

Analysis, Design and Applications of Reflectarrays

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Abstract— A brief overview of reflectarray antennas mainly focused on some efficient analysis and design techniques and on recent developments has been presented. A technique based on the local periodicity and Method of Moments in Spectral Domain has been presented as very efficient for the analysis of reflectarray antennas. The technique has been validated by comparing simulations and measurements in several breadboards. Based on the previous analysis technique, several design procedures have been implemented for different antenna performances, including requirements of broad-band, dual-frequency and stringent contoured beams. Finally some recent developments for applications in space and LMDS antennas are presented.

Index Terms—Reflectarray, printed antennas, contoured beam, multi-beam.

I. INTRODUCTION

A reflectarray is made up of an array of radiating elements which provide a pre-adjusted phasing to form a focused or shaped beam when it is illuminated by a feed, see Fig. 1. The necessary phase shift at each element is obtained by varying one of the geometrical parameters in the reflectarray element. Different implementations of phase-shifters have been demonstrated, as printed patches with attached or aperture-coupled delay lines [1, 2], varying-sized patches in single and stacked configurations [3-6], apertures of different length on the ground plane [7], and others [8-9]. In this paper we consider the reflectarray elements shown in Fig.2, namely stacked patches of varying size and patches aperture-coupled to delay lines, because they provide very good bandwidth performances.

Printed reflectarrays combine certain advantages of reflector antennas and phased arrays. They are manufactured on a planar substrate using printed circuit technology and offer the possibility of beam steering as phased arrays. The feeding method (as in a reflector antenna) eliminates the complexity and losses of the feeding network used in planar arrays, thus providing a higher efficiency. The major limitation of reflectarrays is the narrow-band behavior, but recent

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developments based on the elements shown in Fig. 2 have significantly overcome this limitation.

Reflectarrays have demonstrated their capability to produce fixed focused and contoured beams, using simple photo-etching techniques. Recently, a lot of work has been done to develop reconfigurable-beam reflectarrays by introducing control devices on the reflecting elements, also some potential applications of reflectarrays in space have been researched such as, contoured beam antennas for Direct Broadcast Satellites (DBS) and very large inflatable antennas.

The purpose of this paper is to present a brief overview of reflectarray antennas, including the analysis and design techniques, bandwidth issues and wideband techniques, as well as recent developments for space and Local Multipoint Distribution System (LMDS) applications.

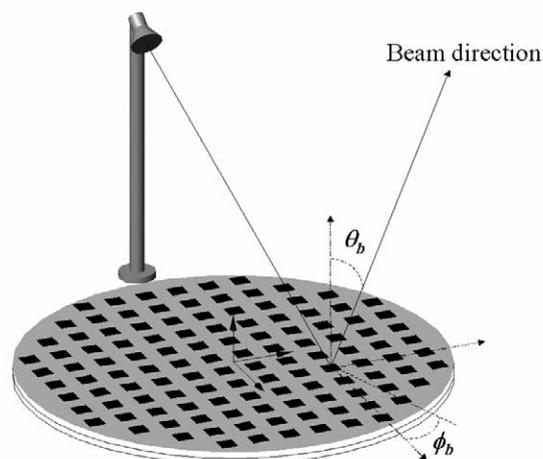


Fig. 1. Reflectarray antenna.

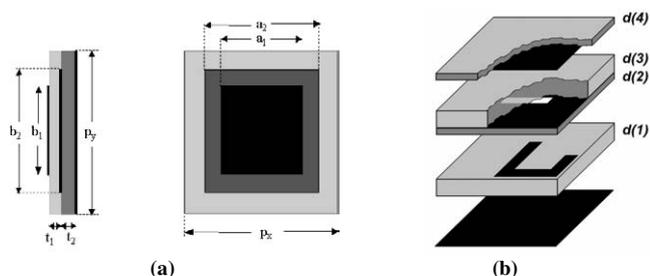


Fig. 2. Reflectarray element. (a) Stacked patches of varying size, (b) patch aperture-coupled to delay line.

II. ANTENNA ANALYSIS TECHNIQUES

The reflectarray is a relatively complex antenna, and an accurate analysis technique is essential for precise predictions of the radiation features, such as efficiency, gain, co- and cross-polar radiation patterns and bandwidth.

