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Numerical Study of a Switchable Polarization for Reflect-array Unit-cell for Satellite Communications

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Abstract

The purpose of this paper is to design and simulate a unit cell that is wideband and multi-polarized for a reflect-array antenna. Bandwidth of structure is greater than 70% of X and Ku bands for satellite applications that reached from two printed dipoles and asymmetric arrow head shape in structure for multi electric and magnetic resonances and used thicker substrate for enhancement of BW by stack up of substrate with different layers. Depending on the antenna usage, the proposed structure can provide dual or triple polarization switching through the use of one or two control bits. Among the innovations of this structure compared to other activities, it can be said that the switching capability to support multiple polarizations occurs in a common wide bandwidth, or in other words, each of the switching modes is not in different single frequency or a bandwidth of frequencies. Comparing the switching modes of the proposed design with other existing control structures, the feature of maintaining the polarization of the feeding antenna or converting it to orthogonal polarization in different bits distinguishes the proposed structure. The proposed design has a new geometrical structure and considering that it can have the main polarization of the feeding antenna, its orthogonal polarization and even circular polarization in any switching mode, it has a relatively simple geometry, which reduces the complexity of the construction mechanism.

Keywords: Reflect-Array, Wideband unit Cell, Multi-Polarized unit Cell, Configurable Structure.

1- Introduction

When it comes to array antennas, one of the most common array structures are phased array antennas whose most important application is to rotate the radiation pattern electrically. In phased array antennas, the technique of rotating the main beam of the radiation pattern creates a suitable phase difference between the elements of the array. Reflect-array antennas were suggested by some researchers to be a combination of phased array antennas and plate reflector antennas, but in new studies, the reflect-array is defined by the properties of the unit cell. In modern commercial applications, subscribers expect better quality and speed for telecommunication services, such as video calls and internet, so wide bandwidth and maximum utilization are necessary.

The capability of sending and receiving multiple polarizations of waves is a significant feature of antennas. If the reflect-array antenna has a unit cell that is capable of supporting multiple polarizations, a simple single-polarization feed antenna can receive any wave that has an unexpected change in polarization along its propagation path. The structures investigated in Refs. [1] - [6] can achieve a wide bandwidth in the X or Ku bands; their methods include increasing the dielectric thickness, using multiple resonance elements, layering the structure and so on. For example, in [1], the bandwidth increased by using multiple resonance elements, which were printed dipoles. However, increasing the number of resonators made the structure look like a high-pass filter for rotating the incident wave polarization. The broadband characteristic was achieved in [3] by combining the use of a multi-resonant element and a slotted rectangular patch element. Reference [4] investigated a novel bandwidth improvement method, which combined the multilayer approach with the sub wavelength element technique. A taper resonator and a thick substrate were utilized for the design and construction of an ultra-wideband polarization conversion meta-surface, which was made using a double-head arrow structure [6].
Wave polarization conversion may occur unintentionally due to scattering or reflection from objects on the wave

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propagation path, so the antenna should support all types of polarizations, especially circular polarization, to receive the wave. The designs in Refs. [6] - [10] were proposed particularly for the conversion of polarization types. In [6], an ultra-wideband linear polarization rotator was designed by combining two typical symmetry-broken structures, i.e., oblique V-shaped and cut-wire resonators, which were capable of rotating a linear polarization to orthogonal one. In [7] coupled split ring resonators (SRRs) functioning as meta-atoms or unit cells comprise two concentric rings. Each of the rings has a slit positioned at the corner and rotated by 180° with respect to the other ring. The polarization transforming capability is stable for wide oblique incidence angles up to 60° for both transverse-electric and transverse-magnetic polarizations. Moreover, this capability acts as a meta-mirror, which preserves handiness of the circular polarization upon reflection. The structure in [9] consists of a square with two curves on the top right and lower left corners and a square SRR responsible for linear-to-linear and linear-to-circular polarization conversions in two frequency bands. A single layer mirror-symmetric anisotropic meta-surface is proposed in [10] using a novel unit cell having fish-like structure. The polarization conversion of the fish-like structure is achieved by different geometries along the x and y axes, as a result of different phase responses along the two orthogonal axes.

In this article, the proposed structure has reached a wide bandwidth in the X and Ku bands from the combination of multi frequency resonators that include two printed dipoles and asymmetric arrow head along with increasing the thickness of the substrate. The proposed simple structure can support multiple polarizations in ultra wide bandwidth compared to the other unit cells. The multiple polarizations are achieved by changing the impedance in a part of the structure, so it is adjustable. Maintaining feed antenna polarization, converting linear to orthogonal polarization and linear to circular polarization conversion in a simple structure distinguishes it from the other investigated unit cells. In addition, the ability to support multiple polarizations occurs in a same bandwidth. Another advantages of this structure is that the number of control bits can be reduced according to the application. In other words, if the types of conversion polarization are limited, the structure can be controlled with fewer control bits. In the following, we have theory, design, simulation, performance analysis sections. In the theory section, the concept of microstrip reflect array and polarization and its conversion and the introduction of important parameters of polarization converter structures are explained, in the next section, we will focus on the design and simulation and how it works and solve the challenges of its construction with alternative designs.

2- Theory

2-1- Microstrip Reflect-Array Structures

The first subject that needs to be mentioned is whether the microstrip reflect-array can be a suitable alternative to parabolic reflectors, which is supposed to work specifically on the design of a unit cell with specific characteristics for the reflect-array? To compare these two types of reflectors, the first one is the ability of the structure to focus and reflect the reflected wave when the feed antenna is not in front. As can be seen from the fig. 1, for the parabolic reflector, the reflected field is non-resonant, and due to the curvature of the geometry of the structure, the reflection of the waves will be in the direction in front of the reflector, while in the microstrip reflection array, there are two types of reflected fields: resonant and non-resonant fields. The noteworthy point is that such structures reflect the non-resonant field structure in the opposite direction of the incident wave but with the same incident angle due to the substrate space and the flatness of the ground plane. Resonant fields that are caused by the layer of resonant elements, despite being flat, naturally radiate in the direction perpendicular to the normal vector of the structure plane, so the resonant fields are reflected in the direction in front of the reflector likes parabolic reflectors [11].

