

Broadband single-layer reflectarray antenna for X-band applications

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Abstract: A new type of X-band (8–12 GHz) unit cell structure on a single-layer for broadband reflectarray antennas is presented in this study. To obtain a broadband performance, a unit cell composed of a circular ring and a complementary diagonal patch ring is proposed. This new type unit cell is designed on a $0.183 \times \lambda_0$ (air-dielectric) thin dielectric substrate and has a 430° phasing range with slow phase variation. Based on the wide phase variation of the proposed unit cell, a centre-fed broadband reflectarray antenna is designed with 9×9 unit cells, 81 elements on a square plane geometry. The designed reflectarray has 40% aperture efficiency and 96% antenna efficiency at 10.5 GHz. The validity of the reflectarray antenna is verified through measurement and simulation results. The experimental and simulation results are in good harmony. The measured and simulated results show that the maximum gain of the reflectarray antenna is 21.6 dBi at 10.5 GHz and has 23% 1 dB gain bandwidth and 29% 3-dB gain bandwidth. Also, the minimum cross-polarisation discrimination is 31.2 dB at 11 GHz frequency.

1 Introduction

A reflectarray antenna is a combination of phase shifting elements on a reflecting surface with an illuminating feed antenna. The phase shifting elements provide a proper phase response to form a collimated, shaped or pencil beam when illuminated by the feed [1–3].

In recent years, because of its attractive advantages for example low profile, light weight, easy development and low manufacturing cost, the majority of researchers have begun to investigate these antennas. For this reason, reflectarray antennas have become an interesting topic compared with the traditional parabolic reflectors. Beside these advantages, reflectarray antennas have some shortcomings. The major drawback of the reflectarray antennas is narrow bandwidth that limits their practical applications. This is the result of the narrow band characteristic of phasing elements [4]. The phasing elements of a reflectarray antenna have a non-linear S-shaped phase curve. This situation makes it very sensitive to frequency variations. To improve the bandwidth of a conventional reflectarray, several techniques and approaches have been developed in the literature. Using stacked or multi-layer phase shifting elements is one of them [5]. This technique slows up the phase variation versus frequency and makes S-shaped phase curve more linear. However, this approach is costly and difficult for practical applications because of surface effects at millimetre wave frequencies. Also, it generates a thick substrate and a negative effect on gain and radiation efficiency. Beside this, aperture coupling to true-time delay lines, single-layer multi-resonant elements are some of the other reported techniques.

Using variably sized patches, rings or dipoles [6] are other techniques to broaden the bandwidth. Variable-sized phasing elements have different phases due to recovering the different feed-pads delays. For this purpose, the size of phasing elements in the reflectarray must be adjusted to compensate the spherical wave from the feed. At the desired frequency, the phasing range of the element should be 360° to achieve this task. 360° phasing range can be obtained by using patches or rings on a thin substrate. However, this application causes a sharp phase variation versus phasing element size. Consequently, it brings narrow bandwidth and a smaller tolerance to manufacturing errors. To slow up the phase variation, thicker dielectric substrates can be used. However,

this approach reduces the phasing range to be $<360^\circ$ and causes a reduction in reflectarray antenna gain. The prior research began to have a considerable effort on designing the reflectarray antenna on a single-layer structure with new shapes of phasing elements due to the mentioned issues. Some of the reported new shapes are square and rectangular rings, windmill ring, Malta cross, cross loop [7], and Quasi-spiral lines [8]. Also, the majority of reported X-band reflectarray antennas have 1 dB gain bandwidth below 20%. Beside this, these phasing elements have high cross-polarisation levels.

Therefore, the aim of this study is to design a new type unit structure for enhancing the bandwidth of the reflectarray antenna. This novel phasing element is composed of a circular ring and a complementary diagonal patch ring. It is designed on a $0.183 \times \lambda_0$ (air-dielectric) thin dielectric substrate and has a 430° phasing range with slow phase variation for X-band applications. The designed 9×9 reflectarray is illuminated by a pyramidal horn antenna is designed, manufactured and measured. The simulation and experimental results show that designed reflectarray antenna achieves 23% 1 dB gain and 29% 3-dB gain bandwidth at 10.5 GHz centre frequency. Also, the proposed antenna has a maximum gain of 21.6 dBi at 10.5 GHz with an aperture efficiency of 40%, antenna efficiency of 96% and has a 31.2 dB cross-polarisation discrimination (XPD) level at 11 GHz frequency. Simulated and measured results present a good harmony.