The first step in the analysis of the reflectarray antenna is the characterization of the phasing elements. A full-wave analysis technique must be used to compute the ohmic losses and phase-shift produced on the reflected field on each element. Usually in reflectarrays, mutual coupling cannot be neglected, particularly in the case of varying-sized patches, because the dimensions of some patches are larger than half-wavelength in the dielectric, and the separation between patches is small.

In the case of reflectarrays, which have a large number of elements, the infinite array model can be used and, applying the Floquet's theorem, the analysis is reduced to only one periodic cell [10-11]. This technique takes automatically into account the mutual coupling among elements and gives good predictions of each element in the array environment.

For multi-layer reflectarray elements, as stacked patches of varying size or aperture-coupled patches, a modular approach based on Spectral-Domain MoM in a periodical environment, described in [12-13], has been used. Spectral Domain Method of Moments is very appropriate and numerically efficient for a full wave analysis of periodical structures, assuming planar arrays of patches or apertures in a single or multi-layer configuration. In this case, the CPU time for the analysis is very low (in the order of 1 second), and the analysis routine can be integrated into an optimization loop for a more accurate design of reflectarray antennas.

The infinite array approach can be used, in principle for any type of phase-shifter element. For elements with stubs of different length (attached or aperture-coupled), all the radiating patches are exactly the same and only the stub length varies from one element to the next. In this case, the infinite array approach will be very accurate, because the coupling produced by the stubs is less significant, assuming a minimum of separation between stubs and other metallic lines or patches.

The complete reflectarray is analyzed by assuming local periodicity, i.e. each element is considered in an array environment with all the elements identical. This approach is accurate when the variation in patch dimensions is smooth from one cell to the next, because it takes into account all mutual coupling between patches. Only in the small number of patches where the surrounding patches are of very different dimensions, the local periodicity approach is not accurate. Normally these elements are a small percentage of the total number of elements and the overall radiation pattern of the reflectarray is slightly affected, as shown in [14].

As an alternative to the local periodicity approach, several full-wave techniques have been applied recently to analyze the reflectarray as a whole [15-17]. These methods take into account all the individual couplings between elements, and then the CPU time is drastically increased. The full wave

techniques are appropriate for an accurate analysis of the reflectarray, but the large CPU times make unaffordable their use in optimization processes.

III. REFLECTARRAY DESIGN

Once the reflectarray element has been defined and characterized, the reflectarray antenna must be designed to produce a given focussed or shaped beam. Once the antenna geometry is defined, the phase-shift distribution to be implemented on the reflectarray is obtained at a given working frequency. Then, the dimensions of the reflectarray elements are adjusted to achieve the required phase-shift. For the case of a reflectarrays based on stacked patches, the dimensions of each patch are determined using an iterative routine for zero finding. This routine calls the analysis program and adjusts the dimensions of each element until the required phase-shift is achieved for each polarisation. After this process, the reflectarray has been design for a given frequency and the radiation patterns fulfil the initial requirements at this frequency, but they suffer some distortion at other frequencies.

The most severe drawback in reflectarray operation is its narrow frequency band, and much effort has been made in recent years to overcome this limitation. First of all, different broad-band elements have been proposed for reflectarray antennas. The two types of reflectarray elements shown in Fig. 2, can provide a broad-band behavior. Using these elements, the design at a single frequency gives enough bandwidth for moderate size reflectarrays [18].

To overcome the frequency band limitation in large reflectarrays, a method has been proposed in [19] for stacked patches of varying size, in which the phase delay is compensated locally at different frequencies with the phase of the reflection coefficient. This means that the patch dimensions are adjusted to match not only the required phase-shift distribution, but also its variation with frequency. The design of a reflectarray in a frequency band is described in [19] and it is summarized as follows: First, using the patch dimension obtained for the design at the central frequency, an optimization routine based on the Fletcher-Powell algorithm is applied to adjust all the dimensions of the stacked patches to match the required phase-shift at central and extreme frequencies. It has been demonstrated that using three stacked patches, a 1-m reflectarray in Ku-band can be designed for a 10% bandwidth [14], [19], for a 15% bandwidth [20], or even for two frequency bands (transmit and receive frequencies) [21].

