

Folded Multilayer Microstrip Reflectarray With Shaped Pattern

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Abstract—A folded multilayer printed reflectarray with shaped pattern is demonstrated. The configuration consists of a multilayer twister reflectarray, a centered feed embedded in its structure and a polarizing grid, which acts as reflector and radome for each polarization, respectively. A design procedure, valid for obtaining any arbitrary shaped pattern, has been implemented. In order to achieve the pattern specifications along a frequency band, initially a multifrequency pattern synthesis method, which relies on a phase-only synthesis, is applied to obtain the required phase-shift on the reflectarray surface. Afterwards, each stacked patch is individually optimized to generate the required phase-shift previously synthesized. The method has been successfully applied to a LMDS base station antenna, characterized by a sectorial cosecant squared beam in the band 24.5–26.5 GHz. A breadboard consisting of a folded 3-layer circular reflectarray is presented. Measurements show a good concordance with theoretical patterns at 25 GHz, and good shaping of the beam along 24–26 GHz.

Index Terms—Folded reflector, multilayer, printed reflectarray, shaped beam.

I. INTRODUCTION

A folded printed reflectarray basically consists of a microstrip passive reflector with a feed embedded in its structure, and a polarizing grid placed parallel to the reflectarray at a certain distance h [1]. The field coming from the feed and reflected on the polarizing grid impinges on the passive array that properly focuses the beam and twists the polarization 90° , so the radiated field passes through the polarizer. The aim of using a folded antenna is to achieve a low profile compact antenna, and therefore, the parameter h , must be reduced as much as possible.

Millimeter-wave folded printed reflectarrays have been proposed for radar and communication applications [2]–[5], where compact and robust antennas are required. High gain, omnidirectional, sectorial beam, mechanically steerable and multifeed multibeam antenna solutions have been successfully demonstrated for different configurations of single layer microstrip patches. However, all of them present the electrical disadvantage inherent to reflectarray antennas, i.e., a narrow bandwidth [6].

Manuscript received December 7, 2004; revised June 20, 2005. This work was supported in part by the Spanish Ministry of Science and Technology under Projects TIC 2001-2744 and TEC-2004-02155.

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Digital Object Identifier 10.1109/TAP.2005.863101

In order to overcome that limitation, the use of several stacked layers have been proved as the best choice [7]. References [8] and [9] deal with the design of 2- and 3-layer printed reflectarrays respectively.

The breadboard of a large contoured beam reflectarray for space applications is presented in [10]. Besides, a fan-beam microstrip reflectarray with cosecant squared pattern in elevation has been demonstrated for radar applications [11]. Nevertheless, in both antennas the shaped patterns are achieved by means of an approximate simple technique, and no bandwidth enhancement is considered, as in the folded reflectarray with an azimuthal sector beam quoted in [3]. Recently, a design procedure has been applied to multilayer printed reflectarrays, which provides enough bandwidth and the required shaped pattern by using a suitable power pattern synthesis [12]. By combining both technologies, folded reflectarrays and multilayer shaped pattern reflectarrays, a mechanically compact antenna with improved electrical performances can be achieved.

The aim of this paper is the demonstration of a folded multilayer printed reflectarray with shaped pattern for a LMDS central station antenna. An independent design of the polarizer and the passive twister multilayer flat reflector is considered by assuming ideal response of the polarizing grid. The twister reflectarray design, based on the method presented in [12], carries out a previous multifrequency synthesis of the desired shaped pattern followed by the adjustment of each reflectarray element to get the shaped pattern and twist the polarization 90° . The whole antenna configuration and design method, described in Section II, is applied to the particular case of interest: a sectorial antenna for LMDS base station [13]. The application works in the band 24.5–26.5 GHz and requires a shaped pattern of cosecant squared beam in elevation and fan beam in azimuth with linear polarization. Section III presents the design, measurements and results of a 3-layer manufactured breadboard. Finally the conclusions will be addressed in Section IV.

II. CONFIGURATION AND DESIGN

Fig. 1 shows a sketch of a folded reflectarray and its associated equivalent imaginary configuration, i.e., same passive array and feed defined as the mirror image of the real one considering the polarizing grid as symmetry plane. The height of the folded structure can be expressed as

$$h = 0.25 \cotan(\alpha_{F_{\max}}) D \quad (1)$$

where $\alpha_{F_{\max}}$ is the maximum incident angle and D is the diameter of the reflectarray, assuming it is circular. Common values

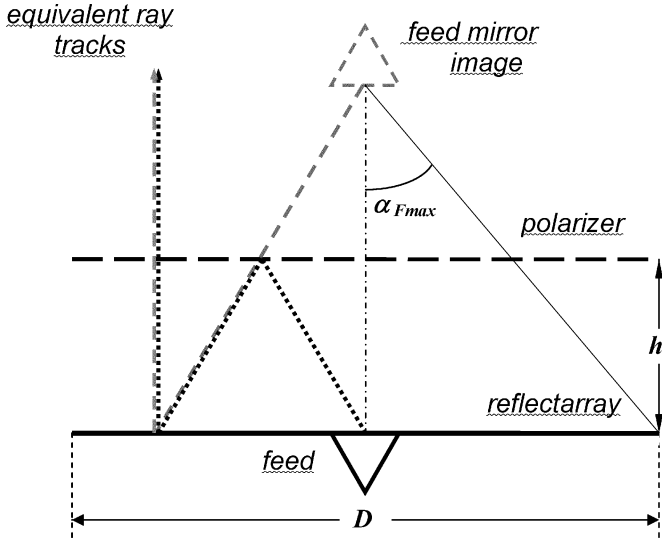


Fig. 1. Sketch of a folded reflectarray and its equivalent standard reflectarray.

for α_{Fmax} do not exceed $40\text{--}45^\circ$, and thus, the achievable minimum height is not less than a quarter of the antenna dimension. In order to get a low profile, the value of h is restricted to several centimeters, otherwise the antenna becomes too thick and the folded configuration loses all its mechanical advantages. Therefore, and taking into account (1), a maximum antenna dimension must be not greater than 20 cm. In communication applications, arrays are usually required at least 10-wavelength large to get directive antennas. This fact constrains the use of these antennas at Ka-band or higher frequency applications, as those proposed in [1]–[5] and in the present paper.

