Design and Analysis of Reflectarray Compound Unit Cell for 5G Communication

Tahir Bashir [1], Han Xiong [1,2*], Abdul Aziz [3], Muhammad Ali Qureshi [3], Haroon Ahmed [1], Abdul Wahab [1], and Muhammad Umaid [4]

[1] School of Microelectronics and Communication Engineering, Chongqing University, Chongqing, 400044, China
{tahircqu, haroonahmed97, wahab.engr55}@gmail.com

[2] Collaborative Innovation Center of Light Manipulations and Applications
Shandong Normal University, Jinan, 250358, China
hxiong@cqu.edu.cn*

[3] Department of Telecommunication Engineering, The Islamia University Bahawalpur, 63100, Pakistan
{abdul.aziz, ali.qureshi}@iub.edu.pk

[4] School of Electrical Engineering, Chongqing University, Chongqing, 400044, China
umaidrao@gmail.com

Abstract **─** In this paper, a single-layer compound unit element is proposed for reflectarray antenna design operating in Ka-band (26.5-29.5GHz) at the center frequency of 28GHz. A systematic study on the performance of a compound unit element is examined first. The structure of the proposed unit element is a unique combination of two different shape simple patches i.e. cross dipole and square patches. The desired phase range is achieved due to the multi-resonance of both patch elements with a single layer without any air-gap. The compound unit element is simulated by computer models of CST Microwave studio based on the Floquet approach (infinite periodic approach) and it has achieved 348.589º reflection phase range. Furthermore, the analysis of the reflection phase range, S-curve gradient, reflection magnitude, fabrication tolerance, and surface current density is also simulated and demonstrated. Based on the remarkable performance, the proposed element can be considered as the best element of single-beam or multi-beam reflectarray antenna design for 5G applications.

Index Terms **─** Floquet approach, reflectarray, reflection phase range, single-layer, 5G.

I. INTRODUCTION

Reflectarrays are the innovative alternative of conventional parabolic reflectors and phased array antennas due to its novelty and advantages such as light weight, small size, electronic beam steering capability, ease in deployment, and low design complexity [1-3]. Reflectarrays are flat reflectors array antennas consisting of isolated variable-size unit elements on a grounded dielectric substrate with a certain tuning to produce the progressive phase distribution and generate the single-beam or multiple-beams when illuminated by a feed antenna [4-6]. The unit elements on the reflectarray aperture are pre-designed with a specific phase shift to retransmit the incident waves in the form of a beam. The required phase shift is acquired from the reflection phase range curve that is generated by varying one of the geometrical parameters of the unit element according to the design consideration [7,8]. Two main characteristics are important for the designing of unit elements: one is maximum reflection phase range with low fabrication tolerance and the second is minimum reflection loss [9,10]. The unit element is the basic component for the reflectarray antenna design that reflects the incident waves in a specific direction with progressive phase distribution by making a beam. Several designed methods have been proposed over the years to control the reflection phases such as the same size patches with variable stub length, variable size patches, and element rotation technique for circular polarized design [11,12].

Characterization of unit elements in the implementation and analysis of a reflectarray antenna is the most significant part regardless of the choice of the phasing mechanism. The reflection phases of the radiating unit elements are approximated by some degree due to some limitations of fullwave simulation for the reflectarray antenna. The mutual coupling effect between elements of a reflectarray is approximated by using an

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infinite periodic boundary. This technique is valid because several reflectarray antennas based on this technique have been demonstrated.

Different models are available to investigate the mutual coupling between the reflectarray unit elements using periodic approximation such as waveguide simulator approach, TEM waveguide approach, and infinite array approach [13-15]. In the infinite array approach, the unit element is simulated by using a periodic boundary condition [16]. This approach is more general than other approaches. Since the periodic environment of the unit element can be simulated more accurately in order to obtain the reflection characteristics for the oblique excitation angle. The infinite array approach is a conventional method to analyze the reflection characteristics of the reflectarray unit element. Due to easy analysis, the most preferred shapes for reflectarray are square and rectangular but a unique compound unit element is presented in this paper.

The purpose of this research work is to increase the phase range of a single thin layer unit cell without any air-gap between ground and the patch element to reduce fabrication complexity by using a combination of different simple multi-resonant elements. The new multi-resonant reflectarray unit cell has successfully achieved almost 360^o phase range at 28 GHz and it can be used to design any single-beam or multi-beam reflectarray antenna for 5G applications. In order to investigate the performance of the proposed element, the reflection characteristics including reflection phase range, reflection magnitude, fabrication tolerance, and surface current density are also studied in this paper. The element design and simulation results are discussed in the following section.