2 Unit cell structure and design

The unit cell structure is shown in Fig. 1. It is composed of a circular ring and a complementary diagonal patch ring to obtain the required phase variation. The proposed new unit cell is designed on a thin 0.508 mm ($0.016 \times \lambda_0$) dielectric substrate with a 6.15 relative permittivity. The proposed reflectarray antenna is designed for X-band applications so the unit cell dimension is set as $D = 16$ mm which is $0.53 \times \lambda_0$ at the centre frequency of 10 GHz. Also, an air gap between the dielectric substrate and ground is applied to perform a smoother phase curve.

The proposed unit cell phase characteristic must be correctly investigated due to unit cell performance plays an important role on the reflectarray antenna. CST Microwave Studio is used for

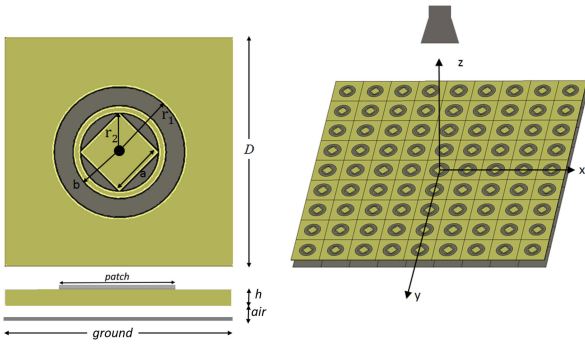


Fig. 1 Geometry of the unit cell structure and reflectarray antenna

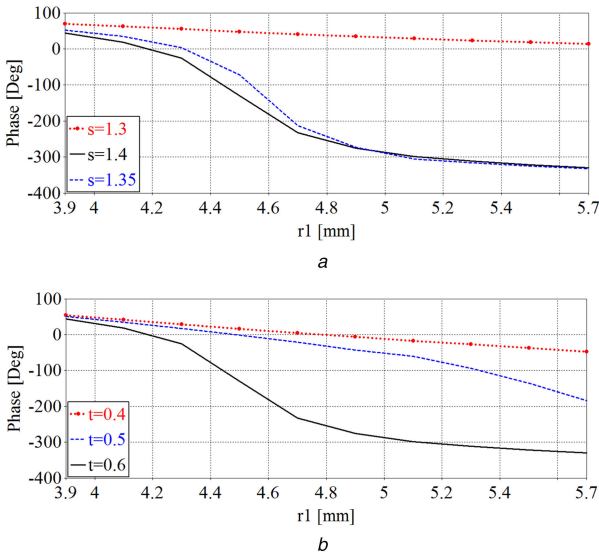


Fig. 2 Phase curve
(a) s factor for $t=0.6$ at 10 GHz, (b) t factor for $s=1.4$ at 10 GHz

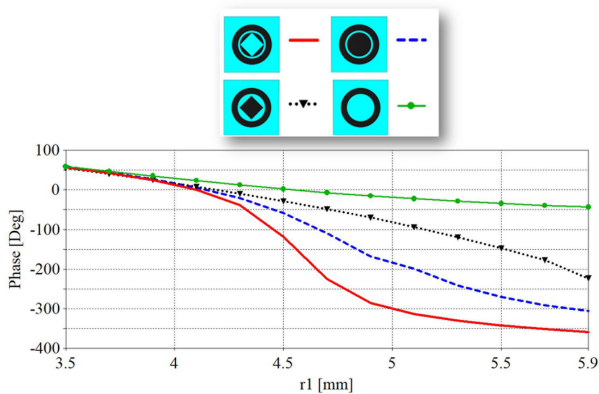


Fig. 3 Phase curves for different geometries

analysis of a unit cell and reflectarray antenna. In this work, the equivalent waveguide approach is chosen to obtain reflected phase variation of the unit cell [9]. For an equivalent waveguide approach, the periodic boundary conditions are implied under normal wave incidence. For this purpose, the tangential component of the incoming electric field is set as a perfect magnetic conductor and the vertical wall is set as a perfect electric conductor under the boundary conditions. To obtain the phase characteristic, it is assumed that a y -polarised (vertically) plane wave impinges on an infinite periodic array. The reflected phase response is determined from the phase of reflection coefficient (S_{11}).

