Study of Rectangular Waveguide Broad-wall Compound Slot Equivalent Circuit Model

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1. Introduction

Nowadays, communications and radar technologies that work on high frequency bands are increasing noticeably. Focusing in transmission and propagation aspects, waveguide slot antennas have been widely used due to their properties of reliability and low loss, even for micro and millimetre-wave bands. Longitudinal and transverse slots are the most common radiator for this kind of projects; centre-inclined slots and compound slots (tilted and displaced from the centre) are easy to find as feeding coupling elements in multi-layered antennas, although they can be also used as radiators [1][2]. This document firstly shows the validity of the Π network as the equivalent circuit model in the compound slot characterization and the possibility to extend its use to every kind of slot.

2. Compound Slot Equivalent Circuits

The purpose of this project is to design a two-dimensional multilayered-fed waveguide array with linear polarization, using 45º compound radiating slots on the millimetre-waveband (Figure 1). The use of these slots is interesting for physically obtaining a linearly polarized field on the low side-lobe-level planes, $\varphi = 45º$ and $\varphi = 135º$ (Figure 2) at the same time that grating lobes are avoided since the slots can be placed $\lambda g/2$ far from each other. As in previous works [3][4], equivalent circuit procedure has been employed for the analysis and characterization of the radiating slot [5]. According to the property of reciprocity of the scattering matrix of the slot, two reciprocal networks have been deeply studied; T and Π network (Figure 3), even though limitations of these schemes have been reported [6].

The first one consists on a shunt admittance between two serial impedances. For large offsets (slot parameters can be seen in Figure 4.), real part of serial impedances is zero and imaginary parts are conjugated, so that shunt admittance is the responsible of the radiation. Furthermore, if the resonance condition is achieved, susceptance becomes zero and slot does not alter the feeding wave phase. Limitations comes when the slot gets closer to the axis of the waveguide, since the value of the longitudinal components rises rapidly due to a mathematical singularity during the components calculation (Figure 5). Despite this issue, T network can be used as equivalent circuit as long as the offset is large enough without exceeding waveguide edges, as can be seen in [1] where a successful linear array of three elements in the X band is designed. In 2D arrays, the presence of grating lobes limits the width of the waveguide, so that small offsets are frequently used and T network cannot be applied.
The latter contains serial impedance and two conjugated shunt admittances. In addition, under resonance condition Z_c is purely real and for wide tilting angles, admittances become susceptances (Figure 6). Limitation arises when the tilting angle is close to zero, since real part of shunt element becomes relevant in power matters (Figure 7), although in this model components computation never brings a mathematical singularity. Table 1 compares the suitability of both networks for being used as electrical model of different kinds of slots.

In short, both networks are dual each other so that, if it is possible to mathematically approximate the behaviour of one of the components in T-network, the inverse function will predict the performance of the dual component in Π-network and vice versa. As it can be seen in Figure 6, Y^A and Y^B are pure imaginary for all values of offset. On the other hand, Z^A and Z^B have non-negligible real part even for large offset, as shown in Figure 5.

After Π model has been approved as valid, an array design technique based on full-wave method of moments (MoM) analysis combined with the equivalent circuit network will be ready to be used to develop the array antenna with a particular aperture distribution [3][4].

3. Compound slot power management and Π - Network

Once the dimensions of the waveguide are established regarding to the working frequency and construction limitations (w=0.73λ_0, h=0.16λ_0), inclination angle θ, slot length l and offset D are the most important parameters in the slot performance. According to our purpose, angle θ=45º is fixed, a two-dimensional parameter sweep (D,l) in the X-band is carried out and S parameters are obtained for each case. From them, the admittance matrix and components value are calculated. This reveals that for every length and offset, the real part of the shunt admittances is always zero, so that serial impedance is the responsible of the radiation. In the array designing step, resonance offset and length of the slot (D_r, l_r) that make the imaginary part of Z_c to become zero will be used.

Firstly and for all cases, waveguide height and slot offset play a role in the amount of power that is coupled to the slot: the thinner the waveguide and the larger the offset are, the more power is radiated. From a microwave point of view, our system can be described as lossy two ports system, where power is reflected to the source, power is transmitted to the load and power consumed (radiated) by the network. At the same time, from the circuit analysis we can derive the expressions of voltage and current in every point of the network (Figure 3) and relate them with the power handling.

$$P_L = |S_{21}|^2 \qquad P_{REF} = |S_{11}|^2 \qquad P_{RAD} = 1 - |S_{11}|^2 - |S_{21}|^2$$

$$P_L = re\left(Z_L \cdot |-I_2|^2\right) \qquad P_{REF} = \left|\frac{Z_G - Z_{IN}}{Z_G + Z_{IN}}\right|^2 \qquad P_{RAD} = re\left(\frac{|V_1 - V_2|^2}{Z_C}\right) \tag{1}$$