Fig. 2 depicts the geometry of the reflectarray under study, where the feed is a conical horn and the polarizing grid consists of a strip grating. A center-fed printed reflectarray composed of variable-size stacked rectangular patches arranged in a square lattice is considered. A full-wave analysis of the structure is not computationally affordable, mainly because its complexity demands a huge amount of memory and computation time. Therefore, the analysis and later design of a shaped pattern folded reflectarray is split into two parts: the reflectarray and the polarizer. That division is feasible, as it has been demonstrated in [1]–[5]. By considering the polarizing grid as ideal, a design of the reflectarray relying on the mirror image feed is carried out. The polarizer is designed to perform close to its required “ideal” response. Regarding the reflectarray, on the one hand, there is the design of the feed, necessary for the overall reflectarray design. On the other hand, there is the design of the multilayer passive flat reflector, which must be carried out in several stages due to its complexity, as it has been successfully proposed in [12]. Each part of the folded reflectarray is explained in detail below.

A. Feed Design

The used feed, centered and integrated in the multilayer passive array, is a conical horn. The dimensions of the horn (mainly the aperture) are chosen to: a) achieve an appropriate illumination on the reflectarray’s edge that fits the taper required by the synthesis process; b) ensure far field condition of the feed field in the polarizing grid and; c) define a reasonable spill-over loss.

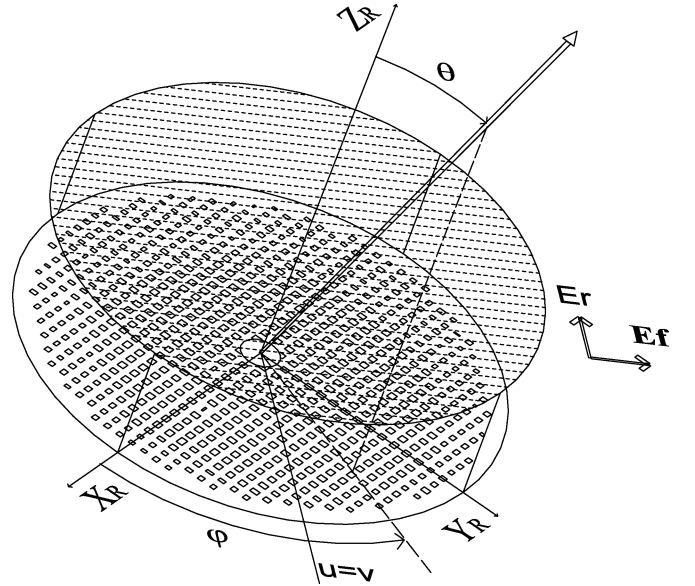


Fig. 2. Geometry of the studied folded multilayer printed reflectarray.

The feed aperture must be as small as possible to reduce the effect of eliminating the central elements in the reflectarray, as it will be shown later. The choice of a centered conical horn is due to mechanical considerations and simplicity of manufacture. The extension to an offset configuration is electrically feasible.

B. Polarizing Grid Definition

The polarizing grid consists of a strip grating sandwiched by a dielectric substrate. The total thickness of the substrate is approximately half a wavelength, to allow the field orthogonal to the grid to go through the dielectric slab with minimum insertion losses. The computation is accomplished for normal and oblique incidence by considering appropriate number of modes in the dielectric layers. The separation between strips and its width are defined to achieve return losses for the orthogonal field low enough (usually less than 20 dB) along the working frequency band. This configuration assures a reliable polarizer, and therefore the assumption of perfect polarizer can be applied afterwards to the reflectarray design. The use of a strip grating is justified for its better performance in frequency with respect to other possible choices as for instance slot grids.

C. Multilayer Passive Reflector: Synthesis and Design

In order to carry out the synthesis and design process, the equivalent nonfolded reflectarray, which is defined by the imaginary feed, is considered. Both synthesis and design rely on a procedure generalized for dual linear polarization and used for large contoured beam reflectarrays [12]. Firstly the phase of the reflected field on each reflectarray element that gives the desired shaped radiation pattern is synthesized by means of a phase-only synthesis method [14], [15]. Then, the stacked printed elements of the reflectarray are designed individually, in order to achieve the previously synthesized phase-shift distribution. However, the polarization of the antenna under study is oblique linear in the reflectarray coordinate system, and therefore the process of synthesis and design must be modified.

Fig. 2 shows the vectors of the electric fields radiated by the feed and by the reflectarray, $\mathbf{E}_f$ and $\mathbf{E}_r$, respectively. Whereas the former is parallel to the strip grating and thus reflected, the latter is 90° twisted and therefore can pass through the polarizing grid. The polarization of $\mathbf{E}_r$ is 45° tilted with respect to the reflectarray coordinate system $X_R Y_R Z_R$.

In order to get the required 90° rotation of the polarization, the rectangular patches must be disposed 45° tilted with respect to the incident field [4]. Then they are designed to maintain a phase difference of 180° between the phases of the two reflected field components defined along the axes X_R and Y_R , parallel to the patches sides. In addition, the reflected field must be synthesized to obtain the desired shaped pattern.

According to [14], the electrical field patterns radiated by a reflectarray with dual linear polarization, $\mathbf{E}_X$ and $\mathbf{E}_Y$, can be expressed respectively as a function of the fields reflected on each element (m, n) , $A_x^{m,n} \exp(j\phi_x^{m,n})$ and $A_y^{m,n} \exp(j\phi_y^{m,n})$, considered uniform on the whole periodic cell, by the following equations:

$$\mathbf{E}_X(u, v) = \frac{jk(u\boldsymbol{\theta} - v\sqrt{1-u^2-v^2}\boldsymbol{\varphi})}{2\pi\sqrt{u^2+v^2}} S \times \sum_{m,n} A_x^{m,n} e^{j\phi_x^{m,n}} e^{jk(umd_x+vnd_y)} \quad (2)$$

$$\mathbf{E}_Y(u, v) = \frac{jk(u\boldsymbol{\theta} + v\sqrt{1-u^2-v^2}\boldsymbol{\varphi})}{2\pi\sqrt{u^2+v^2}} S \times \sum_{m,n} A_y^{m,n} e^{j\phi_y^{m,n}} e^{jk(umd_x+vnd_y)} \quad (3)$$

where bold case denotes a vector, k is the propagation constant at frequency f , $d_x \times d_y$ defines the periodic cell, $u = \sin(\theta)\cos(\varphi)$ and $v = \sin(\theta)\sin(\varphi)$ are the direction cosines, and the term S is defined as

$$S = \frac{4 \sin(0.5kud_x) \sin(0.5kvd_y)}{k^2 uv}. \quad (4)$$

The vectorial expressions (2) and (3), referred to $X_R Y_R Z_R$, are defined for spherical components in the $u-v$ plane. For the particular case of 45° oblique linear polarization, the radiation pattern is a linear combination of (2) and (3), where the phases of the reflected field components must be equal. Otherwise, the polarization would not be preserved and simply two independent x - and y -linearly polarized fields would be radiated.

$$\mathbf{E}_r = \mathbf{E}_X + \mathbf{E}_Y \quad \text{with } \phi_x^{m,n} = \phi_y^{m,n}. \quad (5)$$