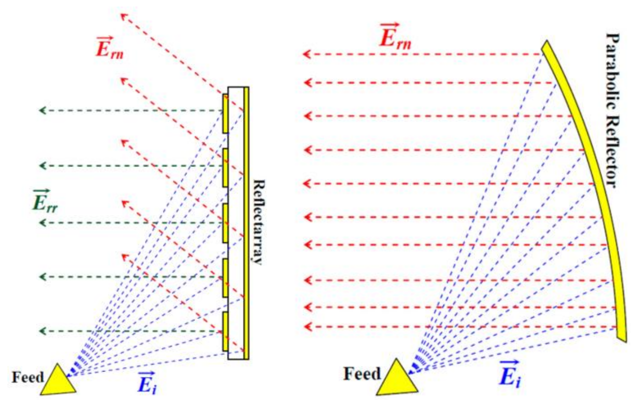


Fig. 1 Reflection of the incident signals from the surface of the reflect-array and parabolic reflector [11]

Another important point is the incident and reflection phase of the wave in the reflect-array antenna. In parabolic reflector antennas, according to the geometry of the structure, if the feeding antenna is in front of the reflector, the phase difference caused by different locations of the reflector structure is geometrically compensated to a great extent, but this case for the reflect-array that has a flat geometry cannot be compensated in this way but several techniques have been proposed for microstrip reflect-array structures that solve this problem. One method is to use microstrip patches of the same size with stubs of variable length to control the reflection phase but a better approach is to use patches of variable size to control the phase. The concept of using variable size rectangular patch elements to vary the reflection phase can be extended to other types of elements, such as circular patches, annular ring elements, and crossed dipole elements.

These elements will respond to both vertical and horizontal polarizations, which is an advantage for dual linear or circularly polarized antennas. Another method is to use multiple layers of the structure in such a way that the phase compensating elements are placed in another layer compared to the layer containing resonance elements. Finally, it should be said that with such methods, the incident phase can be compensated in different feeding locations and also the reflected phase can be controlled, and this issue should be taken into account if the proposed unit cell were to be designed as an array [12].

2-2- Wave Polarization

The theory behind the subject needs to be explained first. In this section, it is necessary to define the polarization of the propagation wave that will be supposed the desired unit cell of the reflect-array has capable of conversion polarization. The property of an electromagnetic wave that identifies the time-varying direction and relative magnitude of the electric field vector is what defines polarization of a radiated wave [13]. In order to increase the conceptualization of this sentence, we must focus on an example to continue the explanation. If the relationship between the electric field of an arbitrary wave at the time and the phase domain from [14] is as follows:

$$\overrightarrow{E(z)} = \overrightarrow{a_x}E_1(z) + \overrightarrow{a_y}E_2(z) = \overrightarrow{a_x}E_{x0}e^{-jkz} + \overrightarrow{a_y}E_{y0}e^{-jkz}e^{j\varphi} \quad (1)$$

$$\overrightarrow{e(z,t)} = \overrightarrow{a_x}E_{x0}\cos(\omega t - kz) + \overrightarrow{a_y}E_{y0}\cos(\omega t - kz + \varphi) \quad (2)$$

By knowing the relationship between the time domain of the electric field, it is possible to plot the pattern of polarization of the electric field of the wave, or in better words, its type of polarization will be achieved. First step, in relation to the time domain of the electric field, a fixed plane in the direction of propagation should be considered, which is usually considered to be the z = 0 plane for simplicity, so the above relation is simplified as follows:

$$z = 0 \rightarrow \overrightarrow{e(t)} = \overrightarrow{a_x}E_{x0}\cos(\omega t) + \overrightarrow{a_y}E_{y0}\cos(\omega t + \varphi) \quad (3)$$

We are now required to examine the field's relationship during a time cycle and then connect the ends of the electric field vector at various times in the right-handed Coordinate axis system. As it can be seen from the relation (3) obtained, the parameters E_{x0},E_{y0} show the amplitude of the electric field components and the parameter φ which represents the phase difference between the two components of the electric field. The difference in the kind of wave's polarization originates from the different values of these parameters. So the question arises as to what kind of problem the polarization difference between the waves create which can be answered that the difference in polarization of the fields will directly affect the amplitude of the field received by the receiving antenna which has a different polarization compared to the transmitting antenna, so in the communication links, it is necessary to use co-polarization antennas or suitable structures that convert polarization with maximum efficiency.

2-3- Kind of Polarization Conversion

The wave amplitude and phase parameters determine the polarization of the wave. In general, the types of polarization are divided into linear, elliptical and circular polarization. Linear polarization is formed when there is no phase difference between the components of the electric field, and the type of linear polarization is different for different conditions between the amplitude of the components. For example, in equation (3) if E_{y0}=0, the linear polarization will be horizontal and if E_{x0}=0, it will be vertical. Another condition of linear polarization is oblique when $E_{x0}\neq0, E_{y0}\neq0$ will be reached. Circular polarization is formed when their amplitude is the same, the phase difference between the components is 90 degrees. Also, for elliptical polarization, a phase difference of 90 degrees between the components is necessary, with the difference that the amplitude of the components will be unequal.

By knowing the important parameters in determining the polarization, the type of polarization can be easily recognized. Now are going to discuss about conversion of polarization into each other. Polarization conversion is usually done with the help of elements that transmit or reflect electromagnetic waves with a specific polarization that are radiated to them with another type of polarization. Considering that our research in this article is based on reflector structures, parameters should be defined for polarization conversion, which are obtained from the parameters extracted from the simulation or measurement of reflector structures. In reflector structures, the reflection coefficient is the most important parameter that can be reported.

To show the degree of polarization change, reflection coefficient can be used in such a way that is checked separately for two specific types of polarization. For example, the reflection coefficient can be defined as, in the first case, Co-polarization reflection coefficient is the ratio of the reflected wave with horizontal polarization to the incident wave with horizontal polarization (R_{xx}), and in the next case, Cross-polarization reflection coefficient is the ratio of the reflected wave with the polarization Vertical to the incident wave with horizontal polarization (R_{yx}). Therefore, for polarization conversion, the parameter of polarization conversion ratio (PCR) and polarization maintenance ratio (PMR) are defined from [7] with the help of reflection coefficients concept as follows:

$$\mathrm{PCR} = \frac{|R_{yx}|^2}{|R_{yx}|^2 + |R_{xx}|^2} \quad (4)$$

$$\mathrm{PMR} = \frac{|R_{xx}|^2}{|R_{yx}|^2 + |R_{xx}|^2} \quad (5)$$

The axis ratio is another important parameter that actually shows the degree of circular polarization, and this parameter is reported in the research because of investigate circular polarization. When we change the polarization from a horizontal or vertical linear state to a 45 degree inclined linear polarization or to a circular polarization, we go to the axis ratio to distinguish between the two states, because the reflection coefficients alone do not show the difference between the said two states. According to the contents of the polarization theory section, the amplitude of both components is equal, but the phase difference between the components determines whether it is linear at 45 degrees or circular, and both amplitude parameters and phase difference exist in relation to the ratio of the axes taken from [8]. The axial (AR) relation is given by:

$$AR = \left\{\frac{|R_{xx}|^2 + |R_{yx}|^2 + \left(|R_{xx}|^4 + |R_{yx}|^4 + 2|R_{xx}|^2|R_{yx}|^2\cos(2\Delta\varphi)\right)^{\frac{1}{2}}}{|R_{xx}|^2 + |R_{yx}|^2 - \left(|R_{xx}|^4 + |R_{yx}|^4 + 2|R_{xx}|^2|R_{yx}|^2\cos(2\Delta\varphi)\right)^{\frac{1}{2}}}\right\}^{\frac{1}{2}} \quad (6)$$

$\Delta\varphi$ refers to phase difference between co- and cross-polarized reflection coefficients. If this ratio is below 3 dB on the logarithmic scale or below 1.41 on the linear scale, the polarization can be considered circular and above it elliptical or linear.

