Leaky Wave Enhanced Feeds for Single Aperture Multi Beam Reflectors

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***Abstract*— This work is the fourth of a series on the use of super-layers to shape the radiation pattern of each of the feeds composing a focal plane imaging array. Using dielectric or Frequency Selective Surface type of super-layers the spill over from the reflectors is reduced without increasing the dimensions of each aperture. This effect is achieved when the inter-element distance between the feeds is 2.4 wavelengths which is typical for satellite based multi beam telecommunication systems. The shaping of the pattern is obtained with the excitation of a pair (TE/TM) of leaky waves, that radiate incrementally as they propagate between the ground plane and the super-layer. The super-layer can be realized with a single dense dielectric slab ($\epsilon_r = 20.25$), a double dielectric slab ($\epsilon_r = 4.5$) or an equivalent frequency selective surface. The maximum edge of coverage enhancement, with respect to reference free space configuration, that can be obtained in these three different cases is equivalent. However, the bandwidth over which the enhancement is maintained depends on how the super-layer is realized. The predicted embedded patterns provide an increase of the edge of coverage gain, with respect to the free space case, of at least 2 dB in an operating bandwidth of $\approx 1.7\%$.**

I. Introduction

Present and next generation telecommunication satellite systems often require multiple beam capability. The simplest way to achieve high edge of coverage gain is to use a single aperture and a single feed per beam [1]. In the series of works [2]- [4] an approach based on the use of dielectric super-layers to enhance the radiation properties of small apertures to improve the excitation of reflector antenna systems has been proposed. In particular [4] shows the results for a demonstrator used as feed of a dual reflector system, with an increase of edge coverage gain of 1.3 dB over a bandwidth of about 6%. However these performances were demonstrated only for systems characterized by moderate values (0.85) of the F/D (Focal distance to diameter ratios). In this contribution the same strategy based on the use of super-layers is adapted to the design of reflector systems that use larger F/Ds which in turn are necessary to achieve small degradation of the performances for the off focus beams.

II. Pattern Synthesis Based on Leaky Wave Enhancement

In [3], [4] a super-layer configuration, characterized by $h_1 = 0.5\lambda_0$; $h = 0.25\lambda_d$ and dielectric constant $\epsilon_r = 4.5$ was discussed. There was demonstrated that the mutual coupling between neighboring elements in an hexagonal lattice configuration was dominated by the first couple of TE/TM leaky waves supported by the structure. When the inter-element spacing was such that the mutual coupling between neighboring wave-guides was lower than $-30\ dB$ the embedded and the isolated beams would coincide. Wide scanning angles for telecom applications require large inter-element period and a large F/D for the system to be designed. Following the design strategy discussed in [4], it turns out that these specifications can be met using a unique dielectric super-layer characterized by dielectric constant $\epsilon_r = 20.25$. When an array configuration as shown in Fig. 1, characterized by irises loaded compact

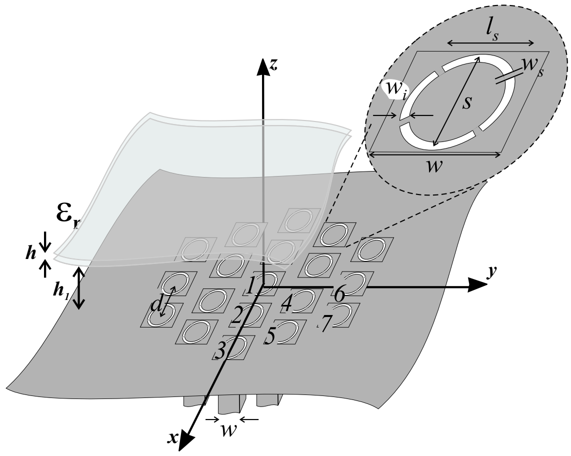

Fig. 1. Final design of the prototype waveguide array. The area of each unit cell is significantly larger than the dimension of each waveguide

square wave-guides, and inter-element period $d = 2.4\lambda_0$ (λ_0, central operating frequency) is used, the radiation patterns turn out to be clean, symmetric, in all azimuth cuts. Their directivity depends on the dielectric constant of the super-layer slab. In order to dimension the dielectric slab the most important trade-off is the edge of coverage gain against the frequency. For this reason Fig. 2 shows the edge of coverage gain as a function of the frequency for a number of different dielectric slabs, assuming $F/D = 1.71$. It is apparent that