The 45° tilted linear polarization must be taken into account in the appropriate definition of co- and cross-polarization given by Ludwig's third definition [16]. The equations that translate E_θ , E_φ , spherical components obtained by substituting (2) and (3) in (5), into co- and cross-polarization components are defined as follows:

$$\begin{aligned} E_{co} &= E_\theta \sin(\varphi + \alpha) + E_\varphi \cos(\varphi + \alpha) \\ E_{cross} &= E_\theta \cos(\varphi + \alpha) - E_\varphi \sin(\varphi + \alpha) \end{aligned} \quad (6)$$

being α the rotation angle around Z_R axis that gives the orientation of the co-polar component. For the case under study $\alpha = 45^\circ$. The amplitude of the co-polar component of (6) defines the radiation pattern of the folded multilayer printed reflectarray to be optimized in the pattern synthesis process. Folded reflectarray presents low cross-polarization because of the polarizing grid, and therefore, no synthesis process is required to reduce cross-polarization levels.

A multifrequency phase-only pattern synthesis [15] is applied to achieve the desired shaped pattern in a required bandwidth. Initially, the *intersection approach* method [17] is applied to achieve the required phase-shift on each reflectarray element at central frequency. In this first stage, the non existence of central elements where the feed is placed, must be taken into account. From this phase distribution and assuming the phase delay variation with frequency for a pencil beam, the required phase shift on each reflectarray element is computed at any frequency in the working band [9]. These phases are used as starting point in the synthesis process, which is applied again at extreme frequencies. The resulting phase delay at any frequency within the working band generates radiation patterns that fulfill the requirements. The multifrequency synthesis ensures a smooth variation of phase distribution with frequency, which is important for the later design of the reflectarray patches.

The *intersection approach* method seeks the shortest distance between two sets; on the one hand, the set of realizable patterns with the geometry and amplitude distribution of the reflectarray, and on the other hand the radiation patterns that match the requirements imposed by the mask of specifications. For accomplishing that purpose an alternating projection technique is revealed as the most suitable. Mainly due to its high computing efficiency by means of using two-dimensional (2-D) FFT algorithms in its implementation and, secondly because it is quite simple to include the amplitude constraints imposed by the feed inherent to any reflectarray. The convergence of the method to undesired local minima is highly dependent on the starting pattern, and therefore, a suitable initial point must be chosen in order to avoid them.

So far, the phases of the reflected field are synthesized at central and extreme frequencies. But the synthesis procedure has not accomplished the 90° twist of the polarization. Therefore, the patch design must implement the twist. The dimensions of the stacked rectangular patches are adjusted to achieve the phase shift associated to the synthesized phase (objective phase) and to ensure that the reflected field on each element is orthogonally twisted. This second fact is implemented in the design process by enforcing a phase difference of 180° between the phases of the reflection coefficient associated to each patch side, when optimizing the dimensions of the stacked rectangular patches in the design procedure described in [12].

III. APPLICATION OF INTEREST: LMDS CENTRAL STATION SECTORED ANTENNA

The aim of this section is to demonstrate a folded 3-layer printed reflectarray with shaped pattern. The pattern specifications for the LMDS sectored antenna are defined as a 90° fan

beam in azimuth and a 6° -tilt cosecant squared pattern in elevation, for a 7.8% bandwidth centered at 25.5 GHz. The antenna dimensions are chosen to achieve the specified 13 dBi bore-sight gain level defined by the European Standard for a 90° wide sector [13]. Therefore a 181.4 mm diameter circular geometry is proposed.

A. Synthesis and Design

The reflectarray is made up of 749 three-stacked rectangular patches arranged in a 5.85 mm side square grid of 31×31 elements. The imaginary feed is centered placed 10 cm far from the flat reflector, and hence, the height of the folded configuration becomes 5 cm. This height ensures that the polarizing grid is in far field condition with respect to the feed. By substituting the dimension and height data in (1), a 40° maximum angle of incident at the reflectarray's edge is obtained, which ensures a good performance of the reflection coefficient for the external patches.

In order to get an antenna radiating with linear polarization in elevation, i.e., vertically oriented with respect to the ground, the elevation plane must be defined as $u = v$ (see Fig. 2). Despite the difficulty on carrying out a successful synthesis, it is possible to achieve an initial shaped pattern close to the requirements that eases the process by firstly, taking into account a separate nature of the pattern specifications and afterwards applying an appropriate interpolation.

Initially, the antenna is meant to radiate 45° -oblique linear polarization defining the elevation plane in $v = 0$. The 3-D specifications M can be expressed as the product of two 2-D patterns: sectored azimuth beam M_2 , in $u = \sin(6^\circ)$ plane and, the elevation shaped pattern M_1 , in $v = 0$ plane. Therefore a separate function is defined as

$$M(u, v) = M_1(u)M_2(v) \quad (7)$$

where M_1 and M_2 are defined as two templates of minimum and maximum permitted levels with a 3 dB gain separation. An analytical phase-only synthesis technique [18], conveniently modified for reflectarrays, is used independently for the 2-D separate patterns in (7). That technique determines the phase distribution of a linear array required for achieving a specific radiation pattern when the amplitude of the excitation is fixed. As a consequence of applying it, two linear phase distributions are obtained for the main pattern cuts defined in ZX and YZ planes, which fit respectively the desired masks M_1 and M_2 . Then, and bearing in mind (7), the 2-D phase distribution required to fulfill M , can be approached by a sum combination of the previous synthesized linear phases on each reflectarray element. So far, a suitable initial shaped pattern has been achieved with oblique linear polarization.

The pattern specifications given in (7) must be twisted 45° to obtain a linearly polarized field oriented along the elevation plane. In order to accomplish that task, the previous synthesized phases are associated to a fictitious reflectarray rotated $\varphi = 45^\circ$ with respect to the one depicted in Fig. 2. This auxiliary rotated phase distribution, which gives the required twisted pattern, is evaluated (sampled) in an irregular grid in $X_R Y_R Z_R$. However, the elements belonging to the reflectarray are arranged

