Three-bit Unit-cell with Low Profile for X-Band Linearly Polarized Transmitarrays

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Abstract **─** In this paper, we present a three-bit phase resolution and low profile unit-cell structure for X-band passive transmitarrays. The unit-cell is implemented using four metallic layers printed on two substrates separated by an air gap. The phase shift is achieved by a combination between current flow modification on middle layers and the variation of the size of path elements. Eight unit-cells are optimized to provide eight phase states with a step of 45°. Experimental results are conducted by using WR-90 waveguide to validate the design. These eight unit-cells cover a wide -3 dB transmission bandwidth of 15% and exhibit a low thickness of $0.18\lambda_0$.

Index Terms **─** Cut-ring patch, reflectarray, ring slot, transmitarray, unit-cell design.

I. INTRODUCTION

Microstrip transmitarray antenna is currently received many attentions for applications which require high gain antennas such as point-to-point wireless communications, satellite communications and radar applications. The microstrip transmitarray antenna offers many advantages over classic lens antenna in terms of light weight, low profile and low cost. A typical microstrip transmitarray antenna consists of a feeding source placed at the focal point and an array of transmitarray unit-cells. The operating principle of a transmitarray is based on the phase compensation. Each unit-cell is designed to provide a required phase shift in order to collimate the incident power from the source into a desired direction. To compensate for any required phase, the unit-cell should have a phase range of at least 360° while maintaining low transmission loss to maximize the efficiency.

Currently, unit-cell structures based on multi-layer frequency selective surfaces (FSS) are widely applied in transmitarray antennas [1-5]. The advantages of these structures are simple manufacturing process and low transmission loss. However, they are usually bulky due to large number of dielectric layers separated by an air gap of $\lambda_0/4$ between layers. As presented in [8], a maximum phase range for a single layer is 90° for -3dB transmission coefficient. To achieve a full 360° phase range, the unit-cells using four-layer structure have been proposed in [1-2]. The spacing between two layers of $\lambda_0/4$ makes the total thickness of these unit-cells to $3\lambda_0/4$. Different efforts have been devoted to reduce the profile of transmitarray unit-cells by reducing the number of layers to three [3-5]. Although the number of layers is reduced, the phase range of these proposed unit-cells cannot achieve 360° for -3 dB transmission coefficient. A transmitarray unit-cell based on a combination of C-patches and a ring slots loaded with rectangular gap was investigated [6]. The unit-cell was designed by using two substrates with only one air gap. This helps reduce the unit-cell complexity and the cost to precisely align multiple layers. Simulation results showed that the unit-cell can provide a large phase range and a low thickness.

In this paper, experimental validation for the transmitarray unit-cell structure using C-patch and ring slot loaded with rectangular gap is presented. We demonstrate that a low profile unit-cell structure can provide a large transmission phase range, wide -3 dB transmission bandwidth. A set of eight unit-cells are optimized for providing eight phase states with a step of 45° at 11.5 GHz. Prototypes of the eight unit-cells have been fabricated to validate the performance of the proposed unit-cell structure.

II. TRANSMITARRAY UNIT-CELL

A. Transmitarray unit-cell structure

The unit-cell structure is shown in Fig. 1. It is fabricated using two identical substrates which are Roger 5870 with a thickness of 1.575 mm and ε_r = 2.33. The two substrates are placed in cascade and separated by 1.6 mm of air. For each substrate, a C-patch is printed on the top while a ring slot loaded by rectangular gap is printed on the bottom. The structure operates with a linear polarization. In this case, the orientation of E-field is perpendicular to the gap of the C-patch, as shown in Fig. 1.

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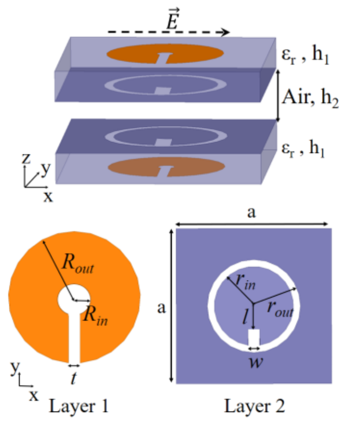


Fig. 1. Geometry of the proposed transmitarray unit-cell structure.

