rx feed lines may be provided for communicatively coupling the Rx core chip to the Rx antenna elements 106E, 106F, 106G, and 106H. For example, if the Rx antenna elements 106A, 106B, 106C, and 106D are arranged in a 2 x 2 lattice, the Rx core chip may be positioned substantially at the center of the 2 x 2 lattice.

In the example embodiment, the phased array antenna 100 may comprise one or more Tx core chips. Each Tx core chip may be associated with a Tx subarray of Tx antenna elements. The phased array antenna 100 may further comprise one or more Tx feeding networks. Each Tx feeding network may comprise a plurality of Tx feed lines for

communicatively coupling the Tx core chip to the Tx antenna elements of the associated Tx subarray. Each Tx core chip may be positioned substantially at the center of the Tx antenna elements of the associated Tx subarray such that the plurality of Tx feed lines have substantially equal length. The substantially equal length of the plurality of Tx feed lines may allow the Tx antenna elements to be excited with substantially identical feeding paths. For example, a Tx core chip may be associated with the Tx subarray 110A with Tx antenna elements 112A, 112B, 112C, and 112D. Another Tx feeding network comprising a plurality of Tx feed lines may be provided for communicatively coupling the Tx core chip to the Tx antenna elements 112E, 112F, 112G, and 112H. For example, if the Tx antenna elements 112A, 112B, 112C, and 112D are arranged in a 2 x 2 lattice, the Tx core chip may be positioned substantially at the center of the 2 x 2 lattice.

In the example embodiment, the phased array antenna 100 is a dual band phased array antenna. The Rx antenna elements, e.g., 106, may be configured to operate in the first frequency band. The Tx antenna elements, e.g., 112, may be configured to operate in the second frequency band. The second frequency band may be the same as, or different from, the first frequency band. The second frequency band may be higher or lower than the first frequency band. The frequency bands include but not limited to S-band (Tx: 2.5-2.7 GHz, Rx: 2.1-2.3 GHz), C-band (Tx: 5.9-6.4 GHz, Rx:3.7-4.2 GHz), X-band (Tx: 7.9-8.4 GHz, Rx: 7.28-7.75), Ku-band (Tx: 14.0-14.5 GHz, Rx: 11.7-12.2 GHz), Ka-band (Tx: 27.5-31.0 GHz, Rx: 17.7-21.2 GHz), and Q-band (Tx: 33.0-36.0 GHz, Rx: 36.0-42.0 GHz). For example, the first frequency band may be the K-band of 20 GHz and the second frequency band may be the Ka-band of 30 GHz. The K-band frequency range is typically defined within the microwave spectrum and may range from 18 GHz to 26.5 GHz. The Ka-band frequency range spans from 26.5 GHz to 40 GHz.

In the example embodiment, the phased array antenna 100 is a shared aperture phased array antenna, as the Rx antenna array 102 and Tx antenna array 108 share the same aperture. Advantageously, the architecture of combining the Tx and Rx antenna elements into a single antenna panel may result in a compact low-profile system. In practice, the Tx and Rx antenna elements, together with a feeding network, and beam forming Tx and Rx core chips may be integrated into a modular antenna panel with a multilayer substrate.

In the example embodiment, the phased array antenna 100 is an interleaved phased array antenna. An interleaved configuration in a phased array antenna means that multiple

antenna subarrays, designed for different frequencies, polarizations, or functions, are interwoven within the same physical aperture. Advantageously, this arrangement allows the phased array antenna to efficiently operate over multiple frequency bands without significantly increasing the overall size of the antenna.

In the example embodiment, the phased array antenna 100 is a modular phased array antenna, wherein the phased array antenna 100 may be treated as a unit module. Advantageously, multiple unit modules of the phased array antenna 100 may be combined/assembled to form a larger antenna system.

While FIG. 1 illustrates two Rx subarrays 104A and 104B and two Tx subarrays 110A and 110B, it will be appreciated that the phased array antenna is not limited as such and may comprise other numbers of Rx subarrays and Tx subarrays. The number of Rx subarrays and the number of Tx subarrays may be the same or different. While FIG. 1 illustrates four Rx antenna elements, e.g., 106A – 106D, for each Rx subarray, e.g., 104A, and four Tx antenna elements, e.g., 112A – 112D, for each Tx subarray, e.g., 110A, it will be appreciated that the phased array antenna is not limited as such and may comprise other numbers of Rx antenna elements phased array and Tx antenna elements. For example, the number of Tx antenna elements may be twice the number of Rx antenna elements in the phased array antenna. For example, in an antenna comprising M Rx antenna elements and 2M Tx antenna elements, there may be M/4 Rx subarray(s) and M/2 Tx subarrays, where M is a multiple of 4.

FIG. 2A is a schematic diagram of a phased array antenna 200 in an example embodiment. The phased array antenna 200 comprises an Rx antenna array, said Rx antenna array comprising an Rx subarray of four Rx antenna elements R1, R2, R3 and R4 arranged in a 2 x 2 lattice. The phased array antenna 200 further comprises a Tx antenna array, said Tx antenna array comprising a first Tx subarray of four Tx antenna elements T1, T2, T5, and T6 arranged in a 2 x 2 lattice, and a second Tx subarray of four Tx antenna elements T3, T4, T7, and T8 arranged in a 2 x 2 lattice. The Rx antenna elements R1, R2, R3, and R4 and Tx antenna elements T1, T2, T3, T4, T5, T6, T7, and T8 are arranged in a 4 x 4 lattice.

In the example embodiment, the Rx antenna array and Tx antenna array are disposed on the same aperture, e.g., physical aperture. As shown in FIG. 2A, eight Tx antenna elements and four Rx antenna elements are alternatively positioned in a square aperture 202, e.g., square surface, square panel, measuring 15 mm by 15 mm. The top row of the 4 x 4 lattice is

referred to as the first row, with each subsequent row below it numbered sequentially; and the leftmost column of the 4 x 4 lattice is referred to as the first column, with each subsequent column to its right numbered sequentially.

The Rx antenna elements R1, R2, R3, and R4 of the Rx subarray are positioned at intersections of the second and fourth (bottom) rows with the second and fourth (rightmost) columns of the 4 x 4 lattice. In other words, Rx antenna elements R1 and R2 are positioned at the second and fourth positions of the second row of the 4 x 4 lattice; and Rx antenna elements R4 and R3 are positioned at the second and fourth positions of the fourth row of the 4 x 4 lattice.

The Tx antenna elements T1, T2, T5, and T6 of the first Tx subarray are positioned at intersections of the second and fourth (bottom) rows with the first and third columns of the 4 x 4 lattice. In other words, Tx antenna elements T1 and T5 are positioned at the first and third positions of the second row of the 4 x 4 lattice; and Tx antenna elements T2 and T6 are positioned at the first and third positions of the fourth row of the 4 x 4 lattice.

The Tx antenna elements T3, T4, T7, and T8 of the second Tx subarray are positioned at intersections of the first (top) and third rows with the second and fourth columns of the 4 x 4 lattice. In other words, Tx antenna elements T3 and T7 are positioned at the second and fourth positions of the first row of the 4 x 4 lattice; and Tx antenna elements T4 and T8 are positioned at the second and fourth positions of the third row of the 4 x 4 lattice.

