SYNTHESIS OF CIRCULARLY POLARISED RADIAL LINE SLOT ARRAY

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ABSTRACT
In previous articles, an easy way to analyse a slot array fed through a radial line was presented. The analysis was based on a circuit approach where circuit parameters have been estimated using the first propagation mode in the radial line and the far field theory. Here we study the design of a particular application for circularly polarised broadside antenna. The design defines the length, position and orientation of the slots in the antenna surface. The final analysis of the antenna gives a good behaviour in field diagrams and gain.

INTRODUCTION
Antennas based on narrow slots directly coupled to a radial line have been used previously in Direct Broadcast Satellite (DBS) receivers [1] and mobile communications [2]. One of the most important features for such antennas is their low cost and low loss feeding line. This paper shows a synthesis method to define the length, position and orientation of slots on the antenna surface. The basic model is based on the assumption that fundamental TEM mode keeps is original structure over the radial line, except for the attenuation due to the slot power coupling. Changes in phase in the coupled field due to the slot resonance must be taken into account to obtain an uniform phase aperture field. Finally second order effects like the change in the field phase or field reflections must be included in the design process. The antenna final analysis using the equivalent circuit analysis method developed by the authors [3], [4] give a good behaviour of the antenna.

ANTENNA BASIC STRUCTURE: FIRST DESIGN
The radial line is a parallel plate structure, fed at it centre by the penetration of the inner conductor of a coaxial probe. The space between the plates (h) is less than half wavelength, so only the TEM mode can propagate between them. The slots are placed on the upper plate of the radial line. Figure 1 shows the antenna structure and the design variables for each slot: slot length (L_i), tilt angle between the slot and the radial line (α_i) and slot position referred to the feeding point (ρ_i, ϕ_i). Other parameters are considered as constants: slot with (w), metal thickness (t) or dielectric inside the waveguide (ε). The original field inside the radial line can be considered as an ideal TEM mode with symmetry of revolution, and far from the coaxial probe can be written like :

$$\overline{\mathrm{E}}(\rho) = \sqrt{\frac{2}{\pi k \rho}}\left[\mathrm{E}_1 e^{-j\left(k\rho - \frac{\pi}{4}\right)}\right]\hat{z} \tag{1}$$

$$\overline{\mathrm{H}}(\rho) = -\frac{1}{\eta}\sqrt{\frac{2}{\pi k \rho}}\left[\mathrm{E}_1 e^{-j\left(k\rho - \frac{\pi}{4}\right)}\right]\hat{\phi} \tag{2}$$

TWIN SLOTS FOR CIRCULARLY POLARISED FAR FIELD
The slots are narrow and close to resonance, so we can assume uniform field in the narrow dimension and cosine in the resonant dimension, giving a linearly polarised radiated field. To obtain the circular polarisation we must combine at least two slots as shown in figure 2. The relative field in the slots must satisfy the condition :

$$R = \left|\frac{E_1 \cdot L_1}{E_2 \cdot L_2}\right| = 1 \tag{3}$$

$$Phase\left(\frac{E_1}{E_2}\right) = -k_g \Delta r = \pm\theta \tag{4}$$

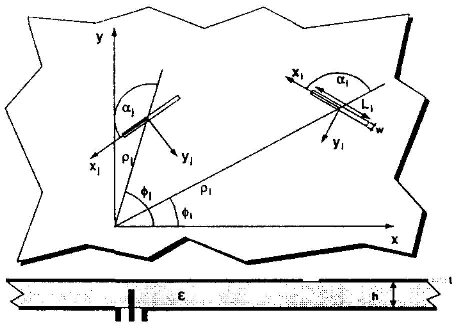

Figure 1. Antenna basic structure

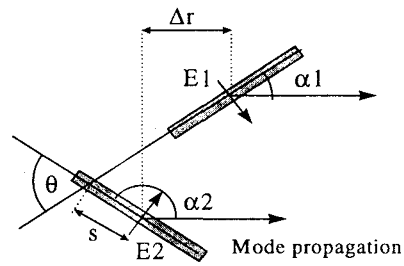

Figure 2. Twin slots angles

The field phase can be obtained moving the slots along the radial direction (Δr). The sign of previous equation depends on the desired polarisation. The parameter "s" is a final free parameter defining the relative position of the slots, and has been adjusted to minimize the coupling effect on the radiated field polarisation.