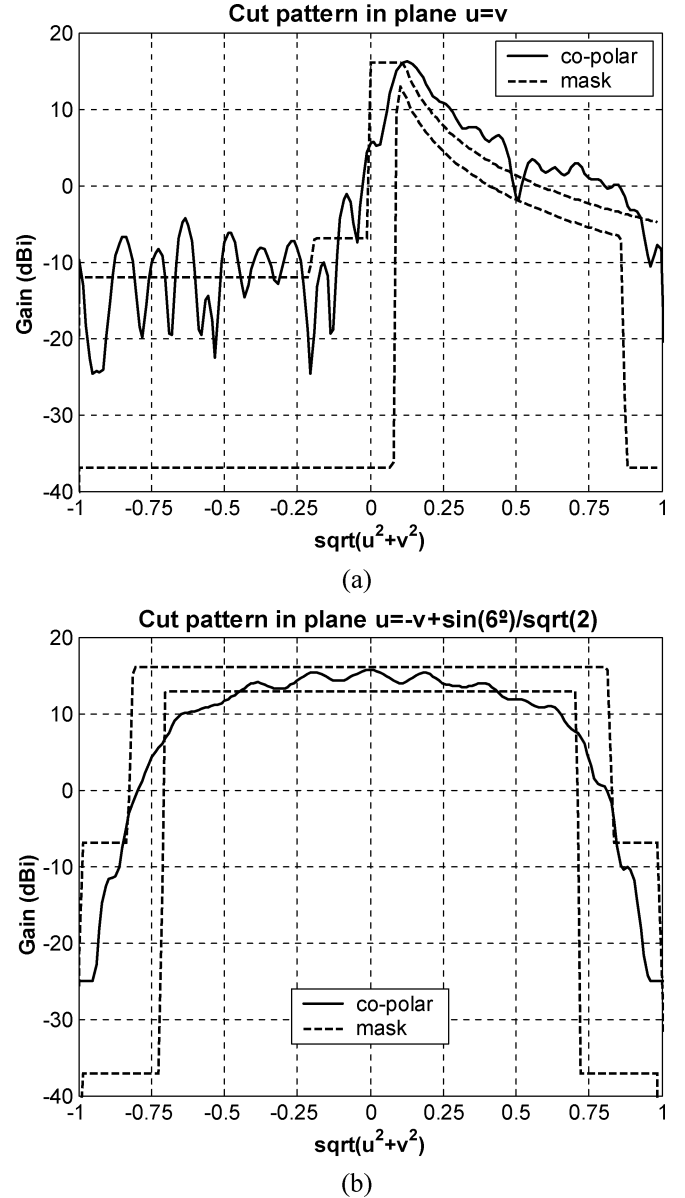


Fig. 3. Specifications and starting pattern used in the phase-only synthesis. Main cuts: (a) Cosec² pattern in elevation; (b) sector beam in azimuth.

in a square grid, and therefore, an interpolation of the phase distribution on each element position must be performed. As a result, the new interpolated phases on each reflectarray element achieve the required rotated shaped patterns. Fig. 3 shows the elevation and azimuth cuts for the initial pattern used in the synthesis process superimposed onto the specifications. Although the separate synthesis and later interpolation is just an approximation, the obtained results are close enough to the specifications. The presented cuts are defined in $u = v$ plane and $u = -v + \sin(6^\circ)/\sqrt{2}$ as a consequence of the 45° rotation of the pattern. Fig. 4 presents the 3-D pattern and its required phase-shift on the reflectarray. The pattern 45° turn with respect to the $u - v$ axes is seen. In a similar way, if a linear polarization oriented in azimuth is desired, a -45° rotation of the pattern is required.

The synthesized phase is used as starting point for the full synthesis method procedure explained in previous section.

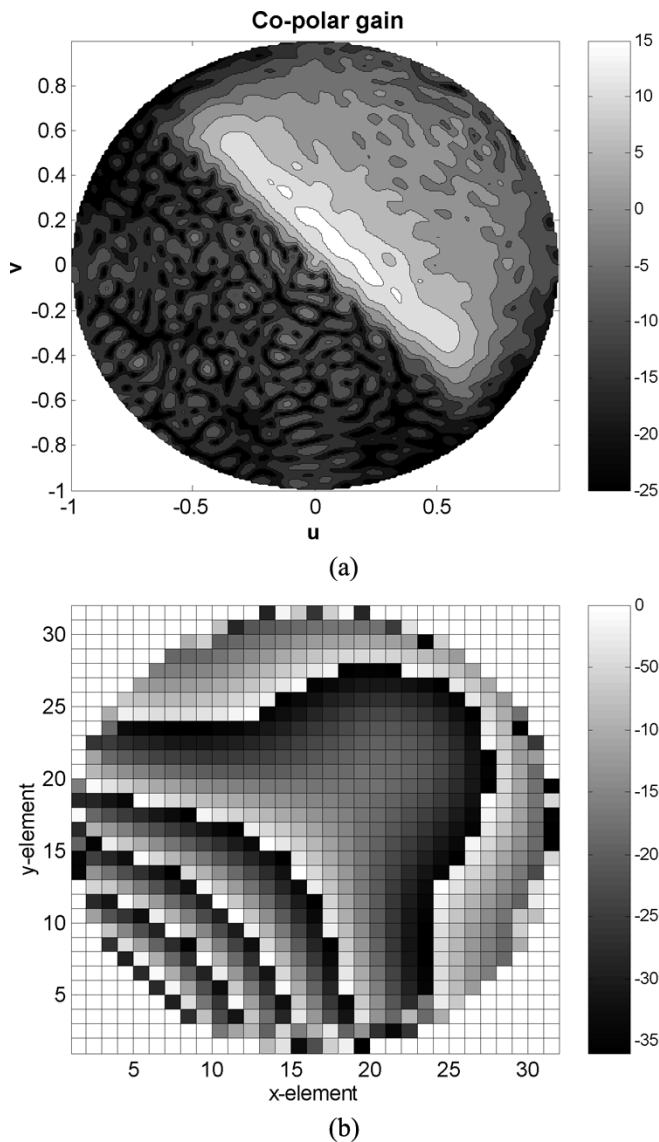


Fig. 4. Initial pattern in the synthesis at 25.5 GHz. (a) 3-D gain co-polar pattern; (b) objective phase distribution on the reflectarray surface.

Firstly, a synthesis at central frequency is carried out without taking into account the elimination of central elements. The achieved patterns almost fulfill specifications as a consequence of the good starting pattern in the process. Nevertheless, nine central elements are affected by the integration of the horn in the multilayer structure, and are totally or partially eliminated (see Fig. 2). The fact that these elements do not contribute to the radiation pattern must be taken into account in the synthesis process, since it has been checked that the simulated radiation pattern is modified by increasing the side lobe levels behind the cosecant beam and by distorting the shaped pattern in elevation at the same time. To take into account this effect, the amplitude of the incident field is set to zero in the synthesis process where there is no element, starting with the phase distribution previously synthesized.