II. DESIGN AND ANALYSIS OF THE PROPOSED COMPOUND UNIT ELEMENT

A. The design of compound unit element

We conducted the fullwave simulations using the CST microwave studio to investigate the scattering characteristics of the proposed unit element based on the Floquet approach (infinite periodic approach). This approach is useful to approximate the mutual coupling between elements because it has considered each element as taken from an infinite periodic array structure. The periodic boundary conditions are applied to the unit element when it is surrounded by a uniform infinite environment and the unit element excitation is achieved by a plane wave as shown in Fig. 1. The proposed unit element is a combination of two different patches, i.e., cross dipoles and square patches as shown in Fig. 2. Roger RT5880 is used as a separator between the ground plane and reflecting patch with standard substrate thickness, permittivity, and loss tangent 0.127*mm*, 2.2, and 0.0009 respectively that is available in the datasheet and the element periodicity is 0.5λ at operating frequency 28GHz. We used periodic boundary conditions along the *x*-axis and the *y*-axis while the *z*-axis is kept open. The configuration and parameters of the proposed element are mentioned in Fig. 2 and Table 1 respectively.

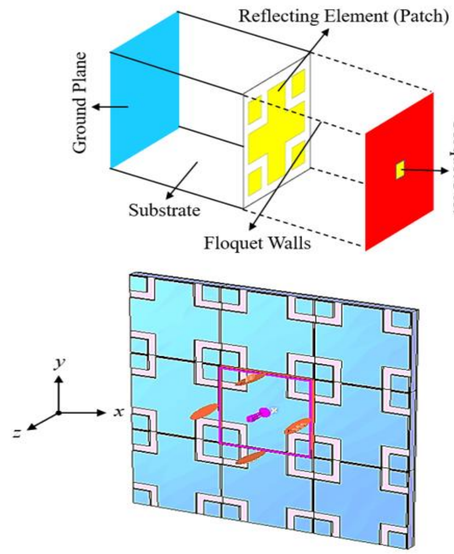

Fig. 1. Infinite periodic array structure with the unit element in CST.

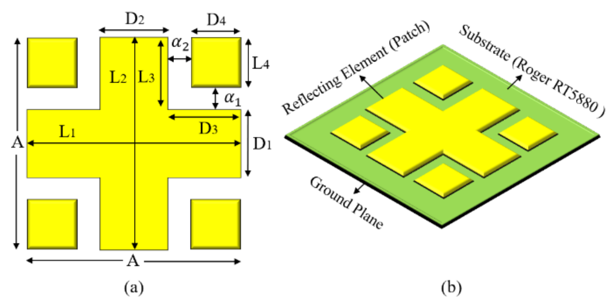

Fig. 2. The geometry of the compound unit element: (a) top view of the patch, and (b) 3D view of the unit element.

Table 1: Design parameters of the compound element

Parameters	Description	Values
$L_1 = L_2$	Length of *x* and *y* dipoles	5.25mm
$D_1 = D_2$	Width of *x* and *y* dipoles	2.272mm
$L_3 = D_3$	Arm length of cross dipoles	1.136mm
$L_4 = D_4$	Length and width of a square patch	1mm
$\alpha_1 = \alpha_2$	The gap between dipoles and square patch	0.5mm
A	Length and width of complete patch	5.25mm

III. SIMULATION RESULTS AND DISCUSSION

In order to control the reflection phase response, the variable-patch size method is used for the proposed unit element design. The proposed element has achieved a maximum reflection phase range of 348.589º by varying the patch size (including cross dipoles and square patches) from 2.5mm to 5.25mm as shown in Fig. 3. All the geometric parameter changes accordingly as the patch size varies. The reflection magnitude is the reduction in magnitude of the incident field after reflection, it depends on the dielectric properties of the substrate and the conductor used in the ground and it is close to 1 as shown in Fig. 4:

$$R_L = \alpha_d + \alpha_c \,, \tag{1}$$

where, R_L is the reflection loss and α_d and α_c are the attenuation due to the dielectric substrate and conductor loss respectively. Reflection phase variations are acquired by varying the geometrical parameter of the element, but in most cases, only one geometrical parameter is needed to adjust the reflection phase value. The substrate thickness, dielectric permittivity, incidence angle, and array periodicity are also important quantities for reflection phase performance instead of element shape and size. Table 2 shows the performance comparison between the proposed element and other single-layer unit elements in terms of the reflection phase range and proves that the proposed element is best for reflectarray antenna design. The maximum reflection phase range is a relevant figure of merit to characterize the performance of the reflectarray element [8]:

$$\Delta = \varphi_{max} - \varphi_{min}, \tag{2}$$

where, φ_{max} and φ_{min} are the maximum and minimum reflection phases respectively at the operating frequency 28GHz shown in Fig. 3. The reflection phase curve shows variation near the resonance patch size, it means a small variation in the patch size significantly changes the reflection phases. Therefore, fabrication tolerance is the second figure of merit for reflectarray unit element performance. The fabrication tolerance is defined as the partial derivative of the observing variation in the reflection phases to the patch size as shown in Fig. 5. The fabrication tolerance is assumed to be 0.01 mm. Therefore, continuous phase resolution can used to design reflectarray:

