

Reconfigurable antenna assembly having a metasurface of metasurfaces

FIELD OF THE INVENTION AND TECHNOLOGICAL BACKGROUND

The invention concerns reconfigurable antennas based on a 'metasurface of
5 metasurfaces' or digital metasurfaces.

The invention can be used in various applications: High data-rate communications (Terabit Wireless), Internet of Things, Homeland security, Space technologies, Avionics and Aerospace Radar, Extended sensing systems for UAVs (incl. insertion in Air Traffic), Automotive systems, Naval systems.

10 Well-known reconfigurable antennas are electronically scanned phased array antennas and are based on two major technological approaches:

- reflect arrays which appears as the main low-cost approach for electronically scanned antennas but this approach suffers from the requirements of phase shifters per radiating elements which increase the
15 final cost and the need of an out-of-plane primary RF source;
- transmit/receive arrays, the main limitation is also the requirement for transmit/receive modules per radiating elements including RF amplifiers and phase shifters increasing the thickness and the cost of the antennas.

Therefore, there is a need for having reconfigurable antennas which are
20 reconfigurable without the need of individual phase shifters (one phase shifter per element of the phased array antenna), which is as planar or conformable as possible so that the size/dimensions and the weight of the antenna are lower than the ones of conventional phased array.

SUMMARY OF THE INVENTION

The invention proposes a reconfigurable metasurface antenna assembly without the above-mentioned drawbacks.

In particular, the invention proposes a reconfigurable antenna assembly based on the leaky wave mechanism through which a surface electromagnetic wave
30 is transformed into a radiated wave when propagating along surfaces with special distributions of surface-impedance.

To this end, the invention concerns an antenna assembly according to Claim 1

The antenna assembly of the invention may also comprises at least one of the following features, possibly in combination:

- the patches (or extreme elements) have dimensions smaller than $\lambda/40$ and preferably comprised between $\lambda/70$ to $\lambda/40$, where λ is the wavelength corresponding to the frequency of the waves to be radiated and are preferably comprised between $\lambda/70$ to $\lambda/40$;
- 5 - each switch comprises a phase change material;
- each switch comprises electronic elements such as diodes or micro-electro-mechanical systems;
- the elements (or textural elements) in the second-scale metasurface have a geometrical area delimited by any arbitrary contour and may have disconnected vertexes in this area of the following pattern: discs, squares, rectangles.
- 10 - The isotropic source is configured for generating electromagnetic waves on the upper surface of the substrate on which the antenna element is formed;

15 The invention thus concerns a metasurface of metasurfaces, which is intended to be referred to the two different scales of the elements.

A metasurface antenna, generally speaking is composed of a set of patterns (eventually self-complementary) as a chessboard antenna for example: meaning that the metallic part of the antenna (set of patches deposited on a substrate) and
20 the complementary part of the surface are equal and can be obtained by a two-dimensional translation).

A metasurface of metasurfaces is a set of metasurfaces, each including a set of patterns much smaller than the wavelength/frequency to be radiated.

The invention has several advantages.

25 The set of patterns of a metasurface of metasurfaces does not depend on the frequency/wavelength to be radiated.

The patterns of self-complementary structures form a planar diffractive grating for which its arrangement allows to select a diffraction order specific to the generation of evanescent waves emitted out of plane.

30 The patterns can be interconnected to form patterns of larger size and shaped to be adapted to the radiation pattern of the antenna assembly and to the polarization of the corresponding waves.

The use of the ground plane on the lower surface of the substrate contributes to the propagation of the waves on the upper surface of the substrate.

Phase shifters are not needed in this antenna; the phase shift is achieved by exploiting the electromagnetic propagation through the array of (meta)material patches forming the metasurface.

With this antenna, it is possible to design the position of the connections
5 between the patches in order to achieve the desired antenna characteristics of beam scanning and reconfigurability.

Advantageously, the connections among the vertexes of the patches will allow to establish a code which can be associated with a particular configuration of beam pointing, almost undetectable by reverse engineering. Therefore, we can consider
10 the antenna as "cryptoed".

The shape/profile of elementary set of metasurfaces allows the control of the incident/radiated signal polarization.

BRIEF DESCRIPTION OF THE DRAWINGS

15 Other features and advantages of the invention will appear in the following description. Embodiments of the invention will be described with reference to the drawings, in which:

- Figure 1 illustrates an antenna assembly according to one embodiment of the invention;
- 20 - Figure 2 illustrates patches of the antenna assembly of Figure 1;
- Figure 3a and Figure 3b illustrate the principle of the connection between vertices of patches of the antenna assembly of the invention;
- Figure 4 illustrates the elementary design of an antenna element of an antenna assembly of the invention;
- 25 - Figures 5a to 5h illustrate several patterns of an antenna element of the antenna assembly of the invention;
- Figure 6 illustrates the corresponding metasurface of the design of figure 4;
- Figure 7 illustrates the excitation of the antenna element;
- 30 - Figure 8 illustrates performances of the antenna assembly of Figure 5.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 illustrates an antenna assembly comprising a single substrate 1, an antenna element 2 formed on the substrate. The substrate comprises an upper

surface 12 on which the antenna element 2 is formed and a lower surface 11 on which a ground plane (not shown) is formed.

