RLSA with Broadband Corporate Feed for Near-Field Focusing

SENDING INSTITUTION

Institut d'Electronique et des Télécommunications de Rennes (IETR), UMR CNRS 6164
Département Antennes et Dispositifs Hyperfréquences
Equipe Systèmes Rayonnants Complexes
Université de Rennes 1
35042, RENNES, FRANCE

HOST INSTITUTION

Dipartimento di Ingegneria dell'Informazione
Universita' degli Studi di Siena
Via Roma 56, 53100 Siena, Italy

1. PURPOSE OF THE VISIT

Radial line slot antennas (RLSA) [1],[2] are attractive solutions for high-gain, low-cost beam-forming networks in the millimeter wave region, and as such have been extensively developed as potential backbones of DBS TV and WLAN networks. They are typically realized as arrays of slots etched on the top plate of a radial parallel plate waveguide, fed by traveling waves. The slots can be arranged in a multitude of ways, depending on the desired radiation pattern, and a variety of such arrangements have been implemented over the years, e.g. [3],[4],[5]. Recently, the RLSA concept was employed in near-field shaping applications [3], demonstrating its flexibility and simplicity. Moreover, in a recent paper [6], an optimization technique for single-layer RLSA devices was presented, enabling novel radiation patterns and both the efficiency enhancement and side-lobe level reduction.

Unfortunately, since RLSAs mostly belong to the class of traveling wave arrays, their operation is limited to a relatively narrow band due to the long-line effect. This presents a detriment, since it considerably limits their application. Therefore, collaboration was struck between IETR and University of Siena in order to investigate the possibilities of enhancing the bandwidth of such devices so as to make them more robust and stable with respect to the change in operating frequency. The basic idea was to develop a corporate fed RLSA, relying on double-layer RLSA configurations, allowing one to split an array into a number of subarrays. To do so, one has to be in possession of a reliable analysis method that can be used as the backbone of optimization. The aforementioned optimization technique [6], developed at the University of Siena, relies on a homebrewn method of moments solver [7], capable of analyzing single-layer RLSA configurations, rendering it inadequate for the bandwidth enhancement investigation. The suitable method applicable for that purpose, was developed at IETR [8], and is based on a mode-matching/method of moments approach. It was specifically developed for the analysis of parallel plate waveguides coupled by rectangular slots, making it an apt tool for the task at hand. Consequently, it was concluded that the merging of the optimization technique with the numerical code based on methods presented in [8] would be mutually beneficial to IETR and University of Siena. Finally, the tasks were then defined to be the following:

1. Investigate the configurations which could lead to reduction of the long-line effect in RLSA devices

2. Come up with a first design of a bandwidth-enhanced RLSA to be fine-tuned in the subsequent optimization

3. Adapt the optimization technique presented in [6] to be applicable to optimization of double-layer RLSA configurations, and merge it with the numerical code based on [8].

4. Fine-tune the initial design to preserve the high-gain operation while maximizing the bandwidth

2. DESCRIPTION OF THE WORK AND MAIN RESULTS

During the first stage of the visit, geometries that could serve as potential candidate for a wide-band RLSA were investigated. The criteria which were to be fulfilled are simplicity, flexibility and, finally, ease of fabrication. To achieve this, we “rearranged” the radiating slots of a classical RLSA layout on the uppermost plate in such a way that instead of having a single array fed from the center (as is common practice in RLSA devices), one obtains two subarrays. These can then be fed by a common feed, resulting in the reduction of the long line effect, i.e. reduction of the overall phase error caused by progressive phasing of the aperture field. The geometry thus obtained is shown in the following figure.