To achieve a wide and smoother phase range, a parametric study is investigated. The effects of s and t variables on phase curves are presented in Fig. 2. The s variable of 1.4 and t variable of 0.6 values have the most suitable and smoother phase range. These parameters are controlling the inner diameter radius and the

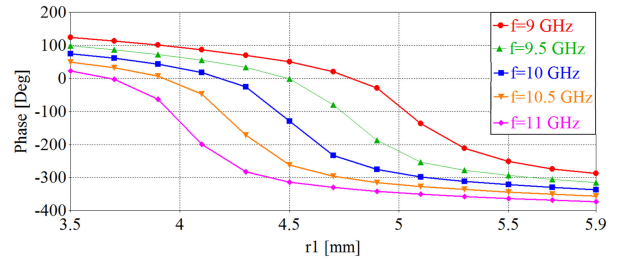


Fig. 4 Phase curves for different frequencies

space between the outer ring and complementary diagonal patch. With the best value of these factors, optimal phase compensation is obtained. The final parameters which are used in the structure geometry are $r_1 = \text{variable}$, $r_2 = t \times r_1$, $a = s \times 2r_2$, $b = s \times 2r_1$, $s = 1.4$, $t = 0.6$, $\text{air} = 5.5 \text{ mm}$ and r_1 is changing from 3.5 to 5.9 mm. The variable-size method is used for compensating the phase delay. Varying the length of the r_1 leads to changing the impedance of unit element. In addition, it causes different phases of reflection whenever a wave hits on the unit cell. Thereby, when the unit cell size is adjusted properly, the required phase variation can be obtained.

To investigate the broadband performance of the new structure, phase variations of different geometries are studied. These unit cells composed of a ring, a diagonal patch and circular patch elements are presented in Fig. 3. The effects of patch elements on reflection phase diagrams are illustrated. It is clearly seen that they have different phase variations. When the unit cell is composed of a circular ring, the smallest phase variation is obtained. Besides this, the circular ring and complementary diagonal patch element have the largest and smoothest phase variation. Therefore, a unit cell that consists of a circular ring and a complementary diagonal patch element is used in the reflectarray antenna geometry to enhance the bandwidth of the antenna.

The computed phase of reflected wave versus diameter r_1 is presented in Fig. 4. It can be seen from Fig. 4, the absolute phasing range is 430° . For making wideband antenna design, the reflection phase characteristics of the unit cell must be parallel to each other at different frequencies. From Fig. 4, it can be seen that the phase characteristic has a constant slope for different frequencies. This is the evidence of having a large bandwidth for the proposed reflectarray element. Also, it indicates that the reflectarray antenna will be independent of differential phase errors versus frequency.

3 Reflectarray antenna design and simulation results

The reflectarray phasing elements which are fed by a horn antenna will reflect the electromagnetic (EM) waves to backward. In Fig. 5, the reflection mechanism of the reflectarray antenna is schematically presented. From this illustration, the EM wave will reach each unit cell with different phases due to the cell position on the reflectarray. To direct this reflected wave towards a certain direction, the phase delay should be compensated by unit cells. For this purpose, the required phase distribution of each unit cell can be obtained as follows:

$$\varphi_R(x_i, y_i) = k_0(d_i - (\cos \varphi_b x_i + \sin \varphi_b y_i) \sin \theta_b), \quad (1)$$

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

When the reflectarray antenna is fed by the center-fed configuration and the maximum radiation is oriented along the z -axis, (1) can be expressed as

$$\varphi_R(x_i, y_i) = k_0 d_i, \quad (3)$$

where k_0 is the free space propagation constant, x_i and y_i give the coordinates of the i th element of the reflectarray antenna. $\varphi_R(x_i, y_i)$ is the phase shift of the i th element, d_i is the distance source and