Comparing both analyses, Figure 8 and Figure 9 reveal the concordance between S-parameters analysis and circuit in terms of power given to the load and radiated. According to the physical phenomena, as the slot is closer to the centre of the waveguide, the radiated power decreases and the transmitted power achieves its maximum value. If inclination angle is large enough, Y^A and Y^B are pure imaginary and therefore they do not contribute to the radiation, as it is plotted in Figure 6 where θ = -45º. As the tilting angle becomes closer to zero, the value of the real part of the shunt element grows and consequently, these elements start to consume/radiate power and must be taken into account (Figure 8). In Figure 7, for θ = -5º radiation due to Y^A and Y^B becomes dominant over Z^C, that rapidly decreases. Only for θ = 0º it becomes zero, allowing the combination of Y^A and Y^B in only one shunt element, which means that even for this case, Π network fulfils the physical conditions and can be used for modelling compound, centred-tilted, transverse and longitudinal slots.

$$P_{RAD} = re\left(\frac{|V_1 - V_2|^2}{Z_C}\right) + re\left(|V_1|^2 \cdot Y_a\right) + re\left(|V_2|^2 \cdot Y_b\right) \tag{2}$$

4. Conclusion

Radiating slots placed in the wide face of a rectangular waveguide can be modelled by means of an equivalent circuit with a Π network distribution, regardless of the inclination or offset of the slot and it is easier than T-network for array design. Longitudinal, transverse, centred-tilted and compound slots for several angles have been simulated and their equivalent circuit perfectly fits the real slot behaviour. In addition, since power management in Π network is completely analyzed, it is ready to be used as equivalent circuit as in Figure 10 for array design.

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	Longitudinal	Transverse	Centre-Inclined	Compound
T - Network	Applicable	NA	NA	Applicable
Π - Network	Applicable	Applicable	Applicable	Applicable

Table 1: applicability of equivalent circuit for different slots.