APERTURE PHASE: SLOT POSITION

Keeping constant the slot radial tilt angle (a), the far field phase from each slot twin depends on it orientation and must be compensated through the distance to the feeding point. This condition gives the position of slots over an spiral. To keep the space between slot pairs constant, an iterative formula is applied :

$$\rho_{i+1} = \rho_i \pm \frac{d}{\sqrt{1 \pm \frac{2\pi d}{\lambda_g} + \left(\frac{2\pi\rho_i}{\lambda_g}\right)^2}} \tag{5}$$

$$\phi = \pm\frac{2\pi\rho}{\lambda_g} - \alpha + \gamma_0 = \pm\frac{2\pi\rho}{\lambda_g} + \phi_0 \tag{6}$$

where γ_0 is a constant and d is the distance from slot pairs. Figures 3 shows the relative slot position obtained in the case of $\alpha=\pi/4$, $d=\lambda_g/2$ and $\gamma_0=0$.

APERTURE MAGNITUDE: SLOT LENGTH

The coupled field to slots depends on the slot position, tilt angle and length. Keeping constant the angle, the field inside the guide spreads and attenuates in previous slots and the slot length must grow from the centre to the antenna border. Assuming each slot turns as a coupling element and the field attenuation is uniform (keeping the symmetry), a closed formula for the slot coupling can be developed as :

$$\eta_p(\rho_k) = \frac{2\rho_k}{\frac{\rho_{max}^2 - \rho_{min}^2}{1-t} - \left(\rho_k - \rho_{min} - 0.5\lambda_g\right)\frac{\left(\rho_k + \rho_{min} - 0.5\lambda_g\right)}{\lambda_g}} \tag{7}$$

where ρ_{max} and ρ_{min} are the maximum and minimum distances from the feeding point, and t is the power fraction over the final load. Figure 4 shows the coupling versus distance from the centre for a 6λ antenna radius. The slot coupling depends on the slot length like a resonant cavity and can be computed from an equivalent circuit like shown in figure 5. Not always is possible to reach the estimated coupling and the maximum is assumed for the last slots.

PHASE CHANGE DUE TO SLOT RESONANCE

The slot field phase changes from the ideal field inside de guide due first to the slot resonance and second to field phase changes when coupled to previous slots. In general these changes are lower than $\pi/4$ but add with the same sign and can lower the antenna efficiency as much as 3dB. To compensate them, the slots are moved toward the centre of the antenna. This change in slot position allows reducing the wavelength in the guide keeping the grating lobes under control, without using any dielectric. The phase change due to the slot resonance is shown in figure 6. In figure 7 we present the change in phase and amplitude of the wave after a ring of several slots. Both graphics can be written depending on the parameters of the circuit approach.

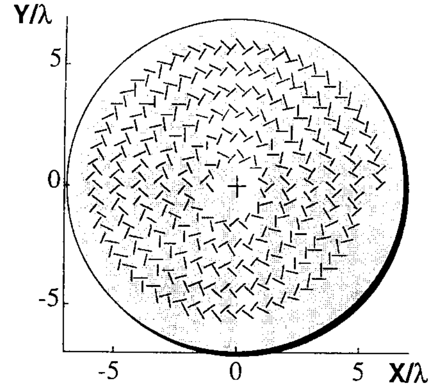

Figure 3. Initial slot position for antenna.