After the whole phase-only synthesis process the synthesized pattern approximates the desired specifications quite well although the elimination of some central cells produces slight

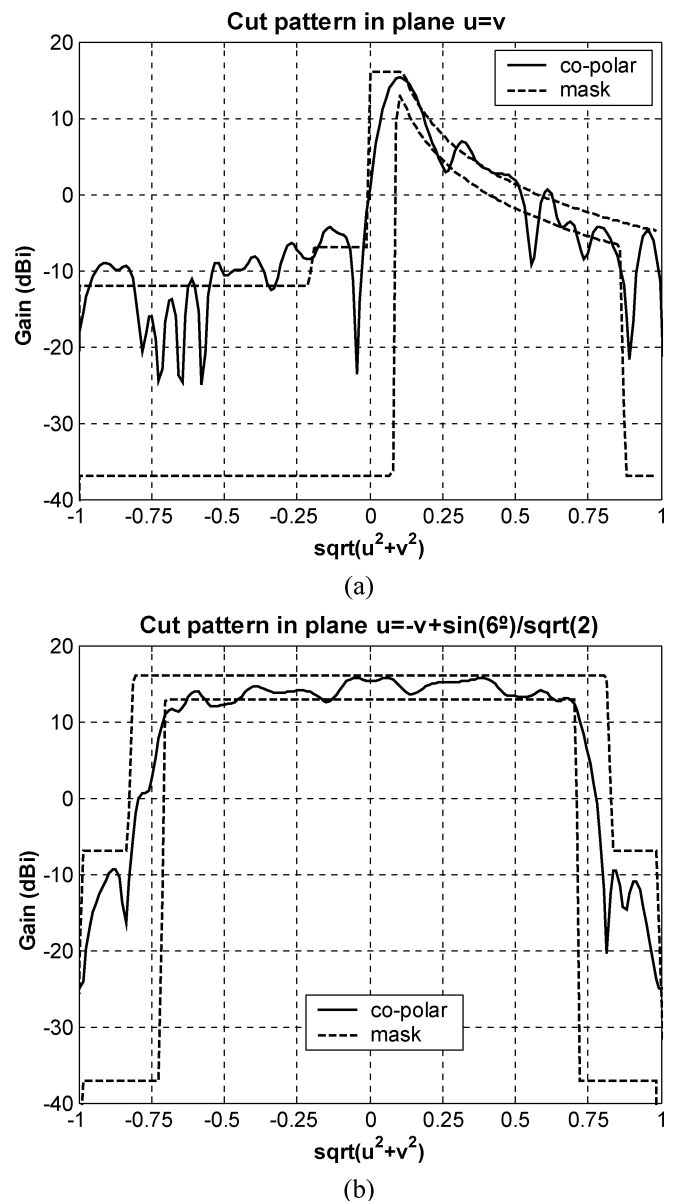


Fig. 5. Main cuts of the synthesized pattern eliminating the central elements. (a) Cosec² pattern in elevation; (b) sector beam in azimuth.

distortions in the final simulations and the appearance of some small holes that the synthesis method cannot avoid. Both undesired effects are mainly due to the fact that the chosen starting point is not as close to the requirements as it was when all the reflectarray radiating elements were considered. Fig. 5 and Fig. 6(a) depict the main cuts and the whole synthesized pattern respectively. The final objective phases, shown in Fig. 6(b), present a similar pattern to the initial one of Fig. 4(b), which demonstrates the suitable choice of the starting phase in the synthesis process, despite the effect of canceling phase in the synthesis process.

Once the radiation pattern has been synthesized at 25.5 GHz, the patterns at the extreme frequencies of the band are synthesized. Thus, syntheses at 24.5 and 26.5 GHz are realized based on the previous phase distribution achieved at central frequency. Figs. 7 show the final 3-D synthesized patterns, which present

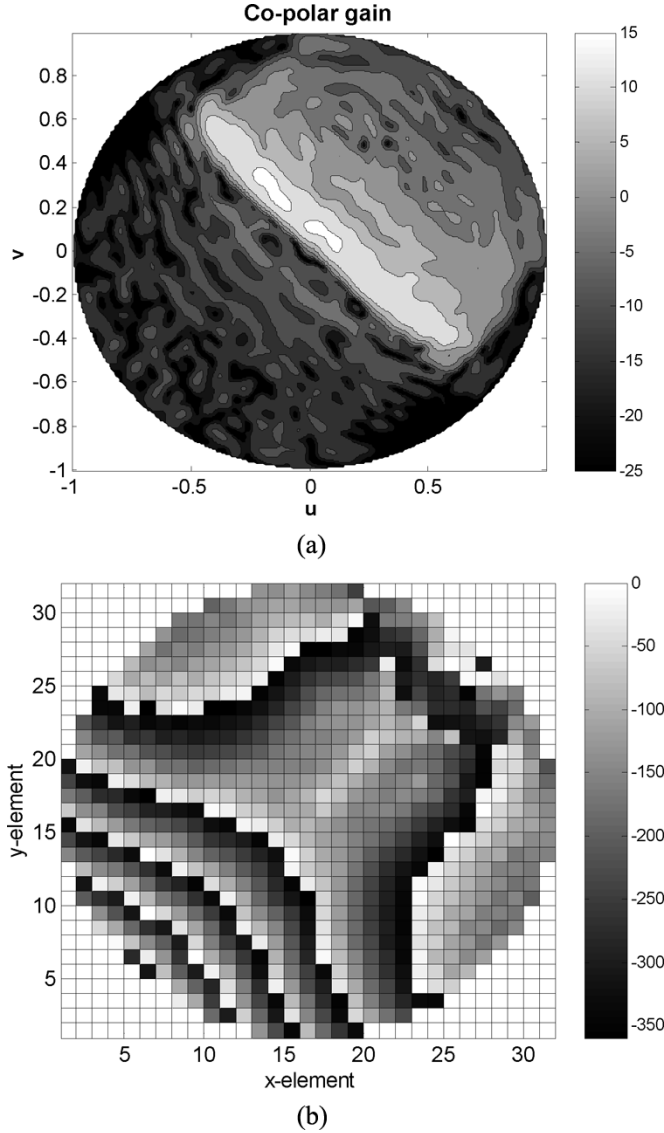


Fig. 6. Synthesized pattern at 25.5 GHz. (a) 3-D gain co-polar pattern; (b) objective phase distribution on the reflectarray surface.

suitable shaped beams. It must be mentioned that all the presented patterns are computed by using the simulated radiation pattern of the conical horn.

The used feed is a nonstandard conical horn with 16 mm-diameter aperture, 6.5 mm flare length and 8 mm throat, which complies with the requirements stated in Section II-A. The choice of the feed is mainly constrained to the illumination required in the edge of the reflectarray. An 8 dB taper at reflectarray's edge is chosen for two reasons. Firstly, it defines an efficient illumination and secondly, the radiation pattern synthesized with such taper is very close to specifications. The feed is modeled in the synthesis process by using a $\cos^{3.5}$ function to get the required 8 dB edge illumination. A full-wave simulation of the feed pattern has been carried out by using a commercial software [19]. In addition, the main pattern cuts were measured as well. The cosine model, the simulations and the measurements present similar patterns.