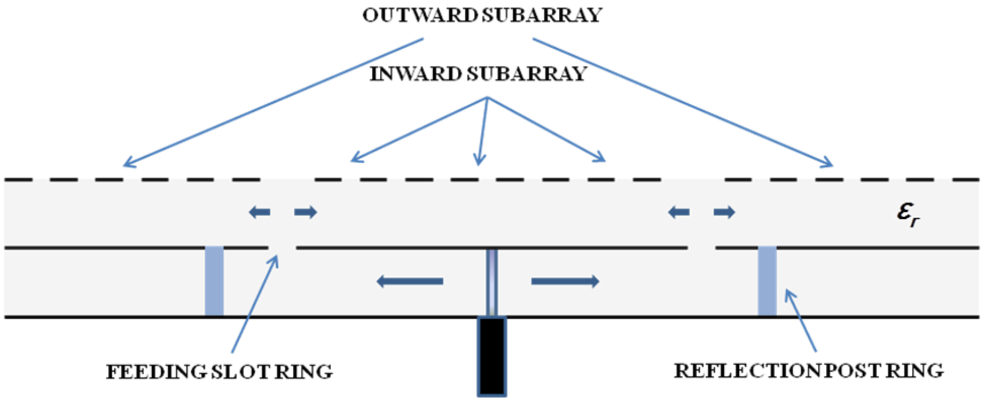

Figure 1. Layout of the wide-band RLSA

This double-layer structure consists of two adjacent radial waveguides. The bottom one is fed at the center by a coaxial probe which launches a TEM radial line mode waveguide toward a ring of resonant slots etched in the intermediate plate, and are directed along $\hat{\phi}$. The slot ring couples the outgoing TEM wave in the lower waveguide to an outward and inward traveling TEM wave in the upper waveguide (since the height of the upper waveguide is below $\lambda_d / 2$) having the form

$$\mathbf{H}_{inc} = \begin{cases} \hat{\phi} C e^{-j\varphi_{feed}} \dfrac{H_1^{(1)}\left(k_d \rho\right)}{H_1^{(1)}\left(k_d \rho_{feed}\right)} & \rho \le \rho_{feed}, \\ \hat{\phi} C e^{-j\varphi_{feed}} \dfrac{H_1^{(2)}\left(k_d \rho\right)}{H_1^{(2)}\left(k_d \rho_{feed}\right)} & \rho \ge \rho_{feed} \end{cases}, \qquad (2.1)$$

φ_{feed} being the phase delay of the feeding wave at the position of the feeding slots ρ_{feed}. Each of these waves impinges on a subarray, each designed to radiate a broadside beam of same polarization. This is achieved by placing the slots on a particular curve which should ensure the proper phasing of the aperture distribution. The procedure can be shortly summarized as follows. As done in [6], radiating slots are first approximated as magnetic dipole moments, with the moment related to incident magnetic field as $\mathbf{M} = \underline{\alpha}\mathbf{H}_{inc}$, $\underline{\alpha}$ being the polarizability dyad, which can be expressed for a slot directed along $\hat{u}$ as $\underline{\alpha} = \alpha_m \hat{u}\hat{u}$. For an aperture distribution which will produce the desired pattern, we define the target magnetic dipole moment $\mathbf{M}_0 = A(\rho_i)\,\hat{p}_{RH/LH}$, $A(\rho_i)$ being the target amplitude at the center of the slot/slot pair, and $\hat{p}_{RH/LH}$ being the unit right/left-hand circular polarization vector. In order to produce the desired pattern, the realized dipole moments should be parallel to the target moments, i.e. $\mathbf{M}(\rho_i) = Ce^{j\gamma}\mathbf{M}_0(\rho_i)$, or

$$\begin{gathered} \angle \mathbf{M}_0^* \cdot \mathbf{M}(\rho_i) = \gamma, \\ \left|\underline{\alpha}(\rho_i)\mathbf{H}_{inc}(\rho_i)\right| = C\left|A(\rho_i)\right|. \end{gathered} \tag{2.2}$$

These constraints are the master equations, the first one determining the curve upon which slot pairs need to be placed in order to have the proper phasing, whereas the second one dictates the proper slot length distribution (related to α_m), which will result in the desired aperture distribution. Solving for these equations for each subarray leads to the initial slot pair positions (ρ_i, ϕ_i) and slot lengths. The outward array, as show in the following figure, has a classical spiral winding, with slot pairs distributed on a positively wound spiral, slots being $\lambda_d / 4$ spaced and making an angle of $\pm\pi/4$ with the $\boldsymbol{\rho}$ vector, respectively. We stress here that the upper/lower sign corresponds to the slot in a pair which is closer to/further away from the origin. Thus, they will radiate an RHCP beam, being quadrature-fed and orthogonal. For the inward subarray to radiate the same polarization, it has to be wound in the negative direction, with the direction of slots in a pair reversed with respect to the slots of the outward array, $\mp\pi/4$ respectively.