The ground plane is constituted by a metallic deposit on the entire lower surface 11 of the substrate 1.

5 The antenna assembly also comprises an isotropic source of spherical electromagnetic waves configured for emitting surface waves on the upper surface of the substrate 1. The electromagnetic waves are preferably microwaves.

10 The substrate is for instance a dielectric such as polymers, glass-epoxy, ceramic, Teflon, glass reinforced hydrocarbon/ceramic laminates or sheets of paper, or semiconducting material, confined liquid crystal, or vanadium dioxide. Any shape can be used and according to the radiation frequency of the antenna a thickness in the range from a few μm to a few cm could be used.

The antenna element 2 and the ground plane are made from conductive materials for instance copper or gold etc.

15 The antenna element is preferably constituted of a two-dimensional periodic array of an alternance of metamaterial micro-patches 21, 22, 23 and apertures 24, 25, 26 defining a first-scale metasurface. In particular, the antenna element is constituted by a multiscale texture of extreme subwavelength patches denoted as "extreme elements" (having dimensions that are small in terms of the wavelength).
20 Each patch cannot radiate independently of each other due to the structure of the antenna element.

The extreme elements are based on conductive materials such as copper or gold for examples, deposited by low-cost conventional technological processes (two or three steps) such as optical or electrical lithography, or inkjet/3D printing.

25 The period and the dimensions of the extreme elements constituting the first-scale metasurface is extremely subwavelength and can range from $\lambda/70$ to $\lambda/40$ at any operative antenna frequency. A preferred period is smaller than $\lambda/65$. As illustrated on **Figure 2**, the antenna element comprises gaps 200 between the vertexes of the extreme elements 21, 22, 23 and switches 211, 212 are disposed in
30 the gaps.

The switches permit to electrically connect the extreme elements through the vertexes for defining a second-scale metasurface having a pattern thus forming the antenna element. **Figure 3a** and **Figure 3b** illustrates the connection or the missing

connection of the patch vertices that determines the equivalent transmission line load.

The second-scale metasurface is thus constituted of patches each constituted of the extreme elements of the first metasurface. The patches of the
5 second metasurface have dimensions larger than the ones of the patches of the first-scale metasurface. The second-scale metasurface is also denoted as a surface of "textural elements" i.e., the patches each constituted by the extreme elements that are connected. The antenna element is a metasurface which is a function of another metasurface that has been tuned. Area numbered 3 on Figure 1 shows
10 textural element of the second-scale metasurface which is constituted of extreme elements of the first-scale metasurface.

In a preferred embodiment, the switching between states may be achieved through either diodes or micro-electro-mechanical systems (MEMS) as localized (relatively) self-contained switches between two points between the extreme
15 elements, due to the small size of the vertex region. Furthermore, other switching mechanisms such that the use of phase changing materials are possible.

By designing the pattern of the metasurface of metamaterial it is possible to modify the antenna radiation pattern and to adjust the surface impedance modulation.

20 In particular, by introducing the possibility to connect the extreme elements of the first-scale metasurface it is possible to consider a first-scale metasurface composed of only two materials and to combine the two materials in order to mimic other materials with dielectric permittivity values that are not only within the values of permittivity of the two media, but also outside of this range.

25 The possibility of mimicking a big range of surface impedances with only two materials is very advantageous in terms of reconfigurability of the antenna element since the reconfiguration is not very complex.

Further, the large possibility of the combination of extreme elements and gap provides a large number of degrees of freedom for the design of the antenna
30 element.

Another advantage to configure the antenna pattern through connections of the extreme elements of a first metasurface is that these connections are not visible to the naked eye. Thus, the antenna element can be considered as "crypted" and not directly obtained by reverse engineering.

An additional benefit can come from the fact that the connections between the extreme elements are only present when the connections are switched on by electronic means. In that case, the modifications of the connections are used to scan the radiated beam and accordingly the connections between the extreme elements will change from time to time.

As mentioned below, the dimensions of the patches (or extreme elements) of the first metasurface are around $\lambda/40$ to $\lambda/70$ compared to the wavelength of the antenna. As an example, for a radiation at 10GHz, $\lambda=30\text{mm}$, the dimensions of the extreme elements are around $500\mu\text{m}$ with a gap between adjacent extreme elements around $10\mu\text{m}$ (under the resolution limit of the naked eye).

In order to design the antenna element, a full wave modeling of the metasurface structure as illustrated on Figure 4 is used. This illustrates an antenna element comprising elliptical patches or circle patches.

Having this analytical design, the antenna element is then designed from a first metasurface.

In particular, by properly connecting several patches, we obtain a so called digital metasurface antenna.