After the multifrequency synthesis procedure, the patch dimensions are optimized, element by element, as described in

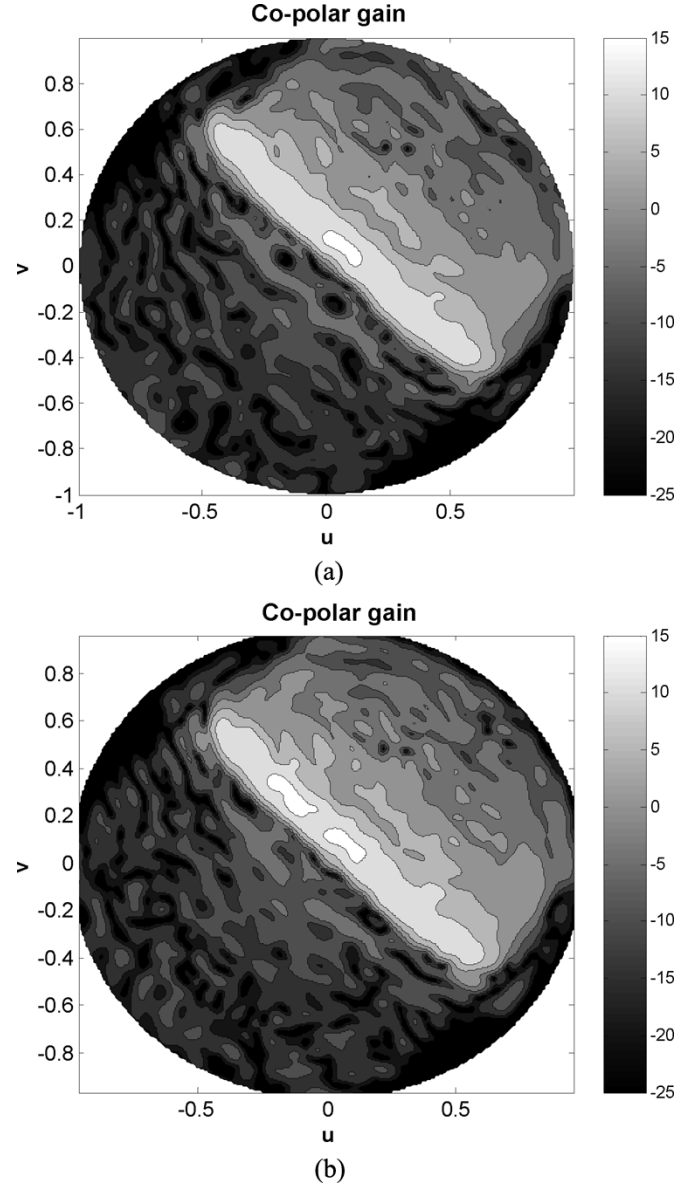


Fig. 7. Synthesized patterns at extreme frequencies: (a) 24.5 GHz; (b) 26.5 GHz.

[12] to achieve the required phases at central and extreme frequencies. To ensure that the incident field is properly twisted, the phase distribution for y -polarization in the reflectarray coordinate system is obtained by adding 180° to the synthesized phase distribution which is used for x -polarization. The lay-up of the three-layer configuration is detailed in Fig. 8.

The polarizing grid is formed by a strip grating sandwiched between two substrate layers: 0.508 mm-thick Duroid5870 and Duroid5880 of thickness 3.218 mm. The printed strip is $200 \mu\text{m}$ wide and the separation between them is $190 \mu\text{m}$. The polarizing grid has been analyzed for different angles of incidence. At normal incidence, this configuration gives return losses lower than -22 dB in the whole band for the polarization with electric field perpendicular to the grating, and transmission lower than -30 dB for the orthogonal polarization. However, insertion losses increase with the angle of incidence up to -12 dB for 40° incidence. In the same way, transmission of the orthogonal polarization increases up to -19 dB for 50° incidence. In

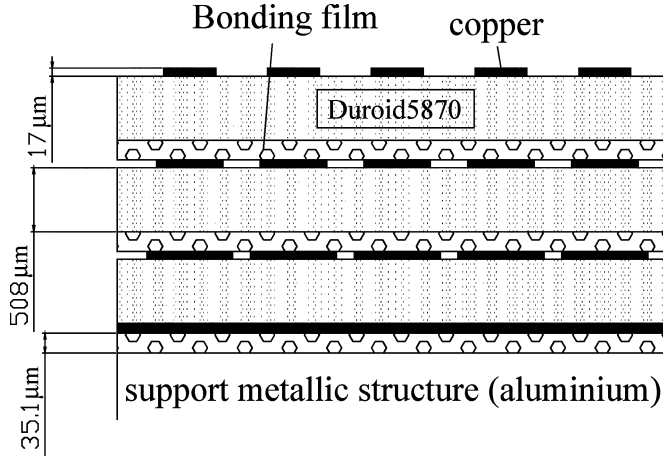


Fig. 8. Lay-up of the 3-layer structure used for the implemented reflectarray.

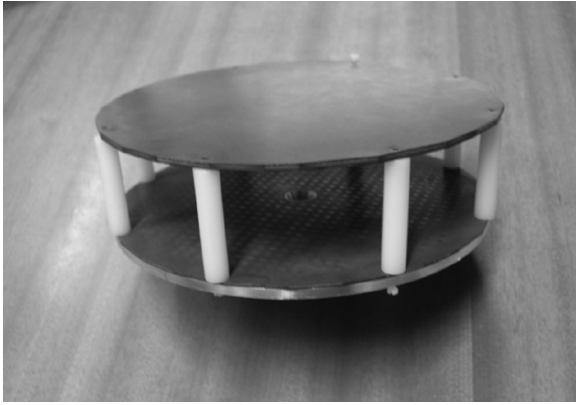


Fig. 9. Manufactured folded 3-layer printed reflectarray for LMDS base station antenna.

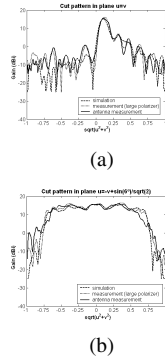


Fig. 10. Comparison of simulations and measurements at 25 GHz. (a) Elevation plane pattern $u = v$; (b) azimuth plane pattern $u = -v + \sin(6^\circ)/\sqrt{2}$.

conclusion, these results are good enough in the range of angles considered in the breadboard, up to 40° .

