Efficient Design of a Frequency Selective Surface for a Multi Functional Radar: Theory and Measurements

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***Abstract*— This paper describes an efficient methodology for the design of steep roll-off Frequency Selective Surfaces (FSS's). The proposed technique is based on the Multimode Equivalent Network (MEN) approach, which was originally developed for the analysis of waveguide junctions. The MEN has been extended to the study of multi-layer patch based and aperture based FSS's. The result is a general formulation that allows characterizing complex structures, consisting of radiating apertures and FSS's, in the same framework used to account for feeding and filtering elements inside the waveguides. Moreover, thanks to the modularity of this approach, it will be shown in the paper that it can be used as agile design tool. In particular, this paper describes the design procedure for a multi-layer FSS to be integrated with the X-band phased array of a Multi Functional Radar (MFR) in order to prevent interference from an antenna located in its proximity and operating in a partially overlapping frequency range. The analysis results of this integrated structure, obtained with our tools, were compared with those produced by a commercial code, showing very good agreements. The designed FSS has been manufactured and measured for different incidence angles.**

I. MEN FORMULATION

Nowadays, stringent requirements in naval and airborne radar systems push toward the integration of different sensors on the same platform. Correspondingly, if antennas located close to each other operate in an overlapping frequency band, an interference problem has to be solved.

Since the first introduction of Frequency Selective Surfaces (FSS's) in the 70's, a large amount of documentation has been published about analysis and design techniques for FSS's used as frequency and angular filters for antennas, (just as an example the well known book of Prof. Munk [1]). However, in most of the cases, the FSS is designed separately from the target antenna.

This paper shows how to design a FSS that has to be integrated with an array antenna in order to prevent interference from another antenna located in its proximity.

The design procedure is based on the Multimode Equivalent Network (MEN) technique. This approach, originally developed for closed waveguides, [2], has proved to be particularly suitable for the analysis of integrated antenna systems, in particular consisting of waveguide arrays and cascaded FSS's. It studies multi-layer structures as a cascade of Transmission Line (TL) components and impedance matrix associated to the transition between two discontinuity free regions. A typical example of system that can be studied with the MEN method is shown in Fig.1, where an infinite periodic array of open ended waveguides is integrated with a FSS, consisting of multiple planar dielectric layers loaded by resonant folded dipole elements. Each layer is treated as an open waveguide, where the fields are represented as a superposition of modes, defined with respect to the z direction. The concept of *accessible* and *localized modes* is used. The former are defined as the modes, propagating or below cutoff, that contribute to the electromagnetic interaction between two adjacent discontinuities, while the latter are associated to the energy stored in the vicinity of the transition. Therefore, the number of TL's used to represent the field in each discontinuity free region is equal to the number of accessible modes and the transition equivalent networks are also multi-mode as they relate the modes in different regions.

Tipically, in multi-mode representations an unique Integral Equation characterizes the complete problem. The novelty of the MEN, instead, resides in the fact that the number of Integral Equations (IE), to be solved in order to derive the equivalent network for a discontinuity, is equal to the corresponding number of accessible modes, and their kernel includes only localized modes (*reduced kernel IE*). The equivalent network for a transition can be either in parallel or in series with respect to the z oriented TL's, depending on the kind of discontinuity [3]. For a patch based FSS, the problem is formalized in terms of an Electric Field Integral Equation (EFIE), resulting in a shunt multi-mode admittance network. For a slot based FSS, it is formalized in terms of a Magnetic Field Integral Equation (MFIE), which results in a series multi-mode impedance network.

II. DESIGN PROCEDURE

The main feature of the MEN approach resides in its modularity, which makes it particularly suitable as basis tool for the design of multi-layer structures.