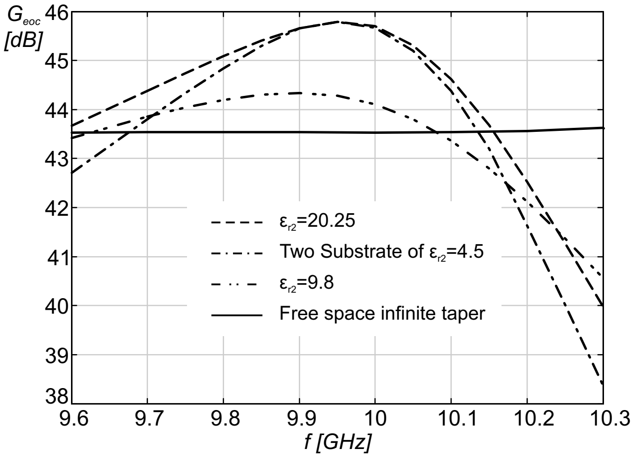

Fig. 2. G_{EoC} for different super-layer configurations with different dielectric permittivities and with more than one super-layer. The circular horn feed with infinite taper is taken as reference case. The equivalent F/D of the system is set at 1.71.

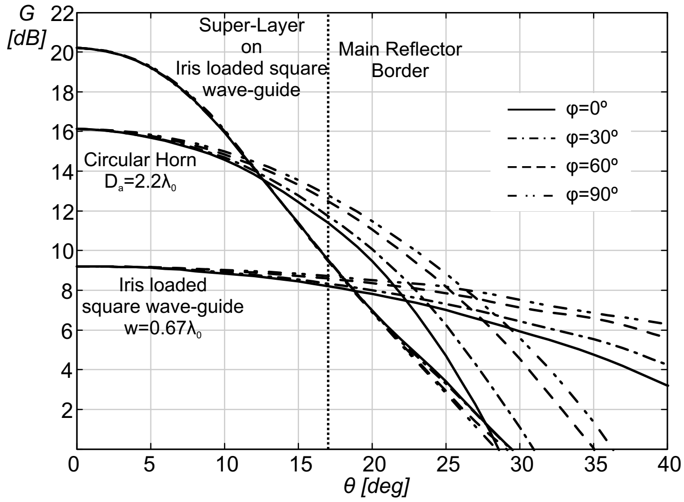

Fig. 3. Amplitude of the calculated primary radiation patterns at $f = 9.95\ GHz$ for $\phi = 0°, 30°, 60°, 90°$ of a super-layer configuration with $\epsilon_r = 20.25$ compared to same field cuts of the reference case with infinite taper and with the iris loaded compact square wave-guide without super-layer stratification.

larger dielectric leads to higher edge of coverage gains over smaller bandwidth. The selection of an optimal dielectric layer depends only on the eventual required bandwidth. One should note that the configuration resorting to two dielectric layers of dielectric constant $\epsilon_r = 4.5$, separated by $\lambda_0/4$, is equivalent to a unique layer of $\epsilon_r = 20.25$ at the central operating frequency. However the single slab configuration is eventually associated to slightly larger useful bandwidth. Thus single slabs configurations could be preferred from an electric performance point of view. However the availability of lower ϵ_r dielectric slabs sets a preference for the double dielectric configuration. The mutual coupling between the neighboring wave-guides is assumed not to disturb the radiation pattern of the isolated wave-guides because a reuse scheme x4 will be implemented, thanks to which the wave-guides closest to the central one are effectively short circuited either by cross polarized irises or by the frequency filters as discussed also in [4].

The predicted directivity patterns for a dielectric slab characterized by $\epsilon_r = 20.25$, in four significant planes, are reported in Fig. 3 at the frequency of $9.95\ GHz$. They are also compared with the ones that would be achieved by the reference (infinite taper) circular apertures and by iris loaded compact square wave-guide without the super-layer stratification. It is apparent that the leaky wave enhanced patterns are much more directive than the isolated one in both cases and thus, over a small frequency range more suited to feed efficiently a reflector with large F/D.