B. Manufacture, Measurements and Discussion

A picture of the manufactured folded reflectarray is presented in Fig. 9. The required 5-cm separation between the reflectarray and the polarizing grid is achieved by means of eight small nylon posts 5-mm thick.

A comparison between antenna gain simulations (dash line) and measurements (black solid line) for the main cut planes at 25 GHz is shown in Fig. 10. Good agreement between the simulated and measured gain patterns is observed. However, the mea-

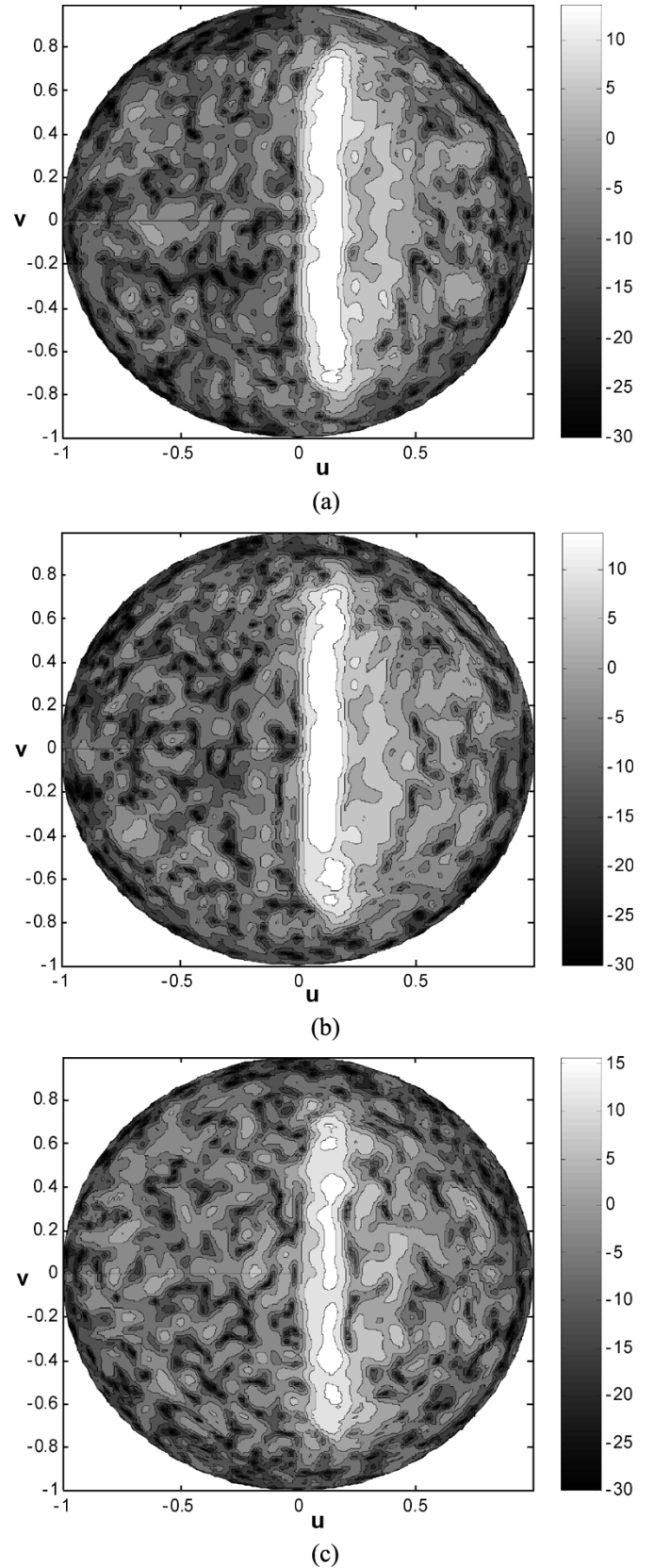


Fig. 11. Measured directivity co-polar patterns at *E.T.S. I. Telecomunicación de Madrid's* anechoic chamber. (a) 24 GHz; (b) 25 GHz and (c) 26 GHz.

sured pattern presents sidelobe levels higher than it would be expected and a sectorized beam narrower than the simulations. In

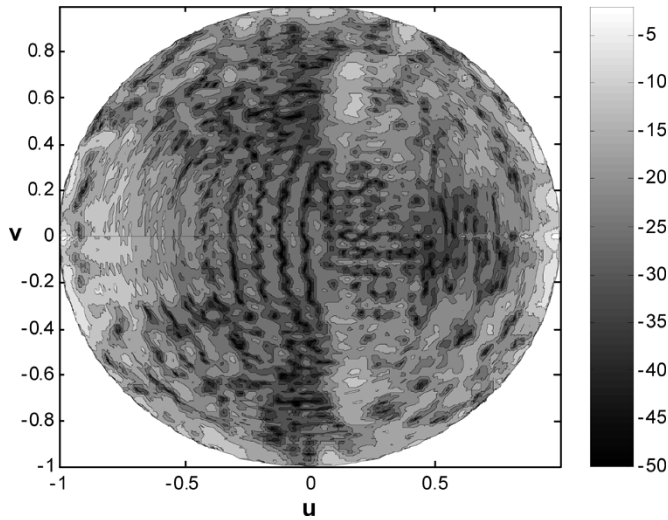


Fig. 12. Measured cross-polar pattern at 25 GHz.

order to establish the influence of the finite polarizer, the measurements have been repeated with a larger (320×290 mm) rectangular grating. The obtained results, displayed in dotted line in Fig. 10, shows a better shaping of the azimuthal beam whereas no significant improvements are observed in the elevation plane cut. The lack of improvement observed in the elevation plane cut is justified by the smaller dimension in elevation of the polarizer (290 mm).

Fig. 11 shows 3-D co-polar measured patterns for the breadboard with the large polarizer at 24, 25 and 26 GHz referred to the anechoic chamber reference system, 45° rotated with respect to coordinate system of Fig. 2. The expected shaped pattern is obtained at the three frequencies, although at extreme frequencies the sectored beam starts distorting. The distortion is more significant at the top of the band. In addition, the initial working band defined from 24.5 to 26.5 GHz has been shifted down (24–26 GHz). Both issues are due to material and manufacturing tolerances [20], respectively in the standard values of thickness and dielectric constant of the substrate and, in the photo-etching of each printed layer (the small wavelength, around 11.75 mm, increases the sensitivity of electrical performances with manufacturing tolerances). To assess the latter, several patches of the upper layer have been measured, given values larger than the nominal dimensions in a range between 20 and $100 \mu\text{m}$. The average error is 55 microns in one dimension and 45 microns in the other. These errors justify the frequency shift toward lower frequency and some distortion in the patterns, since the variation of the phase with the dimension is not linear.