In particular, a very efficient design procedure for FSS's integrated with a waveguide array has been developed. First, a preliminary design is performed using a single-mode TL model, similar to the one in [4], [5]. With this agile tool the relevant parameters of the structure can be tuned very efficiently in order to achieve the requested performances. Second, this model is refined including higher order modes and resorting to a MEN formulation. This procedure has been applied to a design problem, concerning a FSS structure to be integrated with a MFR antenna, as in Fig.1. The array antenna consists of waveguide apertures of width $a = 20mm$ and

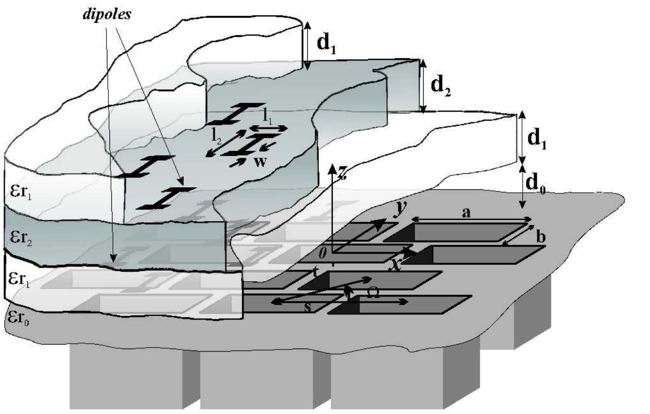


Fig. 1. Geometry of the MFR array integrated with a multi-layer dipole based FSS

height $b = 8mm$, arranged in a triangular grid characterized by $s = 21mm$, $t = 13.83mm$, $\Omega = 40.6$. It operates with $(-10dB)$ reflection coefficient over the entire X-band $(8 - 12GHz)$ and is capable of scanning in the H-plane until 30^o. Fig.2 shows the magnitude of the reflection coefficient of the array, assumed infinitely extended and periodically excited, for different scanning angles.

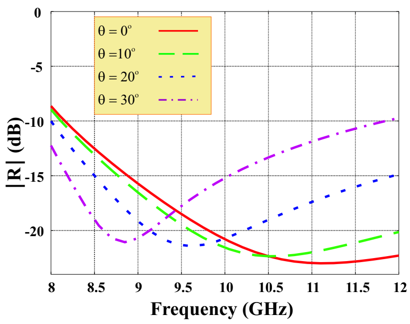


Fig. 2. Magnitude of the reflection coefficient of the array in Fig.1 assumed infinitely extended, for incidence angles $\vartheta = 0^o, 10^o, 20^o, 30^o$

Another antenna, located in the proximity of the array, operates in a partially overlapping frequency range. In order to prevent interference, an FSS has to be designed with a stop band behavior in the frequency range 11 GHz - 12 GHz, maintaining unaltered, as much as possible, the original performances in the frequency band 8 GHz - 10.5 GHz, as the angle is scanned between 0^o and 30^o in the H-plane. Being the transmission band larger than the rejection band, a dipole based FSS is the most convenient choice. In particular, in order to achieve a resonant frequency of 11.5 GHz, folded dipoles were chosen,with dimensions l_1 and l_2 along the x and y axis respectively and width w (Fig.1). The dipoles, under TE incidence, can be characterized by a simple load (Y_p) connected in parallel to the transmission line equivalent to the main propagating Floquet mode, which has characteristic admittance (free space) $Y_c = \frac{\cos\vartheta}{\sqrt{\frac{\mu_0}{\varepsilon_0}}}$ where ϑ is the incidence angle (Fig.3). Note that similar considerations would apply also for the array scanning in the E-plane. The actual value of Y_p, as a function of the frequency, can be obtained using the MEN approach. It has been found that the corresponding reactances can be approximated linearly in the surrounding of the resonance f_r, leading to the following expression for the admittance:

$$Y_p(f)_{f \approx f_r} \approx \frac{1}{Z_p'(f_r)} \frac{1}{f - f_r}. \qquad (1)$$

Therefore, once the resonating frequency is roughly known, a simple evaluation of the patch impedance for two frequency points allows approximating the admittance over a wide frequency range.
A single free standing FSS dos not allow to meet the requirements in terms of pass-band and roll-off.
A second FSS plane, located in free space at $\lambda_0/4$ distance from the first one, allows achieving a faster roll-off transition.