In the example embodiment, the Rx antenna elements R1 to R4 are separate from the Tx antenna elements T1 to T8. As shown in FIG. 2A, all the antenna elements occupy their respective positions in the 4 x 4 lattice, and no two antenna elements occupy the same position on the 4 x 4 lattice. All the Rx antenna elements R1 to R4 are separated by the same distance D along a first direction (i.e., X-axis or horizontal direction) and a second direction (i.e., Y-axis or vertical direction) perpendicular to the first direction. Any two immediately adjacent Rx antenna elements are separated by distance D along the first direction and the second direction. All the Tx antenna elements T1 to T8 are separated by the same distance D in the horizontal and vertical directions. Any two immediately adjacent Tx antenna elements are separated by distance D along the first direction and the second direction. It will be appreciated that two Rx antenna elements that are immediately adjacent to each other and separated by a gap of distance D may have a Tx antenna element positioned between said gap. Similarly,

it will be appreciated that two Tx antenna elements that are immediately adjacent to each other and separated by a gap of distance D may have an Rx antenna element positioned between said gap. In the example embodiment, the distance D is $0.5\lambda_F$, where λ_F is the wavelength of an electromagnetic wave at the center frequency of the lower of the first and second frequency ranges. F GHz, for example, may be 20 GHz. It will be appreciated that a distance of 0.5λ at 20 GHz is equivalent to 0.75λ at 30 GHz. For implementation convenience, the separation should be half-wavelength at the lower band frequency (such as 20 GHz).

In the example embodiment, the Rx antenna array is configured to receive via a first frequency range and the Tx antenna array is configured to transmit via a second frequency range. As shown in FIG. 2A, the Rx antenna element and Tx antenna element operate at 20-GHz and 30-GHz bands respectively.

It will be appreciated that the phased array antenna is not limited to the eight Tx antenna elements and four Rx antenna elements alternatively positioned in a square aperture in a 4 x 4 lattice as shown in FIG. 2A. Other variations of the phased array antenna may include different numbers of Tx antenna elements and Rx antenna elements arranged in a different lattice size. In other variations of the phased array antenna, the Rx subarray and Tx subarray may be arranged differently from the phased array antenna 200 of FIG. 2A.

FIG. 2B is another schematic diagram of the phased array antenna 200 in the example embodiment.

In the example embodiment, the phased array antenna 200 further comprises an Rx core chip Rx-C1 associated with the Rx subarray of Rx antenna elements R1 to R4. The Rx core chip Rx-C1 is communicatively coupled to the Rx antenna elements R1 to R4 via an Rx feeding network comprising a plurality of Rx feed lines. The Rx core chip Rx-C1 is positioned substantially at the center of the 2 x 2 square lattice of the Rx antenna elements R1 to R4, such that the plurality of Rx feed lines have substantially equal length.

In the example embodiment, the phased array antenna 200 further comprises a first Tx core chip Tx-C1 associated with the first Tx subarray of Tx antenna elements T1, T2, T5 and T6. The first Tx core chip Tx-C1 is communicatively coupled to the Tx antenna elements T1, T2, T5 and T6 via a first Tx feeding network comprising a plurality of Tx feed lines. The first Tx core chip Tx-C1 is positioned substantially at the center of the 2 x 2 square lattice of

the Tx antenna elements T1, T2, T5 and T6, such that the plurality of Tx feed lines have substantially equal length. As shown in FIG. 2B, the first Tx core chip Tx-C1 is disposed under the Tx antenna element T4 of the second Tx subarray.

In the example embodiment, the phased array antenna 200 further comprises a second Tx core chip Tx-C2 associated with the second Tx subarray of Tx antenna elements T3, T4, T7 and T8. The second Tx core chip Tx-C2 is communicatively coupled to the Tx antenna elements T3, T4, T7 and T8 via a second Tx feeding network comprising a plurality of Tx feed lines. The second Tx core chip Tx-C2 is positioned substantially at the center of the 2 x 2 lattice of the Tx antenna elements T3, T4, T7 and T8, such that the plurality of Tx feed lines have substantially equal length. As shown in FIG. 2B, the second Tx core chip Tx-C2 is disposed under the Tx antenna element T5 of the first Tx subarray.

In the example embodiment, the antenna elements and core chips are configured for achieving an identical feeding path to all antenna elements. Each feeding network comprising a plurality of feed lines is configured for communicatively coupling each core chip to the antenna elements of the associated subarray. Each core chip is positioned substantially at the center relative to the antenna elements of the associated subarray such that the plurality of feed lines have substantially equal length. Specifically, the antenna elements are grouped with four antenna elements per subarray, namely, two Tx antenna element groups with T1/T2/T5/T6 under the first Tx subarray and T3/T4/T7/T8 under the second Tx subarray, and one Rx antenna element group with R1/R2/R3/R4 under the Rx subarray. The antenna elements are positioned in a square manner and fed by the core chip allocated in the center of the square. As shown in FIG. 2B, the first Tx core chip Tx-C1 is configured to excite the four Tx antenna elements of T1/T2/T5/T6, the second Tx core chip Tx-C2 is configured to excite the four Tx antenna elements of T3/T4/T7/T8, and the Rx core chip Rx-C1 is configured to feed the four Rx antenna elements of R1/R2/R3/R4. With three core chips, the eight Tx antenna elements and four Rx antenna elements are all excited with identical feeding paths. While the Rx and Tx feed lines are not shown in FIG. 2A and 2B, it will be appreciated that a person skilled in the art would be able to implement such feed lines for coupling the core chips to their respective antenna elements in the phased array antenna.

Advantageously, the interleaved array configuration of the phased array antenna 200 in the example embodiment, with Rx and Tx subarrays having separate Rx and Tx antenna elements sharing the same aperture results in a compact dual-band array antenna design.

Even more advantageously, the configuration of the phased array antenna 200 addresses a number of key design considerations for a phased array antenna, including, for example, identical path/routing from the core chips to antenna elements, efficiency of the phased array antenna, scan range of the phased array antenna without the occurrence of grating lobe, and scalable capability.

In the example embodiment, the phased array antenna 200 advantageously addresses the design consideration of identical path/routing from the core chips to antenna elements. Unequal path/routing from the core chips to antenna elements results in larger path loss and phase lag to certain feeding ports, which degrades the array antenna performance in terms of lower antenna efficiency/gain and thus reduced equivalent isotropic radiating power (EIRP) for transmitting and gain to temperature ratio (G/T) for receiving, higher side-lobe, and smaller scan range without grating lobe occurring, in particular, at 20/30 GHz and higher frequency bands.

FIG. 3A is a schematic diagram showing a first possible array lattice for a Tx array of a first phased array antenna 300 in an example embodiment. FIG. 3B is a schematic diagram showing a second possible array lattice for an Rx array of the first phased array antenna 300 in the example embodiment.

In the example embodiment, the first phased array antenna 300 is constructed in substantially the same manner as the phased array antenna 200 of FIG. 2. The first phased array antenna 300 comprises an Rx antenna array, said Rx antenna array comprising an Rx subarray of four Rx antenna elements R1, R2, R3 and R4 arranged in a 2 x 2 lattice. The first phased array antenna 300 further comprises a Tx antenna array, said Tx antenna array comprising a first Tx subarray of four Tx antenna elements T1, T2, T5, and T6 arranged in a 2 x 2 lattice, and a second Tx subarray of four Tx antenna elements T3, T4, T7, and T8 arranged in a 2 x 2 lattice. The Rx antenna elements R1, R2, R3 and R4 and Tx antenna elements T1, T2, T3, T4, T5, T6, T7, and T8 are arranged in a 4 x 4 lattice. The Rx subarray is associated with an Rx core chip. Each Tx subarray is associated with a respective Tx core chip.