3- Design and Simulation

In the structure design section, the subjects such as geometry of the structure, converting polarizations, widening the bandwidth with a high percentage polarization conversion energy, controlling multiple polarization states, and the effects of the design parameters are investigated. The proposed structure is simulated in the CST software. Including the unit cell boundaries and Floquet port, the final dimensions of the unit cell are 5.5 $mm \times 5.5\ mm \times 3\ mm$, with the substrate consisting of two layers of RO4003 and one layer of PTFE.

3-1- Analysis of Structure Geometry

Fig. 2 shows the proposed structure that the main resonances elements can be placed at different angles to the coordinate system, but what angle can create the optimal and suitable state for polarization conversion? In general, α determines the degree of polarization conversion with horizontal or vertical polarization of the incident wave. According to the determination of this angle, the reflection components of the wave are affected and change the amount of conversion. For example, if we are looking for a linear conversion of the polarization of the structure, the created dominant surface current should be perpendicular to the incident wave component.

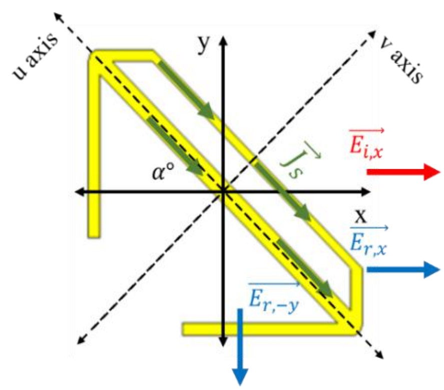


Fig. 2 Placement of proposed geometry in unit cell

For the fig. 2 that shows the placement of a resonant element such as a printed dipole with an arbitrary angle 0<α<90, if it is assumed that the incident field emitted in the z direction has a horizontal polarization, according to the previous sections, the electric field from the relation (2) with the assumption $\varphi = 0, E_{y0}$=0 can be rewritten as follows:

$$\vec{e_i} = \vec{a_x}E_{ix0}\cos(\omega t - kz) \quad (7)$$

According to the boundary conditions, a surface current will be created on the surface of the structure, which can be extracted according to the electromagnetic relations. In general, according to the geometry of the surface current structure, surface current will have both x and y components:

$$\vec{J_s} = \vec{a_x}J_{sx}\cos(\omega t + kz) + \vec{a_y}J_{sy}\cos(\omega t + kz + \varphi_j) \quad (8)$$

Also, we have the following relationship between electric field and surface current:

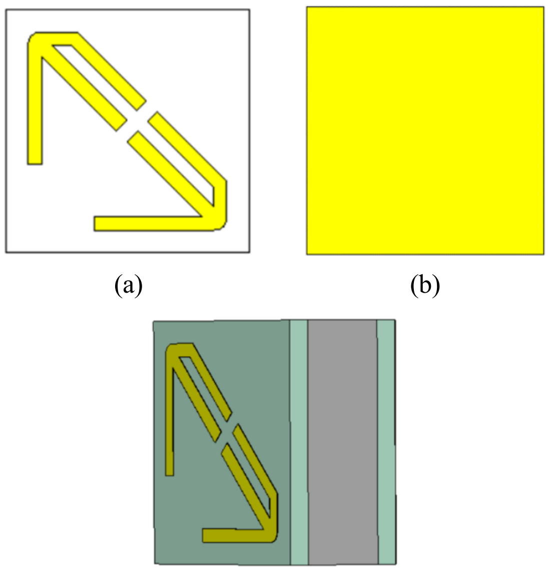
$$\vec{J} = \sigma\vec{E} \quad (9)$$

$$\vec{E_r} = \vec{a_x}\frac{J_{sx}}{\sigma}\cos(\omega t + kz) + \vec{a_y}\frac{J_{sy}}{\sigma}\cos(\omega t + kz + \varphi_j) \quad (10)$$

The reflected electric field created by the structure has the ability to remove the x or y component of the incident field. If we pay attention to the arbitrary angle α, we will realize that according to its value, the range of the x, y component of the surface current and then the reflected electric field can be controlled. Considering that this design is supposed to be controllable for multi-polarization, it is better that this angle is such that both x and y components are created, so for the design of such a unit cell, the optimal value is α=45°. It should be mentioned that the control points of the structure will be determined in such a way that the change of the impedance of the structure makes various coefficients of the surface current components in different states.

3-2- Electric and Magnetic Resonances

In [6], an arrowhead structure is proposed to achieve a wide bandwidth and converting linear to orthogonal polarization. The capability of control the rotated structure was added in the unit cell presented in [2]. Our proposed unit cell with changes in the arrowhead structure and adding another printed dipole creates the bandwidth required for satellite applications. The proposed unit cell has also some more advantages compared to [6] and other researches. These are supporting multi-polarization such as maintaining polarization of feed antenna, conversion of the feed antenna`s linear to orthogonal and circular polarizations. The Fig. 3 shows the final structure as a 3D model.



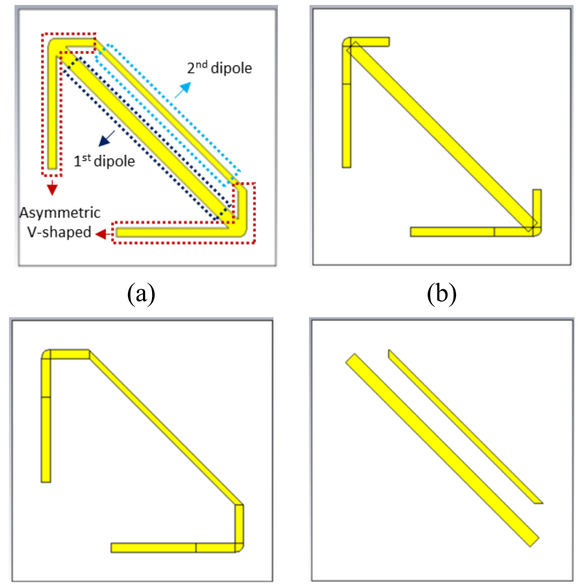
(a) (b)

(c)

Fig. 3 Schematic of proposed structure a) top view b) bottom view c) 3D view

First, simulation investigates the number of natural electric and magnetic resonances of the structure with the presence or absence of the considered resonator in the structure, as shown in Fig. 3. It should be noted that if the structure creates more resonances with closer frequencies in the spectrum, a wider bandwidth can be achieved; how these natural resonances are identified? It is evident that the plasmon resonance Eigen-modes of the structure can be excited when electric components are along the v and u axes [6]. In other words, to extract the Eigen-modes of a structure, the field radiation should be in the direction of the structure geometry axes. The proposed structure uses an asymmetric V-shaped and two dipoles. The fields excitation should be in the direction of u and v axes. Different electrical length of each excitation is seen for the V-shaped structure, so the desired frequency spectrum is investigated for creating resonance in different modes. To judge whether a resonance is electric or magnetic, it is better to determine the resonance type through surface current distribution.

