Single- and double-beam reflectarrays for Ka band communication

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Abstract. The Ka band has found applications in satellite, and radar communications. It is also expected that this band will be utilized for 5G applications. This paper presents single- and double-beam microstrip reflectarrays with single layer and compact size for Ka band communications at 28 GHz. Three different unit cells are investigated in this paper. Single- and double-beam reflectarrays are investigated. The reflectarrays are designed at 28 GHz with a physical size of $10\lambda \times 10\lambda$. A pyramidal horn antenna is used for the feeding purpose. The focal-length-to-diameter (F/D) ratio is equal to one. Two different scenarios for single-beam reflectarrays are presented: one with a broadside direction and the other with a 10° tilt angle. The simulation results show that for the broadside single-beam scenario, it is possible to achieve a gain up to 28.5 dB, and a 1-dB gain-bandwidth up to 30.7%. On the other hand, the presented reflectarray for the single-beam design at 10° tilt angle gives a gain of about 26.4 dB, a side lobe level (SLL) of about -15.6 dB, and a 19.3% gain-bandwidth. For the double-beam reflectarray, four different designs at different angles of 5° , 10° , 15° , and 20° have been simulated and compared. Moreover, the simulation results on the double-beam reflectarray show that the double-beam design at 10° is better from the gain and SLL perspectives. Two prototypes for broadside single-beam reflectarrays have been fabricated and measured. The measurement results show a good match with the simulation results. Gain flatness is guaranteed for both the simulated and measured results over the band of interest.

Keywords. Ka band; reflectarray; 5G; single-beam reflectarray; double-beam reflectarray.

1. Introduction

In future 5G wireless communication systems, large bandwidths are required. To achieve this objective, there is a need to work at high frequencies [1]. This, in turn, makes the Ka band a good candidate for future-generation wireless communication systems. Operation at the Ka band has several advantages such as the large bandwidth and consequently the large capacity, and the reduction of the antenna sizes due to the small wavelengths [1]. The main problem in this band is the high path loss and the attenuation due to the rain and atmospheric absorption [1, 2]. In this paper, reflectarray antennas are designed at 28 GHz, because the level of attenuation due to atmospheric absorption at this frequency is not too high. It is equal to

about 0.7 dB per 100 m [1]. In future 5G communication systems, it is required to divide cells into micro- and pico-cells to increase the capacity through frequency reuse. Omni-directional antennas will no longer be suitable, because they increase interference [1]. Therefore, antennas, which can give pencil beams with high gain to minimize interference and at the same time maximize the gain, will be needed.

Two of the most common antennas that produce pencil beams and high gains are the parabolic reflectors and the phased-array antennas. A parabolic reflector depends on a primary feed horn to illuminate a metallic reflecting surface, which is designed by a method making all the path lengths from the focal point to any point on the parabolic surface equal in order to guarantee a unified direction for the reradiated field. The main disadvantages of the parabolic reflector is its huge size and large mass, especially at

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Figure 1. Reflectarray antenna.

high frequencies in the millimeter wave range. Moreover, parabolic reflectors exhibit high cross polarization levels [3]. In addition, phased-array antennas are composed of discrete elements and beamforming networks to produce the desired beam. The main disadvantage of the phased-array antennas is the power loss in the feeding network as it uses phase shifters to adjust the phases of the elements. When they are equipped with controllable phase shifters, they become very expensive due to the complicated beamformers and the use of several high-cost amplifier modules. Although phased-array antennas are light-weight, low-profile antennas with low cross polarization levels, they have small bandwidths and large losses at microwave and millimeter wave frequencies [3].

Reflectarrays have the merits of both parabolic reflectors and phased arrays with compact size and efficient simple feeding [4]. Unlike the parabolic reflector, a classical reflectarray consists of a flat dielectric substrate material sandwiched between two conducting materials: the ground plane at the bottom surface and the conducting array patches on the top surface as shown in figure 1 [5]. Similar to the parabolic reflector, a reflectarray is fed by a horn antenna located at the focal point. The reflectarrays eliminate the complicated and expensive beamforming networks existing in phased-array antennas [4].

