Two design methods for Radial Line Slot Antennas with arbitrary or beam pattern

Tamara Salmerón Ruiz(1), Manuel Sierra Castañer(1)
tamarasalme@gr.ssr.upm.es, mscastaner@gr.ssr.upm.es
(1) Dpto. de Señales, Sistemas y Radiocomunicaciones; Universidad Politécnica de Madrid.
Avda. Complutense, 30, 28040 Madrid, Spain.

***Abstract*- Two design procedures for Radial Line Slot Antennas (RLSAs) with circular polarization and either maximum gain or an arbitrary shaped pattern are proposed. Firstly, a method to design a RLSA with any desired pattern is presented. It is based on an optimization algorithm and some measures to ensure its fast convergence and stability need to be taken. Secondly, a fast technique to calculate the length and the position of every slot in a high gain RLSA with uniform field distribution is described. Both procedures are validated with the design of three antennas with different characteristics.**

I. INTRODUCTION

Radial-Line Slot Antennas (RLSAs) have been used over the past few decades for microwave and millimeter-wave applications, such as receiving direct broadcast satellite (DBS) systems. There is a growing interest in them due to their suitability for low cost mass production and their high efficiency.

In order to achieve structural simplicity, a single-layered RLSA (SL-RLSA) was first proposed in [1], where slots are excited by a radially outward traveling wave mode. Several design methods for circular polarization and maximum gain SL-RLSAs have been presented, as in [2]. However, not all the telecommunication systems require maximum gain and there is a growing demand for arbitrary shaped patterns. The design of these cases is still an open issue.

The goal of this paper is to obtain a design procedure for SL-RLSAs with either a beam or an arbitrary shaped pattern. To achieve this goal, the help of a fast analysis tool is needed. An analysis model based on a simplified method of moments (MoM) and developed by Sierra et al [4] is applied. Two different design methods are proposed:

1) The first of them is based on an optimization scheme that was presented in [3] and is valid for any desired radiation pattern. The length and the position of each slot pair is modified until a match between the actual pattern and the target one is achieved.

2) The second is a new and fast approach in the design of maximum gain SL-RLSA, based on [1]. Using the Archimedean spiral as a starting point, the lengths and positions of every slot pair are analytically calculated in order to obtain uniform amplitude and phase field aperture distribution. An iterative process is applied.

In Section II, the first design procedure for a RLSA with an arbitrary shaped pattern is presented. Then, a different and specific design method for pencil beam RLSAs is described in section III. The effectiveness of both methods is verified with simulations in section IV and the pencil beam design method is also validated with measurement data in section V. Conclusions are drawn in section VI.

II. DESIGN OF A RLSA WITH AN ARBITRARY SHAPED PATTERN

A. Optimization procedure

The starting point of the optimization algorithm is an Archimedean spiral with N turns, distance S_ρ between successive turns and spacing S_ϕ between adjacent slot pairs. The classic circular-polarized RLSA slot arrangement [5] is followed.

The goal of the procedure is to find the slot lengths and positions that minimize the error between the actual radiation pattern and the target one.

In order to ensure the stability and fast convergence of the optimization method, the length and position of each slot cannot be modified individually. Therefore, a sampling is made. Two sampling points, located at $\phi = 0$ and $\phi = \pi/2$, are chosen in each turn (Fig. 1). A virtual radiating element is placed in every sampling point, with length L_{Pi}. The coordinates of the sampling points can be expressed as

$$\rho_{Pi} = \rho_{min} + \frac{S_\rho}{2}(i-1) + \Delta\rho_i \quad (1)$$

$$\phi_{Pi} = -\pi(i-1) \quad (2)$$

where ρ_{min} is the distance from the center to the beginning of the spiral and $\Delta\rho_i$ is the variation in the position of the sampling point with respect to the perfect spiral curve.

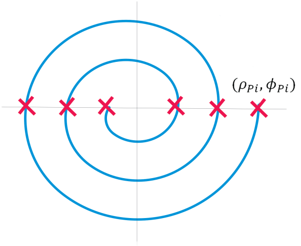

Fig. 1: Spiral sampling

The algorithm optimizes the parameters S_ρ, L_{Pi} and $\Delta\rho_i$, thus reducing the set to 4N+1 parameters due to the sampling.