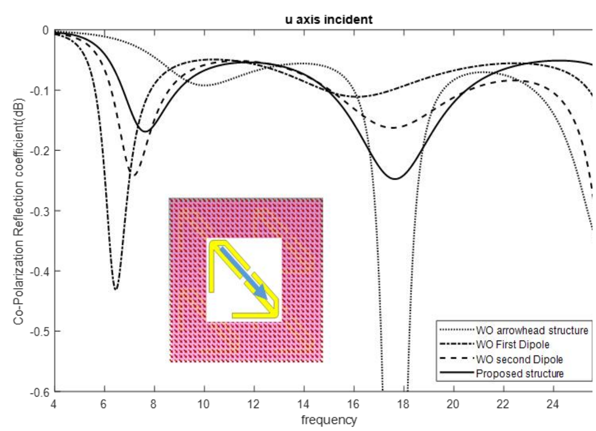
The investigation of natural resonances is done as in the schematics given in Fig. 4 for the cases where one of the resonators does not exist, and a comparison is made with the proposed final state. Fig. 5 shows the reflection coefficient of the structure when incident wave is in the direction of the u and v axes, so the final structure produces resonances with appropriate number and value (solid line) compared to other states for the desired bandwidth. It should be pointed out that this investigation was done only for one of the switching states with the primary dimensions.



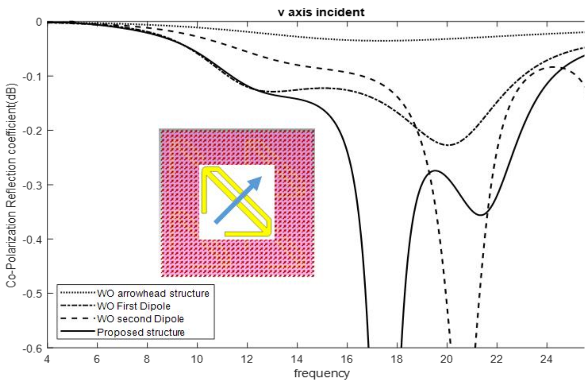
(a) (b)

(c) (d)

Fig. 4 Different cases of structure for investigation of natural resonances a) proposed structure b) Without second dipole c) Without first dipole d) Without arrowhead structure



(a)



(b)

Fig. 5 Co-polarization reflection coefficient for different cases fig.3 in a) u axis incident b) v axis incident

3-3- Control Bits for Polarization Conversion

As shown in Fig. 6, the structure has two control points, which can reduce the number of command bits according to the usage. Table 1 shows different switching states and polarization conversion. According to this table, by controlling the impedance of these points (with different operating devices such as PIN diodes) in different states, it is possible to change the linear polarization from vertical to horizontal and vice versa or reflect the same polarization of the incident wave (polarization of feed antenna). Moreover, for this purpose, both control points are commanded with the same bit, so one command bit is enough. Another mode of control adds the ability to convert linear polarization to circular polarization based on the difference between the command bits, so we have to use two control bits. If actual control devices are placed in the structure, the inductive and capacitive effects of the control devices can be neutralized by several techniques. For instance, using a radial stub structure achieves the above goal. The radial stub structure is only visible in terms of direct current and is eliminated at high frequencies by the inductive and capacitive effects of the control device.

It should be noted that conversion is defined for a unit cell, and if the unit cell has to be used in the design of a reflect-array, the unit cell rotation technique can be used to create a 180-degree phase difference. Therefore, this structure has no weakness compared to the design in Ref. [2] in terms of creating a phase difference in the array by the unit cell rotation technique. Furthermore, in this structure, for the rotation of the main beam of the radiation pattern with the mentioned states, we have several phase differences between the unit cells. This creates smaller phase differences and increases the accuracy of rotation.

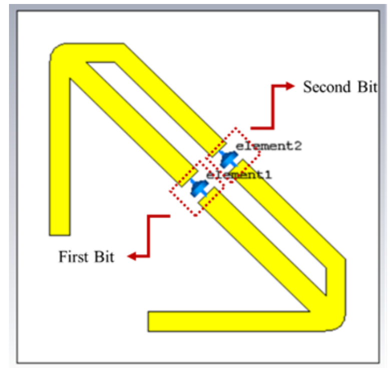


Fig. 6 control point of unit cell in schematic

Table 1: States of switching unit cell

Bits	Impedance of Bits	Polarization of Incident Wave	Polarization of Reflected Wave
00	LL[1]	Vertical/Horizontal	Horizontal/Vertical
11	HH[2]	Vertical/Horizontal	Vertical/Horizontal
10	HL	Vertical/Horizontal	Circular Polarization
01	LH	Vertical/Horizontal	Circular Polarization

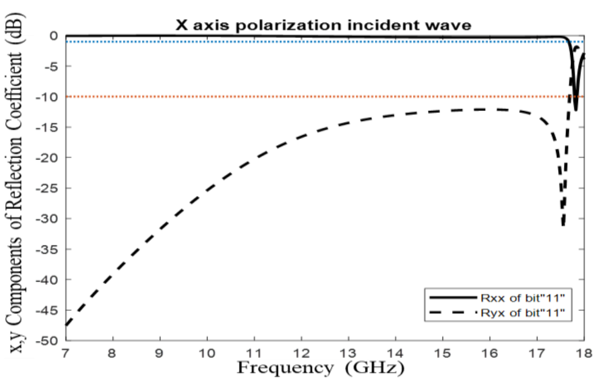
As mentioned, this structure can be used for the conversion of several polarizations. In the first state, when bits are "1", according to Fig. 7-a, the response of R_{xx} is higher than -1 dB and that of R_{yx} is lower than -10 dB in the bandwidth of 8-17 GHz. Therefore, the wave polarization does not change from horizontal to vertical because the reflected wave also has a good amount of horizontal polarization, and the linear polarization of the feed antenna is reflected. In the second state, when bits are "0", according to Fig. 7-b, the response of R_{xx} with a lower value of -10 dB and that of R_{yx} with a higher value of -1 dB indicate the conversion of the polarization from horizontal to vertical. The degree of linearity is determined by the axial ratio (AR), the results of which are given below. For the third and fourth states of the bits, i.e. "10" and "01", Figs. 7-c and 7-d show the response amplitudes of R_{xx} and R_{yx} in both states around -3 dB, with the difference that the third state has better response. Accordingly, we have relatively equal values of both x and y components in the reflected wave. However, to prove polarization conversion from linear to circular, it is better to obtain the AR parameter value as well.