In the example embodiment, each of the Rx antenna elements R1 to R4 and Tx antenna elements T1 to T8 comprises two orthogonal feeding ports. The Tx or Rx antenna element with two orthogonal feeding ports may be excited with identical amplitude and 90°

phase difference. Left-handed circularly polarized (LHCP) or right-handed circularly polarized (RHCP) radiation may be achieved by configuring the Rx and Tx core chips accordingly. Typically, a Tx or Rx core chip has eight channels each and thus one Tx or RX core chip may be used to excite four Tx or Rx antenna elements, respectively.

In the example embodiment, the Rx antenna elements R1 to R4 of the Rx subarray are configured to be excited with identical amplitude and 90° phase difference. The Tx antenna elements of the Tx subarrays, i.e., Tx antenna elements T1, T2, T5, and T6 of the first Tx subarray and Tx antenna elements T3, T4, T7, and T8 of the second Tx subarray, are configured to be excited with identical amplitude and 90° phase difference.

Advantageously, the grouping of the Rx antenna elements and Tx antenna elements in the first phased array antenna 300 may provide identical feeding paths from the respective core chips to the associated antenna elements.

FIG. 4A is a schematic diagram showing a first possible array lattice for a Tx array of a second phased array antenna 400 in an example embodiment. FIG. 4B is a schematic diagram showing a second possible array lattice for an Rx array of the second phased array antenna 400 in the example embodiment.

In the example embodiment, the second phased array antenna 400 is constructed in substantially the same manner as the phased array antenna 200 of FIG. 2. The second phased array antenna 400 comprises an Rx antenna array, said Rx antenna array comprising an Rx subarray of four Rx antenna elements R1, R2, R3 and R4 arranged in a 2 x 2 lattice. The second phased array antenna 400 further comprises a Tx antenna array, said Tx antenna array comprising a first Tx subarray of four Tx antenna elements T1, T2, T5, and T6 arranged in a 2 x 2 lattice, and a second Tx subarray of four Tx antenna elements T3, T4, T7, and T8 arranged in a 2 x 2 lattice. The Rx antenna elements R1, R2, R3 and R4 and Tx antenna elements T1, T2, T3, T4, T5, T6, T7, and T8 are arranged in a 4 x 4 lattice. The Rx subarray is associated with an Rx core chip. Each Tx subarray is associated with a respective Tx core chip.

In the example embodiment, each of the Rx antenna elements R1 to R4 and Tx antenna elements T1 to T8 comprises two orthogonal feeding ports. The second phased array antenna 400 differs from the phased array antenna 300 of FIG. 3 in that the Tx antenna

elements may be excited in a triangular lattice formation. Any three neighboring Tx antenna elements of the Tx subarrays may be configured to be excited with identical amplitude and 120° phase difference. The three neighboring Tx antenna elements may be from two adjacent rows of the 4 x 4 lattice. The three neighboring Tx antenna elements may be Tx antenna elements from different Tx subarrays. For example, three Tx antenna elements between two adjacent rows of the 4 x 4 lattice may be configured as a triangular lattice, such that the three Tx antenna elements are configured to be sequentially excited with a 120° phase lag. As shown in FIG. 4A, Tx antenna elements T1 and T5 from the first Tx subarray and Tx antenna element T3 from the second Tx subarray form a triangular lattice. Tx antenna elements T3 and T7 from the second Tx subarray and Tx antenna element T5 from the first Tx subarray form a triangular lattice. Tx antenna elements T2 and T6 from the first Tx subarray and Tx antenna element T4 from the second Tx subarray form a triangular lattice. Tx antenna elements T4 and T8 from the second Tx subarray and Tx antenna element T6 from the first Tx subarray form a triangular lattice. For the Tx array antenna, a triangular lattice may be desirable for grating lobe suppression. For the Rx array antenna, the conventional square lattice may be implemented as shown in FIG. 4B because of the adequate half-wavelength inter-element spacing.

FIG. 5A is a schematic diagram illustrating different modular array antenna configurations in an example embodiment. A first array antenna 500 with 1 module, a second array antenna 502 with 4 modules, and a third array antenna with 16 modules are illustrated in FIG. 5A.

In the example embodiment, a modular phased array antenna system, e.g., 502, 504, is provided. The modular phased array antenna system comprises a plurality of unit modules wherein each unit module is based on the first array antenna 500. The first array antenna 500 is constructed in substantially the same manner as the phased array antenna 200 of FIG. 2. Each unit module 500 comprises an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range. The Rx antenna array and Tx antenna array are disposed on a same aperture. The Rx antenna element is separate from the Tx antenna element. Any two immediately adjacent Rx antenna elements and any two immediately adjacent Tx antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction.

The example embodiment demonstrates the scalable capability of the presently disclosed array antenna. Using the first array antenna 500 as a unit module with 8 Tx antenna elements and 4 Rx antenna elements (8Tx+4Rx), a larger array antenna with multiple modules such as the second array antenna 502 with 4 modules (32Tx+16Rx) and the third array antenna 504 with 16 modules (128Tx+64Rx) may be configured by assembling the unit modules in a lattice formation. It will be appreciated that an even larger array antenna can be configured accordingly depending on the system requirements. In general, the modular phased array antenna system may comprise N by N unit modules arranged in a square lattice configuration, wherein N is an integer of at least 2. Any two immediately adjacent Rx antenna elements and any two immediately adjacent Tx antenna elements between two immediately adjacent modules are separated by a distance D along a first direction and a second direction perpendicular to the first direction.

FIG. 5B is a schematic diagram of the different modular array antenna configurations demonstrating multi-level sequentially rotated excitation for enhancing circular polarization (CP) performance in the example embodiment. The CP radiation performance of the array antenna may be further enhanced by using multi-level sequentially rotated excitation technology.

Referring to the circled area on the left-hand side of FIG. 5B, for the first array antenna 500 acting as a single module, a 0°/90° difference may be applied between the two feeding ports for each Tx and Rx antenna elements. A sequentially rotated excitation technology may also be applied to the Tx array with triangular lattice and Rx array with square lattice, i.e., 120° phase lag for the 3 Tx antenna elements (0°/120°/240°) and 90° phase lag for the 4 Rx antenna elements (0°/90°/180°/270°).

In the example embodiment, the sequentially rotated excitation technology may be applied to a dual-band array antenna with multiple modules. The phase excitation arrangement of 0°/90°/180°/270° may be applied to each module of the second array antenna 502 with 4 modules. That is, when N is 2, the four modules may be configured to be sequentially excited with a 90° phase difference. The phase excitation arrangement of 0°/90°/180°/270° may also be applied to a combination of 4 modules of the third array antenna with 16 modules. For larger array antenna, the arrangement may be applied to combination of more modules accordingly. For example, the modular phased array antenna system may

comprise four groups of unit modules, each group having a plurality of unit modules arranged in a square lattice configuration. Each group of unit modules may be configured to share a same phase of excitation, and the four groups of unit modules may be configured to be sequentially excited with a 90° phase difference.

FIG. 6 is a schematic flowchart 600 for illustrating a method of making a phased array antenna in an example embodiment. At step 602, an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range is formed, such that any two adjacent Rx antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction. At step 604, a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range is formed, such that the Rx antenna array and Tx antenna array are disposed on a same aperture, that the Rx antenna element is separate from the Tx antenna element; and that any two adjacent Tx antenna elements are separated by a distance D along the first direction and the second direction.