The length and position of every slot pair in the antenna is calculated from this thinned set through a linear interpolation. A smooth variation from one slot pair to the next is achieved with this approach, thus avoiding the loss of the spiral layout.

Moreover, some lower and upper bounds on the optimization parameters need to be included to reduce the complexity and obtain physically feasible solutions:

1) $0.6\lambda_g \leq S_\rho \leq \lambda_g$. The distance between turns cannot be too small, to avoid slot overlapping. However, it should be lower than a guide wavelength in order to suppress grating lobes.
2) $-0.05\lambda_g \leq \Delta\rho_i \leq 0.05\,\lambda_g$. A large variation in the position of the sampling points would mean losing the spiral layout.
3) $0.4\lambda_{eff} \leq L_{Pi} \leq 0.5\,\lambda_{eff}$. To enhance efficiency, the slot lengths should be near the resonance. In this case, an intermediate value λ_{eff} between the wavelength in the guide λ_g and in the air $\lambda_0$is considered [5]:

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{0.4+0.6\cdot\varepsilon'+0.21\sqrt{\frac{t}{w}}\cdot(1-\varepsilon')}}, \tag{3}$$

where w is the width of the slot, t is the height of the upper plate and ε' the relative dielectric constant in the radial line.

B. Error minimization

An important part of the optimization method is the definition of the error function to be minimized.

Two different types of error functions are introduced here:

1) Type I is used in those intervals with maximum and minimum requirements. In our case, it is useful for the main beam interval.

$$F_{error1} = \sum_i \sum_j \left(\frac{D(\theta_j,\phi_i) - \frac{D_{máx}(\theta_j,\phi_i)+D_{mín}(\theta_j,\phi_i)}{2}}{\frac{D_{máx}(\theta_j,\phi_i)-D_{mín}(\theta_j,\phi_i)}{2}} \right)^{2p} \tag{4}$$

2) Type II is necessary in intervals where there are only maximum requirements, such as the side lobes. Cross-polarization is also reduced using this error function.

$$F_{error2} = \sum_i \sum_j q^{[D(\theta_j,\phi_i)-D_{máx}(\theta_j,\phi_i)]} \tag{5}$$

In our approach, both the error between the target radiation pattern and the achieved one, ε_{RP}, and the error that is caused by the cross-polarization, ε_{XP}, are taken into account in the global error ε_T:

$$\varepsilon_T = \varepsilon_{RP} + \alpha \cdot \varepsilon_{XP} \tag{6}$$

α is a weighting factor, and its value is a design parameter that depends on how strict the cross-polarization requirements are.

For a given antenna layout, the radiation pattern and the cross-polarization can be obtained with the analysis tool described in [5]. Then, $\varepsilon_{RP}$and ε_{XP} are calculated to compare these values with the requirements of the specific design. Finally, the slot lengths and positions are modified until the global error ε_T is minimized.

III. DESIGN OF A PENCIL BEAM RLSA

The aim of this second design method is to synthetize faster and with more accuracy than the general optimization procedure RLSAs with maximum gain. To reach this target, uniform amplitude and phase field aperture distribution is required.

A. Slot pair length design

The amplitude field aperture distribution can be controlled by the slot pair lengths.

Uniform amplitude illumination is achieved if the ratio of radiation $\tau(\rho)$ (relation between the radiated power and the incident power) in every slot pair satisfies the following condition:

$$\tau(\rho) = \frac{2\cdot d\cdot\rho}{K-\rho^2} \tag{7}$$

$$K = \frac{\rho_{max}^2 - t\cdot\rho_{min}^2}{1-t} \tag{8}$$

where d is the height of the guide, t is the power dissipated at the termination and ρ is the mean value of the distance from the center of the antenna to the center of the two slots that form a pair.

The ratio of radiation depends on the length of the slot pair. As in the previous algorithm, efficiency will be enhanced by choosing the working range $0.4\lambda_{eff} \leq L_s \leq 0.5\,\lambda_{eff}$.

Therefore, the two steps that are taken to obtain the slot pair lengths are the following:

1) Initially, we consider that the information about the antenna layout and the coordinates (ρ, ϕ) of each slot are known. Applying the condition (7), the ratio of radiation $\tau(\rho)$ is obtained for each slot pair.
2) Finally, the polynomial that relates τ and L_s is used to calculate every slot pair length.