Fig. 4 shows the secondary patterns as a function of the frequency using a reflector of $F/D = 1.71$. In these two figures the highest useful frequency is $10.05\ GHz$ which corresponds to the first frequency at which a beam splitting is observed in the primary fields and then also the first frequency at which the beam isolation (defined as gain at the edge of coverage-the first side lobe level) is lower than $12\ dB$.

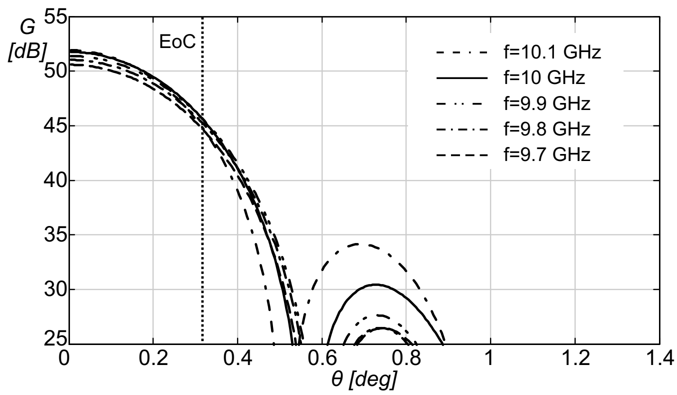

Fig. 4. Secondary patterns in the band $9.7 - 10.1\ GHz$, considering a reflector with $F/D = 1.71$.The feed patterns can be used until the upper frequency of $10.05\ GHz$, where the beam isolation is lower than $12\ dB$.

III. Metallic Super-layer

When the requirements demand for dielectric layers characterized by dielectric constants higher than those that are easily commercially available, or the operative environment does not allow the use of materials that can trigger ionizing discharges, it makes sense to look for alternative super-layer solutions to obtain equivalent performances. A simple and effective way to achieve a similar gain enhancement is the use of a metallic frequency selective surfaces (FSS) [5], [6]. The equivalence between these super-layer geometries is due to the similarities of their Green's Functions (GF). In one case the relevant GF is that of a slot etched on an infinite ground plane and covered by an FSS while in the other it is the GF of a slot covered by a dielectric layer [7]. In both cases the lower portion of the spectrum of the GF's is dominated by a couple of dominant leaky TE/TM poles.

In selecting a specific FSS geometry the driving considerations were the manufacturability, the possibility to be operated in dual polarization and the quality of the radiated beams. It was decided that the FSS would have been slot based in such a way that the slots could be machined on a robust metallic plane of finite thickness without resorting to dielectric support. Secondly the slots were chosen of circular shape so that they would support well both possible polarizations. Finally the FSS was designed with an hexagonal lattice. In fact the FSS and a planar uniform slab behave similarly if the propagation constants of the leaky waves launched by a feed present similar propagation constants in all radial direction. The final configuration for the FSS is shown in Fig.5. The dimensions of the FSS design with hexagonal lattice are the following: $r = 4.05\ mm$, $D = 9mm$, $\alpha = 60^o$ and the thickness of the metal plate, where the holes of the FSS are drilled, is $h_t = 0.25\ mm$. These dimensions ensure the equivalence in term of patterns between the FSS and the super-layer case with $\epsilon_r = 20.25$. The final patterns turn out to be circularly symmetric pencil beams. To get an idea of the patterns, Fig.6 reports two cut planes of the primary pencil beam patterns at $\phi = 0°$ and $45°$ respectively, at $f = 9.9\ GHz$.

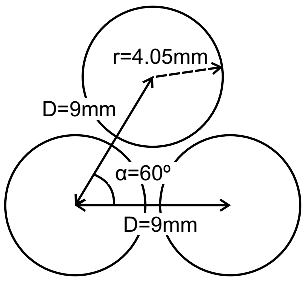

Fig. 5. Geometrical detail of the FSS used to replace the dielectric of $\epsilon_r = 20.25$. The FSS presents a hexagonal lattice and is made by holes.

