Frequency Selective Screens in Multi-Layer Cylindrical Antennas

G. Gerini*, L. Zappelli#
* TNO - Physics and Electronics Laboratory,
P.O. Box 96864, 2509 JG The Hague, The Netherlands. E-mail: gerini@fel.tno.nl
Dept. Electronics and Automatics, University of Ancona,
Via Brecce Bianche, 60131 Ancona, Italy. E-mail: l.zappelli@ee.unian.it

Abstract— **The new trends in the communication market are demanding for wider bandwidths and consequently higher frequencies and higher bit rates. The traditional hardware development, based on the manufacture and measurement of test components, is too expensive and time consuming. The availability of novel integrated design tools and manufacturing techniques is therefore an essential requirement. In this paper, we present an accurate and efficient tool for the analysis of multilayer conformal cylindrical structures, based on a Multimode Equivalent Network (MEN) formulation.**

I. INTRODUCTION

The electromagnetic problem that must be solved in presence of an array antenna is very complex, if the coupling between the radiating elements has to be taken into account. In many cases, this effect has to be considered if a correct solution is needed.

The planar case was solved in the early seventies, for different radiating elements, both slits and open-ended waveguides [1], introducing the concept of "unit cell". This approach reduces the problem to the study of the transition between a single radiating waveguide and a phase-shift wall waveguide (PSWW) that represents the free-space region under the periodic conditions dictated by the array. The complete spectrum representation of the PSWW is provided by the Floquet's theorem.

The same approach was used for the conformal cylindrical array, once the 'radial' Foquet's modes were defined [2], [3], [4], [5]. The effect of a conformal dielectric sheet cover was then introduced in [6]. More recently, both accurate and approximate approaches have been used to study the effect of various radome configurations. In [7], the authors studied the effect of a circular cylindrical radome consisting of an array of thin metal strips parallel to the axis (metal grating) or, similarly, of alternating metal strips and dielectric shells forming a cylindrical surface (metal-dielectric grating).

In this paper, we present the analysis of cylindrical Frequency Selective Surfaces (FSS) consisting of thick metal screens with apertures, integrated with a cylindrical conformal array antenna and dielectric radomes (Fig.1). The theoretical approach that we have developed for the analysis of such structures is based on the Multimode Equivalent Network formulation (MEN) presented in [8] and [9], and the Unit Cell approach [1].

Thanks to the efficiency and modularity of this approach, where the complete structure is decomposed into the cascade of waveguide sections, complex integrated structures, like the ones shown in Fig.1, can be analyzed. In the analysis, the waveguide array, radomes and metal gratings are considered at the same time, as a single multi-layer structure. An accurate and efficient design can be successfully applied, thanks to the number of different options and different degrees of freedom available in the design process.

II. THEORY

Examples of structures that can be analyzed with our approach are shown in Fig. 1a,b. In addition to the infinite circular cylindrical array of open-ended waveguides, these structures may include an arbitrary number of dielectric radomes and Frequency Selective Screens (FSS). The FSS's are modelled as thick cylindrical metal surfaces with rectangular apertures.

Since the array is geometrically symmetrical, and all the apertures are fed with the same amplitude, but with a progressive phase shift between two successive apertures, it can be treated as a periodic structure. This allows the reduction of the problem to the analysis of a single Unit Cell [1].

Within each cell, as illustrated in Fig. 2, we can identify a number of metallic waveguides (the rectangular waveguide and the radial waveguide representing the hole in the screen) and PSWW's (dielectric layers and free space). Floquet's theorem provides the complete orthogonal set of modes to describe the field in the radial PSWW's. In general, in a radial waveguide, the electromagnetic field cannot be represented in terms of transverse to (ρ) vector modes.

The transverse field representation must consequently be effected on a scalar basis as a superposition of E-type and H-type modes. The desired modal representation is:

$$
\begin{aligned}
E_z &= \sum_i V_i(\rho) e_{zi}(z,\phi) & H_z &= \sum_i I_i(\rho) h_{zi}(z,\phi) \\
\rho E_\phi &= \sum_i V_i(\rho) e_{\phi i}(z,\phi) & \rho H_\phi &= \sum_i I_i(\rho) h_{\phi i}(z,\phi)
\end{aligned}
\qquad (1)
$$

where the z-components of the electromagnetic field satisfy the following differential equations:

E-type modes

$h'_{zi}=0 \qquad \left[\frac{\partial^2}{\partial z^2}+\frac{1}{\rho^2}\frac{\partial^2}{\partial \phi^2}+(k^2-\kappa_i^2)\right]e'_{zi}=0 \qquad (2a)$