In the example embodiment, the method may further comprise providing one or more Rx core chips, each Rx core chip associated with an Rx subarray of Rx antenna elements. The method may further comprise forming one or more Rx feeding networks, each Rx feeding network comprising a plurality of Rx feed lines for communicatively coupling the Rx core chip to the Rx antenna elements of the associated Rx subarray. Each Rx core chip may be positioned substantially at the center of the Rx antenna elements of the associated Rx subarray such that the plurality of Rx feed lines have substantially equal length.

In the example embodiment, the method may further comprise providing one or more Tx core chips, each Tx core chip associated with a Tx subarray of Tx antenna elements. The method may further comprise forming one or more Tx feeding networks, each Tx feeding network comprising a plurality of Tx feed lines for communicatively coupling the Tx core chip to the Tx antenna elements of the associated Tx subarray. Each Tx core chip may be positioned substantially at the center of the Tx antenna elements of the associated Tx subarray such that the plurality of Tx feed lines have substantially equal length.

In the example embodiment, the method may further comprise forming an Rx subarray of four Rx antenna elements arranged in a 2 x 2 lattice. The method may further comprise forming a first Tx subarray and a second Tx subarray, each Tx subarray comprising four Tx

antenna elements arranged in a 2 x 2 lattice. The Rx antenna elements and Tx antenna elements may be arranged in a 4 x 4 lattice.

In the example embodiment, the method may further comprise positioning the Rx antenna elements of the Rx subarray at intersections of the second and fourth (bottom) rows with the second and fourth (rightmost) columns of the 4 x 4 lattice. The method may further comprise positioning the Tx antenna elements of the first Tx subarray at intersections of the second and fourth rows with the first (leftmost) and third columns of the 4 x 4 lattice. The method may further comprise positioning the Tx antenna elements of the second Tx subarray at intersections of the first (top) and third rows with the second and fourth (rightmost) columns of the 4 x 4 lattice.

In the example embodiment, the method may further comprise providing two orthogonal feeding ports for each of the Rx antenna elements and Tx antenna elements.

FIG. 7 is a schematic diagram showing simulation set-ups of an array antenna 700 in an example embodiment. The array antenna 700 (compare 504 of FIG. 5A) comprises 128 Tx antenna elements and 64 Rx antenna elements formed from 16 array antenna modules (compare 200 of FIG. 2B). The Tx and Rx antenna elements each comprise two orthogonal feeding ports and the ports are fed by core chips (compare Tx-C1 and Rx-C1 of FIG. 2B) with identical amplitude and 90° phase difference respectively for CP radiation. By configuring the phase lag between the ports such as 0°/90° or 90°/0°, left-handed circularly polarized (LHCP) or righthanded circularly polarized (RHCP) radiation can be generated. In the simulation, an element pattern of $Cos^2(\theta)$ is used for both Tx and Rx array. The simulation results are described below with reference to FIG. 8A – 8I to FIG. 13A – 13I.

FIG. 8A to FIG. 8I are plots of simulated patterns of the Tx array at 30 GHz with beam scanning along x-axis (ϕ=0°) in the example embodiment. FIG. 8A is a plot of a contour line directivity pattern for a beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 8B is a plot of a contour line directivity pattern for a beam at (θ=30°, ϕ=0°) in the example embodiment. FIG. 8C is a plot of a contour line directivity pattern for a beam at (θ=60°, ϕ=0°) in the example embodiment. FIG. 8D is a plot of a contour line axial ratio (AR) pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 8E is a plot of a contour line AR pattern for the beam at (θ=30°, ϕ=0°) in the example embodiment. FIG. 8F is a plot of a contour line AR pattern for the beam at (θ=60°, ϕ=0°) in the example embodiment. FIG. 8G is

a plot of a 2-D directivity pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 8H is a plot of a 2-D directivity pattern for the beam at (θ=30°, ϕ=0°) in the example embodiment. FIG. 8I is a plot of a 2-D directivity pattern for the beam at (θ=60°, ϕ=0°) in the example embodiment.

FIG. 8A to FIG. 8I exhibit the simulated patterns of the Tx array at 30 GHz with beam scanning along x-axis (ϕ=0°). FIG. 8A to FIG. 8C show the contour line directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=60°, ϕ=0°). FIG. 8D to FIG. 8F show the contour line axial ratio (AR) patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=0°) and (θ=60°, ϕ=0°). Desired CP radiation (AR≤3) is achieved for all angles. FIG. 8G to FIG. 8I show the 2-dimensional (2-D) directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=0°) and (θ=60°, ϕ=0°), where a scan loss of about 2.5 dB (compared with directivity at boresight) and a side-lobe level of about 12 dB are achieved at scan angle of 60°, no grating lobe occurs.

FIG. 9A to FIG. 9I are plots of simulated patterns of the Tx array at 30 GHz with beam scanning along diagonal line (ϕ=45°) in the example embodiment. FIG. 9A is a plot of a contour line directivity pattern for a beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 9B is a plot of a contour line directivity pattern for a beam at (θ=30°, ϕ=45°) in the example embodiment. FIG. 9C is a plot of a contour line directivity pattern for a beam at (θ=55°, ϕ=45°) in the example embodiment. FIG. 9D is a plot of a contour line AR pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 9E is a plot of a contour line AR pattern for the beam at (θ=30°, ϕ=45°) in the example embodiment. FIG. 9F is a plot of a contour line AR pattern for the beam at (θ=55°, ϕ=45°) in the example embodiment. FIG. 9G is a plot of a 2-D directivity pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 9H is a plot of a 2-D directivity pattern for the beam at (θ=30°, ϕ=45°) in the example embodiment. FIG. 9I is a plot of a 2-D directivity pattern for the beam at (θ=55°, ϕ=45°) in the example embodiment.

FIG. 9A to FIG. 9I exhibit the simulated patterns of the Tx array at 30 GHz with beam scanning along diagonal line (ϕ=45°). FIG. 9A to FIG. 9C show the contour line directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=55°, ϕ=45°). FIG. 9D to FIG. 9F show the contour line axial ratio (AR) patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=45°) and (θ=55°, ϕ=45°). Desired CP radiation (AR≤3) is achieved for all angles. FIG. 9H to FIG. 9I show the 2-D directivity patterns for beam scanning from boresight (θ=0°,

ϕ=0°) to (θ=30°, ϕ=45°) and (θ=55°, ϕ=45°), where a scan loss of about 2.5 dB (compared with directivity at boresight) and a side-lobe level of about 9 dB are achieved at scan angle of 55°, no grating lobe occurs.

FIG. 10A to FIG. 10I are plots of simulated patterns of the Tx array at 30 GHz with beam scanning along y-axis (ϕ=90°) in the example embodiment. FIG. 10A is a plot of a contour line directivity pattern for a beam at boresight (θ=0°, ϕ=90°) in the example embodiment. FIG. 10B is a plot of a contour line directivity pattern for a beam at (θ=30°, ϕ=90°) in the example embodiment. FIG. 10C is a plot of a contour line directivity pattern for a beam at (θ=60°, ϕ=90°) in the example embodiment. FIG. 10D is a plot of a contour line AR pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 10E is a plot of a contour line AR pattern for the beam at (θ=30°, ϕ=90°) in the example embodiment. FIG. 10F is a plot of a contour line AR pattern for the beam at (θ=60°, ϕ=90°) in the example embodiment. FIG. 10G is a plot of a 2-D directivity pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 10H is a plot of a 2-D directivity pattern for the beam at (θ=30°, ϕ=90°) in the example embodiment. FIG. 10I is a plot of a 2-D directivity pattern for the beam at (θ=60°, ϕ=90°) in the example embodiment.