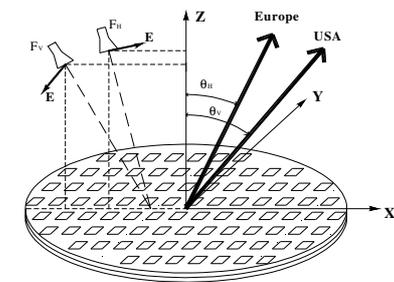
Another alternative to improve the bandwidth in large reflectarrays is based on the implementation of delay lines aperture-coupled to printed patches to compensate for the real phase delay in the whole range (several times 360°). This technique, has been used to design an 80-cm reflectarray in X-band that provides 20% bandwidth (for 1.5 dB gain reduction) and 26.7% (for 0.3 dB gain reduction) [22].

IV. RECENT DEVELOPMENTS

Several recent developments of reflectarrays for applications in space and base station antennas, which include contour-beam and multi-beam reflectarrays, folded low-profile configurations, Cassegrain offset configurations and beam scanning reflectarrays, are presented in this section.

A. Contoured beam reflectarrays for space applications

Several contoured beam reflectarrays have been designed for DBS antennas. The design of a contoured-beam reflectarray is divided in two steps. First, a phase-only synthesis technique is applied to obtain the appropriated phase distribution on the reflectarray that generates a predetermined shaped beam with reduced side lobe levels [23]. Then, the dimensions of the patches are adjusted to match the required phase distribution, by using the technique described in previous section. The required bandwidth for communications and broadcasting applications (10%) can be achieved by optimizing the patch dimensions. An “elegant breadboard” (using Space-proven technologies) of a DBS transmit antenna, with a different coverage in each polarisation has been designed, manufactured and tested [14]. This reflectarray antenna, shown in Fig. 3, guarantees a 10% bandwidth and can replace a very expensive spaceborne dual-gridded reflector. The measured radiation patterns in dBi are shown in Fig. 4 for both linear polarizations. The gain contours for 28, 25 and 20 dBi obtained using the analysis technique described in previous section are superimposed to the measurements, showing a good agreement, see Fig. 5. The complete breadboard has also been analysed as a whole by several full-wave and multi-level techniques [15]-[17] and the results are very similar as those shown in Fig. 5.

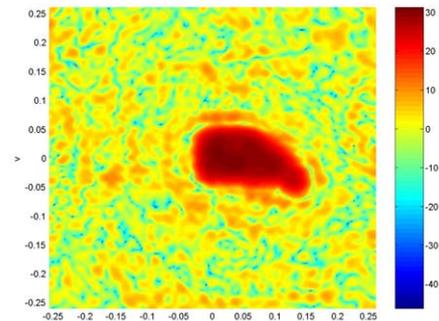


(a)

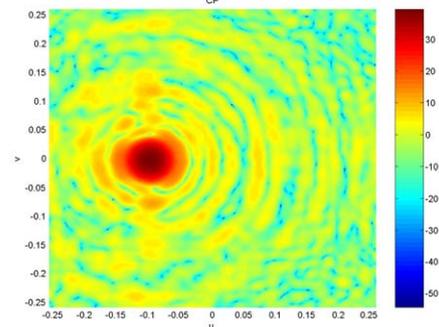


(b)

Fig. 3. Dual-coverage contoured beam reflectarray. (a) Antenna geometry, (b) breadboard.



(a)



(b)

Fig. 4. Measured contoured pattern. (a) for H-pol. (b) for V-pol

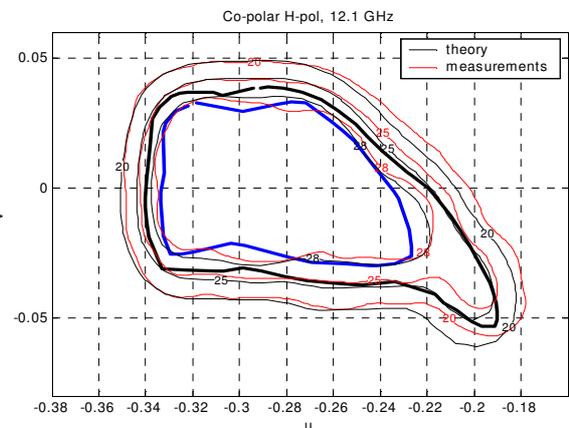


Fig. 5. Measured and simulated gain contours using local periodicity software from UPM.