For a unit-cell using FSS, a full 360° phase range cannot be obtained with a single layer. An approach to increase the phase range is to increase number of layers of relatively wideband patch elements. As demonstrated in [8], the maximum transmission phase range for -1dB transmission coefficient, applying for a separation between layers of $\lambda_0/4$ are 54°, 170°, 308°, and full 360° for single, double, triple, and quad-layer FSS, respectively. In our design, the unit-cell is also made of a four-layer structure, we optimize it to achieve a low thickness while maintaining a large phase range. The method to vary the transmission phase is based on the variation of dimension of patch elements, combining with the modification of the current flow on two middle layers. The modification of the current flow on two middle layers causes a modification of the current on C-patches, which leads to a modification of the transmission phase of the transmission wave. Modifying the current on middle layers is carried out through modifying the rectangular gap length of the ring slots, as shown in [7]. In this work, eight unit-cells are optimized to provide eight phase states with a phase step of 45° at 11.5 GHz. These eight unit-cells can be divided into two groups. The first group comprises three unit-cells (cell No.1, No.2 and No.3) in which the rectangular gap is terminated at the centre of the ring slot, while the rectangular gap of the unit-cells in the second group is terminated at a distance *l* of about 1.75 mm from the centre of the ring slot. The distance (*l*) of 1.75 mm is chosen so that the current directions on the C-patch when l = 1.75 mm is opposite to that when l = 0 mm. The opposite of the current directions leads to a large difference of transmission phase between two cases. The variation of the transmission phase of unit-cells in each group is obtained by varying the dimension of C-patches and ring slots. Table 1 shows detailed dimension of the eight unit-cells. Total thickness of a unit-cell is 4.75 mm corresponding to $0.18\lambda_0$ and the cell size equals $0.54\lambda_0$, where λ_0 is the wavelength in free-space.

Table 1: Dimensions of the eight unit-cells

Unit Cell	Cut-ring Patch (mm)	Ring Slot (mm)	Normalized Phase (°) at 11.5 GHz
No.1	R_{out}=5.4, R_{in}=1.3, t=1	r_{out}=6, r_{in}=5.1, w=0.3, l=0	0°
No.2	R_{out}=5.5, R_{in}=0.7, t=0.5	r_{out}=6, r_{in}=5.4, w=0.3, l=0	-45°
No.3	R_{out}=5.7, R_{in}=0.7, t=0.5	r_{out}=6, r_{in}=5.6, w=0.3, l=0	-90°
No.4	R_{out}=5.1, R_{in}=1.5, t=1	r_{out}=5.7, r_{in}=4.6, w=1, l=1.8	-135°
No.5	R_{out}=5.3, R_{in}=1.5, t=1.2	r_{out}=6, r_{in}=4.7, w=1, l=1.75	-180°
No.6	R_{out}=5.4, R_{in}=1.5, t=1	r_{out} =6, r_{in}=4.8, w=1, l=1.75	-225°
No.7	R_{out}=5.6, R_{in}=1, t=1	r_{out}=6, r_{in}=4.9, w=1, l=1.8	-270°
No.8	R_{out}=5.7, R_{in}=1.3, t=1.2	r_{out}=6, r_{in}=4.9, w=1.2, l=1.75	-315°
	Substrate: h_1 = 1.575 mm, ε_r = 2.33, tanδ = tanδ = 0.0012, a = 14 mm, h_2 = 1.6 mm		

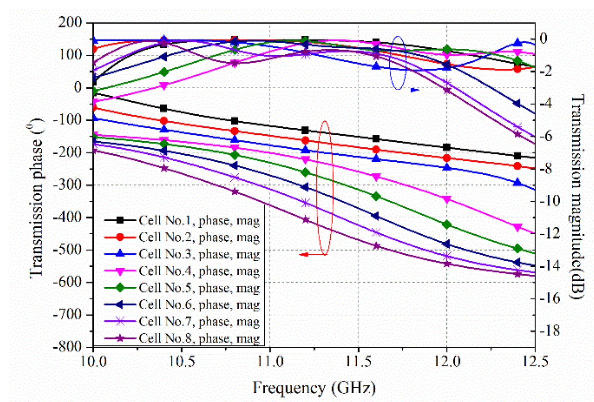


Fig. 2. Simulated transmission coefficients of eight unit-cells.