FIG. 10A to FIG. 10I exhibit the simulated patterns of the Tx array at 30 GHz with beam scanning along y-axis (ϕ=90°). FIG. 10A to FIG. 10C show the contour line directivity patterns for beam scanning from boresight (θ=0°, ϕ=90°) to (θ=60°, ϕ=90°). FIG. 10D to FIG. 10F show the contour line axial ratio (AR) patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=90°) and (θ=60°, ϕ=90°). Desired CP radiation (AR≤3) is achieved for all angles. FIG. 10G to FIG. 10I show the 2-D directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=90°) and (θ=60°, ϕ=90°), where a scan loss of about 2.5 dB (compared with directivity at boresight) and a side-lobe level of about 12 dB are achieved at scan angle of 60°, no grating lobe occurs.

In summary, the Tx array antenna with 128 elements is able to scan the beam up to 60° along x- and y-axis with desired CP radiation (AR≤3 dB), scan loss of about 2.5 dB, low side-lobe level of less than 12 dB, and without grating lobe occurring. The beam scan angle along the diagonal line is slightly smaller, which is up to 55° without grating lobe occurring, with desired CP radiation (AR≤3 dB), scan loss of about 2.5 dB, and acceptable side-lobe level of less than 9 dB.

FIG. 11A to FIG. 11I are plots of simulated patterns of the Rx array at 20 GHz with beam scanning along x-axis (ϕ=0°) in the example embodiment. FIG. 11A is a plot of a contour line directivity pattern for a beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 11B is a plot of a contour line directivity pattern for a beam at (θ=30°, ϕ=0°) in the example embodiment. FIG. 11C is a plot of a contour line directivity pattern for a beam at (θ=60°, ϕ=0°) in the example embodiment. FIG. 11D is a plot of a contour line AR pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 11E is a plot of a contour line AR pattern for the beam at (θ=30°, ϕ=0°) in the example embodiment. FIG. 11F is a plot of a contour line AR pattern for the beam at (θ=60°, ϕ=0°) in the example embodiment. FIG. 11G is a plot of a 2-D directivity pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 11H is a plot of a 2-D directivity pattern for the beam at (θ=30°, ϕ=0°) in the example embodiment. FIG. 11I is a plot of a 2-D directivity pattern for the beam at (θ=60°, ϕ=0°) in the example embodiment.

FIG. 11A to FIG. 11I exhibit the simulated patterns of the Rx array at 20 GHz with beam scanning along x-axis (ϕ=0°). FIG. 11A to FIG. 11C show the contour line directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=60°, ϕ=0°). FIG. 11D to FIG. 11F show the contour line axial ratio (AR) patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=0°) and (θ=60°, ϕ=0°). Desired CP radiation (AR≤3) is achieved for all angles. FIG. 11G to FIG. 11I show the 2-D directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=0°) and (θ=60°, ϕ=0°), where a scan loss of about 2.5 dB (compared with directivity at boresight) and a side-lobe level of about 11 dB are achieved at scan angle of 60°, no grating lobe occurs.

FIG. 12A to FIG. 12I are plots of simulated patterns of the Rx array at 20 GHz with beam scanning along diagonal line (ϕ=45°) in the example embodiment. FIG. 12A is a plot of a contour line directivity pattern for a beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 12B is a plot of a contour line directivity pattern for a beam at (θ=30°, ϕ=45°) in the example embodiment. FIG. 12C is a plot of a contour line directivity pattern for a beam at (θ=60°, ϕ=45°) in the example embodiment. FIG. 12D is a plot of a contour line AR pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 12E is a plot of a contour line AR pattern for the beam at (θ=30°, ϕ=45°) in the example embodiment. FIG. 12F is a plot of a contour line AR pattern for the beam at (θ=60°, ϕ=45°) in the example embodiment. FIG. 12G is a plot of a 2-D) directivity pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 12H is a plot of a 2-D directivity pattern for the beam

at (θ=30°, ϕ=45°) in the example embodiment. FIG. 12I is a plot of a 2-D directivity pattern for the beam at (θ=60°, ϕ=45°) in the example embodiment.

FIG. 12A to FIG. 12I exhibit the simulated patterns of the Rx array at 20 GHz with beam scanning along diagonal line (ϕ=45°). FIG. 12A to FIG. 12C show the contour line directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=55°, ϕ=45°). FIG. 12D to FIG. 12F show the contour line axial ratio (AR) patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=45°) and (θ=60°, ϕ=45°). Desired CP radiation (AR≤3) is achieved for all angles. FIG. 12G to FIG. 12I show the 2-D directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=45°) and (θ=60°, ϕ=45°), where a scan loss of about 2.5 dB (compared with directivity at boresight) and a side-lobe level of about 21 dB are achieved at scan angle of 60°, no grating lobe occurs.

FIG. 13A to FIG. 13I are plots of simulated patterns of the Rx array at 20 GHz with beam scanning along y-axis (ϕ=90°) in the example embodiment. FIG. 13A is a plot of a contour line directivity pattern for a beam at boresight (θ=0°, ϕ=90°) in the example embodiment. FIG. 13B is a plot of a contour line directivity pattern for a beam at (θ=30°, ϕ=90°) in the example embodiment. FIG. 13C is a plot of a contour line directivity pattern for a beam at (θ=60°, ϕ=90°) in the example embodiment. FIG. 13D is a plot of a contour line AR pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 13E is a plot of a contour line AR pattern for the beam at (θ=30°, ϕ=90°) in the example embodiment. FIG. 13F is a plot of a contour line AR pattern for the beam at (θ=60°, ϕ=90°) in the example embodiment. FIG. 13G is a plot of a 2-D directivity pattern for the beam at boresight (θ=0°, ϕ=0°) in the example embodiment. FIG. 13H is a plot of a 2-D directivity pattern for the beam at (θ=30°, ϕ=90°) in the example embodiment. FIG. 13I is a plot of a 2-D directivity pattern for the beam at (θ=60°, ϕ=90°) in the example embodiment.

FIG. 13A to FIG. 13I exhibit the simulated patterns of the Rx array at 20 GHz with beam scanning along y-axis (ϕ=90°). FIG. 13A to FIG. 13C show the contour line directivity patterns for beam scanning from boresight (θ=0°, ϕ=90°) to (θ=60°, ϕ=90°). FIG. 13D to FIG. 13F show the contour line axial ratio (AR) patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=90°) and (θ=60°, ϕ=90°). Desired CP radiation (AR≤3) is achieved for all angles. FIG. 13G to FIG. 13I show the 2-D directivity patterns for beam scanning from boresight (θ=0°, ϕ=0°) to (θ=30°, ϕ=90°) and (θ=60°, ϕ=90°), where a scan loss of about 2.5

dB (compared with directivity at boresight) and a side-lobe level of about 11 dB are achieved at scan angle of 60°, no grating lobe occurs.

In summary, the Rx array antenna with 64 elements is able to scan the beam up to 60° along x-and y-axis as well as diagonal line with desired CP radiation (AR≤3 dB), scan loss of about 2.5 dB, low side-lobe level of less than 11 dB, and without grating lobe occurring.

In the described example embodiments, a dual-band, circularly polarized, interleaved array antenna is disclosed. The fully separated Tx and Rx antenna elements can be excited by core chips with identical feeding path (e.g., path lengths), which minimize the routing loss and phase unbalance and thus enhance the efficiency of the array antenna, simplify the routing and ease the fabrication and thus reduce the cost, in particular, at 20/30 GHz and higher band.