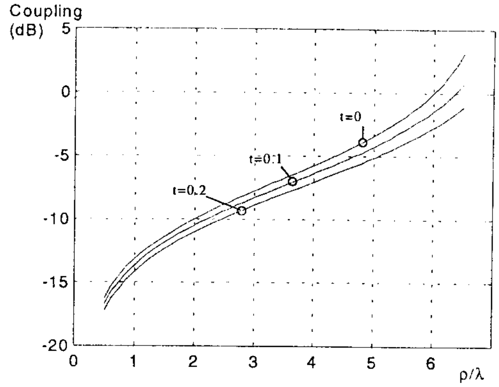

Figure 4. Theoretical coupling vs. Radius

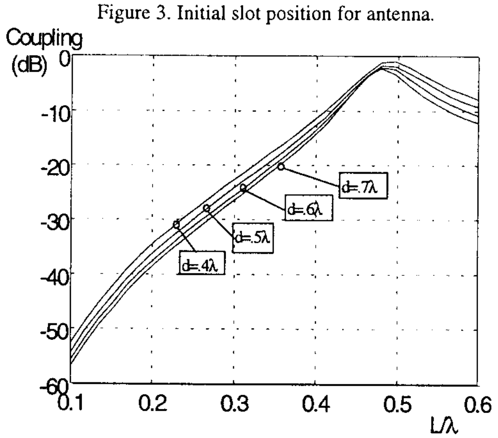

Figure 5. Coupling vs. Slot length

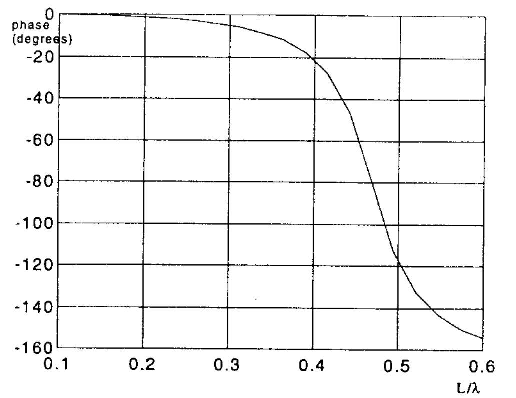

Figure 6: Change of phase in radiation field

These changes of phase produce a change in the position of the slots, that can be written as:

$$\Delta\rho = \frac{\lambda_g}{2\pi}(\phi_r + \phi_c) \tag{8}$$

FIELD REFLECTION

The field reflected in the slots creates an incoming mode that is not absorbed by the coaxial probe and propagates outward. This mode can be described as a TEM mode with a spiral phase front like:

$$E_R = E_1\Gamma\sqrt{\frac{2}{\pi k\rho}}\,e^{j\left(\frac{\pi}{4}\right)}e^{-j(k\rho)}\,e^{j2(\phi-\phi_0)} \tag{9}$$

where Γ is a reflection coefficient that depends on the slot coupling. This field adds to the main field mode and creates an asymmetry in the aperture field, reducing the aperture efficiency and rising the lateral lobes. The asymmetry is more important in small antennas, where slot coupling is larger. To avoid the influence of the reflected mode, the slots are moved again from its previous position but now in a non symmetric way. They are moved a small fraction of the wavelength in a random way. This displacement changes slightly the phase of the reflected field and it influence in the final slot field, although does not avoid the reflection.

After considering all these effects we can calculate the field over each slot with the analysis method described in [4]. In figure 8 we present the magnitude and phase of the field over each slot for a 275 slots antenna.

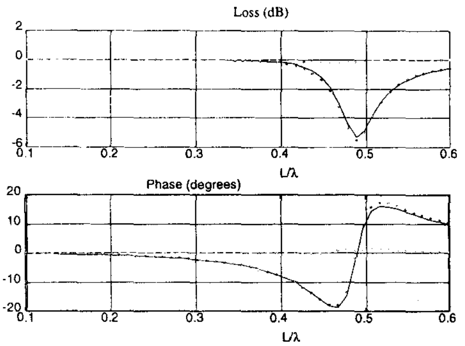

Figure 7: Change of phase after a ring of slots

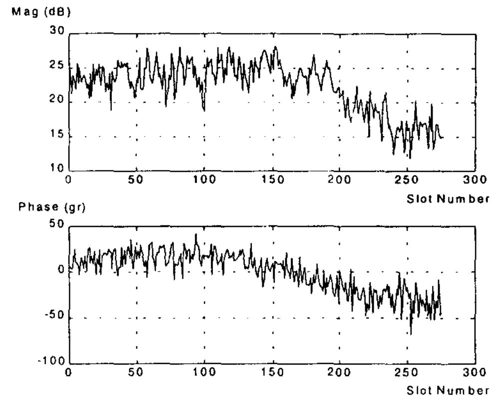

Figure 8. Final field over the slots

ANALYSIS

We designed an antenna based on this philosophy to be used for the reception of DBS with the Spanish Satellite HISPASAT. The frequency band was 12.1 – 12.5 GHz, left circular polarisation. We imposed a maximum diameter of 300 mm . The best design we could get with these limits were:

- Slot width: 1,5 mm
- Metal plate thickness: 0,1 mm
- Distance between metal plates: 8 mm
- The radial guide is finished in a short-circuit.
- Dielectric material: ε = 1,1 (honeycomb)
- Coaxial probe: SMA (50 ohm and 0,65 mm)
- Gain = 29,5 dBi
- SLL better than –13,5 dB in the frequency band
- S11 better than –17 dB in the frequency band
- Beamwidth = 5°

MULTIPROBE FEED: SECOND DESIGN

The effects of the reflection field can be eliminated if we place the slots in concentric rings. That means we have to generate a cilindric wave, whose phase fronts are Archimedes spirals instead of generating a radial wave with the slots placed forming a spiral.

DESIGN OF THE COAXIAL PROBES

This is got if you excite the antenna with four coaxial probes, and you feed each one with phase changes of 90°. The purity of the spiral wave front depends on the separation of the four probes. The mode is better when the probes are closer, but the impedance bandwidth is perturbed when the probes are very close. We got an optimum value for a separation of 4 mm from the centre of the antenna to each probe. An scheme of the coaxial probes is shown in figure 9. With this value we estimate the impedance of each element in figure 10. In figure 11 and figure 12 we show the amplitude and phase of the electric field 81 mm from the centre of the antenna.

The equivalent circuit of the four probes is calculated as a four ports multipole where the mutual impedances follow the next formula:

$$z_{ij} = \frac{-\eta \cdot k}{4 \cdot h} \cdot G_i \cdot G_j \cdot \frac{\sqrt{2}}{k \cdot \pi \cdot \rho_{ij}} \cdot e^{-j\left(k\rho_{ij} - \frac{\pi}{4}\right)} \qquad (10)$$

$$G_i = \frac{\cos(k\delta L_i) - \cos(k(L_i + \delta L_i))}{\mathrm{sen}(k(L_i + \delta L_i))} \qquad (11)$$