$$\sigma = max \; |\frac{\partial \vartheta}{\partial A}|. \tag{3}$$

Fabrication tolerance depends on the reflection phase gradient, smother reflection phase curve offers low fabrication tolerance or highly tolerant with the fabrication error and vice versa. It is important to note here that the partial derivative of reflection phases to dimension A of the element is an important parameter to define the sensitivity and the effect of all other remaining quantities is much lower than the effect of A. While the parameters σ and Δ are calculated at operating frequency f_o. It is interesting to realize how much the reflection phase changes when varying the frequency. If the frequency changes, there are two main effects: the desired reflection phase of elements changes due to the variation of the electrical path length and the reflection phase obtained for a given patch size is also different [17].

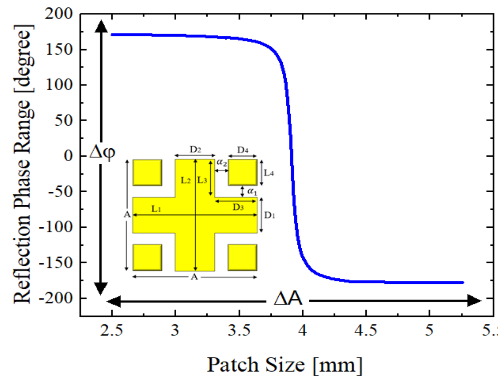

Fig. 3. The reflection phase response of the compound unit element.

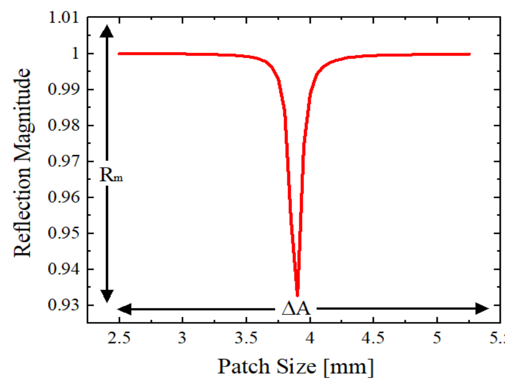

Fig. 4. The reflection magnitude curve of the compound unit element.

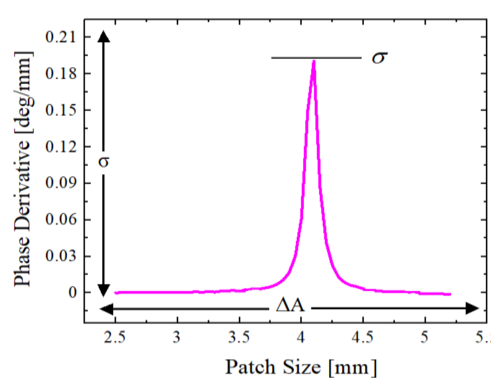

Fig. 5. The plot of the derivative of the reflection phase curve versus patch size at operating frequency of 28GHz.

Table 2: Performance comparison between the proposed element and other published single-layer unit elements

References	Types of Unit Element	Reflection Phase Range
[18]	Square loop with split ring and Circular loop with split ring	280°, 260°
[19]	Square, Triangular, Minkowski, Square loop	315°, 310° 315°, 340°
[20]	Hexagonal	340°
[21]	Radiating element	305°
[22]	Tunable unit cell	330.6°
[23]	Reconfigurable unit cell	330°
[24]	Rectangular slot, Circular slot	279°, 278°
[25]	Time modulated reflectarray unit cell	300°
[26]	Double cutted ring element	290°
[27]	Pair of fractal patches	320°
Proposed	**Compound unit element**	**348.589°**

The interaction of the incident electric field with reflecting element and substrate is demonstrated by surface current distribution as shown in Fig. 6. This is another important figure of merit to understand the electrical behavior of the unit element. The current density on the surface of the resonating unit element is generated by the concentration of the incident field. These fields have reached its maximum values at the resonance frequency f_o and reflectarray also has shown maximum reflectivity at the resonance frequency and it offered a higher loss. The surface current distribution of the reflecting element is 112*A/m* and the maximum current is on the center of the dipoles as depicted in Fig. 6. Surface current density is inversely proportional to the reflection area of the unit element [28]. If reflectarray aperture has an excess of small size elements it increases the reflection losses, surface current density and reduces the overall performance of the reflectarray antenna [29]. The maximum current density and current amount as specified by Maxwell's equation [30,31]:

$$I = \oint \vec{J}.ds. \tag{4}$$

Also, the current density ($\vec{J}$) is related to the incident electric field $\vec{E}$ represented as follow:

$$\vec{J} = \sigma\vec{E}\,, \tag{5}$$

where σ is the electrical conductivity of the material. Table 3 shows the performance summary of the compound unit element.

