Efficient Analysis and Flexible Design of 1D Leaky-Wave Antennas composed by a Parallel-Plate Waveguide loaded with two Metallodielectric FSS

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1. Introduction

2D Fabry-Perot Leaky-Wave Antennas (FPLWA) have been attracting much interest in the last years [1-3]. These antennas offer a simple solution to achieve highly directive patterns from a single point source by using Partially Reflective Surfaces (PRS). FPLWA are normally designed to radiate at broadside [1-3], although conical beam steering has also been proposed [4]. On the other hand, 1D LWA based on the introduction of a printed circuit inside a waveguide has been recently proposed [5-6]. In particular, this hybrid waveguide printed-circuit technology offers a flexible control of the propagating constant of the fundamental leaky-mode. This allows a flexible tapering of the radiation pattern, synthesizing any pointing angle, radiation efficiency and side lobes distributions [5-6]. In this paper, an original 1D FPLWA is proposed by the combination of these two concepts. This structure (shown in Fig1-a), consists of a parallel plate waveguide (PPW) loaded by two dipole-based Frequency Selective Surfaces (FSS) [1-3]. The first FSS is inserted inside the top of the PPW, and acts as a PRS [1-2]. The other FSS is located at the bottom of the PPW and is backed by a metal surface, behaving as an Artificial Magnetic Conductor (AMC) [3].

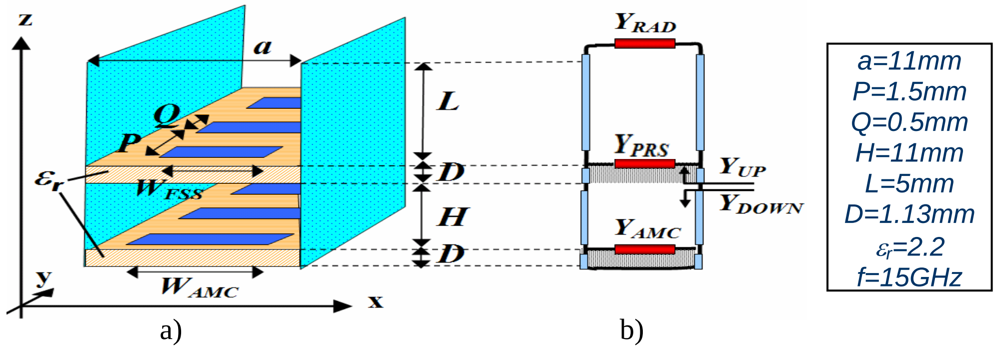

Fig.1-a) Scheme of the leaky-wave 1D structure b) Transverse Equivalent Network

2. Efficient Analysis

The analysis technique is based on a simple Transverse Equivalent Network (TEN) shown in Fig.1-b, which has been specifically developed for the efficient analysis of the TE leaky-modes supported by this structure. TEN analysis techniques have been widely used for the analysis of LWAs [4,7]. In our TEN, both the top PRS and the bottom AMC dipole-based FSS are characterized using the pole-zero matching method proposed by Maci in [7]. In this way, one can analytically express the equivalent admittances of the PRS and the AMC for a given geometry, which will be a function of frequency and the unknown leaky-mode wavenumber k_y ($Y_{PRS}(f,k_y)$ and $Y_{AMC}(f,k_y)$, Fig.1-b). In the same manner, the equivalent admittance of the top open-end of the PPW, $Y_{RAD}(f,k_y)$, can be analytically derived as a function of frequency and wavenumber using Marcuvitz closed-form expressions [8]. The rest of the elements of the TEN shown in Fig.1-b correspond to equivalent transmission line sections, which can easily be described using standard microwave network theory. According to the scheme shown in Fig.1-b, the Transverse Resonance Equation (TRE) can be expressed as:

$$Y_{UP}(f,k_y)+Y_{DOWN}(f,k_y)=0 \tag{1}$$

Notice that, due to the radiation boundary condition imposed by $Y_{RAD}(f,k_y)$, this guiding structure supports the existence of leaky-wave modal solutions, characterized by a complex longitudinal wavenumber (the longitudinal axis of the 1D LWA is the "*y*" axis, see Fig.1-a) of the form $k_y=\beta-j\alpha$. In this expression, β corresponds to the phase-constant (which determines the pointing angle of the LWA measured from broadside, θ_m, according to $\sin\theta_m=\beta/k_0$) and α stands for the leakage rate. With this fast and accurate leaky-mode analysis tool, it is demonstrated in the next section that this novel 1D LWA provides an interesting mechanism to control the radiation properties of TE leaky-modes, thus allowing for versatile designs and flexible synthesis of the LWA radiation patterns.