Parametric analysis and optimization have been performed by using ANSYS HFSS software, version 15. Eight unit-cells are simulated under array environment by using Floquet ports and Master-Slave boundaries, with a normal incident wave (incident angle of 0°). The simulated transmission phase and magnitude of eight unit-cells are shown in Fig. 2. As can be seen, two adjacent phase curves have a distance of 45° at 11.5 GHz. The phase variation of the unit-cells in group 1 is more linear than that of the unit-cells in group 2. Due to the non-linearity of the phase curves, the difference of 45° between two adjacent phase curves are not maintained at the frequencies far from 11.5 GHz. The eight unit-cells cover a large common -3 dB transmission bandwidth, from 10.3 GHz to 12.0 GHz, corresponding to 14.8%. The transmission magnitude is better than -1.5 dB at 11.5 GHz.

B. Equivalent circuit model

To better understand the operation principle of the proposed structure, it would be helpful to represent the structure in the form of the equivalent circuit. In order to simplify the circuit, we assume that the circuit has no ohmic loss, the equivalent circuit contains only capacitors and inductors. The C-patches on the top of two substrates are modeled as two series LC circuits which are placed in parallel (C_{S1}, L_{S1}, C_{S2}, L_{S2}). The modified ring slot loaded with a rectangular gap can be represented as a series LC circuit in parallel with a LC tank (C_{P1}, L_{P1}, C_{P2}, L_{P2}). The substrates are represented by a transmission lines with a length of h_1 and a characteristic impedance of $Z_1 = Z_0/\sqrt{\varepsilon_r}$, where ε_r is the relative permittivity of the substrate and $Z_0 = 377\ \Omega$ is the free space impedance. The equivalent circuit model of our proposed unit-cell is shown in Fig. 3.

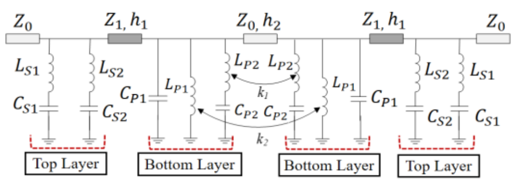


Fig. 3. Equivalent circuit model of our proposed unit-cell.

The equivalent circuit model of each element of the unit-cell structure is derived by using the retrieval method. The first step of this method is the full-wave analysis of the reflection coefficients of the C-patch and ring slot elements by assuming that the reflection coefficients obtained from full-wave simulation are exact. Since the number of capacitors and inductors is proportional to the number of resonances, the resonant behavior of the reflection coefficient suggests us the number of inductors and capacitors and their arrangement. The value of each component of the equivalent circuit can be determined by solving an iterative matching procedure. For this procedure, we compute the value of capacitors and inductors based on the poles and zeros of the reflection coefficient curves. We are first interested in the reflection coefficient of the C-patch and ring slot elements in the free space. In this case, the dielectric permittivity of the substrate is assumed to be 1. From [9], the reflection coefficient of a freestanding FSS is given by:

$$\Gamma_{element} = \frac{-1}{1 + 2Z_{element}/Z_0}, \quad (1)$$

where $\Gamma_{element}$ is the reflection coefficient, $Z_{element}$ is the impedance of the element and Z_0 is the free-space impedance.

Once the value of lumped components of the equivalent circuit of the freestanding C-patch and ring slot is determined, we compute the value of the lumped components when the substrates are presented. The capacitance can be derived by using $C = (\varepsilon_{eff} + 1).C_0/2$ for the case when a dielectric slab is present on one side of the element, where C_0 is the capacitance of a freestanding FSS. The approximated effective permittivity for the case when a dielectric slab is present on one side of the element is given by the equation 2, [9]:

$$\varepsilon_{eff} = \varepsilon_r + (\varepsilon_r - 1)\left(\frac{-1}{e^N(x)}\right), \quad (2)$$

where $x=10*h/D$, h is the thickness of dielectric slab, D is the cell spacing and N is an exponential factor that takes into account the slope of the curve [10]. For the C-patch and ring slot, we select N=1.8.

