Single Polarization Reflectarray Design Based on an Element with Seven Parallel Dipoles to Generate Independent Beams in three frequency bands.

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Abstract— A single layer reflectarray element based on seven parallel dipoles is proposed for single polarization applications. The dipoles of the reflectarray element make it possible a multi-resonant behavior which provides very large phase range, while keeping low loss and low cross-polarization level. A sequential design process of a reflectarray antenna is proposed where the lengths of the dipoles are adjusted in pairs to provide the required phases which generate three independent beams at 20, 25 and 30 GHz. The simulated radiation patterns of the reflectarray antenna exhibit efficiencies of 80%, 62% and 52% at 20, 25 and 30 GHz respectively. The maximum cross-polar radiation obtained is 29.7 dB, 32.9 dB and 39.1 dB below the maximum of the co-polar beam at 20, 25 and 30 GHz respectively. Bandwidths of 14%, 8.2% and 4.3% are achieved at center frequencies of 20, 25 and 30 GHz respectively. These bandwidth results account for a $\pm 0.5^\circ$ of deviation in the main beam direction, for 2dB-gain variations in the two first bands, and for a 3dB gain variation in the last band.

Index Terms—reflectarrays, parallel edge-coupled dipoles, single polarization.

I. INTRODUCTION

Printed reflectarrays are planar reflector antennas made of one or more layers of microstrip patch arrays [1]. Printed reflectarrays present several technological advantages when compared with conventional reflectors and phased arrays such as low cost, low weight, improved polarization performance and elimination of complex feed networks [2].

The main drawback of the first prototypes of reflectarray antennas was their narrow bandwidth due to the intrinsic finite bandwidth of the microstrip elements. This drawback has been overcome by the use of multilayered substrates that host either two or three metallization levels of rectangular stacked patches [3], [4], or aperture-coupled patches [5], at the cost of a more complex manufacturing process derived from the bonding of different layers with printed elements. In the last decade, different single polarization broadband reflectarray elements made of multi-resonant elements printed on a single dielectric layer have been proposed for to improve the bandwidth, while keeping a simple manufacturing process at the same time. Some of these single layer multi-resonant elements are parallel dipoles [6]-

[9], and concentric rectangular or cross loops [10]-[12], where the relative lengths of the dipoles or loops are adjusted to improve the phase range and the bandwidth of the reflectarray element. The use of multiple resonances makes it possible to achieve a variation of phase-shift in a range larger than 360° [13], which can be used as an additional degree of freedom for a further improvement of bandwidth, as demonstrated in [4] and [5].

In this work a single layer reflectarray element based on seven parallel dipoles is proposed for single polarization applications. The reflectarray element made of dipoles shows a multi-resonant behavior which provides very large phase range. This large phase range can't be obtained with the reflectarray elements proposed in [6]-[12]. A sequential design process of a reflectarray antenna is proposed which makes it possible to radiate three independent beams at three different frequencies (20, 25 and 30 GHz). To achieve this performance, the lengths of dipoles are adjusted in pairs to provide the required phases that generate the desired beam direction at each of the three frequencies.

II. REFLECTARRAY ELEMENT

The reflectarray element proposed in this work is made of seven parallel dipoles embedded in a double-layered substrate as shown in Fig. 1. The dipoles are introduced to control the phase-shift in one linear polarization. The seven dipoles are printed on the upper side of the bottom dielectric layer. The top layer is placed above the bottom layer to avoid

Fig. 1. Reflectarray element made of seven parallel dipoles.