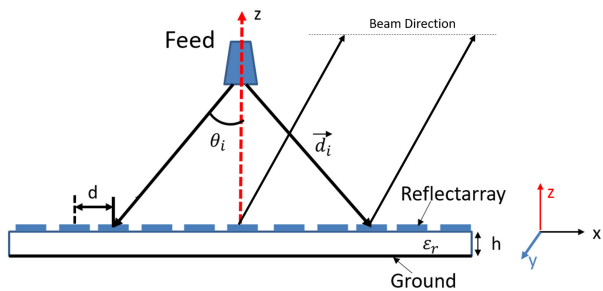


Fig. 5 Mechanism of reflectarray antenna

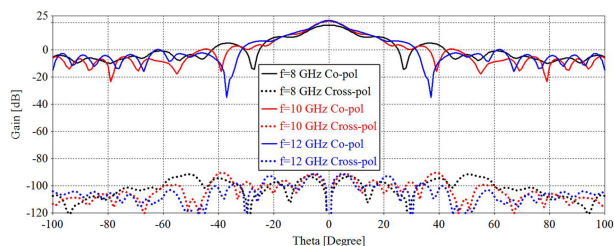


Fig. 6 Simulated radiation patterns for co- and cross-polarisation in principal planes

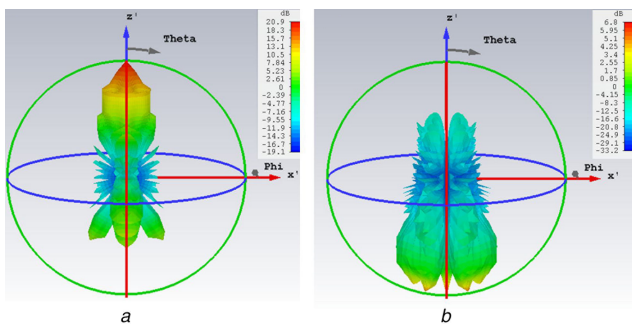


Fig. 7 3D simulated radiation patterns at 11 GHz
(a) Co-polarisation, (b) Cross-polarisation

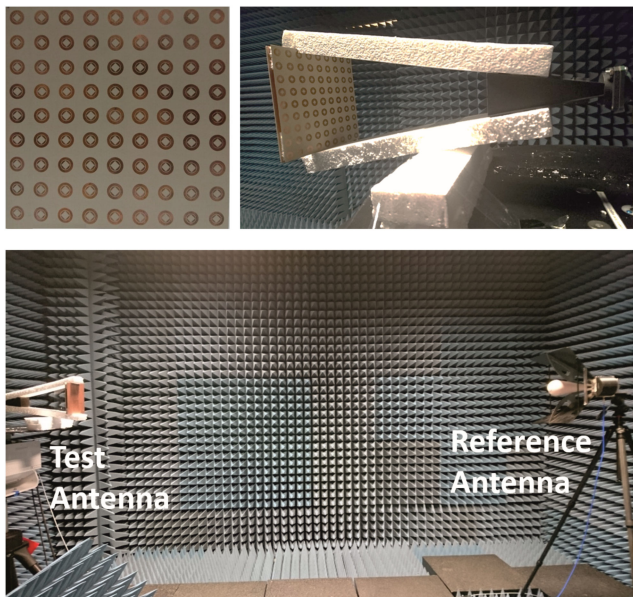


Fig. 8 Measurement set-up of fabricated centre-fed reflectarray antenna

(x_i, y_i) th element and θ_b, ϕ_b is the desired beam direction [10]. x_f, y_f and z_f indicate coordinate of source antenna. Thereby, the size of an element on reflectarray can be determined. For this purpose, from (1) and (2) the required phase delay of each element is calculated.