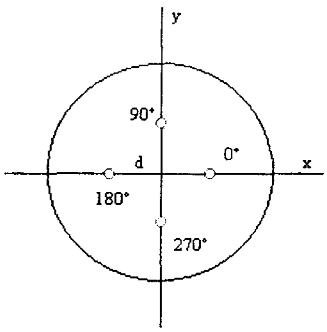

Figure 9: Situation and excitation of the probes

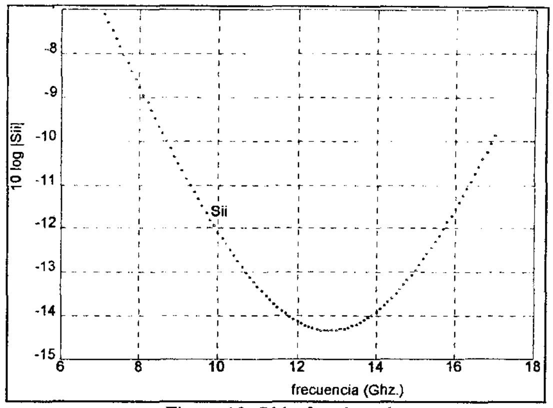

Figure 10: S11 of each probe

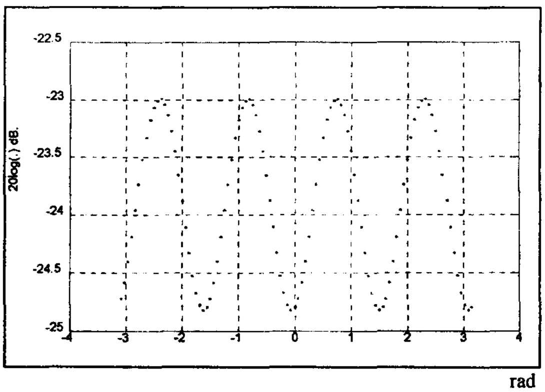

Figure 11: Amplitude in r = 81 mm

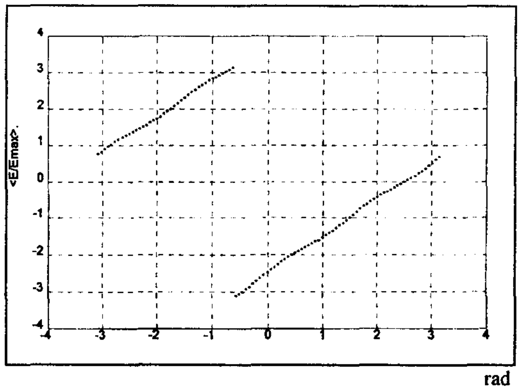

Figure 12 : Phase in r = 81 mm

The excitation circuit must be very simple in order to minimize the final cost of the product. We designed a serial circuit, where we adapt each probe varying the width of the microstrip lines. The circuit is composed by three $\lambda_g/4$ microstrip lines.

DESIGN OF THE SLOTS

We have the same design we had in the previous section in several aspects. We calculate the position of the two slots to get the circular polarisation, the slot length and width and we apply the corrections due to the resonance of the radiant and incident field in the same way we did before. The only difference is we generate now a wave whose phase front is a spiral.

If we want to get a circular polarised antenna we do not have to modify that phase with the different position of the slots. That means we can place the couple of slots in concentric rings, where each ring is separated λ_g of the previous one, in order to add in phase the radiated field of each slot.

When we place the slots in concentric rings the reflected field does not depend on the angle, so we are going to have an uniform field. The position of the first ring is going to fix the effect of the reflected field over the total field.

The position of the short circuit we placed at the end of the antenna is different too. That short circuit has to be placed $\lambda_g/4$ from the centre of the last slot. In the first design it had to be an Archimedes spiral but now it is a circumference, much easier to manufacture. Te reflected field on that short-circuit will no depend on the angle, so the design will be easier to optimise. In this case the electric field in the guide is shown in Ec. 12.

$$E_{in} \propto \frac{1}{\sqrt{k\rho}} e^{j\phi} e^{-jk\rho} \tag{12}$$

An scheme of the array is shown in figure 13. Figure 14 shows the radiated field (copolar and crosspolar) obtained with a five-turns circular array of 9.4-10.2 mm. slots, analyzed at 12.1 GHz. This means a 30 cm. antenna diameter with good characteristics to receive satellite communications.

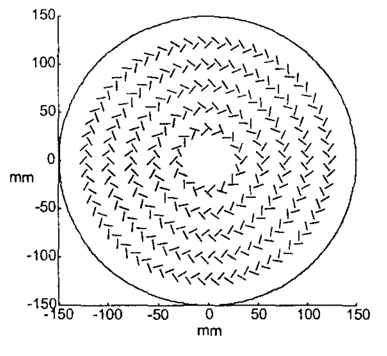

Figure 13. Circular array antenna

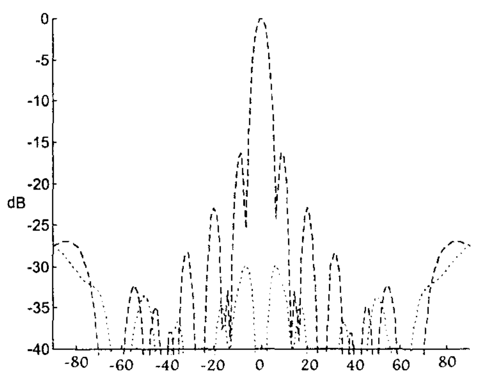

Figure 14 : Copolar-Contrapolar radiation pattern

CONCLUSIONS

This paper describes the way to design the antenna, giving the slot position and angle to get a radial line slot antenna having circular polarisation and broadside main beam. We show two different techniques; with the first one the excitation is very simple, only the coaxial probe, while the position of the slots and the final short-circuit is complicate. This design generates a reflected field that depends on the angle. To solve this problem we complicate the excitation of the antenna (four coaxial probes with one microstrip circuit), but the antenna is perfectly symmetrical. This technique can also be extended to other kind of antennas and it is specially interesting for small arrays.

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