rust or environmental deterioration of the dipoles. The material used for both the bottom and top layers is the commercial low loss material Rogers 4003C. Honeycomb can also be used instead for the bottom layer to reduce the mass in space antennas, and in this case the dipoles would be printed on the lower side of the top layer. If the complex permittivity of the i -th layer of the double-layered substrate is defined as $\epsilon_i = \epsilon_0 \epsilon_{ri} (1 - j \tan \delta_i)$ $-i=1,2$ - (see Fig. 1), then $\epsilon_{r1} = \epsilon_{r2} = 3.55$, $\tan \delta_1 = \tan \delta_2 = 0.0027$. Also, the thicknesses of the layers are $h_1 = 0.5$ mm and $h_2 = 1.5$ mm. The dimensions of the unit cell are $a=5$ mm and $b=5.77$ mm (which correspond to 0.33λ and 0.38λ at 20 GHz, 0.42λ and 0.48λ at 25 GHz, and 0.5λ and 0.58λ at 30 GHz). These values of a and b have been chosen to provide both enough room for the allocation of the dipoles and enough range of phase-shift at the design frequencies (20, 25 and 30 GHz) and, at the same time, to avoid the appearance of grating lobes. The rest of the geometrical parameters have been adjusted to provide a smooth and linear behavior of the phase curves for variations of the lengths of the dipoles, the final dimensions being $l_1 = l$, $l_2 = 0.85l$, $l_3 = 0.77l$, $l_4 = 0.68l$, $l_5 = 0.57l$, $l_6 = l_7 = 0.5l$, $w = 0.5$ mm, $s = 0.3$ mm.

A home-made electromagnetic code that applies the Method of Moments in the Spectral Domain (MoM-SD) has been used for the analysis of the reflectarray cell in a periodic environment. Basis functions accounting for edge singularities have been used in the approximation of the current density of the dipoles [14]. The reflectarray cell is characterized by means of the reflection matrix $\mathbf{R}$, which contains the co-polar and cross-polar reflection coefficients for the two linear polarizations parallel to the axes x and y shown in Fig. 1. The $\mathbf{R}$ matrix relates the cartesian complex components of the reflected and incident tangential electric field on the reflectarray cell in a periodic environment as shown below

$$\begin{pmatrix} E_x^{ref} \\ E_y^{ref} \end{pmatrix} = \begin{pmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{pmatrix} \cdot \begin{pmatrix} E_x^{inc} \\ E_y^{inc} \end{pmatrix} \quad (1).$$

Fig. 2 shows the results for the magnitude and phase of R_{xx} under oblique incidence $\theta_i = 19^\circ$, $\phi_i = 0^\circ$, θ_i and ϕ_i being the spherical angular coordinates of the incidence direction.

Fig. 2. Magnitude and phase of the cell reflection coefficient R_{xx} with respect to the length of dipoles at different frequencies under oblique incidence ($\theta_i = 19^\circ$ $\phi_i = 0^\circ$).

The results of Fig. 2 show that the element of Fig. 1 presents low losses (typically below 1 dB), and a linear and smooth behavior of the phase curves with very large phase range. In fact, a phase range of 569° is obtained due to the resonances of the the dipoles with lengths l_1 and l_2 at 20 GHz, a phase range of 638° is obtained due to the dipoles with lengths l_3 and l_4 at 25 GHz, and finally, a phase range of 632° is obtained due to the dipoles with lengths l_5 , l_6 and l_7 at 30 GHz. This means that a design of a reflectarray antenna with different radiation patterns at the three frequencies can be achieved by means of a sequential adjustment of the lengths of the dipoles in three steps. In the first step of the design, the lengths l_1 and l_2 of the dipoles are adjusted in each reflectarray element to provide the required phase-shift at 20GHz. This adjustment is carried out by sweeping the parameter l while keeping the relations $l_1 = l$ and $l_2 = 0.85l$. In this first step the rest of the dipoles with lengths l_3 , l_4 , l_5 , l_6 and l_7 of each reflectarray element are removed. In the second step of the design, the lengths of dipoles l_3 and l_4 are adjusted in each reflectarray element to provide the required phase-shift at 25 GHz. This adjustment is carried out by sweeping the parameter l while keeping the relations $l_3 = 0.77l$ and $l_4 = 0.68l$. In this second step the lengths l_1 and l_2 previously adjusted for each reflectarray element during the first step are kept constant. Also, in this second step the dipoles with lengths l_5 , l_6 and l_7 of each reflectarray element are removed. Finally, in the third step the lengths of the dipoles l_5 , l_6 and l_7 are adjusted in each reflectarray element to provide the required phase-shift at 30 GHz. This adjustment is carried out by sweeping the parameter l while keeping the relations $l_5 = 0.57l$, $l_6 = l_7 = 0.5l$. In this third step the lengths l_1 , l_2 , l_3 and l_4 previously adjusted for each reflectarray element during the first two steps are kept constant.