The pyramidal horn antenna which is used as a feeder is a Flann 16240-15 model standard gain horn antenna. It is connected to a WR90 waveguide. The feed antenna has a 61 mm \times 45 mm aperture size and a 120 mm tapering length. Also, this pyramidal horn antenna has a 3 dB beamwidth $\sim 30^\circ$. Thereby 9×9 unit cells, 81 elements are set on the reflectarray with a square plane geometry. The pyramidal horn antenna is placed at the centre of the reflectarray at the focal distance (F). Thus, the feeder pyramidal horn antenna is located at $x_f = 0, y_f = 0,$ and $z_f = 246$ mm with respect to the reflectarray antenna. The reflectarray antenna simulation is performed with the time domain solver of the CST Microwave Studio. In the simulation, the symmetry planes are defined to save time. Afterwards, the gain and far field radiation patterns are obtained to validate the designed reflectarray antenna. In Fig. 6, simulated radiation patterns in the H -plane are obtained. The results are obtained in the principal planes. The cross-polarisation patterns are obtained with Ludwig's third definition in CST Microwave Studio [11]. Also, the simulated side lobe level is 12.9 dB, 3 dB beam widths are 10.3° and 9.2° for 10 GHz at the E -plane and H -plane, respectively. In the literature, cross-polarisation levels are investigated in [12–14]. Besides this, XPD which is defined as the difference between the peak of the co-polarised main beam and the maximum cross-polarised signal over an angle twice the 3 dB beamwidth of the co-polarised main beam, must be investigated [15]. In this study, the XPD level is obtained as 31.2 dB at 11 GHz frequency. In Fig. 7, simulated three-dimensional (3D) co- and cross- polarisation radiation patterns at 11 GHz are given.

4 Fabrication and measurements

For a complete study, the reflectarray antenna has been fabricated with a standard etching technique and measured. An Arlon TC600 substrate with 0.508 mm thickness is used for fabrication as in CST simulations. The fabricated reflectarray antenna has a 144 mm \times 144 mm size with 9×9 unit cells. In Fig. 8, the photograph of the fabricated reflectarray antenna is presented. As seen from Fig. 8, the fabricated reflectarray antenna is arranged with a centre-fed horn antenna. Also, the measurement of the reflectarray antenna was done inside a whole anechoic chamber. The chamber is a 3-m anechoic test chamber and the frequency range is 900 MHz to 20 GHz. A horn antenna is used (Model: De0530 SN:22 by Diamond Engineering) as a transmitting (reference) antenna and the reflectarray antenna is used as a receiving antenna. In the measurement set-up, a Rohde & Schwarz ZVB 20 vector network analyser with a low-loss coaxial cable has been used.

Fig. 9 presents the radiation patterns at different frequencies. The radiation patterns in the E -plane ($\varphi = 90^\circ$) at $f = 8, 10,$ and 12 GHz are measured and compared with simulated results. As seen from Fig. 9, the side lobe levels of measured patterns are greater than simulated patterns. This is because of measurement set up imperfection and scattering from the feeder mount. Besides this, measured and simulated results are in good agreement. Also, the main beam radiating in the direction is given by $\theta = 0^\circ, \varphi = 0^\circ$. The maximum gain of the reflectarray antenna is 21.6 dBi and it has 23% 1 dB gain bandwidth and 29% 3 dB gain bandwidth at 10.5 GHz centre frequency, as shown in Fig. 10. In [13, 16], the reported 3-dB gain bandwidths are about 7%. Moreover, in these studies, reported cross-polarisation levels are -25 and -40 dB, respectively. Also, the XPD level has been measured at azimuth = 45° plane for 11 GHz. In Fig. 11, the results are given. From the measured co-polarisation pattern, the half-power beamwidth is calculated as 8.44° and the XPD level is obtained as 24.9 dB. Due to the limitations of measurement conditions (lack of extra power amplifier) the cross-polarisation level < -45 dB cannot be measured. In Table 1, there is a comparison of measured XPD levels of the proposed reflectarray and other works in the literature. Despite the measurement limitations, the proposed reflectarray has an average XPD level among X-band reflectarray antennas.