H-type modes

$e''_{zi}=0 \qquad \left[\frac{\partial^2}{\partial z^2}+\frac{1}{\rho^2}\frac{\partial^2}{\partial \phi^2}+(k^2-\kappa_i^2)\right]h''_{zi}=0 \qquad (2b)$

where

$$\kappa_i^2 = k^2 - k_{zi}^2 - \left(\frac{k_{\varphi i}}{\rho}\right)^2 = k^2 - \left(\frac{2\pi\sqrt{\varepsilon_r}}{c} f_{ci}\right)^2 \qquad (2c)$$

$$f_{ci} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{v_0 - mN}{\rho}\right)^2 + \left(k_{z0} - \frac{2n\pi}{B}\right)^2} \qquad (2d)$$

N: the number of radiating elements;
B: height of the unit cell;
$\Delta\phi$: the angular width of the unit cell;
$v_0\Delta\phi$ and $k_{z0}B$ the inter-element phase shifts.

The following radial transmission line equations hold for the modal voltage and current amplitudes:

$$\left[\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{d}{d\rho}\right)+\kappa_i^2(\rho)\right]\begin{bmatrix}V_i'(\rho)\\ I_i''(\rho)\end{bmatrix}=0 \qquad (3)$$

$$\frac{dV_i'}{d\rho}=-j\kappa_i'(\rho)Z_i'(\rho)I_i' \qquad \frac{dI_i''}{d\rho}=-j\kappa_i''(\rho)Y_i''(\rho)V_i'' \qquad (4)$$

$$Z_i'=-\frac{\left(k^2-k_{zi}'^2\right)}{\omega\varepsilon\rho\kappa_i'(\rho)}\frac{h_{\phi i}'(\phi,z)}{e_{zi}'(\phi,z)} \qquad Y_i''=\frac{\left(k^2-k_{zi}''^2\right)}{\omega\mu\rho\kappa_i''(\rho)}\frac{e_{\phi i}''(\phi,z)}{h_{zi}''(\phi,z)} \qquad (5)$$

It should be noted that $\frac{e'_{\phi i}(\phi,z)}{h'_{zi}(\phi,z)}$ and $\frac{h''_{\phi i}(\phi,z)}{e''_{zi}(\phi,z)}$ are constant w.r.t. ρ-coordinate.

These differential equations hold for the PSWW's, with the following periodic boundary conditions, dictated by the periodic nature of the structure:

$$f(\varphi)=f(\varphi+\Delta\varphi) \qquad g(z)=g(z+\Delta z) \qquad (6)$$

where $\Delta\varphi$ and Δz are the array inter-element distances in φ and z respectively.

Within the MEN approach, the structures are analyzed as a cascade of waveguides coupled through the transition surfaces between two adjacent waveguides. For the characterization of each transition, we adopt the efficient integral equation method that we presented in [8], [9]. These approach leads to the derivation of a Multimode Impedance Matrix of the transition coupling two adjacent waveguides. Cascading the impedance matrix representation of waveguides and transitions we obtain the final matrix system representing the complete structure. The same approach can also be adopted to include any tuning element or filtering structure inside the rectangular waveguides.

The developed code gives the possibility to design the array as a filtering structure, having as final objectives: bandwidth, in-band return loss and out-of-band rejection. These specifications can now be achieved either designing the filter inside the feeding waveguides or by properly designing the FSS's.

III. RESULTS

To better understand the effect of the dielectric layer and the FSS, we report in Fig. 3 the reflection coefficient measured at one input waveguide vs. frequency for a conformal cylindrical array formed by 10 WR90 horizontal waveguides radiating directly in open space. The radius of the cylinder is 0.15 m. The waveguides are all excited with the same amplitude and with a constant phase-shift.

By introducing a single dielectric layer 5 mm thick plus a FSS 2.5 mm thick, with an aperture 19.0 mm large and 8.48 mm high, a resonant behavior is obtained. The return loss of the structure of Fig. 1.a is shown in Fig. 4, for different numbers of radiating elements (in the ϕ-direction). Increasing the number of radiating elements and keeping fixed the radius, the radial section of the unit cell decreases. Hence, the (2.d) cut-off frequency of the radial Floquet's modes grows and the resonance shifts to higher frequencies.

In Figures 5 and 6 the effects of the width and height of the FSS aperture are shown. As expected, increasing the ratio width/height (a/h) of the aperture, the resonance becomes deeper, though the variation of each dimension produces different resonances. This is clearly shown in the same figures, for the ratio a/h=2.