Reflectarray antennas can be designed to produce single or multiple beams using single or multiple feeds at different frequency bands [6–13]. Fang *et al* introduced a double-beam reflectarray using a single feed horn based on the phase synthesis method, and achieved a gain of about 19.5 dB and a 1-dB gain-bandwidth of 16.5% for the frequency range from 5 to 7 GHz [8]. Arrebola *et al* introduced a three-beam reflectarray using three feed horns [9]. Their antenna is designed to operate at a center frequency of 25.5 GHz for a Local Multi-point Distribution System (LMDS). It consists of two layers with 30×30 elements in

each layer. The maximum obtained gain was around 20 dB and the gain-bandwidth achieved was 8%.

Several researchers have investigated the design of reflectarray antennas to work at the Ka band. Abdelhady *et al* presented a single-beam Ka-band double-layer reflectarray antenna and achieved a gain of about 25 dB and a 3-dB-gain bandwidth of about 24% [14]. Nayeri *et al* introduced a quad-beam reflectarray using the alternating projection method to optimize the phase distribution on the reflectarray surface [6, 7]. They designed the reflectarray in the Ka band with a single feed. This array achieved a gain of about 27 dB. Zhang presented a single-beam dielectric resonator reflectarray that works at 30 GHz [15]. This array is three-dimensional in nature with dimensions of $120 \times 120 \text{ mm}^2$. It achieved a gain of 28 dBi at 30 GHz. An *et al* investigated the integration between reflectarray antennas working in the Ka band and solar cells [16].

As the Ka band is a good candidate for 5G communications, design of reflectarrays for 5G applications in Ka band has captured the interest of researchers [17, 18]. Hong *et al* presented some suggestions for reflectarrays in 5G applications [17]. They recommended that multiple beams can be obtained from reflectarrays through the use of multiple horns to feed a single reflectarray. By increasing the number of horns, the number of beams is increased. This scenario of multiple horns may be cost inefficient. Hence, there is a need to generate multiple beams with a single horn. Dahri *et al* presented a review of the utilization of reflectarrays in 5G applications [18]. Several unit cells have been presented and investigated in this study for single-beam reflectarrays with the main target of enhancing the bandwidth at the cost of gain reduction.

Chaharmir *et al* in [19, 20] concluded that the linear phase versus element size is the basis of the broadband performance of a medium-size reflectarray. So, the current paper investigates this issue through the use of the superposition concept. In this paper, three different broadband unit cells are suggested for the design of the Ka band reflectarrays. The main objective is to use a unit cell with high bandwidth in order to enhance the overall reflectarray bandwidth. Based on the selected unit cells, reflectarrays with a single beam at broadside direction and another one with a beam at 10° tilt angle will be introduced. In addition, double-beam reflectarrays generating beams at different angles using a single feed horn will be introduced and compared.

2. Reflectarray theory

The reflectarray shown in figure (1) is composed of an array of patches illuminated with a feed horn located at (x_f, y_f, z_f) . The total phase delay from the feed to a fixed aperture in front of the reflectarray must be constant for all elements. To collimate a beam in a certain direction with

Figure 2. UC_s configuration (a) UC₁, (b) UC₂, (c) UC₃, (d) Side view. The dimensions of the UC are all in mm. $P_x = P_y = 10.7/2$, $R_1 = R - g$, $W_{c1} = 0.2$, $W_{c2} = 0.2$, $W_s = 0.2$, $g = 0.214$, $h_s = 1.5748$, and $\epsilon_r = 2.2$ (Rogers RT 5880).