Fig. 3 shows the results obtained for the magnitude of the cross-polar coefficient R_{yx} under oblique incidence ($\theta_i = 25^\circ$, $\phi_i = 25^\circ$). The results show that R_{yx} goes to zero for two

Fig. 3. Magnitude of the cross-polar cell reflection coefficient R_{yx} with respect to the length of dipoles at different frequencies under oblique incidence $\theta_i = 25^\circ$ $\phi_i = 25^\circ$.

different values of the dipole lengths at 20 GHz. The number

of zero-crossings increases to 4 at 25 GHz, and to 6 at 30 GHz. Note that Fig. 2 also shows there are 2 resonance lengths at 20 GHz, 4 resonance lengths at 25 GHz and 6 resonance lengths at 30 GHz. So, the number of zero-crossings in Fig. 3 is related with the number of resonance lengths appearing in the phase curves shown in Fig. 2. According to [15], this high number of zero-crossings for R_{yx}

Fig. 4. Coordinate system with origin at the reflectarray center and beam directions.

ensures a low level of cross-polar radiation in a reflectarray antenna based on this type of element.

III. REFLECTARRAY DESIGN

A reflectarray antenna made of elements such as that shown in Fig. 2 has been designed to produce a focused beam in the directions $\theta_{b1}=19^\circ$, $\phi_{b1}=0^\circ$ at 20 GHz, $\theta_{b2}=25^\circ$, $\phi_{b2}=0^\circ$ at 25 GHz and $\theta_{b3}=32^\circ$, $\phi_{b3}=0^\circ$ at 30 GHz for X-polarization (see Fig. 4 for the definition of the angles θ_{bi} and ϕ_{bi} - $i = 1, 2, 3$). The reflectarray element has been characterized as described in the previous section. The reflectarray is rectangular and consists of 525 elements arranged in a 25×21 grid with cell size 5mm x 5.77mm. The reflectarray is illuminated by a feed-horn with its phase center located at coordinates $x_{RA} = -63.9$ mm, $y_{RA} = 0$ mm and $z_{RA} = 185.5$ mm with respect to a coordinate system with origin at the center of the reflectarray (see the coordinate system in Fig. 4). The direction of the radiated beam at 20 GHz - $\theta_{b1}=19^\circ$, $\phi_{b1}=0^\circ$ - has been chosen to be the specular reflection direction of the beam arriving at the reflectarray center from the feed horn, which prevents the beam squint effect from appearing at frequencies around 20 GHz [16]. Since the radiated beam directions at 25 and 30 GHz are not the specular reflection directions of the feeding beam, beam squint effects are to be expected around those frequencies.

The required phase distribution to produce a collimated beam in the direction $\theta_{b1}=19^\circ$, $\phi_{b1}=0^\circ$ at 20 GHz, $\theta_{b2}=25^\circ$, $\phi_{b2}=0^\circ$ at 25 GHz and $\theta_{b3}=32^\circ$, $\phi_{b3}=0^\circ$ at 30 GHz for X-polarization are shown in Fig. 5(a), Fig. 5(b) and Fig. 5(c)

respectively. The radiation pattern of the feed is modeled as a function $\cos^{20}(\theta)$, which provides an illumination level at the reflectarray edges 10 dB below the maximum.

The reflectarray design follows the three steps described in section II. In the first step the parameter l involved in l_1 and l_2 is adjusted to match the required phase-shift shown in Fig. 5(a) to the phase of the reflection coefficient R_{xx} in each

Fig. 5. Required phase shift to produce a collimated beam for X-polarization in the direction (a) $\theta_{b1}=19^\circ$ and $\phi_{b1}=0^\circ$ at 20 GHz, (b) $\theta_{b2}=25^\circ$ and $\phi_{b2}=0^\circ$ at 25 GHz, and (c) $\theta_{b3}=32^\circ$ and $\phi_{b3}=0^\circ$ at 30 GHz.

reflectarray element at 20GHz. In the second stage, the parameter l involved in l_3 and l_4 is adjusted to match the required phase-shift shown in Fig. 5(b) to the phase of the reflection coefficient R_{xx} in each reflectarray element at 25GHz. Finally, in the third stage, the parameter l involved in l_5 , l_6 and l_7 is adjusted to match the required phase-shift shown in Fig. 5(c) to the phase of the reflection coefficient R_{xx} in each reflectarray element at 30GHz. In all the three

steps of the design process, local periodicity is assumed and the angle of incidence in each element of the reflectarray is explicitly considered.

