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Dual-Polarized Planar Lens Antenna designed with a Quad-Ridged Frequency Selective Surface

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Abstract—This letter presents a microwave planar lens illuminated by a radially corrugated horn antenna. The lens is formed by a set of 5×5 multilevel unit cells working as a frequency selective surface. Each layer of the unit cells is formed by a square metallic ring with two sets of orthogonal stubs. The length of each set of stubs controls the transmission phase shift for each polarization, so that the lens can be configured independently for two orthogonal polarizations. The lens presented in this letter makes use of this operation to compensate the phase profile of the radiation pattern generated by the feeder. A prototype, with the lens located at 0.59λ from the feeder, has been fabricated. Measured results show a maximum gain above 14.44 dBi within the operating frequency band (12.55-13.10 GHz), and a crosspolar level below -32 dB within the HPBW.

Index Terms—Frequency selective surfaces (FSS), lens antennas, reflector antenna feeds, satellite antennas.

1. INTRODUCTION

Frequency Selective Surfaces (FSS) have been extensively studied during the last 60 years. These low-profile structures generate a frequency response that depends on the angle and polarization of the incident wave. This particular response has fostered the use of FSS in many applications such as radomes [1] absorbers [2] or metamaterials [3], to improve the performance of the primary radiators.

FSS have also been considered in advanced communication satellites to combine several operating bands in a single aperture [4], thereby reducing the number of reflectors, and, in turn, the weight and volume of the satellite. These aspects are specially important in multiple-spot beam systems [5], where no less than four reflectors and a feed per beam are currently implemented [6]. Several solutions have been proposed to reduce the number of reflectors in these systems, e.g. a circular polarization selective surface at the focus of the reflector to combine two different polarizations in a single reflector [7], or an electromagnetic band-gap structure to generate overlapped beams at the focus of the reflector [8].

This paper proposes an alternative solution based on the use of an FSS working as a microwave planar lens. This operation is similar to the one presented by the so-called transmitarray antennas [9]-[11], in which the phase profile given by the feeder, placed at a medium-long distance (typically F/D≈0.85), is properly flattened. In our case, the FSS is placed at a shorter distance (F/D=0.24) from the feeder (a radially-corrugated horn antenna (RCHA) [12]) to minimize the spill-over losses and, in turn, increment the gain of the feeder. This planar lens behavior permits the use of unit cells capable of offering less than 360º of phase shift.

The unit cell of the FSS is chosen to operate with two orthogonal polarizations. This dual-polarized operation allows the sharing of cells belonging to adjacent lenses with orthogonal polarizations, so that beams can be overlapped at the upper plane of the lenses [13]. This operation may reduce the number of reflectors in multiple-spot beam applications to just two by concentrating four colors in a single reflector.

In order to demonstrate the feasibility of the proposal, this letter shows the design of a single lens formed by 5×5 unit cells, and illuminated by a RCHA, as illustrated in Fig. 1. Unlike designs based on metallic hole arrays [14], in which the response of the cell strongly depends on the period of the cell, the unit cell of the proposed FSS is a quad-ridged cell with orthogonal stubs that control the frequency response of the cell. Thereby, the phase shift produced for each polarization can be adjusted by just tuning the length of the stubs, what facilitates the design process. The optimized lens has been validated through the fabrication and measurement of a prototype.

2. DESCRIPTION OF THE UNIT CELL

The unit cell of the proposed FSS, depicted in Fig. 2, is formed by three layers of square metallic rings on a dielectric substrate separated s=3 mm. Two sets of orthogonal stubs are inserted on the edges of the rings to control the transmission and reflection of the incident plane waves. The thickness (t_s) and the relative permittivity (ε_r) of the substrate are 0.254 mm and 2.2, respectively. The period of the unit cell (p) is set to 12 mm to center the pass band at 13 GHz $(p \approx \lambda_0/2)$, whereas the width and thickness of the metallic rings are w=0.6 mm and t_m=35 μm.

