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Abstract - We report on the design of a 45° incidence diplexer to be used in a millimeter-wave radiometer. This equipment will be flown on a low orbiting satellite and should analyze the natural emissions of the earth and the atmosphere in the bands around 90, 157 and 183 GHz. The diplexer has been realized with two grids of tripoles arranged in an equilateral triangular lattice and printed on the two sides of a quartz slab. Experimental data are presented that are in good agreement with the theoretical predictions.

I Introduction

Several projects are on going at present concerning the determination of water vapour content and temperature profile of the Earth atmosphere. These data should be obtained by means of radiometers working in the millimeter-wave range, to be flown on board satellites and aircrafts.

In the framework of one of these projects we have designed a 45° incidence quasi optical diplexer, which can separate three channels located at 90 GHz, 157 GHz and 183 GHz. The geometry of the diplexer and its frequency behaviour are sketched in fig.1. The specifications require two transmission bands for the lower frequency bands, and a reflection band centered at the upper one. The reflection band and the low frequency transmission band can be realized with a capacitive Frequency Selective Surface (FSS) consisting of a periodic distribution of metallic elements printed on a dielectric support, such as tripoles arranged in a triangular lattice and printed on a quartz slab. To realize the second transmission band and to have a larger reflection bandwidth, it is necessary to add a new grid on the other side of the dielectric support. The specifications are rather tight and require a .3 dB loss, at most, at all frequencies. However, by a proper selection of the thickness of the quartz slab and of the dimensions of the metallic patches, a structure with satisfactory performance has been designed. The measurements confirm the theoretical predictions.

II Analysis

In the last years several numerical methods have been proposed to study Frequency Selective Surfaces: see [1] for an extensive list of references. In the following, for ease of reference, we summarize our method of study [2].

A capacitive FSS consists of a periodic arrangement of metallic patches on a lattice defined by the basis vector $\underline{d}_1, \underline{d}_2$. To obtain a spectral characterization of this structure, we consider a plane wave with a transverse wave vector $\underline{k}_t$ and arbitrary polarization as incident field. Under these assumptions, the structure excites a discrete spectrum of plane waves (Floquet Modes), characterized by the transverse wavevectors $\underline{k}_{pq} = \underline{k}_t + p\underline{k}_1 + q\underline{k}_2$ where $\underline{k}_1$ and $\underline{k}_2$ are the basis vectors of the reciprocal lattice.

Let us consider a multiple grid FSS. Basically two approaches are possible: either a global attack or a "building block scheme". According to the former, the problem is formulated as a system of coupled integral equations where the unknown is the induced current distribution on the various grids. In the latter, the complicated structure is subdivided into a succession of "elementary parts", each of which characterized by its Generalized Scattering Matrix (GSM): the behaviour of the complete FSS is obtained by circuit techniques. It is apparent that the second approach is preferable in the design phase, where it is important to ascertain the role played by each part. At first sight, it could seem possible to characterize separately the grids and the dielectrics. This procedure is, however, highly inefficient from a numerical point of view, since the cascade requires the inversion of very large matrices, with size equal to the number of modes used to represent the Green function of the structure. Much more efficient is to characterize a grid with the adjacent dielectric layers, which leads in a natural way to the classification of the modes excited by the discontinuity as localized and accessible, which couple the part under study to the rest of the structure, [3], [4]. The GSM of a grid embedded in the surrounding dielectric layers between the sections $z = z_l$ and $z = z_r$ has the form:

$$\begin{bmatrix} \underline{\hat{V}}^s \\ \underline{\tilde{V}}^s \end{bmatrix} = \begin{bmatrix} \underline{\underline{S}}^d_{11} - \underline{\underline{\hat{T}}} \cdot \underline{\underline{Z}} \cdot \underline{\underline{W}} \cdot \underline{\underline{\hat{T}}}_t & \underline{\underline{S}}^d_{12} - \underline{\underline{\hat{T}}} \cdot \underline{\underline{Z}} \cdot \underline{\underline{W}} \cdot \underline{\underline{\tilde{T}}}_t \\ \underline{\underline{S}}^d_{21} - \underline{\underline{\tilde{T}}} \cdot \underline{\underline{Z}} \cdot \underline{\underline{W}} \cdot \underline{\underline{\hat{T}}}_t & \underline{\underline{S}}^d_{22} - \underline{\underline{\tilde{T}}} \cdot \underline{\underline{Z}} \cdot \underline{\underline{W}} \cdot \underline{\underline{\tilde{T}}}_t \end{bmatrix} \begin{bmatrix} \underline{\hat{V}}^i \\ \underline{\tilde{V}}^i \end{bmatrix} \tag{1}$$

The symbols $\hat{}$ and $\tilde{}$ distinguish quantities related to left and right side incidence respectively. The ports to which this GSM refers are the N_l accessible Floquet modes, which are interpreted as the points in the spectral plane belonging to the reciprocal lattice. Since a vector transmission line formalism is used to study the dielectric stratification, to each point TE and TM polarizations are associated and the matrix entries are dyadics.