IV. NUMERICAL RESULTS

Figs. 6(a) and (b) show the elevation and azimuth cuts of the computed radiation patterns for the reflectarray designed in Section III at 20, 25 and 30 GHz. These radiation patterns have been computed in terms of the electric and magnetic equivalent currents existing on the reflectarray surface, which are provided by MoM-SD for each reflectarray element (technique II in [17]). The antenna gain is computed in terms of the power radiated by the feed, and the radiation patterns are computed with reference to the isotropic antenna (in dBi) [1]. The numerical results obtained for the radiation patterns indicate a gain of 27.13 dBi (i.e., an efficiency of 80%) at 20 GHz, 27.92 dBi (i.e., an efficiency of 62%) at 25 GHz, and 28.72 dBi (i.e., an efficiency of 52%) at 30 GHz. Moreover, the radiation patterns exhibit very low cross polarization. In fact, the maximum levels of cross-polar radiation have been found to be 29.7 dB, 32.9 dB and 39.1 dB below the co-polar maxima at 20, 25 and 30 GHz respectively. The cross-polarization in the elevation plane in Fig. 6(a) is lower than -20dBi because the elevation plane is a symmetry plane. Note that the cross-polar radiation level is lower as the frequency increases. This result is to be expected since Fig. 3 shows an increment of the number of zero-crossings with increasing frequency, and the larger the number of zero-crossings, the lower the cross-polar radiation [15].

Fig. 6. Main cuts of the radiation patterns generated at 20, 25 and 30 GHz by the reflectarray designed for X-polarization. (a) Elevation cut. (b) Azimuth cut.

Fig. 7(a) shows both the gain and the maximum level of cross-polar radiation as a function of frequency for X-polarization. Fig. 7(b) shows the spherical angular coordinate $\theta_{b,max}$ giving the main beam direction as a function of frequency (see Fig. 4). The results shown in Figs. 7(a) and (b) show a variation of $\pm 0.5^\circ$ in the main beam direction in the range 19-21.8 GHz with 2dB-gain variation (14% bandwidth), in the range 24.9-27 GHz with 2dB-gain variation (8.4% bandwidth), and in the range 29.5-30.8 GHz with 3dB-gain variation (4.3% bandwidth). Note that the main limitation of the bandwidth is due to the variation of $\pm 0.5^\circ$ in the main beam direction. This variation of $\pm 0.5^\circ$ causes a smaller bandwidth around the design frequencies of 25 and 30 GHz, and the reason for this is that the main beam direction is not the specular reflection direction of the feeding beam at those frequencies, which is the origin of beam squint [16]. A wider bandwidth is to be expected at 20 GHz where the main beam direction is the specular reflection direction of the feeding beam.

V. CONCLUSION

A reflectarray antenna made of reflectarray elements based on seven parallel dipoles has been designed to

Fig. 7. (a) Maximum gain of the copolar and cross-polar radiation as a function of frequency. (b) Main beam direction as a function of frequency.

generate three independent beams for single polarization at 20, 25 and 30 GHz respectively. A sequential design process is proposed where the lengths of dipoles are adjusted in pairs to provide the required phases that generate the three independent beams. The simulated radiation patterns of the designed reflectarray antenna exhibit efficiencies of 80%, 62% and 52%, and cross-polar maxima below the main beam of 29.7 dB, 32.9 dB and 39.1 dB, at 20, 25 and 30 GHz respectively. A detailed study has been carried out on the variation of both the gain and the main beam direction as a function of frequency. The results show variations of $\pm 0.5^\circ$ in the main beam direction in the range 19-21.8 GHz with 2dB-gain variation (14% bandwidth), in the range of 24.9-27.0 GHz with 2dB-gain variation (8.4% bandwidth), and in the range 29.5-30.8 GHz with 3dB-gain variation (4.3% bandwidth). The reduction of bandwidth with increasing frequency is attributed to beam squint caused by the fact that the main beam direction is not the specular reflection direction of the feeding beam.

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