The analysis of the unit cell has been performed with CST [15] using Floquet ports, and assuming infinitely periodic boundary conditions on lateral walls. Two orthogonal plane waves, TE $(\hat{x})$ and TM $(\hat{y})$, have been considered. The frequency response of the unit cell is controlled by the length of the stubs parallel to the incident plane wave. These stubs resonate when their length (l_x or l_y) is, approximately, 0.15λ. To illustrate this effect, Fig. 3 shows the surface currents on the metallic paths, and the total electric field in the inner space, of a three-layer unit cell with $l_x = l_y$ =3.5 mm for a TM incidence at 13 GHz. As can be observed, currents are mainly concentrated in the resonant stubs, and the inner field is similar to that of a dual-ridged waveguide.

The frequency shift of the transmission parameter for a $\hat{y}$-directed polarization produced by the change of the vertical length of the stubs is shown in Fig. 4. This behavior permits the use of the *layered scattered approach* [16] to adjust the phase shift produced by the unit cell without altering significantly the amplitude of the transmission parameter [see shadowed region in Fig. 4].

Fig. 5 plots the transmission parameter of the unit cell for a vertical polarization at the central frequency (13 GHz) versus the length of the vertical stubs (l_y). As can be deduced, a three-layer unit cell gives a maximum 127º phase shift for magnitude variations smaller than 1 dB. The maximum phase shift can be increased by adding layers, e.g. 175º for a 4 layers configuration, at the expense of increasing the variability in the magnitude of the transmission parameter.

3. DUAL-POLARIZED MICROWAVE PLANAR LENS

The unit cell described in previous section is the constitutive element of the microwave planar lens proposed in this letter. The lens is illuminated by a RCHA [12] as depicted in Fig. 1. This feeder is able to illuminate the lens more uniformly than a simple rectangular aperture. The distance between the RCHA and the lens (s_l=13.9 mm) has been chosen to illuminate the edges of the 5×5 microwave planar lens, which extension is 60×60 mm^2, with a -10 dB amplitude taper so that a trade-off between spill-over and illumination efficiencies is obtained. The total profile of the structure is 19.9 mm, i.e., 0.86 λ_0.

The RCHA illuminates the microwave lens with a spherical phase profile. Having in mind the period of the unit cells, p=12 mm, and the position of the phase center of the feed (at 7.65 mm from the aperture of the feed), it can be deduced that the angle of incidence of waves on the first (l_{y2}) and outer (l_{y3}) rings are 29.12º and 48.09º, respectively. At these angular positions, the near field of the RCHA shows a phase shift of ΔS_1=30º and ΔS_2=110º in the first (l_{y2}) and outer (l_{y3}) rings of cells, respectively, with regard to the central cell (l_{y1}) [see Fig. 1].

The lens must compensate the previous phase profile so that a nearly uniform phase distribution is obtained on the upper plane of the lens. From Fig. 5, it can be concluded that a three-layer unit cell can cope with the phase shift required. Nevertheless, in order to estimate the length of the vertical stubs of the different cells (note that the polarization of the RCHA is $\hat{y}$), it becomes more appropriate to study the unit cell for the corresponding angles of incidence. Fig. 6 shows the phase shift of a three-layers unit cell for the approximate angles of incidence of interest. The length of the different stubs can be accurately estimated from these results. In particular, if the length of the central element (l_{y1}) is set to 3.75mm, the largest length with an insertion loss below 1 dB for a normal incidence [see Fig. 5], the length for the surrounding rings of cells must be l_{y2}=3.4 mm and l_{y3}=1.9 mm [see Fig. 1].

Previous estimation is valid for an infinite number of unit cells. In order to account for the finite number of cells, an optimization process becomes mandatory. The goals for this optimization have been the maximization of the bandwidth and the directivity, and the minimization of the sidelobe level (SLL). The optimized dimensions are l_{y1}=3.75 mm, l_{y2}=3.5 mm and l_{y3}=2.4 mm, quite similar to the initial estimation.