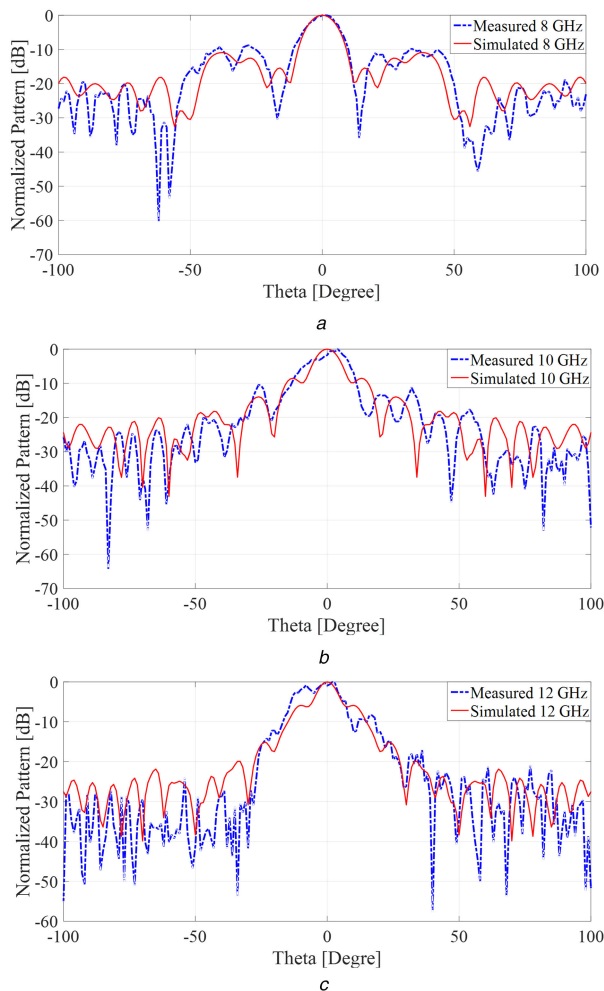


Fig. 9 Measured and simulated radiation patterns in E-plane ($\varphi = 90^\circ$) at (a) $f = 8$ GHz, (b) $f = 10$ GHz, (c) $f = 12$ GHz

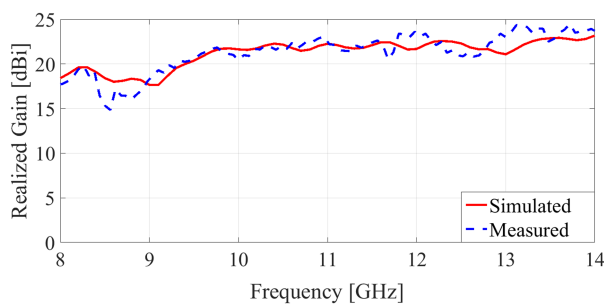


Fig. 10 Realised gain of reflectarray antenna

5 Conclusion

A broadband single-layer centre-fed reflectarray antenna is proposed in this study. By using a new type of phasing element, a slow phase variation and wide phase range are obtained. Each unit element is composed of a circular ring and a complementary diagonal patch ring. It is designed on a $0.183 \lambda_0$ (air-dielectric) thin Arlon TC600 substrate and has a 430° phasing range for X-band applications. The performance of the proposed reflectarray antenna is verified through measurement and simulation results. Both the measurement and simulation results have 21.6 dBi maximum gain of the reflectarray antenna and have 23% 1 dB gain bandwidth and 29% 3-dB gain bandwidth at 10.5 GHz centre frequency. At this frequency, aperture efficiency is 40% and antenna efficiency is 96%. Also, the minimum XPD levels are calculated at the $\varphi = 45^\circ$ plane. At 11 GHz, the simulated XPD level is 31.2 dB, and the measured XPD level is 24.9 dB. With these facilities, the proposed antenna can be easily adopted in broadband applications.

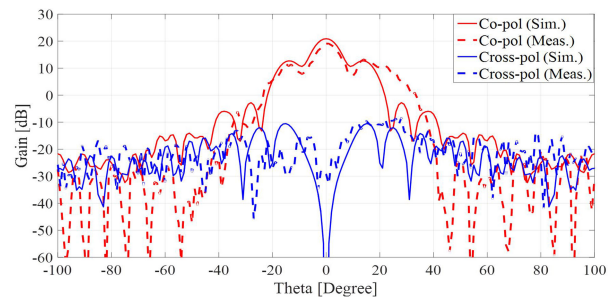


Fig. 11 Measured and simulated co- and cross-polarisation radiation patterns at $\varphi = 45^\circ$ for XPD calculation

Table 1 Measured XPD comparison of the proposed reflectarray with other works in the literature

Reference	Our work	[17]	[18]	[19]
frequency, GHz	11	10	10	19
XPD, dB	24.9	24.5	27.7	27
polarisation	linear	circular	linear	circular