Finally, the reflection coefficient at one input waveguide is shown in Fig. 7 for the structure of Fig. 1.b. By properly choosing the thickness of the two dielectric layers, the corresponding resonances can be shifted in the frequency band.

IV. CONCLUSIONS

In this paper we presented an efficient and accurate full-wave approach for the analysis of multi-layer conformal cylindrical arrays of open-ended waveguides. Thanks to the modularity of the Multimode Equivalent Network formulation and the efficiency of the integral equation approach, dielectric radomes, frequency selective screens and tuning elements inside the waveguides can be easily integrated in the design process, offering therefore new interesting alternative design procedures.

V. REFERENCES

[1] S. Edelberg, A.A. Oliner, "Coupling Effects in Large Antenna Arrays: Part I-Slot Arrays", IRE Trans. on Antennas and Propagation, Vol. AP-8, No.3, May 1960.

[2] G.V. Borgiotti and Q. Balzano, "Mutual Coupling Analysis of a Conformal Array of Elements on a Cylindrical Surface", *IEEE Trans. on Antennas and Propagation*, Vol.AP-18, No.1, January 1970.

[3] J.C. Sureau and A. Hessel, "Element Pattern for Circular Arrays of Waveguide-Fed Axial Slits on Large Conducting Cylinders", *IEEE Trans. on Antennas and Propagation*, Vol. AP-19, No.1, January 1971.

[4] J.C. Sureau and A. Hessel, "Realised gain Function for a Cylindrical Array of Open-Ended Waveguides, Phased Array Antennas", *Proceedings of the 1970 Phased Array Antenna Symposium*, Polytechnic Institute of Brooklyn, New York, June 1970.

[5] A.D. Munger, J.H. Provencher and B.R. Gladman, "Mutual Coupling on a Cylindrical Array of Waveguides Elements", *IEEE Trans. on Antennas and Propagation*, Vol. AP-19, No.1, January 1971.

[6] A. Hessel and J.C. Sureau, "Resonance in Circular Arrays with Dielectric Sheet Covers", *IEEE Trans. on Antennas and Propagation*, Vol. AP-21, No.2, March 1973.

[7] A. Altintas, S. Ouardani and V.B. Yurchenko, "Complex Source Radiation in a Cylindrical Radome of Metal-Dielectric Grating", *IEEE Trans. on Antennas and Propagation*, Vol. AP-47, No.8, Aug. 1999.

[8] G. Gerini, G. Lastoria, M. Guglielmi, "Efficient Integral Equation Formulations for Admittance or Impedance Representations of Planar Waveguide Junctions", *Proceedings of the 1998 IEEE MTT-Symposium*, Baltimore, Maryland, June 1998.

[9] G. Gerini, M. Guglielmi, T. Rozzi, L. Zappelli, "Efficient Full-Wave Analysis of Waveguide Arrays on Cylindrical Surfaces", *Proceedings of the 29th European Microwave Conference*, Munich, Germany, Oct. 1999.

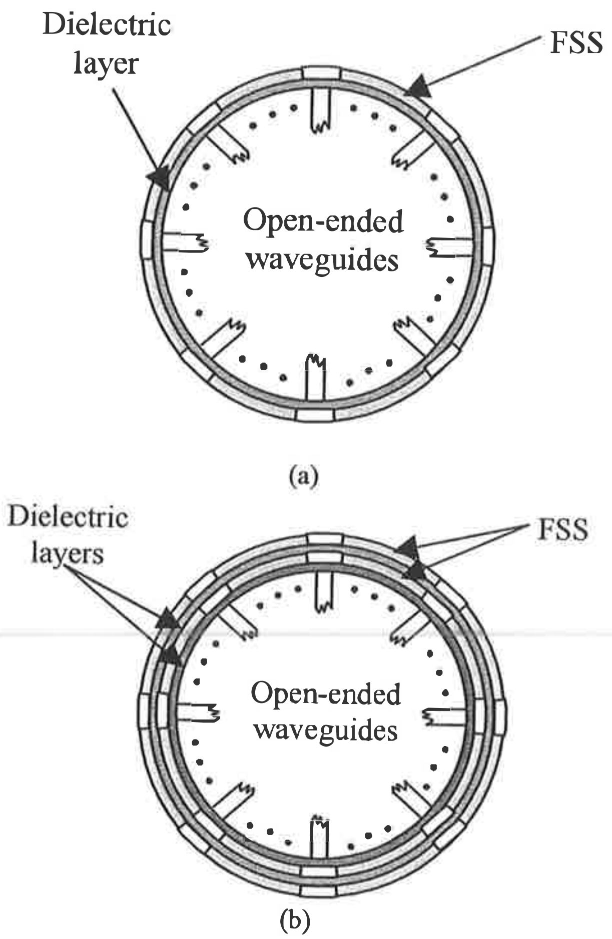


Fig.1: Schematic representation of the simulated multilayer circular cylindrical arrays.