After obtaining the reflection coefficients response, we extract the polarization conversion ratio (PCR) and polarization maintaining ratio (PMR) for different bits from the simulation. Therefore, we can determine the appropriate limits in the optimization of the structure parameters with the percentage of energy conversion to compare the structure with previous designs. Fig. 8 shows the polarization conversion ratio and polarization maintaining ratio of the structure for different command bits. Further analysis of this parameter reminds us that if the limit of the polarization

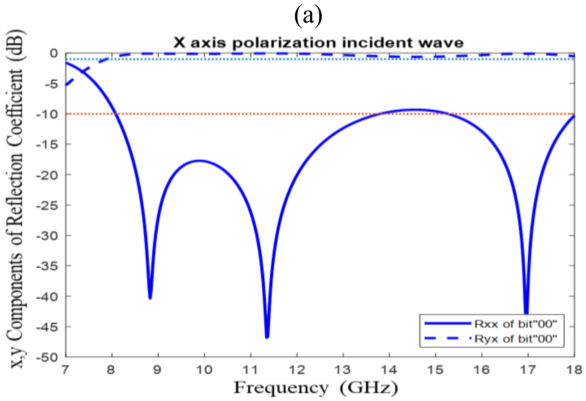
[1]. First bit and Second bit should be low impedance
[2]. First bit and Second bit should be high impedance

conversion ratio is considered to be higher than 70%, it can be claimed that regardless of the AR parameter, the polarization conversion cannot be circular, and the polarization is converted from a linear state to another type of linear state. In some studies, the limit of the conversion ratio is set to 50%. However, a higher limit for the conversion ratio is considered to achieve a higher efficiency of the structure for linear to linear polarization conversion. Therefore, the conversion ratio limit is 80-85% for bits "00", and the same limit is considered for the maintaining ratio of bits "11". With this limit value, a wide bandwidth is obtained for the structure. Of course, for bits "10" and "01", the limit values should be considered around 0.5. This is because the structure converts the polarization from linear to circular, and the first condition of circular polarization is that the x and y components of the wave are equal, so the polarization conversion or polarization maintaining for these bits should be around 0.5.

In addition to obtaining the previously mentioned parameters, AR should also be obtained. This parameter can determine the circularity of the wave polarization, and it is extracted from the relations in Ref. [8]. Fig. 9 shows that bits "10" and "01", which have the same component amplitudes and 90-degree phase difference between the components, have circular polarization. Moreover, the AR diagram of these states is below 1.41 on the linear scale in the desired bandwidth, so circular polarization is confirmed.



(a)



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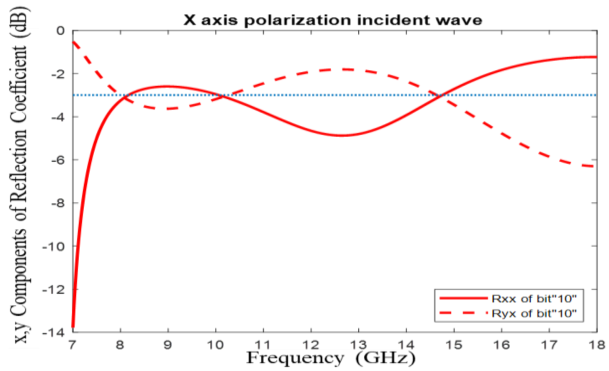

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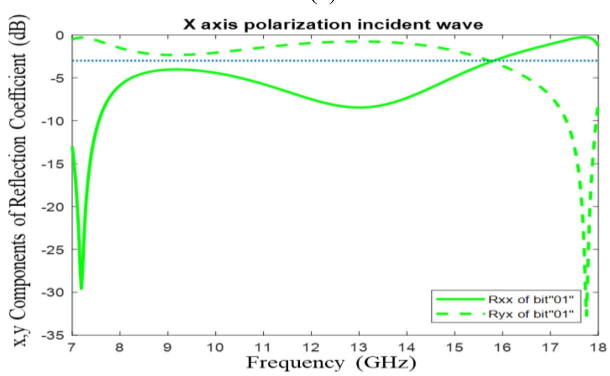


(d)

Fig. 7 Response of R_{xx}, R_{yx} simulation for different bits in x axis incident wave a) bits “11” b) bits “00” c) bits “10” d) bits “01”

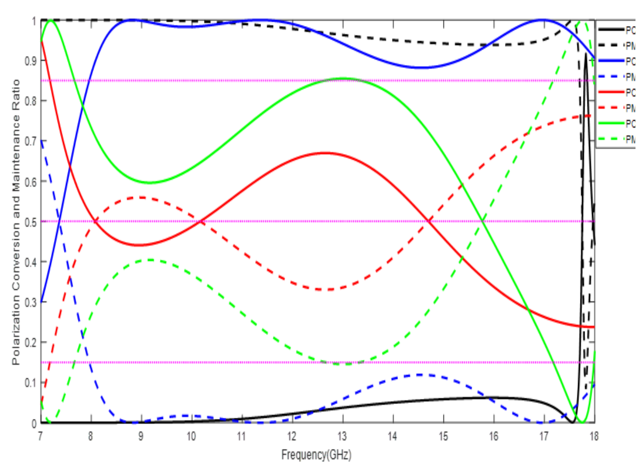


Fig. 8 Polarization conversion and maintenance ratio of different bit control

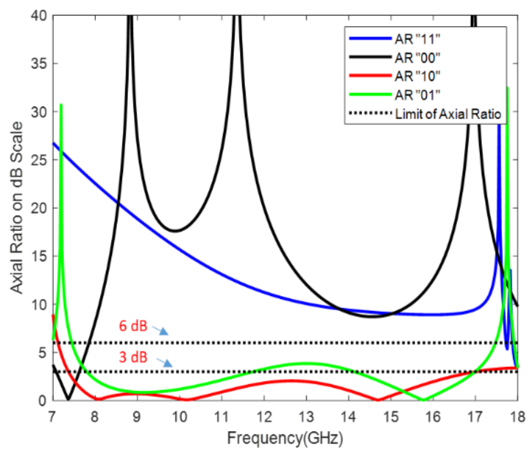


Fig. 9 Axial Ratio on linear scale of different bit control

3-4- Surface Current

In this section, we simulate the surface current generated on the structure. According to Eq. (9), the electric field is produced by the surface current, so it is in the same direction as the surface current. The surface current and the reflected electric field vectors related to different bits of the structure can be shown by simulation and assuming that the incident wave has linear polarization in the x-direction. Fig. 10-a shows the surface current generated in state "11". In this figure, the concentration and intensity of the surface current vectors Js_n are shown in different parts of the structure. According to the current intensity, the final result is dominantly in the x-direction. Fig. 10-b shows the surface current generated in the state "00", where the components of the surface current and the reflected field have larger values in the y-direction. The components of the electric field along x and y in state "10" have almost equal values as shown in Fig. 10-c. States "11" and "10" have similar field concentration, with the difference that in state "11", the current intensity attributed to Js_2 is greater than that in state "10". Therefore, in state "11" current intensity has a greater effect on the x component, and in state "10", it has a slight effect on the x component for the surface current Js_1. Accordingly, in the case of "10", it can be claimed that the x and y components have the same values. Due to the similarity of "01" and "10" bits, one of them was checked. It should be noted that the surface current pattern gives a qualitative indication on the state of the electric field. To determine the exact type of polarization, one should assess the PCR or AR parameters, which report the type of polarization with a number and some criteria, as examined in the previous sections.