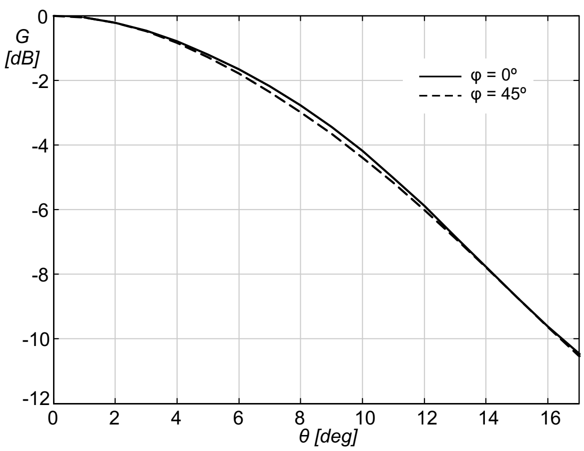

Fig. 6. Field cuts at $\phi = 0°$ and $45°$ for the pencil beam of the FSS feed with hexagonal lattice at $f = 9.9\ GHz$.

The secondary fields have been obtained and then the edge of coverage gain vs. frequency for the FSS feeds. The reflector geometry used for the analysis has again an equivalent F/D of 1.71. Fig.7 shows the edge of coverage gain vs. the frequency for FSS feeds compared with that one of the super-layer configuration with $\epsilon_r = 20.25$ and with that of the reference case of circular horn. Also in this case, it is observed a primary and secondary pattern degradation at the frequency of $f = 10.05\ GHz$. In a band of $300\ MHz$, we achieve with the FSS feeds an enhancement in performances, compered to the free space case, of $1.5\ dB$. The increase becomes $2.1\ dB$ if the band is restricted to $170\ MHz$.

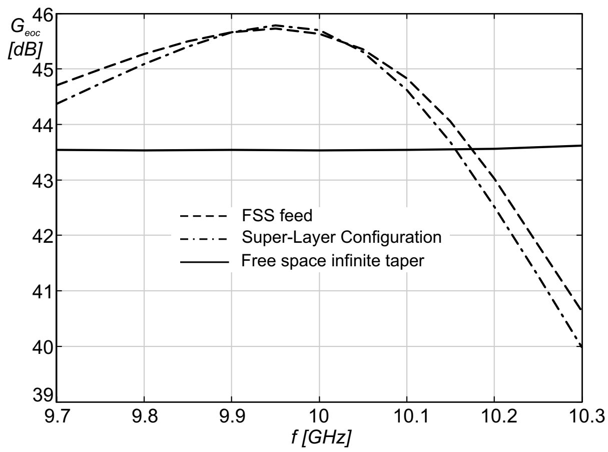

Fig. 7. Edge of coverage gain for the FSS feed considering a reflector with $F/D = 1.71$. The frequency $f = 10.05\ GHz$ is the last useful frequency before secondary and primary pattern degradations, as seen with the super-layer case.

IV. Conclusions and Future Work

This work continues a series of works on the use of dielectric super-layers to shape the radiation pattern of each feed composing a focal plane imaging array. Using dielectric super-layers the spill over from the reflectors are reduced without increasing the dimensions of each aperture. This effects are achieved when the inter-element distance between the feeds is large (2.4 wavelengths) which is typical for satellite based multi beam telecommunication applications. The shaping of the pattern is obtained with the excitation of a pair (TE/TM) of leaky waves, that radiate incrementally as they propagate between the ground plane and the super-layer. The super-layer can be realized with single dense dielectric slab ($\epsilon_r = 20.25$) a double dielectric slab ($\epsilon_r = 4.5$) or an equivalent frequency selective surface. The maximum edge of coverage enhancement, with respect to reference free space configuration, that can be obtained in the different cases is equivalent. However the bandwidth over which the enhancement is maintained depends on how the super-layer is realized. The calculated embedded patterns provide an increase of the edge of coverage gain, with respect to the free space case, of at least $1.5\ dB$ in an operating bandwidth of 3%.

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