(θ_o, ϕ_o) considering that the reflection phase from each reflectarray element is dependent on its position, a compensation phase γ_i is required to satisfy the following equation [3, 4]:

$$k_o(R_i - \vec{r}_i \cdot \hat{r}_b) - \gamma_i = 2N\pi \quad (1)$$

where $k_o = 2\pi/\lambda_o$ is the free-space wave number, i is the element index, N is an integer, and

$$R_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + z_f^2} \quad (2)$$

is the distance from the phase center of the feed horn to the center of the i th reflectarray element, $\vec{r}_i$ is the position vector to the center of the reflectarray element from the reflectarray surface center, $\hat{r}_b$ is the unit vector in the collimated beam direction, N is an integer, and γ_i is the i th element phase required to compensate for the delay resulting from the corresponding path. To satisfy Eq. (1) for

Figure 3. Reflection loss versus frequency for UC₁, UC₂, and UC₃.

each element in the reflectarray, there is a single degree of freedom represented in the value of γ_i , which is varied by varying the element area as will be explained in sections 3 and 4.

3. Structure of the unit cells

In this paper, three different unit cells are presented as shown in figure 2. The first one (UC₁) consists of a concentric ring with a solid circular patch. The second one (UC₂) consists of two concentric rings. The third one (UC₃) consists of two concentric rings with a solid cross loop inside. The dimensions of these unit cells are shown in figure 2, where $p_x = p_y = \lambda/2 = 5.35$ mm. The unit cells are designed to work around 28 GHz. The advantage of using a mixture of different elements in the unit cell is to increase its bandwidth. Consequently, the overall bandwidth of the reflectarray is increased. As each element resonates at a different frequency, this results in different transition regions in the phase-length characteristics of the unit cell [21–24]. The reflection loss curves versus frequency for the suggested unit cells are shown in figure 3. To build the reflectarrays, there is a need to satisfy Eq. (1) at each element of the reflectarray. This means that there is a need to change the dimensions of the unit cell inside the area $p_x \times p_y$ for each element in the reflectarray in order to achieve the required phase shift.

4. Estimation of the reflection phase curve

A reflection phase curve is estimated to relate the element size to its corresponding phase. This step is performed prior to the design of the reflectarray. The idea of estimating the reflection phase curve is based on assuming that a plane

wave is incident on the unit cell and then reflected with a different amplitude due to attenuation and a different phase due to the unit cell size. The phase of the reflected wave is estimated as the reflection phase. This process is repeated for different sizes to produce a lookup table, which is used to plot the reflection phase curve. In this procedure, the infinite array approach is adopted. This approach assumes that for each size of the element, all surrounding elements are identical in size. The main advantage of this approach is that it takes into consideration the mutual coupling between elements.

For the proposed unit cells, the reflection phase curve is computed by varying the radius R shown in figure 4. The CST simulator has been used for this purpose [25]. The reflection phase curve can be calculated using a Floquet port with periodic boundary conditions [4]. By this method, the reflection phase curve can be calculated at different incidence angles for the incident plane wave. Hence, the reflection phase curves can be adopted for different incidence angles. Another possible method for the estimation of the reflection phase curves is to use a parallel-plate waveguide port, where the two plates normal to the electric field direction are electric walls and the other two plates are magnetic walls [4]. The parallel-plate waveguide port enables the calculation of the reflection phase curve for normal incidence. Two main characteristics should be satisfied by the reflection phase curves: linearity to minimize the phase errors in the designed array, and a 360° span at least. Figure 4 shows the reflection phase curves for the proposed unit cells with normal incidence at three different frequencies: 27 GHz, 28 GHz, and 29 GHz.

5. Single-beam reflectarray

Three reflectarrays have been designed based on the three proposed unit cells. All reflectarrays have dimensions of $10\lambda \times 10\lambda$ (107 mm $\times$ 107 mm). The three reflectarrays are composed of 20×20 unit cells with $\lambda/2 \times \lambda/2$ unit cell size. The feeder is a pyramidal horn having aperture dimensions of (14 $\times$ 12.4 $\times$ 25) mm with WR28 waveguide. This horn is placed at a distance of 10λ from the center of the reflectarray such that the F/D ratio is equal to one. The realized horn gain is 12.1 dB at the frequency of 28 GHz as shown in figure 5. Its E - and H -plane half-power beamwidths are 44.3° and 48°, respectively. Figure 6 shows the phase distribution required on the reflectarray aperture to produce a broadside single beam with center feeding. Figure 7 shows the 3D radiation patterns of the three reflectarrays at 28 GHz. The reflectarray with UC₁ gives a gain of about 28.5 dB. The reflectarray with UC₂ gives a gain of about 28 dB, while the one with UC₃ gives a gain of about 25.8 dB. Figure 8 shows a comparison of the 2D radiation patterns in the H -plane for the designed