In one embodiment, the array antenna comprises 8 Tx antenna elements at 30 GHz band and 4 Rx antenna elements at 20-GHz band. The Tx and Rx antenna elements can be excited by two Tx core chips and one Rx core chip, respectively. Larger antenna array can be formed by scaling up the example above. In another embodiment, the array antenna comprises 128 Tx antenna elements at 30 GHz-band and 64 Rx antenna elements at 20-GHz band. The Tx and Rx antenna elements can be excited by 32 Tx core chips and 16 Rx core chips, respectively.

For CP radiation performance enhancement, multi-level sequentially rotated technology can be applied to the Tx and Rx antenna elements as well as the sub-arrays or modules.

The terms “coupled” or “connected” as used in this description are intended to cover both directly connected or connected through one or more intermediate means, unless otherwise stated.

The description herein may be, in certain portions, explicitly or implicitly described as algorithms and/or functional operations that operate on data within a computer memory or an electronic circuit. These algorithmic descriptions and/or functional operations are usually used by those skilled in the information/data processing arts for efficient description. An algorithm is generally related to a self-consistent sequence of steps leading to a desired result. The

algorithmic steps can include physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transmitted, transferred, combined, compared, and otherwise manipulated.

Further, unless specifically stated otherwise, and would ordinarily be apparent from the following, a person skilled in the art will appreciate that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", and the like, refer to action and processes of an instructing processor/computer system, or similar electronic circuit/device/component, that manipulates/processes and transforms data represented as physical quantities within the described system into other data similarly represented as physical quantities within the system or other information storage, transmission or display devices etc.

The description also discloses relevant device/apparatus for performing the steps of the described methods. Such apparatus may be specifically constructed for the purposes of the methods, or may comprise a general purpose computer/processor or other device selectively activated or reconfigured by a computer program stored in a storage member. The algorithms and displays described herein are not inherently related to any particular computer or other apparatus. It is understood that general purpose devices/machines may be used in accordance with the teachings herein. Alternatively, the construction of a specialized device/apparatus to perform the method steps may be desired.

In addition, it is submitted that the description also implicitly covers a computer program, in that it would be clear that the steps of the methods described herein may be put into effect by computer code. It will be appreciated that a large variety of programming languages and coding can be used to implement the teachings of the description herein. Moreover, the computer program if applicable is not limited to any particular control flow and can use different control flows without departing from the scope of the invention.

Furthermore, one or more of the steps of the computer program if applicable may be performed in parallel and/or sequentially. Such a computer program if applicable may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a suitable reader/general purpose computer. In such instances, the computer readable storage medium is non-transitory. Such storage medium also covers

all computer-readable media e.g. medium that stores data only for short periods of time and/or only in the presence of power, such as register memory, processor cache and Random Access Memory (RAM) and the like. The computer readable medium may even include a wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in Bluetooth technology. The computer program when loaded and executed on a suitable reader effectively results in an apparatus that can implement the steps of the described methods.

The example embodiments may also be implemented as hardware modules. A module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using digital or discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). A person skilled in the art will understand that the example embodiments can also be implemented as a combination of hardware and software modules.

Additionally, when describing some embodiments, the disclosure may have disclosed a method and/or process as a particular sequence of steps. However, unless otherwise required, it will be appreciated the method or process should not be limited to the particular sequence of steps disclosed. Other sequences of steps may be possible. The particular order of the steps disclosed herein should not be construed as undue limitations. Unless otherwise required, a method and/or process disclosed herein should not be limited to the steps being carried out in the order written. The sequence of steps may be varied and still remain within the scope of the disclosure.

Further, in the description herein, the word "substantially" whenever used is understood to include, but not restricted to, "entirely" or "completely" and the like. In addition, terms such as "comprising", "comprise", and the like whenever used, are intended to be non-restricting descriptive language in that they broadly include elements/components recited after such terms, in addition to other components not explicitly recited. For an example, when "comprising" is used, reference to a "one" feature is also intended to be a reference to "at least one" of that feature. Terms such as "consisting", "consist", and the like, may, in the appropriate context, be considered as a subset of terms such as "comprising", "comprise", and the like. Therefore, in embodiments disclosed herein using the terms such as "comprising", "comprise", and the like, it will be appreciated that these embodiments provide teaching for corresponding embodiments using terms such as "consisting", "consist", and the like. Further, terms such as

"about", "approximately" and the like whenever used, typically means a reasonable variation, for example a variation of +/- 5% of the disclosed value, or a variance of 4% of the disclosed value, or a variance of 3% of the disclosed value, a variance of 2% of the disclosed value or a variance of 1% of the disclosed value.

Furthermore, in the description herein, certain values may be disclosed in a range. The values showing the end points of a range are intended to illustrate a preferred range. Whenever a range has been described, it is intended that the range covers and teaches all possible sub-ranges as well as individual numerical values within that range. That is, the end points of a range should not be interpreted as inflexible limitations. For example, a description of a range of 1% to 5% is intended to have specifically disclosed sub-ranges 1% to 2%, 1% to 3%, 1% to 4%, 2% to 3% etc., as well as individually, values within that range such as 1%, 2%, 3%, 4% and 5%. The intention of the above specific disclosure is applicable to any depth/breadth of a range.

Different example embodiments can be implemented in the context of data structure, program modules, program and computer instructions executed in a computer implemented environment. A general purpose computing environment is briefly disclosed herein. One or more example embodiments may be embodied in one or more computer systems, such as is schematically illustrated in FIG. 14.

One or more example embodiments may be implemented as software, such as a computer program being executed within a computer system 1400, and instructing the computer system 1400 to conduct a method of an example embodiment.

The computer system 1400 comprises a computer unit 1402, input modules such as a keyboard 1404 and a pointing device 1406 and a plurality of output devices such as a display 1408, and printer 1410. A user can interact with the computer unit 1402 using the above devices. The pointing device can be implemented with a mouse, track ball, pen device or any similar device. One or more other input devices (not shown) such as a joystick, game pad, satellite dish, scanner, touch sensitive screen or the like can also be connected to the computer unit 1402. The display 1408 may include a cathode ray tube (CRT), liquid crystal display (LCD), field emission display (FED), plasma display or any other device that produces an image that is viewable by the user.

The computer unit 1402 can be connected to a computer network 1412 via a suitable transceiver device 1414, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN) or a personal network. The network 1412 can comprise a server, a router, a network personal computer, a peer device or other common network node, a wireless telephone or wireless personal digital assistant. Networking environments may be found in offices, enterprise-wide computer networks and home computer systems etc. The transceiver device 1414 can be a modem/router unit located within or external to the computer unit 1402, and may be any type of modem/router such as a cable modem or a satellite modem.

It will be appreciated that network connections shown are exemplary and other ways of establishing a communications link between computers can be used. The existence of any of various protocols, such as TCP/IP, Frame Relay, Ethernet, FTP, HTTP and the like, is presumed, and the computer unit 1402 can be operated in a client-server configuration to permit a user to retrieve web pages from a web-based server. Furthermore, any of various web browsers can be used to display and manipulate data on web pages.

The computer unit 1402 in the example comprises a processor 1418, a Random Access Memory (RAM) 1420 and a Read Only Memory (ROM) 1422. The ROM 1422 can be a system memory storing basic input/ output system (BIOS) information. The RAM 1420 can store one or more program modules such as operating systems, application programs and program data.