Regarding the cross-polarization, two sources contribute to it: one is the direct radiation of the feed for large angles, and the other is the polarization coupling in the grid for large angles of incidence, i.e., the field parallel to the grid transmitted when a perpendicular field is incident. Although the grid attenuates both components more than 20 dB along the frequency band, the measured values are higher than expected for the breadboard with the circular polarizer. However, the cross-polarization levels are highly reduced when the large rectangular polarizing grid is used, demonstrating the important influence of scattering effects at the edges of the finite polarizing grid. Fig. 12

depicts the measured 3-D cross-polarization pattern at 25 GHz for the breadboard with the rectangular large polarizer. The gain levels are 30 dB lower than the co-polar peak gain in practically all the coverage region. Close to the edge, such figure decreases because of the direct radiation coming from the feed.

Some other reasons justify the slight disagreements between simulations and measurements. Firstly, the real scattering effects produced in the feed horn have not been taken into account. Secondly, the analysis of the central elements close to the feed horn is not accurate enough since the approximation of local periodicity used in the design process [8] is not fulfilled any more. The amplitude field on those central elements is large and therefore, its inaccurate analysis can produce some distortion in the radiation pattern. Finally, the simulations do not take into account the effect of the finite polarizing grid.

IV. CONCLUSION

A design procedure for folded multilayer printed reflectarray with shaped pattern has been presented. Due to the complexity of the whole antenna an independent design of the polarizer and the reflectarray has been carried out. The shaped beam reflectarray is designed, firstly synthesizing the required phase distribution in the reflectarray surface that gives the desired shaped pattern, and secondly, adjusting the dimensions of the stacked patches to achieve the previous synthesized phases and to twist 90° the polarization at the same time.

A compact antenna for LMDS central station applications has been considered as case of interest. The design, manufacture and measurement of a folded 3-layer microstrip reflectarray with shaped beam demonstrate the reliability of the presented method. The design has been successfully accomplished thanks to an appropriate definition of the starting pattern in the synthesis process. The measured radiation patterns are close to the specifications for a LMDS base station sectored antenna. Although good agreement between measurements and simulations has been achieved at central frequency, measurements have shown a 500 MHz shift down in the frequency band produced by the tolerance errors in patch dimensions.

REFERENCES

- [1] D. Pilz and W. Menzel, "Folded reflectarray antenna," *Electron. Lett.*, pp. 832–833, Apr. 1998.
- [2] W. Menzel, D. Pilz, and R. Leberer, "A 77-GHz FM/CW radar front-end with a low-profile low-loss printed antenna," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 12, pp. 2237–2241, Dec. 1999.
- [3] W. Menzel, M. Al-Tikriti, and R. Leberer, "Low-profile folded reflectarray antennas for communication applications," presented at the Eur. Workshop on Integrated Radio Communication Systems, France, May 2002.
- [4] W. Menzel, D. Pilz, and M. Al-Tikriti, "Millimeter-wave folded reflector antenna with high gain, low loss, and low profile," *IEEE Antennas Propag. Mag.*, pp. 24–29, Jun. 2002.
- [5] W. Menzel, M. Al-Tikriti, and R. Leberer, "Compact folded MM-wave reflectarray antennas," in *Proc. 3rd ESA Workshop on Millimeter Wave Technology and Application*, Espoo, Finland, May 2003, pp. 101–106.
- [6] J. Huang, "Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept," in *IEEE Int. Symp. Antennas Propag.*, Newport Beach, CA, Jun. 1995, pp. 582–585.
- [7] D. Pozar, "Bandwidth of reflectarrays," *Electron. Lett.*, vol. 39, no. 21, pp. 1490–1491, Oct. 2003.
- [8] J. A. Encinar, "Design of two-layer printed reflectarrays using patches of variable size," *IEEE Trans. Antennas Propag.*, vol. 49, no. 10, pp. 1403–1410, Oct. 2001.

- [9] J. A. Encinar and J. A. Zornoza, "Broadband design of three-layer printed reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 51, no. 7, pp. 1662–1664, Jul. 2003.
- [10] D. M. Pozar, S. D. Targonski, and R. Pokuls, "A shaped-beam microstrip patch reflectarray," *IEEE Trans. Antennas Propag.*, vol. 47, no. 7, pp. 1167–1173, Jul. 1999.
- [11] D.-C. Chang and M.-C. Huang, "Feasibility study of erecting cosecant squared pattern by planar microstrip reflectarray antenna," in *APMC'93*, vol. 2, Oct. 1993, pp. 19–20.
- [12] J. A. Encinar and J. A. Zornoza, "Three-layer printed reflectarrays for contoured beam space applications," *IEEE Trans. Antennas Propag.*, vol. 52, no. 5, pp. 1138–1148, May 2004.
- [13] *European Standard (Telecommunications Series), Fixed Radio Systems; Point-to-Multipoint Antennas; Antennas for Point-to-Multipoint Fixed Radio Systems in the 11 GHz to 60 GHz Band; Part 2: 24 GHz to 30 GHz*, ETSI EN 301 215-2 v1.3.1, Jun. 2002.
- [14] J. A. Zornoza and J. A. Encinar, "Efficient phase-only synthesis of contoured beam patterns for very large reflectarrays," *Int. J. RF and Microw. Computer-Aided Engin.*, pp. 415–423, Sep. 2004.
- [15] J. A. Zornoza, M. Arrebola, and J. A. Encinar, "Multi-frequency pattern synthesis for contoured beam reflectarrays," presented at the 26th ESA Antenna Workshop on Satellite Antenna Technology, Noordwijk, Holland, Nov. 2003.
- [16] A. C. Ludwig, "The definition of cross polarization," *IEEE Trans. Antennas Propag.*, pp. 116–119, Jan. 1973.
- [17] O. Bucci, G. Franceschetti, G. Mazzarella, and G. Panariello, "Intersection approach to array pattern synthesis," *Proc. Inst. Elect. Eng.*, pt. H, vol. 137, no. 6, pp. 349–357, Dec. 1990.
- [18] A. Chakraborty, B. N. Das, and G. S. Sanyal, "Beam shaping using non-linear phase distribution in a uniformly spaced array," *IEEE Trans. Antennas Propag.*, vol. AP-30, no. 5, pp. 1031–1034, Sep. 1982.
- [19] CST, Computer Simulation Technology, Microwave Studio 5.0, Time-Domain Simulation Tool.
- [20] J. A. Zornoza, J. A. Encinar, M. Frantz, L. Datashvili, H. Baier, M. Sierra-Castañer, P. Caballero, and J. L. Besada, "Experimental demonstration of contoured beam reflectarrays for satellite applications," presented at the ITG-Conference on Antennas INICA, Germany, Sep. 2003.



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