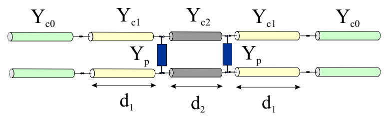


Fig. 3. Equivalent transmission line circuit representing the interaction between the two dipole FSS panels as in Fig. 1 in the single mode approximation

This double FSS structure can be represented by the single mode equivalent transmission line in Fig.3, provided that all the Floquet modes of index different than zero are sufficiently attenuated. A dielectric slab with $\varepsilon_{r2} = 2.2$ was introduced between the two FSS's in order to preserve the performances in terms of roll-off when scanning. Moreover, two further matching dielectric layers of dielectric constant $\varepsilon_{r1} = 1.5 \approx \sqrt{\varepsilon_{r2}}$ and thickness $d_1 = \lambda_1/4$ (at the center of the pass band) were added to prevent the degradation of the transmitted signal in the pass-band, arriving to the configuration depicted in Fig. 1.
This preliminary design, based on the single mode TL model, has then been refined through the MEN method, including 12 accessible modes in the analysis. Fig. 4 shows the reflection coefficient of the complete FSS, consisting of two dipole panels sandwiched between three dielectric layers (the dimensions of the dipoles and the thickness of the slabs are indicated in the inset). The simulations for the first order TL model are also reported for comparison. From Fig. 4 it results that this design meets the initial requirements.

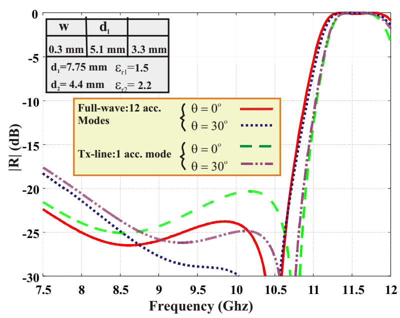


Fig. 4. Magnitude of the reflection coefficient of the complete dipole based FSS, for incidence angles $\vartheta = 0^o, 10^o, 20^o, 30^o$

Finally, the FSS has been tuned with the array and located at an optimal distance of $5.2mm$ from the antenna. The reflection coefficient of the array integrated with the FSS is reported in Fig. 5.

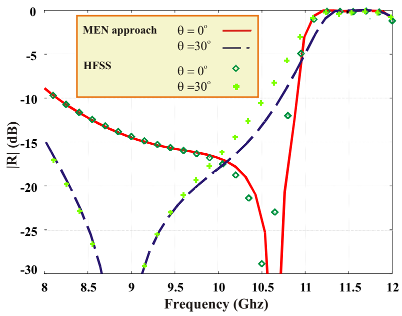


Fig. 5. Magnitude of the reflection coefficient of the MFR array integrated with the designed FSS, for incidence angles $\vartheta = 0^o, 30^o$

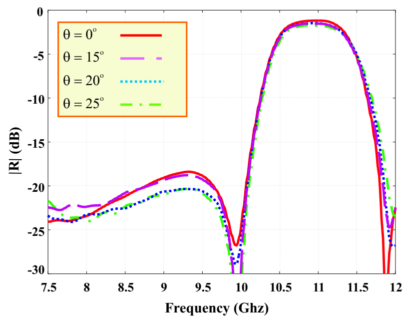


Fig. 7. Measured magnitude of the reflection coefficient of the dipole based FSS for incidence angles $\vartheta = 0^o, 15^o, 20^o, 25^o$

III. Manufacture and Measurements

Based on the design described in Section II, a FSS panel has been manufactured.
Some changes needed to be applied to this initial design because of constraints imposed by the manufacturing process and because of the limited availability of the selected materials. The core was made of Taconic TLY-5, having permittivity $\varepsilon_r = 2.2 \pm 0.02$ in X-band and dissipation factor $tan_\delta = 0.0009$. The material was available in layers of $2.2mm$ only. The external matching layers were made of Bisco Cellular Silicon HT-820, a foam whose nominal permittivity is $\varepsilon_r = 1.5$. Also in this case, the material could be provided just in slabs of thickness $2.54mm$. In order to achieve the thicknesses required in the design, two layers of Taconic and three of Bisco (on each side of the FSS core) were stuck together using a 0.1mm thick bond film, whose nominal permittivity is $\varepsilon_r = 2.32$. Because of these changes, the resulting FSS looks quite different from the original design (Fig. 6).