B. Slot pair positioning

The phase field aperture distribution can be adjusted by making small corrections to the slot pair positions, without losing the spiral layout.

There are two different effects on the phase of the electric field due to the presence of slots: a variation in the phase of the field that is transmitted between the plates of the waveguide φ_{21} and a variation in the phase of the radiated field φ_{rad}. Both of them depend on the slot length.

Uniform phase distribution is achieved when all the slots radiate in-phase. The condition that the distance $\Delta\rho_{ij}$ between a slot pair, i, and the closest one in the next turn, j, must satisfy is the following:

$$\Delta\rho_{ij} = \rho_j - \rho_i = \lambda_g \left[1 + \frac{\varphi_{21}(L_{si}) + (\varphi_{radj} - \varphi_{radi})}{2\pi}\right] \tag{9}$$

Since $\varphi_{21} < 0$ and $\varphi_{radj} < \varphi_{radi}$ (the length of the slots grows with the distance to the center of the antenna and the radiated field phase decreases), it can be deduced that the required distance is $\Delta\rho_{ij} < \lambda_g$.

The algorithm to apply this correction takes the following steps:

1) For each element i in the turn n≥2, the closest element j in the turn n-1 is searched for and the distance needed for them to radiate in phase, $\Delta\rho_{ij}$, is calculated.
2) In order to apply a smooth correction and not to lose the spiral layout, the same modification is made to all the elements that are in the same turn. The new separation between turn n and n+1 will be the mean value of the $\Delta\rho_{ij}$ that have been obtained in the previous step for the M elements that are in turn n:

$$S_{\phi_n} = \overline{\Delta\rho_n} = \frac{1}{M}\sum_i \Delta\rho_{ij} < \lambda_g \tag{10}$$

C. *Iterative design method*

Since a change in the position of the slots brings about a change in the ratio of radiation $\tau(\rho)$, an iterative design method is needed to fulfill both the uniform amplitude and phase requirements:

1) The starting point is an Archimedean spiral with a distance between turns $S_\rho = \lambda_g$. The separation between adjacent slots, S_ϕ, has a constant value around $0.6\lambda_g$ (if it were too small, we would have strong slot coupling, but if it were too large, not enough power would be radiated). The spiral layout determines the coordinates (ρ, ϕ) of each slot.
2) The slot pair length design algorithm is applied to the given geometry, with the aim to obtain uniform amplitude aperture distribution.
3) The position of every slot is modified by the slot pair positioning algorithm to achieve uniform phase aperture distribution.
4) Due to the change of position applied in step 3, the slot pair lengths should be recalculated in order not to lose the uniform amplitude distribution. Therefore, we return to step 2 and then 3 again, iterating until a stable solution is reached.

IV. SIMULATIONS

A. *Example (a): Pencil beam RLSA with design method III*

As a first example, an antenna with maximum gain, designed using the method that was introduced in section III, is presented. Table 1 summarizes its design parameters.

As we can see in Fig. 2 and Fig. 3, both amplitude and phase aperture distributions gain uniformity after applying the method.

Simulations have been carried out to validate the design procedure, both with a software tool based on a fast MoM analysis model [4] and CST Microwave Studio. Fig. 4 shows the radiation pattern and Table 2 presents some of the results of both simulations. Good agreement between them is obtained.

Design frequency	19.9 GHz
Relative permittivity of the material that fills the RLSA	2.17
Distance between the plates	3.175 mm
Slot width	0.4 mm
Antenna maximum diameter	200 mm
Number of slots	1062

Table 1. Antenna (a) design parameters

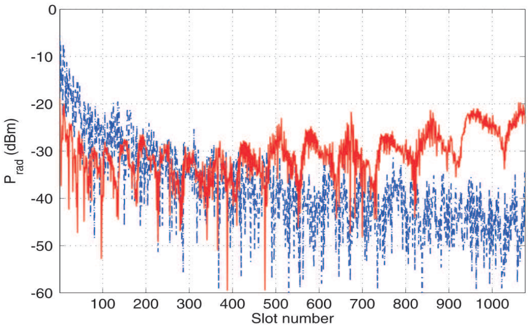

Fig. 2. Amplitude field aperture distribution before and after applying the iteration method