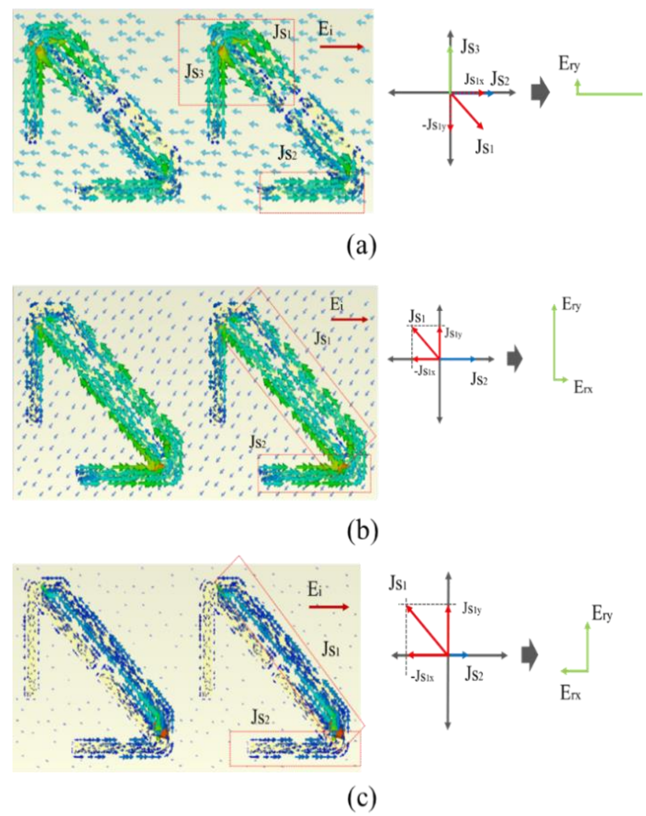


Fig. 10 Surface Currents and analysis of Js_n Vectors have created by x-direction incident wave a) bit "11" b) bit "00" c) bit "10"

3-5- Parameters Study

The design parameters of the structure play an important role in its response and the length/width of dipoles and tentacles. Moreover, the thickness and dielectric constant (ε_r) of the substrate are investigated in the frequency response of the structure in this section. Fig. 11 shows different parameters in the design of the proposed structure. It should be mentioned that the investigations were made only for the reflection coefficient of the polarization conversion of bits "00". Additionally, checking the unfavourable changes of the frequency response is sufficient for only one of the switching modes.

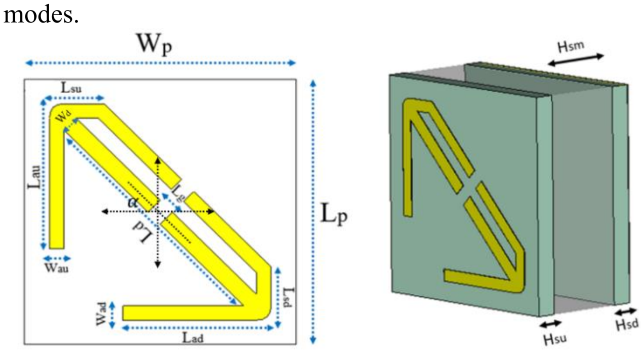
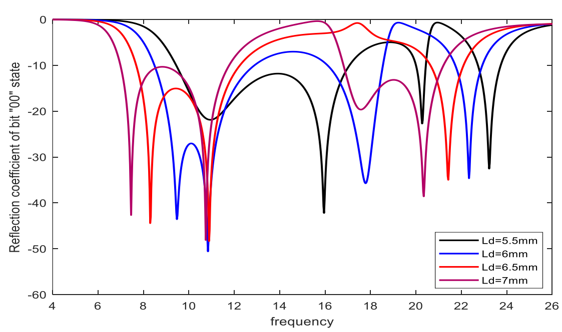


Fig. 11 Designed parameters of structure

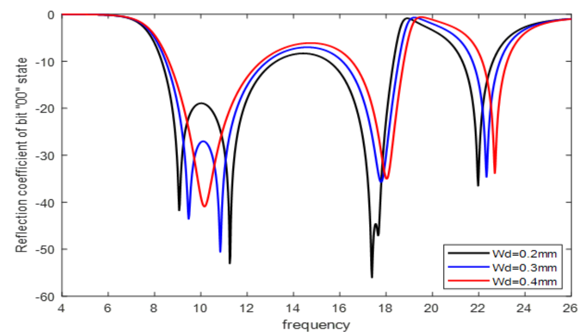
The first parameter, L_d, is the length of the dipoles. If L_d increases, the inductance effect increases in one of the resonant circuits of the structure. In addition, the capacitive effects created between printed dipoles and the ground plane and between two printed dipoles increase, and according to the relation $f=\frac{1}{\sqrt{LC}}$, the frequency of the resonant circuit of the modified element is reduced, and the circuit operates like a filter with a lower high cut-off frequency. Moreover, since the rest of the parameters are fixed, the other resonance frequencies remain constant. Then, according to the change in the resonance frequency of the printed dipole element, multiple resonance frequencies move away from each other. Therefore, this parameter plays an important role in shifting the desired frequency band, as can be seen in Fig. 12-a. It should be noted that because the dipoles are parallel and connected at the corners of the structure, it is not possible to extension only one of them.

The next parameter, W_d, is the width of the first dipole, which creates capacitive effect with the second dipole and the ground plane. W_d did not effect on all created resonances. Increasing W_d lead to both of the aforementioned capacitive effects increase. Because the capacitance between the dipoles increases according to the relation ($C = k\frac{A}{d}$) with the decrease of the distance between the two strips. The capacitance with the ground plane increases due to the increasing surface of the strip, resulting the dependent resonances shift to lower frequencies. Fig. 12-b shows adjacent resonances of structure close to each other, because of the depended resonances shifting due to the increase in W_d.

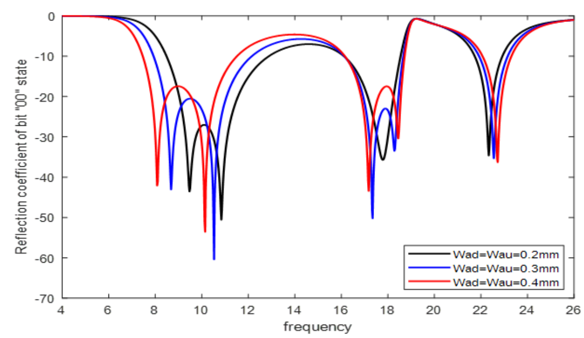
The parameter W_{au} shows the strip width of the entire structure except for the first dipole. Increasing W_{au} shifts the bandwidth towards lower frequencies because of capacitance enhancement of most resonant circuits of the structure. Fig. 12-c shows the effect of changes in W_{au} on the frequency response. Natural resonances change with the length of arrows. Fig. 12-d and 12-e show the effect of changes of L_{sd} (or L_{su}) and L_{ad} (or L_{au}).