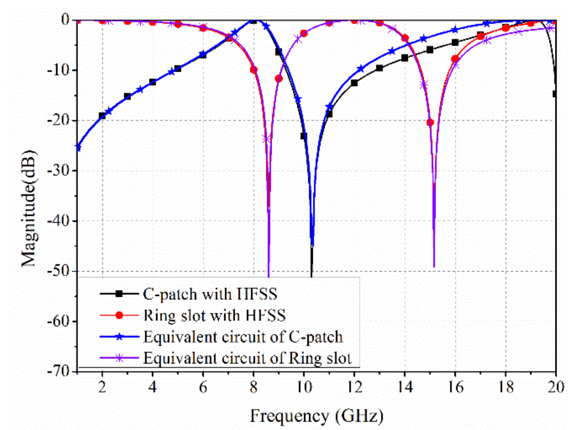


Fig. 4. Reflection magnitude of the C-patch and ring slot of the unit-cell No.1 in free space, obtained by HFSS and by equivalent circuit model (C_{S1}=0.021 pF; L_{S1}=18.42 nH; C_{S2}=0.024 pF; L_{S2}=2.92 nH; C_{P1}=0.135 pF; L_{P1}=1.595 nH; C_{P2}=0.039 pF; L_{P2}=4.52 nH).

Figure 4 shows the reflection coefficients of the freestanding C-patch and ring-slot of the unit-cell No.1, obtained from the full-wave EM simulations using ANSYS HFSS and the reflection coefficients of the equivalent circuit model simulated using Advanced Design System (ADS), version 2011 from Keysight Technologies, Inc. Figure 5 shows the transmission magnitude of the unit-cell No.1, obtained from HFSS and the transmission magnitude of the equivalent circuit model. As it can be seen, the results obtained from equivalent circuit models agree well with that from the full-wave EM simulations. However, there is a difference at high frequency. The difference is due to higher modes of the structure. We note that the equivalent circuit model using the above procedure is an approximate circuit. Although the equivalent circuit model does not totally match with the full-wave simulations, it is a useful tool for understanding the operation of our structure.

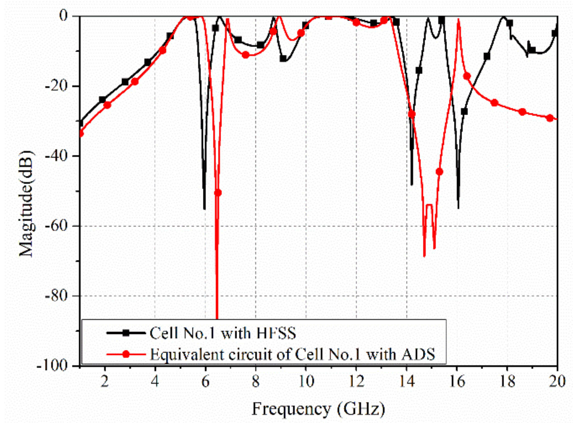


Fig. 5. Transmission magnitude of the unit-cell No.1 obtained by HFSS and by equivalent circuit model (C_{S1}=0.033 pF; L_{S1}=18.42 nH; C_{S2}=0.036 pF; L_{S2}=2.92 nH; C_{P1}=0.22 pF; L_{P1}=1.595 nH; C_{P2}=0.064 pF; L_{P2}=4.52 nH, coupling coefficient k_1=0.14, k_2=0.14).

For a transmitarray using multi-layer FSS structure, to achieve a large phase range, multi-resonant FSS structures are employed [1-2]. For our proposed unit-cell structure, the C-patch and ring-lot loaded with a rectangular gap create multiple resonances. For the ring slot loaded with a rectangular gap, the presence of the rectangular gap creates a second resonance at high frequency. The second resonance frequency is a function of the length of the rectangular gap. When the length of the rectangular gap is reduced the second resonant frequency is shifted towards to the higher frequency. The variation of the second resonance of the ring slot leads to a variation of the transmission phase of the unit-cell. Therefore, in this work, we combine the variation of the size of C-patch, ring slot and the length of the rectangular gap on the ring slot to vary the transmission phase.