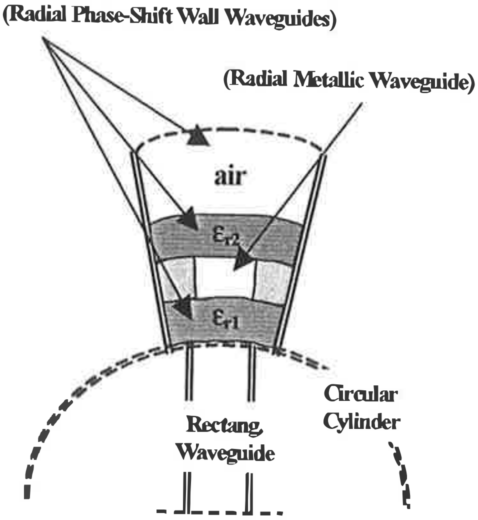


Fig.2: Unit Cell including radomes and FSS.

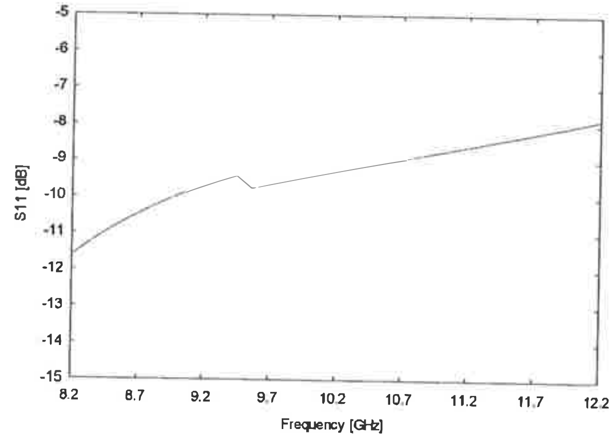


Fig.3: Return loss for the conformal cylindrical array (no radomes and FSS's). Cylinder radius: 0.15 m; Number of radiating elements: 10.

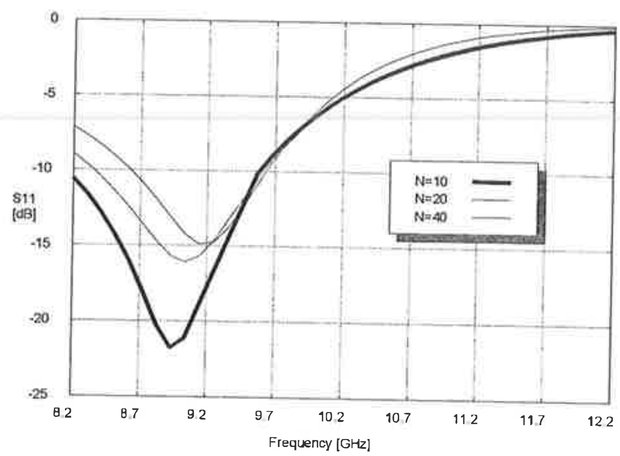


Fig. 4: $|S_{11}|$ vs. frequency for the array shown in Fig. 1.a, varying the radius and the number of elements of the unit cell, and keeping constant the dimensions of the unit cell. The FSS is 2.5 mm thick, 19.0 mm large and 8.48 mm high.

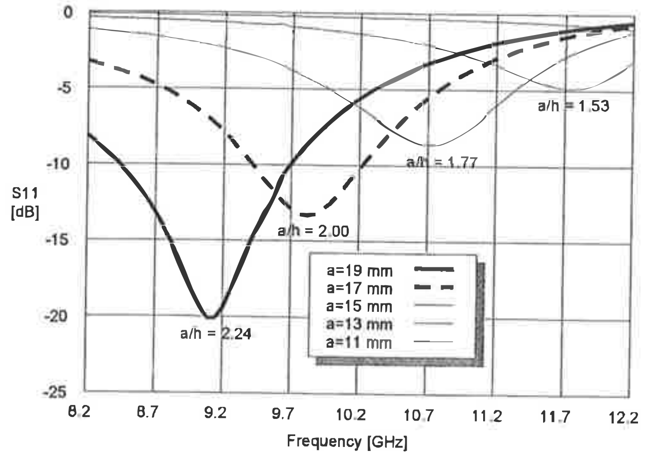


Fig. 5: $|S_{11}|$ vs. frequency of the array shown in Fig. 1.a, varying the width 'a' of the aperture of the FSS (8.48 mm high). Cylinder radius: 0.75 m; Number of radiating elements: 50.