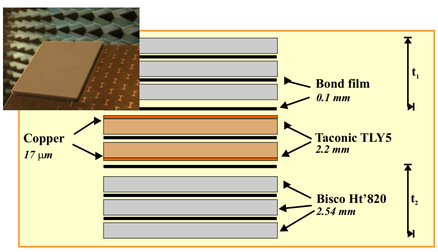


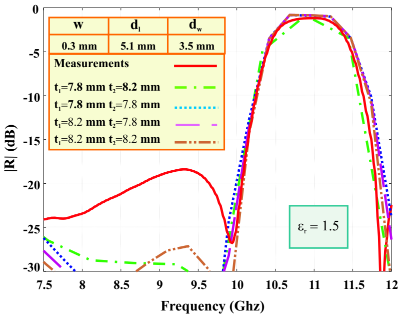
Fig. 6. Layout of the manufactured FSS panel and photo of a particular of the panel from which the layered structure is evident

The reflection coefficient of the two FSS panels has been measured at the Far-Field Anechoic Chamber of TNO-FEL. A bistatic two-horn antennas method was used. In order to simulate plane wave incidence, the panel had to be located on the far field region of the radiating antenna: $2d^2/\lambda$, where d is the side dimension of a square panel. A frame of Radar Absorbing Material (RAM) was used to obtain from the starting FSS panel ($60cm$ a side), a sub-panel of $28cm$. This frame helps also reducing the effect of edge diffraction from the FSS. The FSS panel was fixed to a analogically controlled turntable to obtain alignment with the antennas. At the time of the measurements, scanning in the far-field room was possible just for angles up to 25°.

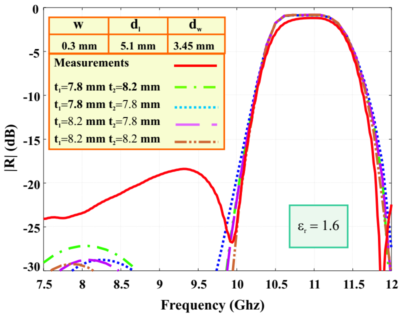
The measured reflection coefficient of the FSS panel is reported in Fig. 7 for incidence angles $\vartheta = 0^o, 15^o, 20^o, 25^o$.

The resonance frequency for normal incidence appears shifted of about 4% with respect to the results in Fig.4. It should be noted that those simulations refer to the original design, where the bond film was not included. Moreover, some inaccuracy sources have been identified which should be taken into account in order to explain the difference between measured and simulated results. The structure appears affected by manufacture errors that exceed by far the guaranteed tolerances. In particular, the total dipole length was etched with an error of about 6%. Further, as results of tests performed by Rogers, the permittivity and the loss tangent of the Bisco foam are quite variable with the frequency. A measured average value of $\varepsilon_r = 1.595$ and $tan_\delta = 0.0981$ is provided by Rogers in the frequency range $7 - 12GHz$. The Bisco foam resulted also a not homogeneous material, having each slab a uniform thick external surface and a bubbly soft interior. This variation in density corresponds to a variation in dielectric properties. Moreover, since the bonding of the foam to the FSS core was particularly troublesome, extra pressure had to be applied onto the structure, resulting in a change in the local thickness and density of the foam. In particular the total thickness of the external FSS layer (including foam and bond film), measured in different points of the panel, varies between $d_1 = 7.8mm$ and $d_1 = 8.2mm$.
In order to evaluate the effect of these problems, a parametric study of the reflection coefficient has been performed, as a function of the dipole dimensions and foam permittivity and thickness. First, the dipole length has been changed, taking into account the values actually measured on the FSS samples, to obtain the measured resonance frequency. The reflection coefficient has then been studied, for normal incidence, for three different values of the foam dielectric constant: $\varepsilon_r = 1.5, 1.6, 1.7$ with fixed losses $tan\delta = 0.0981$, when the total thickness of the foam on each side of the FSS varies from $7.8mm$ until $8.2mm$ (the corresponding dipole dimensions are indicated in the inset of Fig. 8).