III. VALIDATION OF UNIT-CELLS USING THE WAVEGUIDE SIMULATOR

Eight unit-cells have been fabricated to validate the simulation results. To get the transmission phase and magnitude of the unit-cells, a technique is to use the waveguide simulator. In our validation, the WR-90 standard waveguide was used as a waveguide simulator. The measurement system consists of two WR-90 waveguides and two rectangular-to-square transitions, as shown in Fig. 6. The rectangular-to-square transition is used to connect the square unit-cell to rectangular WR-90 waveguide. It has a square aperture of 17x17 mm^2, a rectangular aperture of 22.86x10.16 mm^2, and a thickness of 3 mm. The measurement system was calibrated using Through-Reflect-Line (TRL) calibration procedure. The reference plane is at the open-end of two WR-90 waveguides (it does not include the two rectangular-to-square transitions).

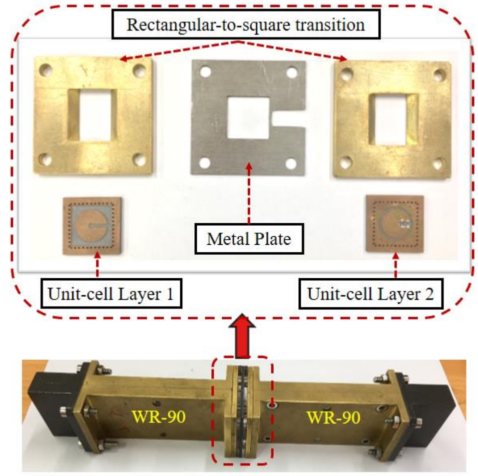


Fig. 6. Photo of the measurement system.

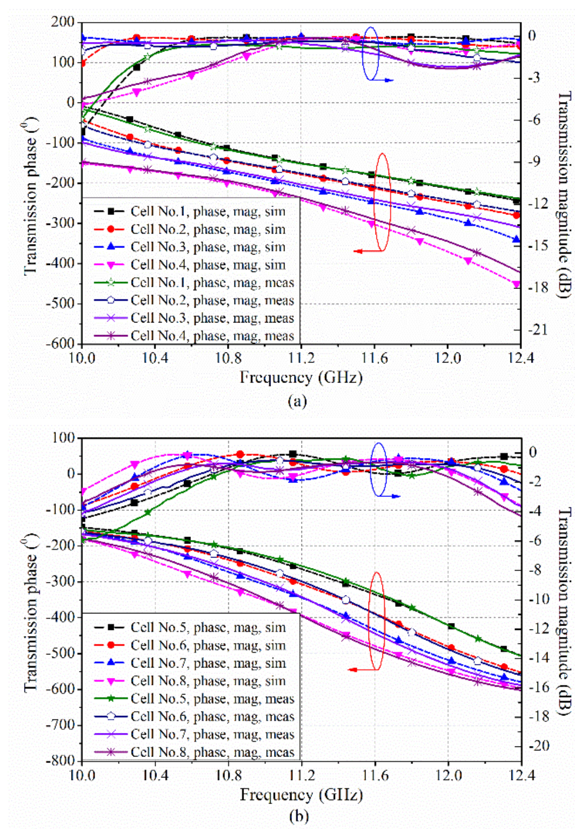
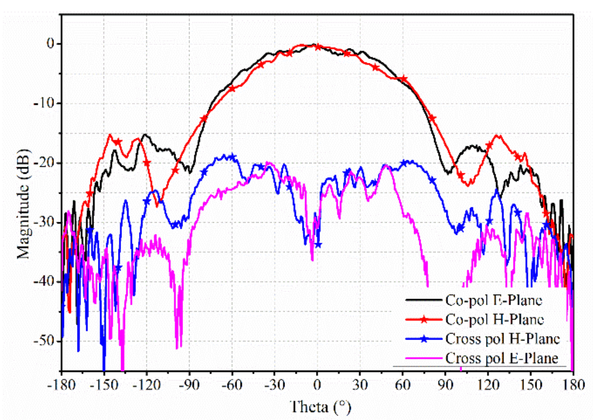