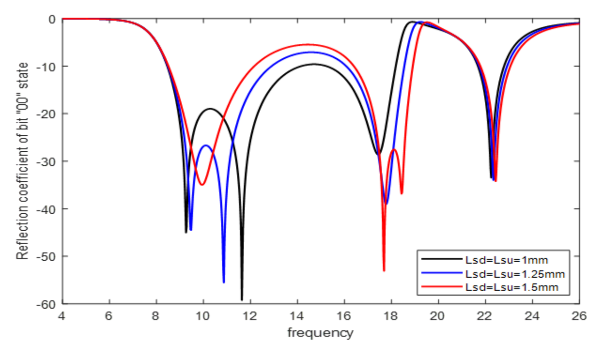
(a)



(c)



(d)



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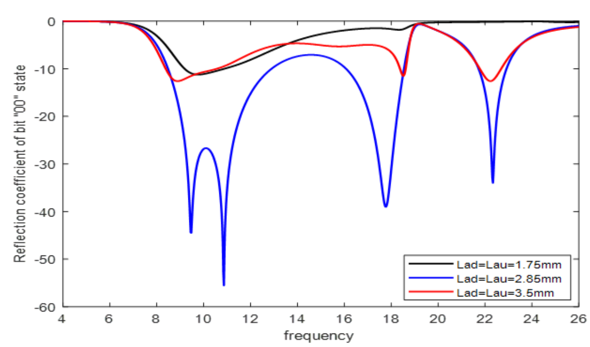
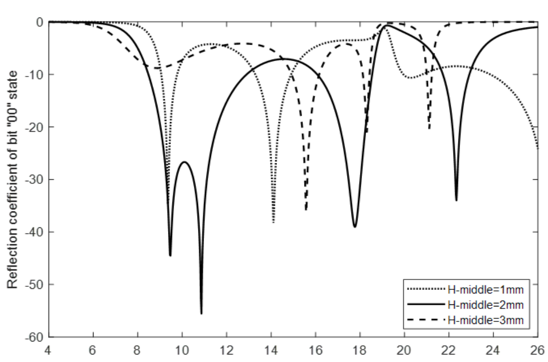


(f)

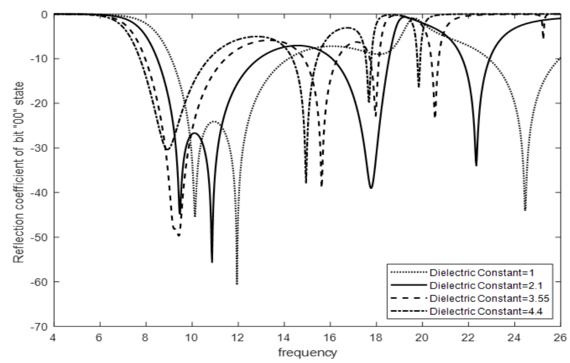
Fig. 12 Investigation on effects of changing parameter value a) constant parameter: $W_d = 0.3$ mm, $W_{ad} = W_{au} = 0.2$ mm, $L_{ad} = L_{au} = 2.85$ mm, $L_{sd} = L_{su} = 1.25$ mm b) constant parameter: $L_d = 6$ mm, $W_{ad} = W_{au} = 0.2$ mm, $L_{ad} = L_{au} = 2.85$ mm, $L_{sd} = L_{su} = 1.25$ mm c) constant parameter: $L_d = 6$ mm, $W_d = 0.3$ mm, $L_{ad} = L_{au} = 2.85$ mm, $L_{sd} = L_{su} = 1.25$ mm d) constant parameter: $L_d = 6$ mm, $W_d = 0.3$ mm, $W_{ad} = W_{au} = 0.2$ mm, $L_{au} = L_{ad} = 2.85$ mm e) $L_d = 6$ mm, $W_d = 0.3$ mm, $W_{ad} = W_{au} = 0.2$ mm, $L_{su} = L_{sd} = 1.25$ mm

After investigating the parameters of the dipoles and arrowhead structure, we study the substrate of the structure. The substrate thickness has the greatest impact on the capacitance between the structure elements and ground plane. The stack up of different substrate layers defines the effective dielectric constant (ε_{eff}). Changing the thickness of the middle layer of substrate in addition to increasing the distance between the capacitor plates also affects the effective dielectric constant, so we do not have a specific frequency shift in the frequency response. Furthermore, a change in the middle layer material shifts the multiple resonances, but the collective effect of these shifts can be such that they do not broaden the bandwidth. Fig. 13-a shows the simulation results for a thickness of 1 mm. A careful look at this figure reveals that both the distance between resonances and the reflection coefficient in the frequency spectrum increase. Moreover, for a thickness of 3 mm, in addition to these increases, an upward frequency shift occurs. The thickness of 2 mm leads to the most optimal results in terms of the previously mentioned parameters and the desired bandwidth range.

Besides thickness, another very important factor is the substrate material, so to choose an appropriate substrate, ε_r of different layers has to be studied. The changes of the dielectric constant of the middle layer directly affect the capacitive effects. By increasing ε_r of the middle layer, the lower frequency limit of the band shifts towards smaller values. As can be seen from Fig. 13-b, air as substrate with $\varepsilon_r = 1$ has a little more bandwidth and increases the efficiency of the structure. Substrates such as RT5880 and PTFE with dielectric constants of respectively 2.2 and 2.1 can be used to achieve the desired frequency response, with the difference that the rest of the parameters need to be adjusted for a better result. To further investigate the effect of other substrates, we simulate the structure with substrates that have greater dielectric constants. After examining the effects of various parameter values of the proposed structure to achieve the desired bandwidth for the four switching modes, these values are adjusted and chosen as given in Table 2. It should be noted that the simulation study results presented in the previous sections are reported with the final optimal parameters.



(a)



(b)

Fig. 13 Investigation on effects of changing parameter value of substrate's middle layer a) Thickness b) Dielectric constant

Table 2: Final values of proposed structure's parameter

Parameters	L_p	W_p	L_d	W_d	L_g	L_{ad}	L_{au}
Value(mm)	5.5	5.5	5.5	0.35	0.35	2.7	2.7
Parameters	L_{sd}	L_{su}	W_{au}	W_{ad}	H_{sm}	H_{su}	H_{sd}
Value(mm)	0.81	0.81	0.3	0.3	2	0.5	0.5

3-6- Radiation Pattern

The basic parameters of a proposed unit-cell have been investigated. The radiation pattern was examined. The unit-cell structure is independent of the linear polarization of the incident wave in the x or y direction, and the defined function is valid for both of these directions. In this section, it is also claimed that the radiation pattern will be the same when excited with either of these polarizations, so only one of these radiation modes is considered. Since the radiation pattern is the same in all bits, only bit 00 is shown. Fig. 14-a and 14-b show the two-dimensional radiation pattern in the φ=0 and 90degrees planes of the unit cell at frequencies of 10 and 14 GHz, respectively. Fig. 14-c shows the gain versus frequency.