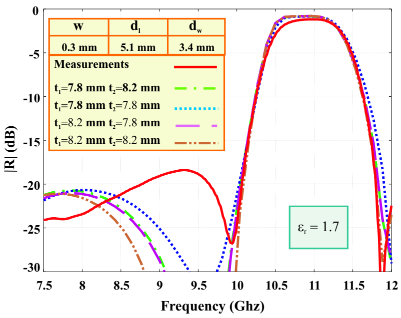
From Fig. 8, it results that the simulated response, when close to resonance, matches very well the measurements. The difference still remarkable for lower frequencies can be associated to the low performances of the foam and to measurement set-up inaccuracies. In particular, because of the weight of the FSS panel, the height of the RAM frame in presence of the FSS is different than the one in empty room conditions, resulting in an incorrect empty room calibration. Also, the effective FSS area contributing to the measured reflection is in general not constant: during the displacement



(a) Foam dielectric constant $\varepsilon_r = 1.5$



(b) Foam dielectric constant $\varepsilon_r = 1.6$



(c) Foam dielectric constant $\varepsilon_r = 1.7$

Fig. 8. Parametric study of the FSS reflection coefficient for three different values of the foam permittivity, when the foam thickness in each side of the panel varies between $7.8mm$ and $8.2mm$

of the FSS panel, the RAM frame around it moves and the number and position of FSS elements actually illuminated by the antenna might be every time different. Finally, the elevation and azimuth alignment of the antennas with respect to the reference plate and to the FSS panel is not enough accurate. The far-field room is now being renovated in order to prevent many of these problems. Moreover, the foam has proved itself not suitable for high precision microwave applications and a careful choice of the materials for manufacturing multi-layer FSS's becomes a key issue for next design, especially if the noise of the far-field room can be significantly reduced.

IV. Conclusion

In this paper it has been shown that FSS's integrated with a waveguide array can be very efficiently studied by means of the MEN approach. Besides being a powerful analysis tool, this method constitutes an agile platform for the design of multi-layer structures, thanks to its modularity.
The design procedure consists in a first order design, based on a single mode model, and in a subsequent refinement, using the full wave MEN approach. The single mode equivalent transmission line model allows a fast design of the FSS, starting from the requirements.
A test case design problem has been presented in this paper. The designed FSS panel has been manufactured and measured. The simulations match very well the measurement results in proximity of the resonance. The difference that can still observed for lower frequencies is due to the not homogeneous dielectric characteristics of the foam material, and to the inaccuracy introduced by the measurement set-up, in terms of empty room calibration. A new FSS design is currently being performed at TNO. In order to achieve a steeper roll-off, materials with higher dielectric constant will been selected, leading to an FSS having a periodicity smaller than the one of the array.

V. Acknowledgement

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References

[1] B.A.Munk, *Frequency Selective Surfaces: theory and design*. New York: John Wiley and Sons, 2000.
[2] G.Gerini, G.Lastoria and M.Guglielmi, “Efficient Integral Equation Formulations for Admittance or Impedance Representations of Planar Waveguide Junctions,” in *IEEE Microwave Theory Tech. Soc. Int. Symp. 1998 Dig.*, Baltimore, Maryland, June 1998.
[3] S.Monni, G.Gerini , A.Neto, “Multimode Equivalent Network Method for the Design and Analysis of Frequency Selective Surfaces Integrated with Waveguide Arrays,” submitted for publication to *IEEE Trans. Antennas Propagat.*.
[4] R.Orta, P.Savi and R.Tascone, “Numerical green's function technique for the analysis of screens perforated by multiply connected apertures,” *IEEE Trans. Antennas Propagat.*, vol. AP-44, no. 6, pp. 756–776, 1996.
[5] S.Maci, M.Casaletti, M.Caiazzo, C.Boffa, “Dispersion properties of periodic grounded structures via equivalent network synthesis,” in *IEEE Antennas and Propagation Soc. Int. Symp. 2003 Dig.*, Columbus, Ohio, June 2003.