Fig. 7 shows the electric field on the YZ axis of the optimized planar lens at 13 GHz. This figure illustrates, on the one hand, the illumination of the complete lens given by the RCHA [see Fig. 7(a)], and, on the other hand, how the phase is transformed from a spherical profile (between the lens and the RCHA) into a flat distribution on the upper plane of the lens [see Fig. 7(b)].

It is worth noting that the same response would be obtained for a horizontally-polarized field if the same stub lengths were applied to the $\hat{x}$-directed stubs. This dual-polarized operation might also be used with circularly-polarized fields. If two orthogonal polarizations with a 90º phase shift were excited in the feeding RCHA, a circularly-polarized field would be obtained, and the lens would properly compensate the phase of each polarization. As an example, Fig. 8 shows the simulated radiation pattern that would be obtained in this case. As can be observed, a low crosspolar gain (LHCP), and a low SLL, would be obtained.

4. PROTOTYPE AND MEASUREMENTS

The optimized lens has been fabricated using a photolithographic process to print the metallic sections on the dielectric substrate (Neltec NY9220 with ε_r=2.2 and $\tan\delta$=0.009), whereas the RCHA has been fabricated in aluminum, as described in [12]. Foam layers (ε_r=1.05 and $\tan\delta$=0.0135) have been inserted between the different layers of the lens, and between the lens and the RCHA, to guarantee the separation between them. Fig. 9 shows two pictures of the prototype. Note that a rectangular-to-circular waveguide transition (not shown in the pictures) has been used to measure the structure with a common rectangular waveguide flange.

Fig. 10 compares the measured and simulated S_{11} parameter of the fabricated microwave planar lens. The measured data show an S_{11} parameter below -10 dB within a 0.5 GHz bandwidth, from 12.55 GHz to 13.1

GHz. The differences between measured and simulated results are produced by the nonperfect characterization of the rectangular-to-circular waveguide transition.

The E-plane and H-plane radiation patterns of the fabricated prototype at 13 GHz are plotted in Fig. 11 and Fig. 12, respectively. As can be observed, the SLL is -18 dB on the E-plane and -16 dB on the H-plane, whereas the crosspolar component is below -32 dB within the HPBW in both planes. Observe that simulated results offer much lower values than measured results due to the limited dynamic range of the measurement system. Yet, the obtained low crosspolar levels enable the proposed structure to be used as a dual-polarized microwave lens, with a high isolation between the two orthogonal components.

The gain of the prototype has been measured to evaluate the losses of the proposed structure. Figs. 13 and 14 compare the measured and simulated maximum gain, and the radiation efficiency, respectively. As it can be seen, the gain of the antenna, quite similar to the simulated values, is above 14.44 dBi, which means an increment of 2 dB with respect to the measured gain of the feeder, and the radiation efficiency is better than 75% within the operating frequency band (12.55-13.1 GHz). Losses are mainly produced by the foam and dielectric layers, though it is worth mentioning that part of the losses are produced by the RCHA, which is made of aluminum and includes a small foam layer [12].

5. CONCLUSION

This letter presents a dual-polarized microwave planar lens designed with a multiple-layer FSS. The lens is fed by a RCHA to completely illuminate the structure, thereby minimizing the spill-over losses. The dual-polarization operation is given by two sets of orthogonal stubs on the edges of the unit cell of the FSS.

A microwave planar lens formed by 5×5 unit cells has been designed and fabricated. Measured results show a good return loss within a 4.3% bandwidth, as well as a high gain (above 14.44 dBi), a good SLL (below -16 dB in all planes), and a crosspolar level below -35 dB within the HPBW.

Despite being designed for a linearly-polarized field, the lens holds the same properties for the orthogonal polarization. Simulated results for a circularly-polarized field confirm this property, which might be used to transmit two orthogonal signals, either using the whole lens or part of the structure, simultaneously. Thereby, orthogonal beams might be overlapped at the focus of the reflector of multiple-spot beam systems, which might reduce the weight and volume of the system.

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