B. Folded compact reflectarray

Passive reflectarrays with contoured beams have been successfully demonstrated for LMDS Central Station sectored antennas at 26 GHz by UPM in collaboration with University of Ulm (Germany) [24], see Fig. 7. A folded multi-layer printed reflectarray with shaped pattern has been designed, manufactured and tested. The configuration consists of a multi-layer twister reflectarray, a centered feed embedded in its structure and a polarizing grid, which acts as reflector and radome for each polarization, respectively. In order to achieve the pattern specifications along a frequency band (24.5-26.5 GHz), initially a multi-frequency pattern synthesis method,

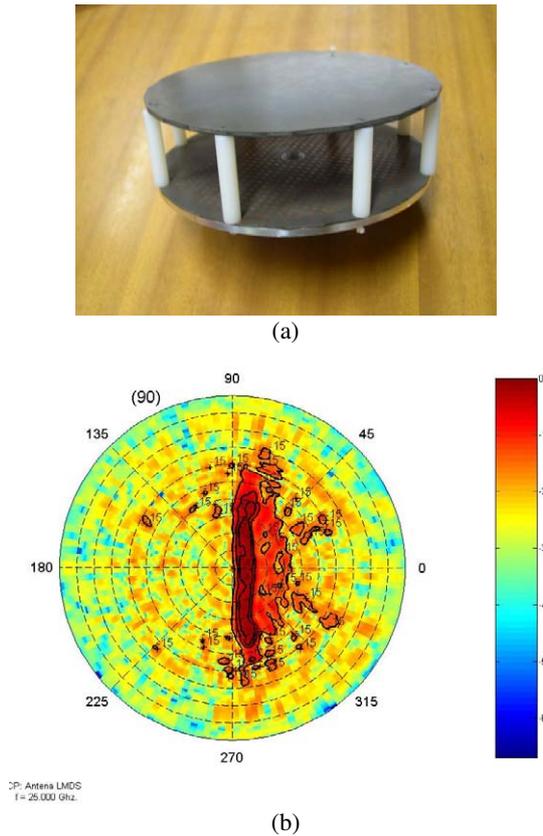


Fig. 6. Breadboard (a) and measured pattern at 25 GHz (b) of a folded reflectarray for LMDS base station antenna

which relies on a phase-only synthesis, is applied to obtain the required phase-shift on the reflectarray surface for the sectorial cosecant squared beam. Afterwards, the dimensions of the stacked patches, in a three-layer configuration, are optimized to generate the required phase-shift previously synthesized. The measured three-dimensional co-polar patterns are shown in Fig. 6(b). Measurements show a good concordance with theoretical patterns.

C. Multi-beam reflectarrays

A multi-fed and multi-beam reflectarray has been designed for a central station antenna for LMDS in the 24.5-26.5 GHz band [25]. The antenna produces three independent beams in an alternate linear polarization that are shaped both in azimuth (sectored) and in elevation (squared cosecant). The design process is divided into several stages. First, the positions of the three feeds are established as well as the antenna geometry to produce the three beams in the required directions. Second, the phase distribution on the reflectarray surface, which produces the required beam shaping, is synthesized. Third, the sizes of the printed stacked patches are adjusted so that the phase-shift introduced by them matches the synthesized phase distribution. A breadboard has been manufactured and measured in an anechoic chamber to validate the design process. The drawing and the breadboard with the feed positioned for one lateral beam are shown in Fig. 7. The 3-D radiation patterns for the central and one lateral beam obtained by the analysis technique described in section II are shown in Fig. 8 for the central and