Since the gain of the unit-cell is low, a significant amount of reflected power is not anticipated. Therefore, it is necessary to investigate that how many cells can be used to achieve a suitable gain. According to other research and rough estimates, a 30 cm× 30 cm physical surface would have a significant gain. Fig. 15-a and 15-b show the two-dimensional radiation pattern in the φ=0 and 90 degrees planes of 52×52 elements at frequencies of 10 and 14 GHz, respectively. Fig. 15-c shows the gain versus frequency.

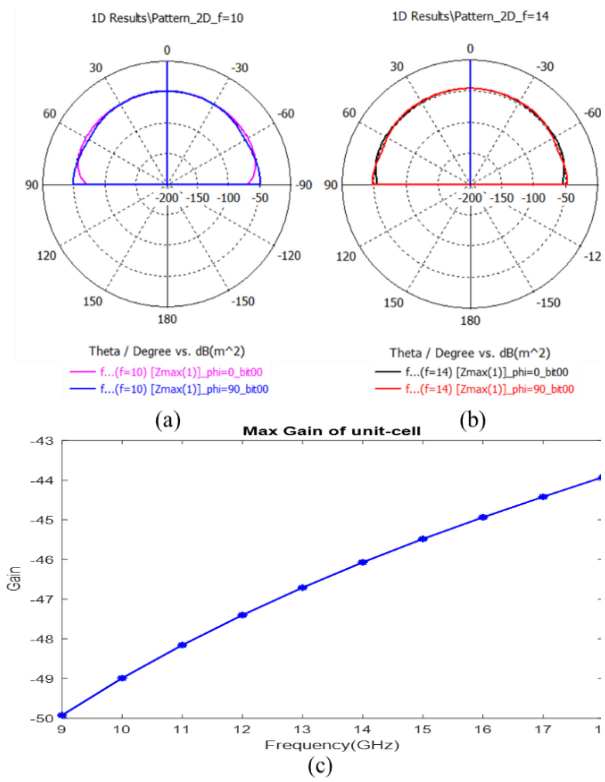


Fig. 14 a) 2-D radiation pattern of $\varphi = 0.90$ plane in f=10GHz b) 2-D radiation pattern of $\varphi = 0.90$ plane in f=14GHz c) gain vs frequency of unit-cell

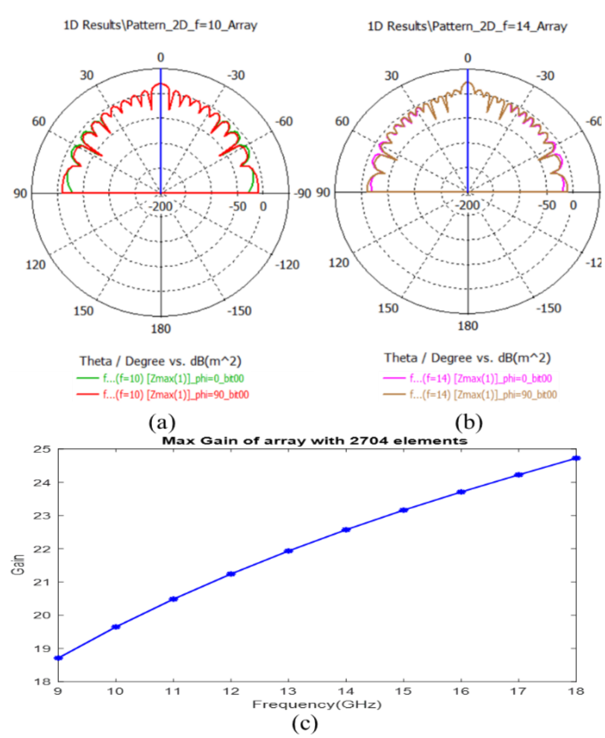


Fig. 15 a) 2-D radiation pattern of $\varphi = 0.90$ plane in f=10GHz b) 2-D radiation pattern of $\varphi = 0.90$ plane in f=14GHz c) gain vs frequency of 52×52 elements

4- Performance Analysis

To analyse the performance of the proposed structure, its capabilities can be compared with other structures. The table 3 shows this comparison. As can be seen in the table 3, the proposed structure has smaller dimensions in a unit cell compared to other structures, and this can be achieved by proper analysis of the structure and geometry parameters to cover the desired bandwidth. The next point is that the ability to convert linear to linear and linear to circular polarization occurs separately in a common bandwidth, which means that each of the states of linear to linear and linear to circular conversion does not occur at different frequencies. In addition, this structure compared to the rest have a larger bandwidth. Another of its most important points is that the Impedance Switching mode supports wave reflection with the polarization of the feeding antenna, which means that it can play both the role of normal reflectors and the role of polarization convertor.

Table 3: Comparison Proposed Unit cell with other works

Ref.	f_1-f_2 , BW%	No. resonance layer	Size (mm^2)	Polarization
[2]	8-12,40%	One layer	6×6	LL,LR,CR
[5]	10-15,40%	Two layer	12×12	LR,CR
[15]	10.4-15.7,41%	One layer	12×12	LR,CR
[16]	11.5-14.5,23%	Multi-layer	13×13	LL
Proposed	8-17,72%	One layer	5.5×5.5	NLL,LL,LC

Note: The criterion for BW is the reflection coefficient of -10±1 dB, **LR**: Linear Rotation conversion (x incident wave convert –x reflected wave or y incident wave convert –y reflected wave), **CR**: Circular Rotation conversion (RHCP convert LHCP or vice versa), **LL**: Linear to Linear conversion (x incident wave convert y reflected wave...), **LC**: Linear to Circular conversion, NLL: No Linear to Linear conversion (x incident wave convert x reflected wave...)

5- Conclusions

In this research, we designed and simulated a unit cell of a reflect-array antenna with wide bandwidth capabilities and the ability to reflect the polarization of the feeding antenna or convert it to another polarization. The designed structure using the appropriate geometry of the upper layer (taper shape of tentacles and the use of two dipoles) and its relatively large thickness, we reached a simple design with a high degree of freedom to shift the frequency spectrum of its response. The ability to DC control and use of unit cell in the arrangement of the array can be future activities. By designing an array of this unit cell, its radiation pattern can be examined and the unit cell rotation technique can be used in its array arrangement to achieve a 180-degree phase difference. It should be noted that for connecting or not connecting control points, metal wire can be used instead of using control devices such as pin diodes for first construction, so that the cost does not increase, because the issue of cost and assembly of control devices in the construction of the array will have more important. Finally, it should be said that the design of the unit cell is the first step of research in this field, and the construction of the unit cell and its application in the array structure can be the next steps of future activity.

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