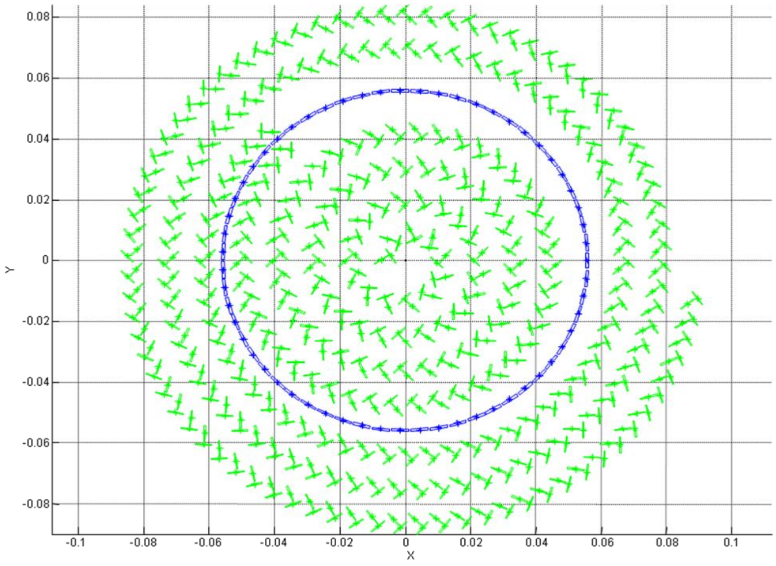

Figure 2. Corporate feed RLSA layout (green slots – radiating, blue slots – feed slots)

A good initial design leads, of course, to faster convergence of the optimization. With this in mind, initial slot length profiles were chosen to obtain a satisfactory initial radiation pattern. First, the dependence of a slot pair radiation efficiency on the length was analyzed using the mode-matching/MoM solver, for both array slots' orientations. Using this result, we adjusted the subarrays in the following manner. The outward subarray slot lengths were linearly increased from $0.35\lambda_d$ to $0.49\lambda_d$ in order to open up the aperture gradually, thus achieving a relatively flat aperture distribution which better matches the target one. The outward array slot lengths, on the other hand, were kept at uniform length of $0.48\lambda_d$ to achieve the uniform aperture distribution as well. The reason for this is that, as the inward wave travels toward the center of the array, it both increases in amplitude because it "compresses" toward the center, and diminishes in power due to slots radiating into the upper half-space. Therefore, a uniform slot length design is a reasonable guess for the initial design which leads to a flat aperture distribution. The analysis of the first design using our solver, thoroughly validated against commercial solvers, confirmed the validity of the approach.

In the second stage of the visit, the optimization technique [6] was adapted to handle the proposed wide-band RLSA geometry. For this, a MatLab optimization routine was implemented that a) generates the initial geometry based on the simplified model of the array, b) generates the layout passed to the optimization loop based on a linearized set of geometrical parameters (coordinates and lengths of slots), c) analyzes the layout and evaluates fitness functions for each subarray, and d) recalculates geometrical parameters based on the values of fitness functions, which are then fed back to the optimization loop. It should be stressed that the optimization technique used is valid if the assumption holds that each subarray is fed only by a traveling wave. This holds for an outward array, but for the same to hold for an inward array, one must ensure that the amplitude of the outgoing wave, generated when the ingoing wave reaches the center and starts propagating outwardly, is sufficiently suppressed. It is then paramount to ensure that the initial design matches this criterion. This is achieved by the described slot length profile, if the inward array is large enough. Therefore, it is restricted to arrays of at least $8\lambda_d$ in radius, as was checked numerically. Otherwise, one needs to use absorbing material at the center of the inward array to minimize reflection.

With the described layout, the optimization was initialized and after 43 passes the optimization converged with a 96% spillover efficiency (as defined in [6]), and an average aperture distribution error of less than 3 %, resulting in an antenna with approximately 10 % bandwidth, i.e. an improvement by factor 1.6 over the single-layer RLSA. It should be noted that the field pattern in the 3 dB band is acceptably distorted.