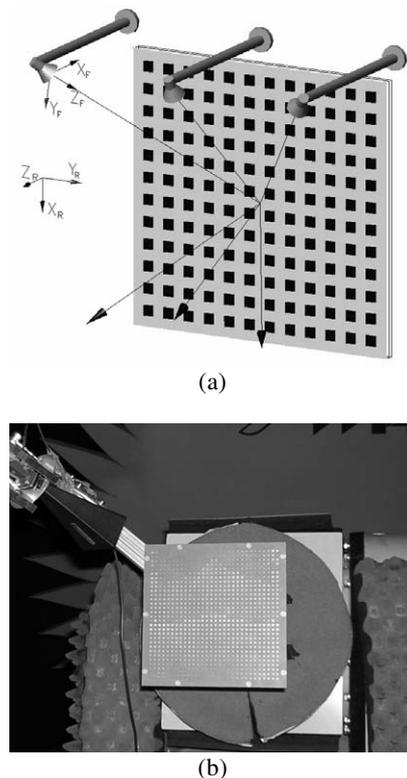


Fig. 7. Multi-fed reflectarray for LMDS base station antenna. (a) Antenna geometry, (b) breadboard with the feed positioned for one lateral beam.

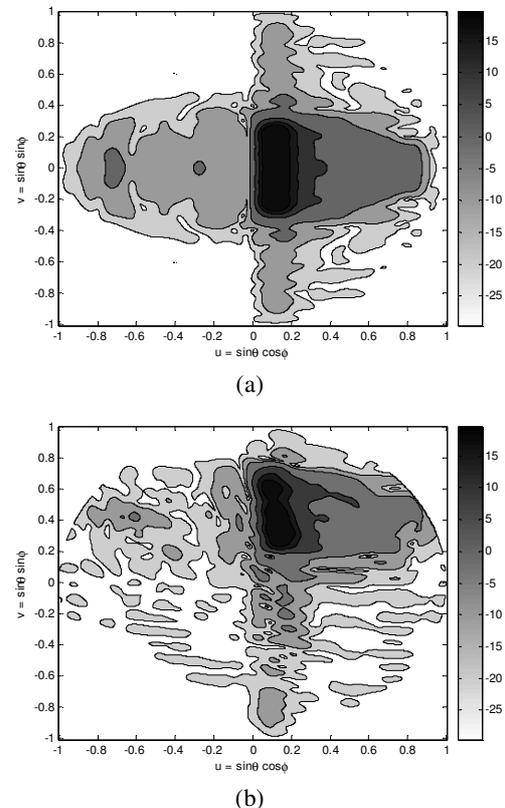


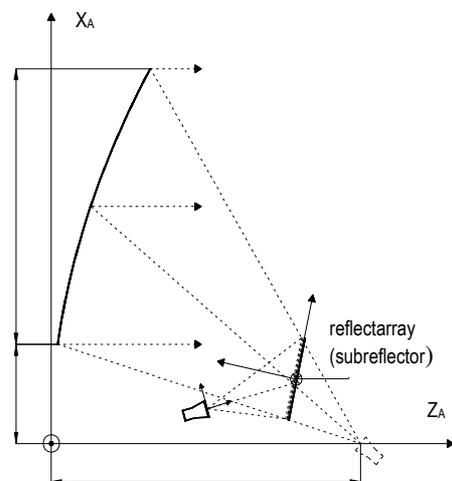
Fig. 8. Simulated 3-D contoured pattern (a) for central beam in V-polarization, (b) for one lateral beam in H-polarization.

one lateral beam. The dimensions of the patches on the reflectarray are symmetrical with respect the XZ plane and so the two lateral beams are symmetrical with respect to the same plane. The measured patterns are in close agreement with the simulations. These results show that several shaped beams can be generated with reflectarray technology in a one feed per beam basis.

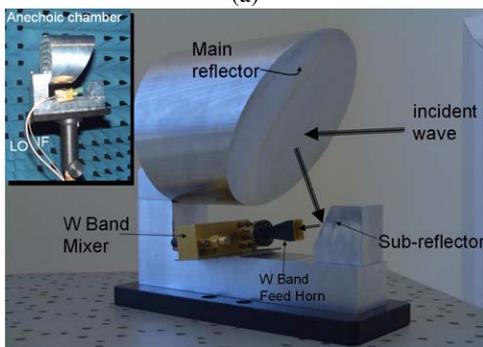
D. Dual-offset antenna configurations

The reflectarray antenna can be designed in a dual-reflector configuration using either a Cassegrain or a Gregorian approach. There are several advantages associated with the dual-reflector configuration, such as increase the focal length without increasing the antenna size, to shape or to scan the beam by adjusting only the phase distribution on a small reflectarray used as subreflector.