This GSM can be decomposed into the sum of two matrices. The first

$$\underline{\underline{S}}_d = \begin{bmatrix} \underline{\underline{S}}^d_{11} & \underline{\underline{S}}^d_{12} \\ \underline{\underline{S}}^d_{21} & \underline{\underline{S}}^d_{22} \end{bmatrix} \tag{2}$$

defines the GSM of the dielectric support structure with the metallic discontinuity removed. $\underline{\underline{S}}^d_{ij}$ are $(N_l \times N_l)$ abstract diagonal matrices representing in the Floquet mode basis the reflection and transmission coefficients of the whole dielectric structure between sections z_l and z_r or viceversa.

The second matrix takes into account the radiation of the electric currents induced on the metallic patches, in presence of the dielectric stratification. Consider, for example, the term $\underline{\underline{\hat{T}}} \cdot \underline{\underline{Z}} \cdot \underline{\underline{W}} \cdot \underline{\underline{\hat{T}}}_t$. The factors $\underline{\underline{\hat{T}}}, \underline{\underline{Z}}, \underline{\underline{\hat{T}}}_t$ are related to the dielectric stratification only and, hence, are diagonal matrices. $\underline{\underline{W}}$ is a full matrix and takes into account the metal discontinuity. In particular, the dielectric transmission coefficient $\underline{\underline{\hat{T}}}_t$ $(\underline{\underline{\tilde{T}}}_t)$ gives the electric field in the grid section when the metal patches are removed in terms of the electric field incident on z_l (z_r). $\underline{\underline{W}}$ represents an admittance type Green function, relating the magnetic field jump at the discontinuity to a couple of opposite magnetic current distributions placed on the faces of the grid. (This particular source distribution is motivated by the electric field continuity at the grid section.) The matrix $\underline{\underline{Z}}$ is the impedance type Green function of the dielectric layers relative to the grid section. Finally, the dielectric transmission coefficient $\hat{\underline{\underline{T}}}$ ($\tilde{\underline{\underline{T}}}$) gives the scattered electric field in z_l (z_r). All the quantities pertaining to the dielectric stratification are easily obtained by the transmission line technique. The matrix $\underline{\underline{W}}$ is obtained by the (Galerkin) method of moments applied directly in the spectral domain by choosing as unknown the Fourier transform of the currents induced on the patches. By introducing a projection matrix $\underline{\underline{Q}}$, whose columns are the vector basis functions $\underline{f}_n(\underline{k})$ evaluated in the points of the reciprocal lattice, the linear system matrix can be written as $\underline{\underline{B}} = \underline{\underline{Q}}^+ \cdot \underline{\underline{Z}} \cdot \underline{\underline{Q}}$ (the superscript + indicating the hermitian adjoint). In terms of these quantities, the previously introduced matrix $\underline{\underline{W}}$ has the expression $\underline{\underline{W}} = \underline{\underline{Q}} \cdot \underline{\underline{B}}^{-1} \cdot \underline{\underline{Q}}^+$.

A critical point in the numerical evaluation of the elements of the matrix $\underline{\underline{B}}$ is the number of Floquet modes to be taken into account. This "relative convergence" problem, due to the fact that the Green function $\underline{\underline{Z}}$ is known only in the Floquet mode basis, has been solved by a spectral criterion, based on the spatial bandwidth of the set of basis functions employed [4].

The basis functions adopted in the method of moment solution are entire domain basis functions defined on each arm of the tripole. Under the assumption of arms with length L much greater than their width w, the current distribution induced on the tripoles can be assumed to be directed along the arms only. In the local reference system centered on each arm, and with the y axis oriented along the longitudinal direction, the basis functions are the Fourier transform of the following set:

$$\underline{f}_n(x,y) = \frac{1}{\sqrt{1-\left(\frac{2x}{w}\right)^2}} \sin\left[\frac{n\pi}{L}\left(y+\frac{L}{2}\right)\right]\hat{y} \quad n = 1, 2... \tag{3}$$

III Design and measurements

To realize the diplexer plate, a symmetrical structure has been chosen: two grids consisting of tripoles arranged in an equilateral triangular lattice and printed on the two sides of a fused quartz slab with $\epsilon_r = 3.78$ (see fig.2). Using a double grid configuration a larger reflection bandwidth and a better separation between the transmission and the reflection band can be achieved with respect to the single grid configuration. Moreover, with a proper choice of the thickness of the dielectric layer, the required matching can be obtained in the transmission bands. Although a material with a lower permettivity would be preferable, quartz was chosen due to its high thermal stability.

The design is carried out in subsequent steps. First, a single grid printed on a quartz slab which resonates at 183 GHz is designed. This resonance frequency is obtained with length $L = 270\,\mu$m, width $w = 20\,\mu$m, and a lattice step $d = 600\,\mu$m. At this stage the correct value of dielectric thickness is unknown, but a value of $s = 500\,\mu$m has been used since this is the minimum thickness of available quartz slabs. It is to be remarked that the resonance frequency changes only slightly if the thickness is increased beyond this value. In figs.3a,b the transmission and reflection coefficients for both polarizations at 45° incidence are shown. Note that none of the requirements of the design are satisfied: the reflection band is too narrow and there is no match at the transmission bands.