The computer unit 1402 further comprises a number of Input/Output (I/O) interface units, for example I/O interface unit 1424 to the display 1408, and I/O interface unit 1426 to the keyboard 1404. The components of the computer unit 1402 typically communicate and interface/couple connectedly via an interconnected system bus 1428 and in a manner known to the person skilled in the relevant art. The bus 1428 can be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures.

It will be appreciated that other devices can also be connected to the system bus 1428. For example, a universal serial bus (USB) interface can be used for coupling a video or digital camera to the system bus 1428. An IEEE 1394 interface may be used to couple additional devices to the computer unit 1402. Other manufacturer interfaces are also possible such as

FireWire developed by Apple Computer and i.Link developed by Sony. Coupling of devices to the system bus 1428 can also be via a parallel port, a game port, a PCI board or any other interface used to couple an input device to a computer. It will also be appreciated that, while the components are not shown in the figure, sound/audio can be recorded and reproduced with a microphone and a speaker. A sound card may be used to couple a microphone and a speaker to the system bus 1428. It will be appreciated that several peripheral devices can be coupled to the system bus 1428 via alternative interfaces simultaneously.

An application program can be supplied to the user of the computer system 1400 being encoded/stored on a data storage medium such as a CD-ROM or flash memory carrier. The application program can be read using a corresponding data storage medium drive of a data storage device 1430. The data storage medium is not limited to being portable and can include instances of being embedded in the computer unit 1402. The data storage device 1430 can comprise a hard disk interface unit and/or a removable memory interface unit (both not shown in detail) respectively coupling a hard disk drive and/or a removable memory drive to the system bus 1428. This can enable reading/writing of data. Examples of removable memory drives include magnetic disk drives and optical disk drives. The drives and their associated computer-readable media, such as a floppy disk provide nonvolatile storage of computer readable instructions, data structures, program modules and other data for the computer unit 1402. It will be appreciated that the computer unit 1402 may include several such drives. Furthermore, the computer unit 1402 may include drives for interfacing with other types of computer readable media.

The application program is read and controlled in its execution by the processor 1418. Intermediate storage of program data may be accomplished using RAM 1420. The method(s) of the example embodiments can be implemented as computer readable instructions, computer executable components, or software modules. One or more software modules may alternatively be used. These can include an executable program, a data link library, a configuration file, a database, a graphical image, a binary data file, a text data file, an object file, a source code file, or the like. When one or more computer processors execute one or more of the software modules, the software modules interact to cause one or more computer systems to perform according to the teachings herein.

The operation of the computer unit 1402 can be controlled by a variety of different program modules. Examples of program modules are routines, programs, objects,

components, data structures, libraries, etc. that perform particular tasks or implement particular abstract data types. The example embodiments may also be practiced with other computer system configurations, including handheld devices, multiprocessor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, personal digital assistants, mobile telephones and the like. Furthermore, the example embodiments may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wireless or wired communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

The example embodiments may also be practiced with other computer system configurations, including handheld devices, multiprocessor systems/servers, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, personal digital assistants, mobile telephones and the like. Furthermore, the example embodiments may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wireless or wired communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

In example embodiments, any two immediately adjacent Rx antenna elements, and any two immediately adjacent Tx antenna elements are separated by the same distance D along a first direction and a second direction perpendicular to the first direction. However, it will be appreciated that the distance between any two immediately adjacent Rx antenna elements and the distance between any two immediately adjacent Tx antenna elements are not limited as such. Any two immediately adjacent Rx antenna elements may be separated by a distance D1 along the first direction and the second direction. Any two immediately adjacent Tx antenna elements may be separated by a distance D2 along the first direction and the second direction. The distance D1 is different from the distance D2. The distances D1 and D2 are determined by the resonant frequency of the Rx and Tx antenna array.

In other example embodiments therefore, there may be provided a phased array antenna comprising an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range; wherein the Rx antenna array and Tx antenna array are disposed on a same

aperture; wherein the Rx antenna element is separate from the Tx antenna element; wherein any two immediately adjacent Rx antenna elements are separated by a distance D1 along a first direction and a second direction perpendicular to the first direction; and wherein any two immediately adjacent Tx antenna elements are separated by a distance D2 along the first direction and the second direction. In other example embodiments therefore, there may be provided a modular phased array antenna system comprising a plurality of unit modules, each unit module comprising a phased array antenna as described in this paragraph.

In other example embodiments therefore, there may be provided a method of making a phased array antenna, the method comprising, forming an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and forming a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range; wherein the Rx antenna array and Tx antenna array are disposed on a same aperture; wherein the Rx antenna element is separate from the Tx antenna element; wherein any two immediately adjacent Rx antenna elements are separated by a distance D1 along a first direction and a second direction perpendicular to the first direction; and wherein any two immediately adjacent Tx antenna elements are separated by a distance D2 along the first direction and the second direction.

In example embodiments, the phased array antenna comprises an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range and a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range. In other words, the combination of the antennas is mixed Rx and Tx. However, it will be appreciated that the phased array antenna is not limited to having a mixture of Rx and Tx antenna arrays disposed on the same aperture. The phased array antenna may comprise a first Rx antenna array configured to operate at a first frequency range and a second Rx antenna array configured to operate at a second frequency range different from the first frequency range, i.e., the phased array antenna comprises only Rx antenna arrays operating at two different frequencies. In other example embodiments, the phased array antenna may comprise a first Tx antenna array configured to operate at a first frequency range and a second Tx antenna array configured to operate at a second frequency range different from the first frequency range i.e., the phased array antenna comprises only Tx antenna arrays operating at two different frequencies. The second frequency band may be higher or lower than the first frequency band. For example, the first frequency may be Rx at Ku-band, and the second frequency can be Rx at Ka-band.

In other example embodiments therefore, there may be provided a phased array antenna comprising a first antenna array comprising one or more first subarrays of first antenna elements configured to operate via a first frequency range; and a second antenna array comprising one or more second subarrays of second antenna elements configured to operate via a second frequency range different from the first frequency range; wherein the first antenna array and second antenna array are disposed on a same aperture; wherein the first antenna element is separate from the second antenna element; wherein any two immediately adjacent first antenna elements and any two immediately adjacent second antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction; and wherein the first and second antenna arrays are both Rx or both Tx antenna arrays. For example, where the first and second antenna arrays are both Rx antenna arrays, the first and second subarrays are both Rx subarrays and the first and second antenna elements are both Rx antenna elements. For example, where the first and second antenna arrays are both Tx antenna arrays, the first and second subarrays are both Tx subarrays and the first and second antenna elements are both Tx antenna elements. In other example embodiments therefore, there may be provided a modular phased array antenna system comprising a plurality of unit modules, each unit module comprising a phased array antenna as described in this paragraph.

In other example embodiments therefore, there may be provided a method of making a phased array antenna, the method comprising, forming a first antenna array comprising one or more first subarrays of first antenna elements configured to operate via a first frequency range; and forming a second antenna array comprising one or more second subarrays of second antenna elements configured to operate via a second frequency range different from the first frequency range; wherein the first antenna array and second antenna array are disposed on a same aperture; wherein the first antenna element is separate from the second antenna element; wherein any two immediately adjacent first antenna elements and any two immediately adjacent second antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction; and wherein the first and second antenna arrays are both Rx or both Tx antenna arrays.