6 Acknowledgments

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7 References

- [1] Huang, J., Encinar, J.A.: 'Reflectarray antennas' (IEEE Press/Wiley, USA, 2008)
- [2] Guo, Y.J., Barton, S.K.: 'Phase efficiency of the reflective array antenna', *IEEE Trans. Antennas Propag.*, 1995, **42**, (2), pp. 115–120
- [3] Li, L., Chen, Q., Yuan, Q., et al.: 'Frequency selective reflectarray using crossed-dipole elements with square loops for wireless communication applications', *IEEE Trans. Antennas Propag.*, 2011, **59**, pp. 89–99
- [4] Pozar, D.M.: 'Bandwidth of reflectarrays', *Electron. Lett.*, 2003, **39**, (21), pp. 115–120
- [5] Encinar, J.A.: 'Design of two-layer printed reflectarrays using patches of variable size', *IEEE Trans. Antennas Propag.*, 2001, **49**, (10), pp. 1403–1410
- [6] Pozar, D.M., Metzler, T.A.: 'Analysis of a reflectarray antenna using microstrip patches of variable size', *Electron. Lett.*, 1993, **29**, (8), pp. 657–658
- [7] Li, H., Wang, B.Z., Shao, W.: 'Novel broadband reflectarray antenna with compound-cross-loop elements for millimetre-wave applications', *J. Electromagn. Waves Appl.*, 2007, **21**, (10), pp. 1333–1340
- [8] Derafshi, I., Komjani, N., Mohammadirad, M.: 'A single-layer broadband reflectarray antenna by using quasi-spiral phase delay line', *IEEE Antennas Wirel. Propag. Lett.*, 2015, **14**, pp. 84–87
- [9] Tsai, F.-C.E., Bialkowski, M.E.: 'An equivalent waveguide approach to designing of reflectarrays using variable size microstrip patches', *Microw. Opt. Technol. Lett.*, 2002, **34**, (3), pp. 172–175
- [10] Carrasco, E., Encinar, J.A., Barba, M.: 'Bandwidth improvement in large reflectarrays by using true-time delay', *IEEE Trans. Antennas Propag.*, 2008, **56**, (8), pp. 2496–2503
- [11] Ludwig, A.: 'The definition of cross polarization', *IEEE Trans. Antennas Propag.*, 1973, **21**, (1), pp. 116–119
- [12] Hasani, H., Kamyab, M., Mirkamali, A.: 'Broadband reflectarray antenna incorporating disk elements with attached phase-delay lines', *IEEE Antennas Wirel. Propag. Lett.*, 2010, **9**, pp. 156–158
- [13] Chang, D.C., Huang, M.C.: 'Multiple-polarization microstrip reflectarray antenna with high efficiency and low cross-polarization', *IEEE Trans. Antennas Propag.*, 1995, **43**, (8), pp. 829–834
- [14] Hasani, H., Kamyab, M., Mirkamali, A.: 'Low cross-polarization reflectarray antenna', *IEEE Trans. Antennas Propag.*, 2011, **59**, (5), pp. 1752–1756
- [15] Albani, M., Balling, P., Datashvili, L., et al.: 'Concepts for polarising sheets dual-gridded reflectors for circular polarisation'. Proc. Int. Conf. on Applied Electromagnetics and Communications, Dubrovnik, Croatia, 20–23 September 2010, pp. 1–4
- [16] Fan, C., Choi, W.W., Yang, W., et al.: 'A low cross-polarization reflectarray antenna based on SIW slot antenna', *IEEE Antennas Wirel. Propag. Lett.*, 2017, **16**, pp. 333–336
- [17] Zhou, M., Sorensen, S.B., Kim, O.S., et al.: 'The generalized direct optimization technique for printed reflectarrays', *IEEE Trans. Antennas Propag.*, 2014, **62**, (4), pp. 1690–1700
- [18] Zhou, M., Sorensen, S.B., Kim, O.S., et al.: 'Direct optimization of printed reflectarrays for contoured beam satellite antenna applications', *IEEE Trans. Antennas Propag.*, 2013, **61**, (4), pp. 1995–2004
- [19] Joyal, M.A., Hani, R.E., Riel, M., et al.: 'A reflectarray-based dual-surface reflector working in circular polarization', *IEEE Trans. Antennas Propag.*, 2015, **63**, (4), pp. 1306–1313