Then, a preliminary design of the double grid structure is performed assuming that only the fundamental Floquet mode couples the two grids. Under this approximation, we can refer to the equivalent circuit of fig.4, where jB is the susceptance of the single grid. Note that although jB refers to the grid alone, its value is computed by taking the dielectric stratification into account. It is well known that the circuit of fig.4 is matched if the thickness s is such that $y_{A^+} = y^*_{B^-}$. This condition should be satisfied at the frequencies corresponding to the two transmission bands and for both TE and TM polarizations. Note that at 45° incidence the modal impedances for the two polarizations are quite different.

Finally, the design is trimmed by an optimization software, by taking into account all the Floquet modes that actually contribute to the coupling. The final configuration is described by the following data: lattice dimension $d = 550\,\mu$m, arm length $L = 265\,\mu$m, arm width $w = 20\,\mu$m, dielectric thickness $s = 785\,\mu$m. Note that the thickness of the fused silicate is sufficient to meet common spacecraft vibration constraints. The frequency response of this structure, shown in fig.5a,b, has been obtained with 10 expansion functions for each tripole arm, 439 points of the reciprocal lattice and the coupling of the two grids has been computed through the first Floquet modes with a nominal attenuation less than 30 dB.

A diplexer has been realized with a 70×70 mm fused silicate substrate, the flatness of which is controlled with $\pm 1\,\mu$m accuracy. This size is compatible with the spotsize (25 mm) of the incident beam, generated by a conical horn. A total of 18704 gold tripoles, with thickness of $3\,\mu$m, have been individually photo-reproduced on a glass mask and then photo-etched on both faces of the substrate. With this technique we have achieved a precision in the alignement of the arrays on the two faces better than $2\,\mu$m and a dispersion of the tripole size of the order of $2\,\mu$m. Direct photo-etching of the tripoles is foreseen in the next future to improve the accuracy of the realization.

In figs. 5a,b the comparison between predicted and free-space experimental results is shown. The predicted results are the $45°$ incidence plane-wave responses, for the two principal polarizations TE and TM, of the diplexer with nominal dimensions. The effects of fabrication tolerances have been investigated assuming a variation of $\pm 2\,\mu$m of the tripoles dimensions. It has been observed that the width variation produces almost negligible changes, whereas the length variation gives rise essentially to a shift of the frequency response of the order of 1%. This effect is more serious for the transmission band T_2 which is originated by a destructive interference phenomenon.

The measured transmission coefficients for V/V and H/H polarizations have been obtained by a network analyzer using the free-space as reference (see fig.5a). The differences between the measured and computed values can be attributed, besides to the effects of the fabrication tolerances, to the fact that the incident field has a plane wave spectrum with a spread of incidence directions centered at $45°$.

As for the reflection coefficients, the measurement has been carried out by a radiometric technique using a solid metal plate as reference (see fig.5b). Both vertical and horizontal polarization have been observed, but since the source is unpolarized, the results are a combination of the diagonal and off diagonal reflection coefficients. This fact may justify the slight discrepancies.

In conclusion, the theoretical model has proved to be satisfactory and the use of two identical arrays allowed to obtain two transmission bands for both polarizations, even if the substrate has a rather high dielectric constant.

References

[1] R.Mittra, C.H. Chan, and T.Cwik, "Techniques for analyzing frequency selective surface - a review", Proc IEEE,vol.76, pp.1593-1615,1988.

[2] R. Orta and R.Tascone, R. Zich, "A unified formulation for the analysis of general frequency selective surfaces", *Electromagnetics*, vol. 5, No. 4, pp. 307-329, 1985.

[3] T.R.Schimert,A.J.Brouns, Chi H.Chan, R.Mittra, "Investigation of millimeter-Wave scattering from frequency selective surfaces", IEEE Trans. on MIcrowave Theory Tech.,Vol.39, No.2, pp.315-322, February 1991.

[4] R. Orta, R. Tascone and R. Zich, "Multiple dielectric loaded perforated screen as frequency selective surfaces", *IEE Proc. H., Microwaves, Opt. & Antennas*, vol. 135, No. 2, pp. 75-82, Apr. 1988.

Figure 1: Diplexer scheme.
$\mathrm{T}_1 : 87 \div 93\,\mathrm{GHz}$; $\mathrm{T}_2 : 155.5 \div 158.5\,\mathrm{GHz}$; $\mathrm{R}_3 : 175 \div 191\,\mathrm{GHz}$

Figure 2: Double grid geometry. Quartz substrate: $\epsilon_r = 3.78$, thickness: $785\,\mu$m. Triangular lattice: $d = 550\,\mu$m. Tripoles: $L = 265\,\mu$m, $w = 20\,\mu$m.

Figure 3: Transmission (a) and reflection (b) coefficients for TE and TM polarization for the single grid configuration

Figure 4: Fundamental mode equivalent circuit of the double grid configuration

Figure 5: Transmission coefficient (a) and reflection coefficient (b) for the double grid configuration. Numerical results: TM ($--$) and TE ($--$) polarization. Experimental results: Vertical ($\triangle$) and horizontal ($\circ$) polarization.