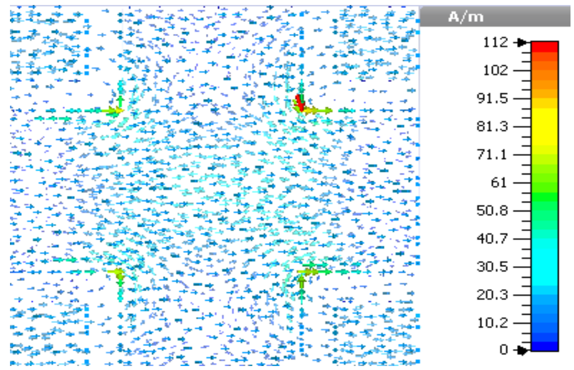

Fig. 6. Surface current density on the reflectarray unit element at the operating frequency of 28GHz.

Table 3: Performance analysis of the compound element

Performance Figures	Compound Unit Element
Frequency Band	26.5-29.5GHz
Operating Frequency	28GHz
Reflection Phase Range	348.589°
Linear Static Phase Range	145°
Reflection Magnitude	0.932
Fabrication Tolerance	0.2
Surface Current Density	112 *A/m*

IV. CONCLUSION

In this paper, we proposed a compound unit element using a single-layer topology for the reflectarray antenna design at an operating frequency of 28GHz. The proposed element is integrated by a variable-size phase shift technique using an infinite periodic array structure in a computer model CSTMv15. From the simulation results analysis, the compound element shows good performance in terms of maximum reflection phase range with minimum reduction in the magnitude of the incident field, fabrication tolerance, and surface current density. The proposed geometry may become a good reflector of single-beam or multi-beam reflectarray antenna for 5G applications.

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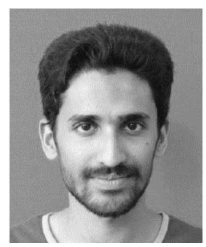
Tahir Bashir received his B.Sc. degree in Telecommunication from Islamia University Bahawalpur, Pakistan in 2018 and M.S. degree in Electronics and Communication Engineering from Chongqing University China in 2020. His current research interest includes metamaterial absorbers, antenna and reflectarray design.

Han Xiong received the M.Sc. degree from Yunnan Normal University, Kunming, China, in 2010, and the Ph.D. degree in Radio Physics from the University of Electronic Science and Technology of China, Chengdu, China, in 2014. He is now an Associate Professor in Chongqing University, Chongqing, China. His research interests include antenna, absorber and metamaterials technology.

Abdul Aziz is working as Assistant Professor in Telecommunication Engineering Department, Islamia University of Bahawalpur, Pakistan since 2009. He received his B.S. degree in Electrical Engineering from Bahauddin Zakariya University, Multan, Pakistan in 2003 and the M.S. degree in Telecommunication Engineering from University of Engineering & Technology, Peshawar, Pakistan in 2008. He completed his Ph.D. from Electronic Engineering Department, Tsinghua University, Beijing, China in 2019. His research interests include design of transmissive and reflective metasurfaces for satellite communications, antenna theory and applied electromagnetics.

Muhammad Ali Qureshi received his B.Sc. in Electrical Engineering from UET Lahore in 2000 and M.Sc. in Telecommunication Engineering from NWFP-UET Peshawar in 2008. He completed his Ph.D. in Electrical Engineering from KFUPM, Saudi Arabia in 2017. He is working as Associate Professor and Chairman at the Department of Telecommunication Engineering at The Islamia University of Bahawalpur, Pakistan. His research interests include image and video processing, image forensics, image quality assessment, and wireless communication. He is a Senior Member of IEEE and Chair, IEEE Bahawalpur Subsection Region 10.



Haroon Ahmed received his B.Sc. degree in Electronics Engineering from Comsats Institute of Technology, Abbottabad, Pakistan in 2015 and M.S in Electronics and Communication Engineering from Chongqing University, Chongqing, China in 2019. Currently, he is pursuing Ph.D. in Information and Communication Engineering from Chongqing University, China. His research interest includes MIMO Antennas and systems for 5G communication.

Abdul Wahab received his B.Sc. degree in Telecommunication from the University of Science and Technology, KPK, Pakistan in 2018 and M.S. degree in Electronics and Communication Engineering from Chongqing University China in 2020. His research interest includes signal processing, MIMO Radars, SAR radars and remote sensing.

Muhammad Umaid received the B.Sc. degree in Telecommunication from The Islamia University Bahawalpur, Pakistan in 2018 and M.S. degree in Electrical Engineering from Chongqing University China in 2020. His current research interest includes reflectarray antenna design and control of renewable energy.