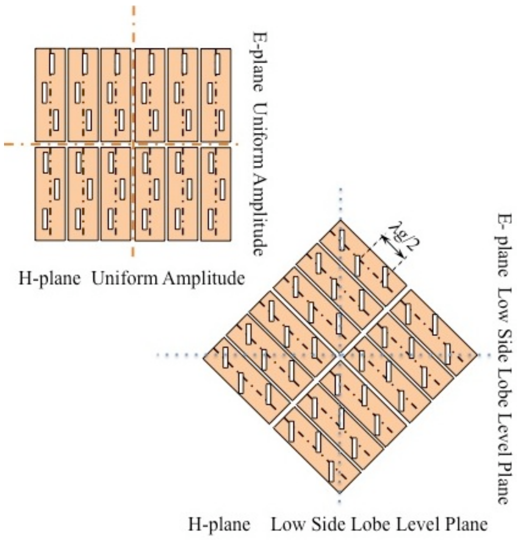

Figure 1: 2D compound slot array

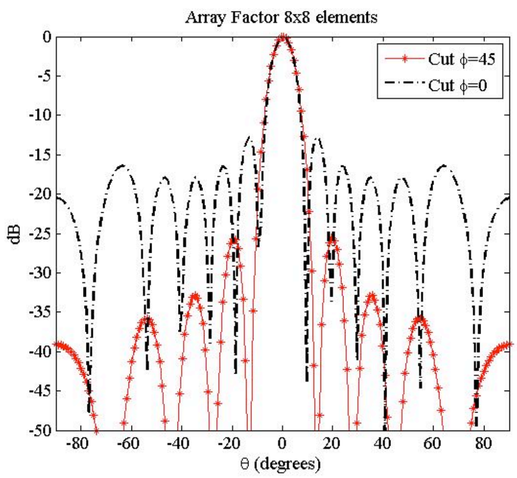

Figure 2: Array factor of 8x8 elements array in two planes, φ=0º and φ=45º

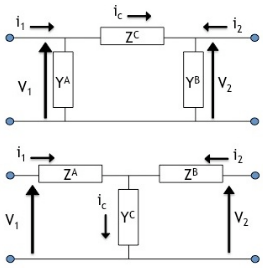

Figure 3: Π and T networks

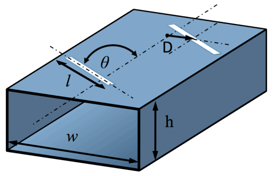

Figure 4: compound slot parameters

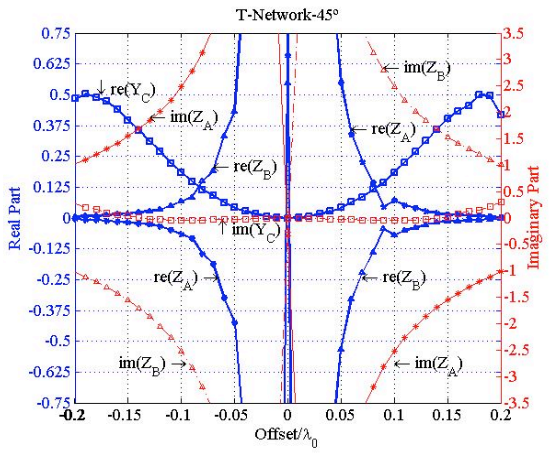

Figure 5: T-network components for -45° tilted slot, l=0.5λ_0

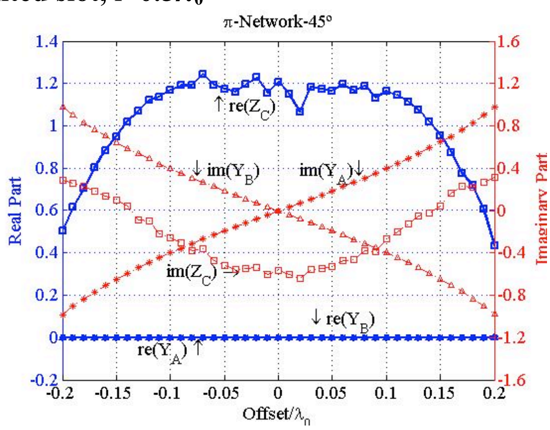

Figure 6: π-network components for -45° tilted slot, l=0.5λ_0

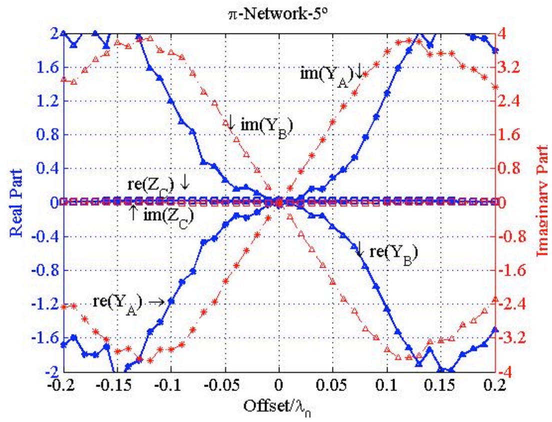

Figure 7: π-network components for -5° tilted slot, l=0.5λ_0

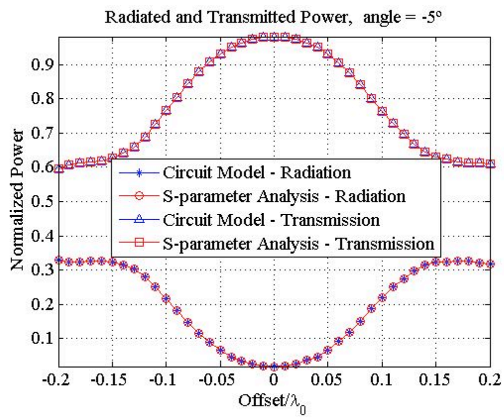

Figure 8: transmitted and radiated power for -5° compound slot, l=0.5λ_0

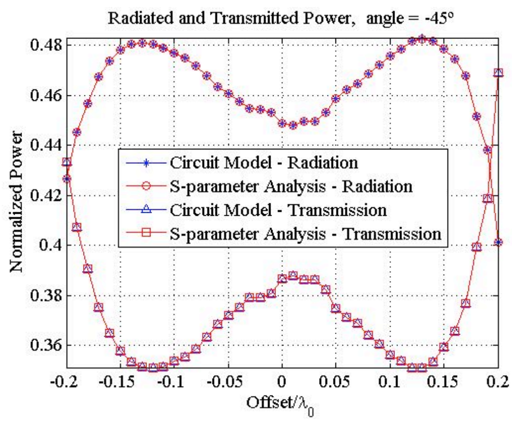

Figure 9: transmitted and radiated power for -45° compound slot, l=0.5λ_0

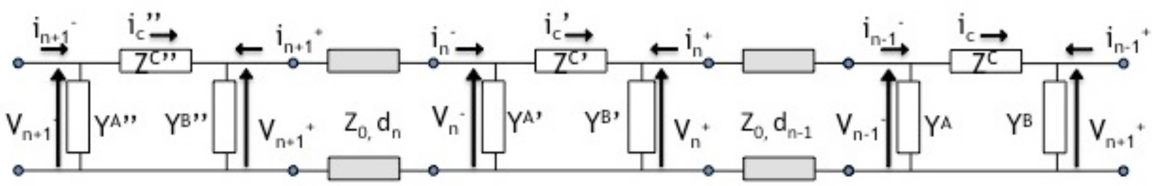

Figure 10: three-slot array equivalent circuit.