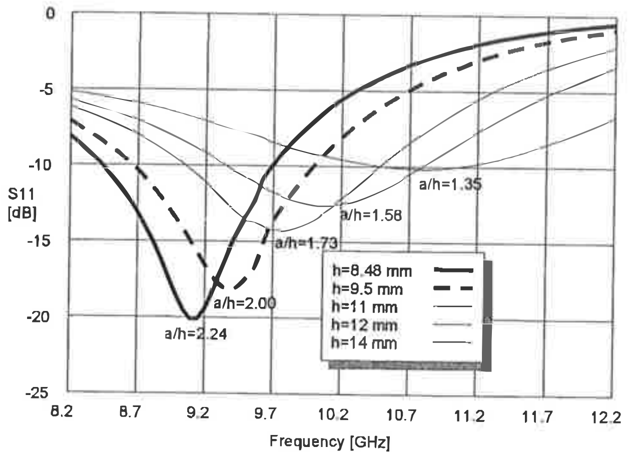


Fig. 6: $|S_{11}|$ vs. frequency of the array shown in Fig. 1.a, varying the height 'h' of the aperture of the FSS (19.0 mm large).

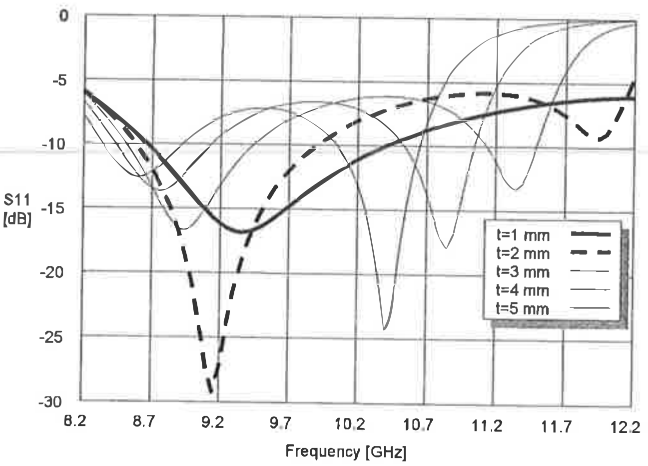


Fig. 7: $|S_{11}|$ vs. frequency of the array shown in Fig. 1.b, for different values of the dielectric thickness 't'. FSS thickness: 2.5 mm, 19.0 mm large and 8.48 mm high. Cylinder radius: 0.75 m; Number of radiating elements: 50.

TNO report
FEL-01-I122

Proceedings of the "2nd European Workshop on Conformal Antennas"

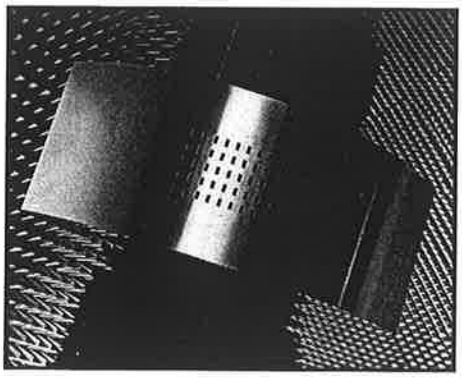
TNO Physics and Electronics Laboratory

Oude Waalsdorperweg 63
PO Box 96864
2509 JG The Hague
The Netherlands

Phone +31 70 374 00 00
Fax +31 70 328 09 61

Date
24 – 25 April 2001

Chairman
ir. H.J. Visser



COST

Sponsor
The workshop is sponsored by the EU COST Action 260 on Smart Antennas: Computer Aided Design and Technology.

Co-sponsor
The workshop is co-sponsored by the Electromagnetics Division of ESA.

The TNO Physics and Electronics Laboratory is part of TNO Defence Research which further consists of:

TNO Prins Maurits Laboratory
TNO Human Factors Research Institute

TNO

Netherlands Organisation for Applied Scientific Research (TNO)