Figure 4. Reflection phase versus R for (a) UC₁, (b) UC₂, (c) UC₃ with normal incidence only at 27, 28, and 29 GHz.

reflectarrays. The far-field gain versus frequency for these reflectarrays is shown in figure 9. From this figure, it is clear that the gain variations with frequency for the

Figure 5. Feeder horn radiation pattern.

Figure 6. The required phase distribution on the reflectarray surface for the single-beam reflectarray at broadside direction.

reflectarray with UC₁ are less than those of the other cases, which means a larger gain-bandwidth value than that of the other cases.

Table 1 presents a comparison between the designed reflectarrays and the reflectarrays in [15] and [16] as they also work in the Ka band. This table shows that the proposed reflectarray based on UC₁ has a gain of about 28.5 dB and a 1-dB gain-bandwidth equal to 30.7% despite having a smaller area than those of the reflectarrays in [15] and [16]. The reflectarray with UC₂ gives the same results in [15] but with smaller dimensions.

For UC₃, another design is presented to produce a single beam at a tilt angle of 10° from the broadside direction to avoid the blocking that occurs when both the feed and the reflectarray radiations are at the same direction. Figure 10 shows the required phase distribution on the reflectarray

Figure 7. 3D radiation patterns for the reflectarrays at 28 GHz with (a) UC₁, (b) UC₂, (c) UC₃.

surface to collimate a beam at 10° direction with center feeding. The 2D radiation patterns for the reflectarray with UC₃ for the broadside and 10° tilt angle are shown in figure 11. The gain is improved from 25.8 dB at 28 GHz to 26.4 dB, and in addition, the 1-dB gain-bandwidth has been improved from 10.6% to 19.3%. The SLL has been

Figure 8. 2D radiation patterns for the proposed reflectarrays at 28 GHz.

Figure 9. Far-field gain versus frequency for the proposed reflectarrays.

improved from -13.1 dB to -14.7 dB at the design-frequency. Figure 12 shows the radiation patterns for both cases at different frequencies from 27 GHz to 30 GHz. It is clear from this figure that the gain variations for the single-beam reflectarray with 10° tilt angle are very small when compared with those of the single-beam reflectarray in the broadside direction with UC₃. Table 2 summarizes the results.

6. Double-beam reflectarrays

Generally, the objective of designing double-beam antennas is to enhance capacity and spectral efficiency of wireless communication systems by serving multiple users at

Table 1. Comparison between the proposed reflectarrays and those in [15] and [16].

Reflectarray with	Aperture size (mm)	Gain at designed frequency (dB)	1 dB gain-bandwidth
UC ₁	107 mm × 107 mm	28.5	30.7%
UC ₂	107 mm × 107 mm	28	10%
UC ₃	107 mm × 107 mm	25.8	10.6%
UC in [15]	120 mm × 120 mm	28	≅ 10%
UC in [16]	160 mm × 160 mm	26.3	8.75%

Figure 10. The required phase distribution on the reflectarray surface for the single-beam reflectarray at 10° tilt angle.