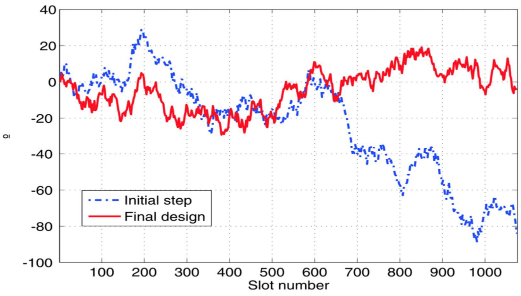

Fig. 3. Phase field aperture distribution before and after applying the iteration method

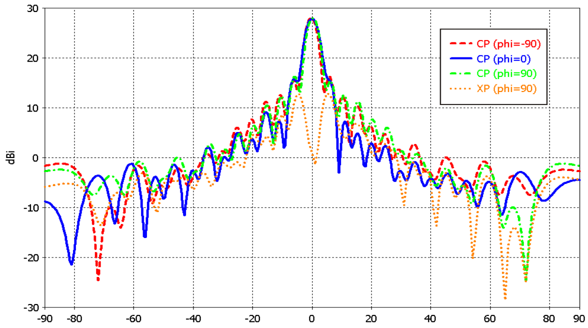

Fig. 4. Antenna (a) copolar and crosspolar gain pattern obtained with CST

Parameter	**MoM analysis tool**	**CST**
Gain @19.9 GHz	28.38 dBi	27.9 dBi
Directivity @19.9 GHz	30.39 dBi	27.5 dBi
Side-lobe level	-12 dB	-12 dB
XP level	-23 dB	-14.8 dB
s_{11}	-13.7 dBi	-17.3 dB
$BW_{-3\,dB}$	4.34º	4.2º

Table 2. Antenna (a) simulations results

B. *Example (b): Pencil beam RLSA with design method II*

Secondly, an antenna with the same requirements than the one in example (a) is designed using the procedure in section II. The design parameters are those presented in Table 1, except the number of slots (724) and the diameter (170 mm).

Fig. 8 shows how the directivity pattern fits to the mask that has been defined and Table 3 presents some results.

Parameter	**MoM analysis tool results**
Gain @19.9 GHz	26.49 dBi
Directivity @19.9 GHz	26.95 dBi
Side-lobe level	-10 dB
XP level	-21 dB
s_{11}	-14.25 dB

Table 3. Antenna (b) simulation results

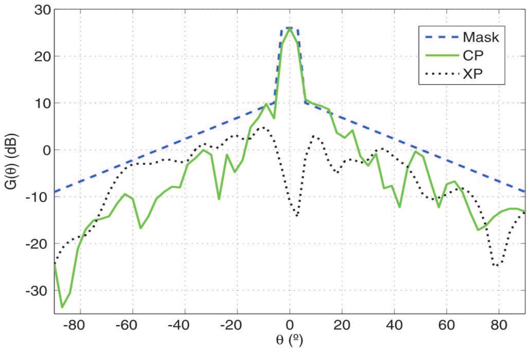

Fig. 5. Example (b). Copolar and crosspolar gain patterns.

C. Example (c): Isoflux pattern

Finally, a different antenna, with an isoflux pattern with an edge of coverage $\theta_{Eoc} = 20^{\circ}$ was designed. Its design parameters are presented in Table 4.

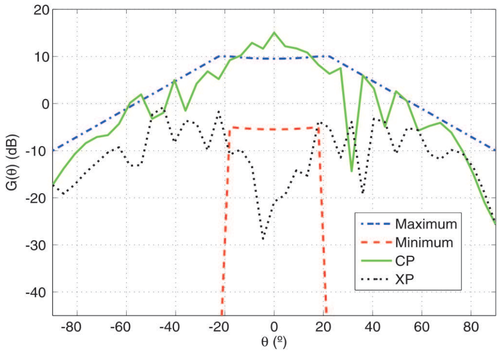

Fig. 6. Example (c). Copolar and crosspolar gain patterns.

Design frequency	7.85 GHz
Relative permittivity of the material that fills the RLSA	1.7
Distance between the plates	7.328 mm
Slot width	1 mm
Antenna maximum diameter	330 mm
Number of slots	226

Table 4. Antenna (c) design parameters

V. VALIDATION

In order to validate the pencil beam design method, the antenna which has been presented in example (a) of section IV was constructed (Fig. 7) and measured.