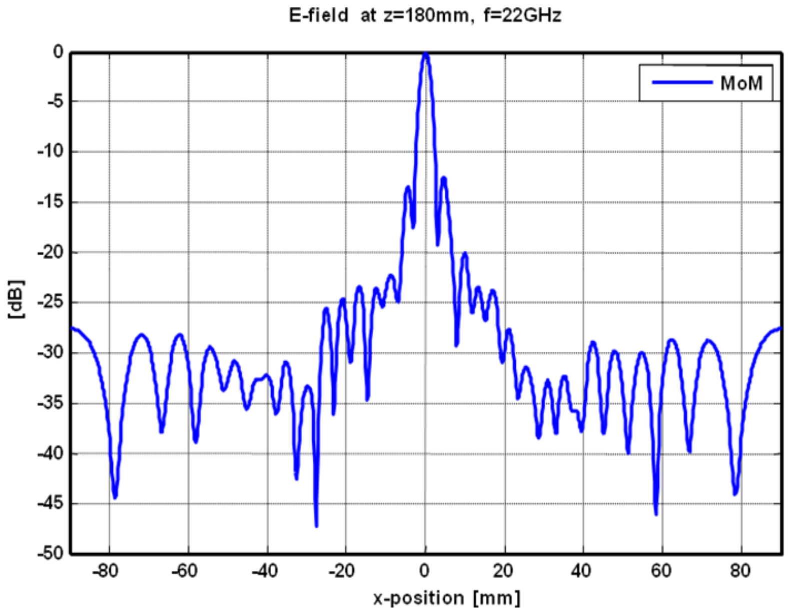

Figure 4. Longitudinal electric field at the focal aperture z=90 mm

The main results of the work undertaken during the visit can be summarized as follows. First, a novel corporate-feed RLSA design has been realized, able to achieve greater bandwidth while maintaining high gain and ease of fabrication (using, e.g. SIW technology). The feed position and the size of subarrays have been optimized to give the optimum bandwidth, previously infeasible to obtain using standard RLSA design techniques. Then, a parametric study of the slot polarizability α dependence on length has been performed for a single slot pair, allowing an approximate initial design. An optimization routine has been devised and used to fine-tune the antenna to reach the required criteria.

3. FUTURE COLLABORATION

We plan to continue collaborating on prototyping antennas designed by the method developed during the visit, RLSA optimization techniques and design, inspecting the possibilities of pushing the corporate feed RLSA concept further by creating a configuration having more than two subarrays. Also, several near and far-field RLSA applications will be explored.

4. PROJECTED PUBLICATIONS

We plan to publish at least a conference paper and a communication/full journal article based on the work undertaken.

REFERENCES

[1] F.J. Goebels, K.C. Kelly, “Arbitrary polarization from annular planar antennas”, IRE Trans. Antennas Propagat., vol. AP-9, no. 4, pp. 342-349, July 1961.

[2] M. Ando, K. Sakurai, N. Goto, K. Arimura, Y. Ito, “A radial line slot antenna for 12GHz satellite TV reception”, vol. AP-33, pp. 1347-1353, December 1985.

[3] M. Ettorre, M. Casaletti, G. Valerio, R. Sauleau, L. Le Coq, S.C. Pavone, M. Albani, “On the Near-Field Shaping and Focusing”, IEEE Transactions on Antennas and Propagation, vol. 62, no. 4, April 2014.

[4] M. Ciattaglia, L. Infante, S. Mosca, M. Albani, A. Crisafulli, “A new near-field array focusing technique for radar system testing”, First European Antenna Measurement Technique Association (AMTA) Symp., Munich Germany, 2006

[5] Y. Miura, J. Hirokawa, M. Ando, Y. Shibuya, G. Yoshida “Double-Layer Full-Corporate-Feed Hollow Waveguide Slot Array Antenna in the 60-GHz Band”, IEEE Trans. Ant. Propagat., vol. 59, no. 8, August 2011.

[6] M. Albani, A. Mazzinghi, A. Freni, “Automatic Design of CP-RLSA Antennas”, IEEE Transactions on Antennas and Propagation, vol. 60, no. 12, December 2012.

[7] M. Albani, G. La Cono, R. Gardelli, A. Freni,“An Efficient Full-Wave Method of Moments Analysis for RLSA Antennas“, IEEE Transactions on Antennas and Propagation, vol. 54, no. 8, August 2012.

[8] M. Casaletti, R. Sauleau, M. Ettorre, S. Maci, “Efficient Analysis of Metallic and Dielectric Posts in Parallel-Plate Waveguide Structures“, IEEE Trans. on Microwave Theory and Techniques, vol. 60, no. 10, October 2012.