different directions. Usually narrow beams are used for this purpose. In wireless mobile communications, there is a need for an antenna that gives multiple beams. A reflectarray that produces two beams has been designed based on the proposed UC₃. There are several methods for designing multi-beam reflectarrays such as superposition of the aperture field method. In this method, to produce M beams using a single feed, the tangential component of the field on the reflectarray surface can be simply written as [12]:

$$E_R(x_i, y_j) = \sum_1^M A_{n,i}(x_i, y_j) e^{j\phi_{n,i}(x_i, y_j)} \quad (3)$$

where $A_{n,i}$ and $\phi_{n,i}$ are the amplitude and phase of each element to radiate a beam in the direction (θ_n, ϕ_n) . In reflectarrays, the amplitude of each element is fixed by the feed position and element location, which are independent of the beam direction. Therefore [12]:

$$E_R(x_i, y_j) = A_i^{feed}(x_i, y_j) \sum_1^M e^{j\phi_{n,i}(x_i, y_j)} \quad (4)$$

Generally, in the reflectarray design with the superposition method, it is required to achieve certain magnitude and phase at each element of the reflectarray. It is possible to achieve the phase requirements, but the magnitude

Figure 11. 2D radiation pattern for the single-beam reflectarray with UC₃. **Figure 12.** 2D radiation pattern for the single-beam reflectarray using UC₃ at 27 GHz, 28 GHz, 29 GHz, and 30 GHz (a) broadside direction, (b) 10° tilt angle.

Table 2. Characteristics of the reflectarray with UC₃.

Single-beam reflectarrays with a beam at	Gain (dB)				1 dB Gain-bandwidth	SLL @ 28 GHz (dB)	Beamwidth @ 28 GHz
	@ 27 GHz	@ 28 GHz	@ 29 GHz	@ 30 GHz			
Broadside direction	24.4	25.8	26.3	26.4	(30.182–27.21) $\cong$ 10.6%	–13.1	5.2°
10°	25.8	26.4	26.6	26.6	(32.076–26.593) $\cong$ 19.3%	–14.7	5.4°

requirements are not attainable with the phase synthesis method. This approach has some shortcomings such as the high SLL and gain reduction due to amplitude error. Another possible design approach is the geometrical approach. In this approach, the reflectarray surface is divided into M sub-arrays, and then each sub-array is designed independently to radiate a beam in a desired direction. In this paper, four double-beam reflectarrays will

be introduced depending on the geometrical design approach. The two beams are designed at different angles of 5°, 10°, 15°, and 20° by dividing the whole array into two sub-arrays such that each sub-array produces one beam with $\theta = 5^\circ, 10^\circ, 15^\circ$, or 20° , and $\phi_{1,2} = 0^\circ, 180^\circ$. The phase distributions required on the reflectarray surfaces for the four antennas are shown in figure 13. These reflectarrays are simulated and compared.

Figure 13. The required phase distributions for the double-beam reflectarrays at (a) $\theta = 5^\circ$, (b) $\theta = 10^\circ$, (c) $\theta = 15^\circ$ and (d) $\theta = 20^\circ$ and $\phi_{1,2} = 0^\circ$ and 180° .

Figure 14. 2D radiation pattern for the double-beam reflectarrays at 27 GHz, 28 GHz, 29 GHz, and 30 GHz at (a) 5° (b) 10° (c) 15° (d) 20°.

7. Simulation results

For the double-beam scenario, a study is presented for the reflectarray designs for two beams with tilt angles of 5°, 10°, 15°, and 20°. Figure 14 illustrates the 2D radiation

patterns for the double-beam reflectarrays using the proposed UC₃ at different angles in the range from 27 GHz to 30 GHz. It is clear from this figure that the best case of distinguishable beams is that for the reflectarray with two beams at a tilt angle of 10°, because at this angle the side

Table 3. Characteristics of the double-beam reflectarrays.

Double-beam reflectarrays with tilt angle at	Gain (dB)								SLL @ 28 GHz (dB)	
	@ 27 GHz		@ 28 GHz		@ 29 GHz		@ 30 GHz			
	1 st beam	2 nd beam	1 st beam	2 nd beam	1 st beam	2 nd beam	1 st beam	2 nd beam		
5°	19	20.2	19.4	19.7	19	19.1	18.7	19.4	4.9°	−7.9
10°	20.6	19.8	21.1	20.2	20.8	20.7	20	21.1	5.7°	−11.2
15°	19	19.2	20.1	18	20.9	17.5	21.6	18.2	5.3°	−8.7
20°	19.7	17.8	19.7	19.7	19.3	20.2	19.5	20.6	5.4°	−9.3

Figure 15. Far-field gain versus frequency for the double-beam reflectarrays.