With this configuration of metasurface of metasurfaces (called also digital metasurface), it is possible to obtain any type of metasurface pattern such as described in figures 5a to 5g:

- Figure 5a: squared pattern (the interconnected patches form a square), the antenna is a set of squares;
- Figure 5b: diamond pattern (the interconnected patches form a diamond), the antenna is a set of diamonds;
- Figure 5c: (the interconnected extreme elements form a rectangle) diamond, the antenna is a set of diamonds;
- Figure 5d: disc pattern (the interconnected extreme elements form a disc), the antenna is a set of discs;
- Figure 5e: oval (ellipsoidal) pattern (the interconnected extreme elements form an oval surface), the antenna is a set of oval surfaces;
- Figure 5f: oval pattern at 45° main axis orientation (the interconnected extreme elements form a oval surface oriented at 45°), the antenna is a set of oval surfaces oriented at 45° ;

- Figure 5g: oval pattern at 90° main axis orientation (the interconnected extreme elements form a oval surface oriented at 90°), the antenna is a set of oval surfaces oriented at 90° ;
- Figure 5h: left: disc pattern "coffee bean" (the interconnected extreme elements form a 'coffee bean' pattern), the antenna is a set of "coffee beans". Right disc pattern "coffee bean" at 90° (the interconnected patches form a "coffee bean" pattern), the antenna is a set of "coffee beans").

An antenna having the following characteristics has been experimented and illustrated on **Figure 6** (the corresponding analytical one is illustrated on Figure 4):

- Diameter 3λ i.e. = 5 cm.
- Beam 30° .
- Frequency 18 GHz.
- Substrate characteristics: *Permittivity*, $\epsilon_r = 9.8$, *Thickness*, $h = 0.762$ mm
- fed by a via connected to a central round patch

As known, the metasurface transforms the surface wave into a leaky wave whose radiation direction is controlled by the periodicity d of the modulation. The tensorial reactance is synthesized by a dense texture of subwavelength metal patches printed on a grounded dielectric slab and excited by an in-plane feeder.

In the experimented antenna, the textural elements of the second-scale metasurface have a circular shape with a narrow slit along their diameter like 'coffee bean'; the reactance tensor depends on both the area covered by the patch and the slit tilt angle with respect to the surface wave direction of incidence.

Modifying the area of the textural element produces a variation of the amplitude of the radiation, whereas, rotating the slit tilt controls the polarization of the radiated field.

To excite a surface wave with rotating phase, a resonant circular patch is placed at the center of the multiscale metasurface. The patch is printed at the same level of the multiscale metasurface and is excited in sequential rotation by four pins disposed symmetrically with respect to the patch center. **Figure 7** illustrates this type of excitation of the metasurface via a resonant circular patch placed at the center of the multiscale metasurface.

The role of the patch is double: to excite a surface wave along the metasurface and to radiate directly in the broadside direction for adjusting the radiation pattern level.

The performances of the analytical antenna and the corresponding digital
5 antenna have been established and compared and then illustrated on **Figure 8**.

The conventional antenna (curves 81, 82) and the metasurface of metasurfaces or digital metasurface antenna (curves 83, 84) have been simulated and the results (curves 82, 84) quite similar thus validating the concept of metasurface of metasurfaces or digital metasurface antenna.

CLAIMS

1. Antenna assembly, comprising:

- a single substrate (1) having a lower surface (11) and an upper surface (12);
- 5 - an isotropic source of spherical electromagnetic waves configured for emitting surface waves on the upper surface (12) of the substrate;
- a ground plane formed on the lower surface (11) of the substrate constituted by a metallic deposit on the entire lower surface (11);
- an antenna element (2) formed on the upper surface (12) of the substrate (1) said
- 10 antenna element (2) being constituted by a periodic pattern metasurface formed on the substrate by a texture of subwavelength patches, said antenna element being constituted of
 - a first-scale metasurface defined by a two-dimensional alternation (2) of
 - 15 metal or metamaterial patches (21, 22, 23) having closely spaced vertices in each contiguous element thus forming small gaps;
 - a plurality of switches (211, 212) disposed in the gap (200) between the vertices of the patches, each switch (211, 212) permitting to connect several patches through the vertices for defining a second-scale metasurface having
 - 20 a pattern thus forming the antenna element; wherein each patch has dimensions which do not depend to the frequency of the waves to be radiated, the antenna element being configured for transforming the emitting surface waves on leaky waves.
- 2. Antenna assembly according to Claim 1, wherein the patches have dimensions
- 25 smaller than $\lambda/40$ where λ is the wavelength corresponding to the frequency of the waves to be radiated and are preferably comprised between $\lambda/70$ to $\lambda/40$.
- 3. Antenna assembly according to one of the preceding claims, wherein each switch comprises a phase change material.
- 30 4. Antenna assembly according to one of claims 1 to 3, wherein each switch comprises electronic element such as diodes or micro-electro-mechanical systems.

5. Antenna assembly according to one of the preceding claims, wherein the second-scale metasurface is formed by one of the following patterns: discs, squares, rectangles.