As observed from Fig. 4 and 8, a good agreement is obtained between simulation and measurement results. Other measurement results are shown in Table 5.

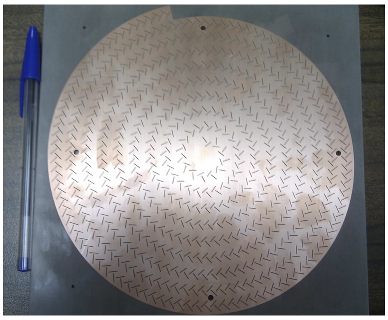

Fig. 7. LHCP maximum gain RLSA (f=19.9 GHz)

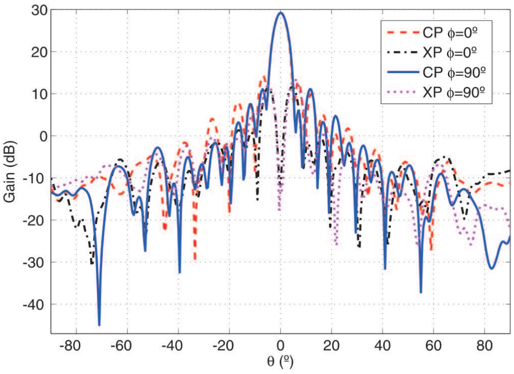

Fig. 8. Measured copolar and crosspolar gain patterns.

Parameter	Measurement results
Gain @19.9 GHz	29.2 dBi
Directivity @19.9 GHz	30.12 dBi
Loss	0.9 dB
Side-lobe level	-13 dB
XP level	-18 dB
s_{11}	-9.5 dB

Table 5. Antenna (a) measurement results

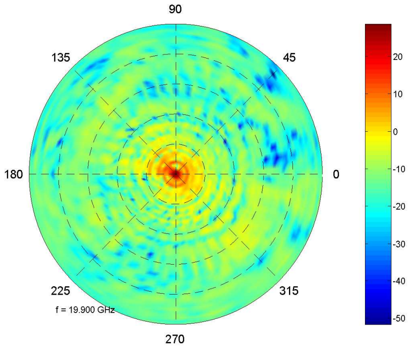

Fig. 9. Measured 3D gain pattern.

VI. CONCLUSIONS

Two design procedures for circular polarization RLSA have been presented: an optimization scheme for arbitrary shaped patterns and a fast iteration method to achieve maximum gain antennas.

Both of them have been applied to the synthesis of three antennas and validated via simulations based on a simplified MoM analysis model [4].

Finally, the second method has been validated with the construction of a pencil beam RLSA. The measurements that have been carried out show good agreement with the simulations.

ACKNOWLEDGEMENT

This work has been supported by the SICOMORO project with reference TEC2011-28789-C02-01.

Some simulations contained in this work have been carried out using CST Microwave Studio Suite 2011 under a cooperation agreement between Computer Simulation Technology (CST) and the Technical University of Madrid.

REFERENCES

[1] M. Takahashi, J. Takada, M. Ando and N. Goto, "A slot design for uniform aperture field distribution in single-layered radial line slot antennas", *IEEE Trans. Antennas Propagat.*, vol. 39, no. 7, pp. 954-959, July 1991

[2] M. Ando, M. Takahashi, J. Takada, and N. Goto, "Characteristics of radial line slot antennas for DBS reception," *IEEE Antennas Propagat. Soc. Int. Symp.*, vol.2 (1991) 936-939

[3] M. Albani, A. Mazzinghi, and A. Freni, "Automatic design of CP-RLSA Antennas," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 12, pp. 5538-5547, Dec. 2012

[4] M. Sierra-Castañer, M. Sierra-Pérez, M. Vera-Isasa, and J. L. Fernández-Jambrina, "Fast analysis model for radial-line slot antennas", Microwave and Optical Technology Letters, vol. 44, no. 1, pp. 17-21, Jan. 2005

[5] M. Ando, K. Sakurai, N. Goto, K. Arimura, and Y. Ito, "A radial line slot antenna for 12 GHz satellite TV reception", *IEEE Trans. Antennas Propagat.*, vol. AP-33, no. 12, pp. 1347-1353, Dec. 1985.