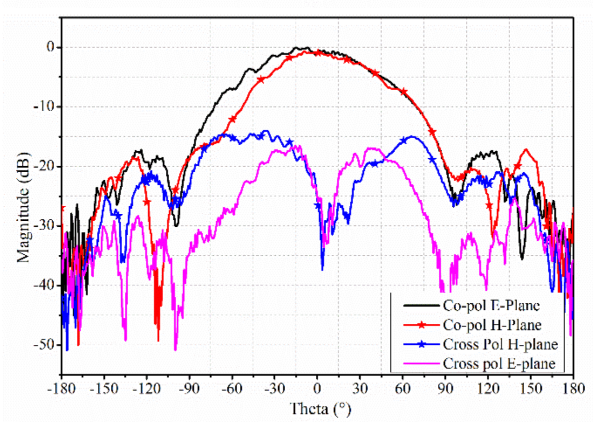
Fig. 7. Measured and simulated transmission coefficients of eight unit-cells in waveguide. (a) Unit-cells No.1, No.2, No.3, and No.4; (b) unit-cells No.5, No.6, No.7, and No.8.

The measured and simulated transmission coefficients of eight unit-cell in WR-90 waveguides are shown in Fig. 7. Measured results show that the transmission phase of eight unit-cells changes with a step of about 45° at 11.5 GHz. The transmission magnitude is better than -1.5 dB at 11.5 GHz. The -3 dB transmission bandwidth is 1.75 GHz from 10.5 GHz to 12.25 GHz, corresponding 15%. A good agreement between simulation and measurement can be observed. Compared to the simulated results shown in Fig. 2; Fig. 7 has a lager phase range of 40°. The difference may due to the oblique angle of incident wave. We note that using the WR-90 waveguide to measure the transmission coefficients, the unit-cells are illuminated by a plane wave with an incident angle of 35° at 11.5 GHz. For the results in Fig. 2, unit-cells are simulated with a normal incident wave (incident angle of 0°).

The radiation patterns of one of unit-cell prototypes have been measured at different frequencies. The co- and cross-polarizations are shown in Fig. 8. In this case, we use a WR-90 waveguide combining with a rectangular-to-square transition to feed the unit-cell prototype that was placed at the open-end of the rectangular-to-square transition. As it can be seen, the co-polarizations in E-plane and H-plane are almost identical. Low side-lobe and good isolation of -15 dB between co-polarizations and cross-polarizations are obtained at 11.5 GHz. The gain of the unit-cell is determined based on the comparison method where the gain of a standard horn is used as the reference. The gain of the measured unit-cell is about 6.9 dBi at 11.5 GHz.



(a)



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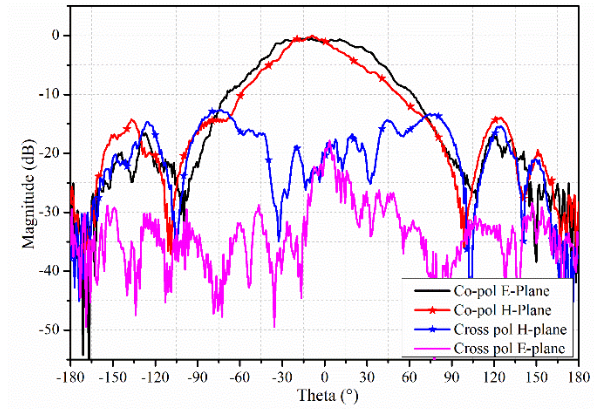

(c)

Fig. 8. Measured radiation pattern of a unit-cell at different frequencies: (a) 10.5 GHz, (b) 11.5 GHz, and (c) 12.4 GHz.

IV. CONCLUSION

A wide phase range and low profile unit-cell structure for X-band transmitarray antennas has been proposed and validated. The structure is made of C-patches and ring slots load rectangular gap printed on two substrates. Eight unit-cells provide eight phase states with a phase step of 45° at 11.5 GHz and a large -3 dB transmission bandwidth of 15%.

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