Figure 16. Reflection coefficient for all reflectarrays

lobes overlap is minimal. The values of the gain are given in Table 3 in detail. From this table, it is clear that the double-beam reflectarray with 10° tilt angle is the best from the gain and SLL perspectives in addition to the 1 dB gain-bandwidth value. The gain variation in this case is small when compared with the other cases.

Figure 15 shows the far-field gain versus frequency for the double-beam cases. The gain variation over the frequency range of interest, for the all cases, is less than 1 dB. This means a high 1-dB gain-bandwidth, which is verified through the reflection coefficient figure. The reflection coefficient for all reflectarrays is shown in figure 16. From this figure, it is clear that the matching condition is guaranteed over the operating frequency range for the designed reflectarrays.

Figure 17. (a) Photo of the fabricated reflectarray with UC_1 , (b) reflectarray with UC_1 under test.

Figure 18. Reflection coefficient versus frequency for the simulation and measurements of the reflectarray with UC_1 .

Figure 19. E-plane radiation pattern comparison between the simulated and fabricated reflectarrays with UC₁.

Figure 20. H-plane radiation pattern comparison between the simulated and fabricated reflectarrays with UC₁.

8. Fabrication and measurements

Two reflectarrays with dimensions 107 mm × 107 mm with unit cell dimensions of 5.35 mm × 5.35 mm have been fabricated and measured. These reflectarrays have been fed with a pyramidal horn placed at the center of the array at a distance of 107 mm from the array surface. The antenna gives one beam at the broadside direction. Figure 17(a) shows a photo of the fabricated reflectarray with UC₁. Figure 17(b) shows the fabricated reflectarray under test. Figure 18 shows a comparison between the simulated and the measured reflection coefficient values for the fabricated reflectarray. Figures 19 and 20 show a good

Figure 21. Comparison between the gains of the simulated and fabricated reflectarrays with UC₁ versus frequency.

Figure 22. (a) Photo of the fabricated reflectarray with UC₃₋, (b) reflectarray with UC₃ under test.

agreement between the measured and simulated radiation patterns for both E- and H-planes. Figure 21 shows a comparison between the measured and simulated gain over

Figure 23. Reflection coefficient comparison between the simulated and fabricated reflectarrays with UC₃.

Figure 25. H-plane radiation pattern comparison between the simulated and fabricated reflectarrays with UC₃.

Figure 24. E-plane radiation pattern comparison between the simulated and fabricated reflectarrays with UC₃.

Figure 26. Comparison between the gains of the simulated and fabricated reflectarrays with UC₃ versus frequency.

the frequency band from 27 to 32 GHz. The difference between the simulated and measured results is due to misalignment in the measurement set-up, fabrication errors and material losses. The simulation results confirm gain flatness of the fabricated reflectarray over the frequency band of interest. Figures 22–25 reveal another measurement experiment with its results for the reflectarray designed based on UC₃. This experiment illustrates also the gain flatness over the frequency band of interest and the good match between simulation and measurement results (figure 26).

9. Conclusion

Different designs for single- and double-beam reflectarrays suitable for millimeter wave communication at 28 GHz have been presented in this study. These designs can be efficiently used in the sectorized mobile cells recommended for future generation mobile communication systems. Simulation results revealed the high gain-bandwidth of the designed reflectarrays. Moreover, two prototypes for a single-beam reflectarray have been fabricated, and their radiation characteristics have been measured. The measured and simulated results are in good match revealing

good gain-bandwidth characteristics over the desired frequency band.

List of symbols

λ_o	free space wavelength
N	integer number
f_o	center frequency
D	the reflectarray aperture diameter
F	focal length
k_o	free-space wavenumber at the design frequency
c	speed of light
γ_i	the i th element phase required to compensate for the delay resulting from the corresponding path

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