A modular technique has been implemented for the analysis of dual-reflector antennas using a reflectarray as a subreflector [26], see Fig. 9. The analysis technique combines different methods for the analysis of each part of the antenna. First, the real field generated by the horn is considered as the incident field on each reflectarray element [27]. Second, the reflectarray is analyzed with the same technique as for a single offset reflectarray, i.e. considering local periodicity and the real angle of incidence of the wave coming from the feed for



(a)



(b)

Fig. 9. Dual-offset configuration with reflectarray as subreflector. (a) Antenna geometry, (b) Breadboard at 94 GHz.

each periodic cell. Third, the main reflector is analyzed using physical optics (PO) technique, where the current on the reflector surface is calculated by summing the radiation from all the reflectarray elements. Finally, the radiation patterns are computed by using the electric field calculated on a projected aperture. This analysis technique has been validated by the design, manufacture and test of a breadboard to focus a beam at an scan angle of 5 degrees with respect the z-axis [28], see Fig. 9(b). The measured patters are in close agreement with the simulations.

E. Beam scanning reflectarrays

The previous dual-offset configuration can be used to scan the beam by adjusting the phase distribution on the sub-reflector, which can be implemented by electronic control, and consequently the beam performances can be changed without mechanic devices. The Scanning capabilities of a dual offset antenna of 1.5-m main parabolic reflector with a focal distance equal to 1.5m, and an 50-cm reflectarray have been investigated considering ideal reflectarray elements [26]. The patterns in the $Y_A Z_A$ are shown in Fig. 10 for the polarization corresponding to the electric field on the X_A direction. The plots show good performances for a $\pm 2^\circ$ scanning angles.

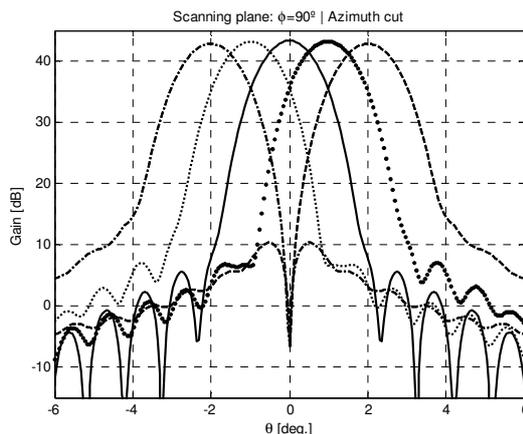


Fig. 10. Radiation patterns on the $Y_A Z_A$ plane for electrical beam scanning produced by a progressive phase on the reflectarray.

V. CONCLUSION

Some efficient analysis and design tools for reflectarray antennas and some recent developments carried out by UPM have been briefly summarized in this paper. The proposed analysis technique based on the local periodicity and Method of Moments in Spectral Domain has demonstrated to be very efficient and accurate for reflectarray antennas. The analysis technique takes into account the angle of incidence and the polarization of the field on each reflectarray element, and considers an accurate model for the feed-horn. The high efficiency of the analysis technique allows its integration in optimization processes, in order to optimize the reflectarray antenna to fulfill the requirements of beam shaping and bandwidth. The analysis and design techniques have been validated by the design manufacture and test of different

breadboards, including contoured-beam and multi-beam antennas. The results presented here show the potential capabilities of reflectarrays for DBS antennas, for LMDS central station antennas, and for reconfigurable and beam scanning antennas.

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Prof. Encinar has published more than one hundred and fifty journal and conference papers, and he is holder of three patents on array and reflectarray antennas. He was a co-recipient of the 2005 H. A. Wheeler Applications Prize Paper Award and the 2007 S. A. Schelkunoff Transactions Prize Paper Award, given by IEEE Antennas and Propagation Society.