It will be appreciated by a person skilled in the art that other variations and/or modifications may be made to the specific embodiments without departing from the scope of the invention as broadly described. For example, in the description herein, features of different

exemplary embodiments may be mixed, combined, interchanged, incorporated, adopted, modified, included etc. or the like across different exemplary embodiments. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A phased array antenna comprising,

an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and

a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range;

wherein the Rx antenna array and Tx antenna array are disposed on a same aperture;

wherein the Rx antenna element is separate from the Tx antenna element; and

wherein any two immediately adjacent Rx antenna elements and any two immediately adjacent Tx antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction.

2. The phased array antenna according to claim 1, further comprising

one or more Rx core chips, each Rx core chip associated with an Rx subarray of Rx antenna elements; and

one or more Rx feeding networks, each Rx feeding network comprising a plurality of Rx feed lines for communicatively coupling the Rx core chip to the Rx antenna elements of the associated Rx subarray;

wherein each Rx core chip is positioned substantially at the center of the Rx antenna elements of the associated Rx subarray such that the plurality of Rx feed lines have substantially equal length.

3. The phased array antenna according to claim 1 or 2, further comprising

one or more Tx core chips, each Tx core chip associated with a Tx subarray of Tx antenna elements; and

one or more Tx feeding networks, each Tx feeding network comprising a plurality of Tx feed lines for communicatively coupling the Tx core chip to the Tx antenna elements of the associated Tx subarray;

wherein each Tx core chip is positioned substantially at the center of the Tx antenna elements of the associated Tx subarray such that the plurality of Tx feed lines have substantially equal length.

4. The phased array antenna according to any one of claims 1 to 3,

wherein the Rx antenna array comprises an Rx subarray of four Rx antenna elements arranged in a 2 x 2 lattice;

wherein the Tx antenna array comprises a first Tx subarray and a second Tx subarray, each Tx subarray comprising four Tx antenna elements arranged in a 2 x 2 lattice; and

wherein the Rx antenna elements and Tx antenna elements are arranged in a 4 x 4 lattice.

5. The phased array antenna according to claim 4,

wherein the Rx antenna elements of the Rx subarray are positioned at intersections of the second and fourth rows with the second and fourth columns of the 4 x 4 lattice;

wherein the Tx antenna elements of the first Tx subarray are positioned at intersections of the second and fourth rows with the first and third columns of the 4 x 4 lattice; and

wherein the Tx antenna elements of the second Tx subarray are positioned at intersections of the first and third rows with the second and fourth columns of the 4 x 4 lattice.

6. The phased array antenna according to any one of claims 1 to 5,

wherein each of the Rx antenna elements and Tx antenna elements comprise two orthogonal feeding ports.

7. The phased array antenna according to any one of claims 1 to 6, wherein the Rx antenna elements of the Rx subarrays are configured to be excited with identical amplitude and 90° phase difference.

8. The phased array antenna according to any one of claims 1 to 7, wherein the Tx antenna elements of the Tx subarrays are configured to be excited with identical amplitude and 90° phase difference.

9. The phased array antenna according to any one of claims 1 to 7, wherein any three neighboring Tx antenna elements of the Tx subarrays are configured to be excited with identical amplitude and 120° phase difference.

10. The phased array antenna according to any one of claims 1 to 9, wherein D is $0.5\lambda_F$, where λ_F is the wavelength of an electromagnetic wave at the center frequency of the lower of the first and second frequency ranges.

11. A phased array antenna comprising,

a first antenna array comprising one or more first subarrays of first antenna elements configured to operate via a first frequency range; and

a second antenna array comprising one or more second subarrays of second antenna elements configured to operate via a second frequency range different from the first frequency range;

wherein the first antenna array and second antenna array are disposed on a same aperture;

wherein the first antenna element is separate from the second antenna element;

wherein any two immediately adjacent first antenna elements and any two immediately adjacent second antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction; and

wherein the first and second antenna arrays are both Rx or both Tx antenna arrays.

12. A modular phased array antenna system comprising a plurality of unit modules, each unit module comprising a phased array antenna as defined in any one of the preceding claims.

13. The modular phased array antenna system according to claim 12, comprising N by N unit modules arranged in a square lattice configuration, wherein N is an integer of at least 2.

14. The modular phased array antenna system according to claim 13, when N is 2, the unit modules are configured to be sequentially excited with a 90° phase difference.

15. The modular phased array antenna system according to claim 13, comprising four groups of unit modules, each group having a plurality of unit modules arranged in a square lattice configuration;

wherein each group of unit modules is configured to share a same phase of excitation; and

wherein the four groups of unit modules are configured to be sequentially excited with a 90° phase difference.

16. A method of making a phased array antenna, the method comprising,

forming an Rx antenna array comprising one or more Rx subarrays of Rx antenna elements configured to receive via a first frequency range; and

forming a Tx antenna array comprising one or more Tx subarrays of Tx antenna elements configured to transmit via a second frequency range;

wherein the Rx antenna array and Tx antenna array are disposed on a same aperture;

wherein the Rx antenna element is separated from the Tx antenna element; and

wherein any two adjacent Rx antenna elements and any two adjacent Tx antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction.

17. The method according to claim 16, further comprising

providing one or more Rx core chips, each Rx core chip associated with an Rx subarray of Rx antenna elements; and

forming one or more Rx feeding networks, each Rx feeding network comprising a plurality of Rx feed lines for communicatively coupling the Rx core chip to the Rx antenna elements of the associated Rx subarray;

wherein each Rx core chip is positioned substantially at the center of the Rx antenna elements of the associated Rx subarray such that the plurality of Rx feed lines have substantially equal length.

18. The method according to claim 16 or 17, further comprising

providing one or more Tx core chips, each Tx core chip associated with a Tx subarray of Tx antenna elements; and

forming one or more Tx feeding networks, each Tx feeding network comprising a plurality of Tx feed lines for communicatively coupling the Tx core chip to the Tx antenna elements of the associated Tx subarray;

wherein each Tx core chip is positioned substantially at the center of the Tx antenna elements of the associated Tx subarray such that the plurality of Tx feed lines have substantially equal length.

19. The method according to any one of claims 16 to 18, comprising,

forming an Rx subarray of four Rx antenna elements arranged in a 2 x 2 lattice; and

forming a first Tx subarray and a second Tx subarray, each Tx subarray comprising four Tx antenna elements arranged in a 2 x 2 lattice;

wherein the Rx antenna elements and Tx antenna elements are arranged in a 4 x 4 lattice.

20. The method according to claim 19, further comprising,

positioning the Rx antenna elements of the Rx subarray at intersections of the second and fourth rows with the second and fourth columns of the 4 x 4 lattice;

positioning the Tx antenna elements of the first Tx subarray at intersections of the second and fourth rows with the first and third columns of the 4 x 4 lattice; and

positioning the Tx antenna elements of the second Tx subarray at intersections of the first and third rows with the second and fourth columns of the 4 x 4 lattice.

21. The method according to any one of claims 16 to 20, further comprising providing two orthogonal feeding ports for each of the Rx antenna elements and Tx antenna elements.

22. A method of making a phased array antenna, the method comprising,

forming a first antenna array comprising one or more first subarrays of first antenna elements configured to operate via a first frequency range; and

forming a second antenna array comprising one or more second subarrays of second antenna elements configured to operate via a second frequency range different from the first frequency range;

wherein the first antenna array and second antenna array are disposed on a same aperture;

wherein the first antenna element is separate from the second antenna element;

wherein any two immediately adjacent first antenna elements and any two immediately adjacent second antenna elements are separated by a distance D along a first direction and a second direction perpendicular to the first direction; and

wherein the first and second antenna arrays are both Rx or both Tx antenna arrays.