3. Flexible Design of the Radiation Pattern

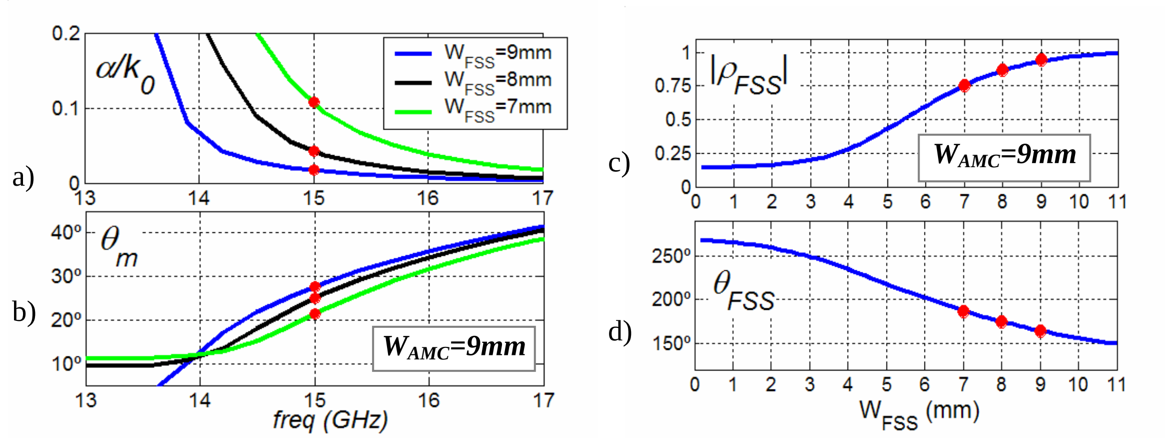

Fig.2- a-b) Frequency dispersion curves for different FSS c-d) Variation of the FSS response at *15GHz* as a function of its dipoles length, showing how the transparency of the PRS is controlled

Solving the TRE (1), one can plot the dispersion curves of the TE leaky-mode as a function of frequency for different FSS and/or AMC geometries. In our case, we use a dipole-type structure printed in a substrate of height $D=1.13mm$ and $\varepsilon_r=2.2$ for the top PRS and also for the bottom AMC. The periodicity of both dipole arrays is fixed to $P=1.5mm$ and the dipoles width to $Q=0.5mm$, so that the two variable parameters will be the dipoles' length, W_{FSS} and W_{AMC} (see Fig.1). The dimensions of the PPW are also fixed to $a=11mm$, $H=11mm$, $L=5mm$, and the frequency of interest is *15GHz*. Fig.2 shows the frequency dispersion curves, illustrating how the pointing angle θ_m (Fig.2-a) and the normalized leakage rate α/k_0 (Fig.2-b) of the main TE leaky-mode are varied when the top FSS dipoles' length W_{FSS} changes among three different values (*9mm, 8mm* and *7mm*), while keeping W_{AMC} constant to *9mm*. Fig.2-c shows the response of the reflection coefficient presented by the PRS at $f=15GHz$, as W_{FSS} is swept from *0mm* to *11mm*. As it can be seen in Fig.2-c, the top FSS becomes more transparent (lower values of $|\rho_{FSS}|$) as W_{FSS} is decreased. This allows the leakage rate at *15GHz* to increase from $\alpha/k_0=0.017$ to $\alpha/k_0=0.108$ as W_{FSS} is decreased from *9mm* to *7mm* (see curves of α/k_0 at 15GHz in Fig.2-a).

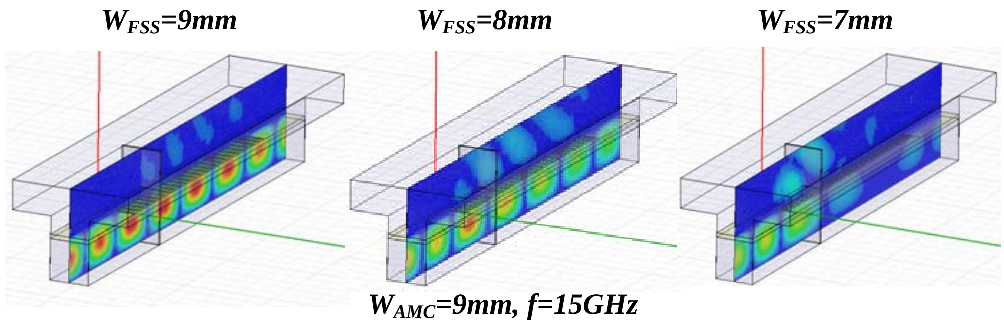

Fig.3-Near propagating and radiating TE leaky-fields for different transparencies of the top FSS

This phenomenon is also qualitatively illustrated by the near field patterns shown in Fig.3, which are obtained at *15GHz* for the proposed 1D LWA with a length $L_A=4\lambda_0$, using a commercial Finite Element Method electromagnetic solver (HFSS©). As it can be seen, the structure with $W_{FSS}=7mm$ induces a higher radiating TE electric field at the top aperture and thus, the field that reaches the far end of the PPW is lower than for the case of $W_{FSS}=9mm$. With all these results, it is demonstrated that the transparency of the top FSS acting as a PRS allows to control the leakage-rate of the TE leaky-mode. It is worth remembering that the leaky-mode radiation-rate α/k_0 allows to determine the radiation efficiency η_{RAD} of a LWA following the well-known expression [9]:

$$\eta_{RAD} = 1 - e^{-4\pi \frac{\alpha}{k_0}\frac{L}{\lambda_0}} \tag{2}$$

Also, for a given LWA length L_A, one can determine the beamwidth in the elevation plane $\Delta\theta$, which can be related to α/k_0 for a 90% efficiency LWA as [9]:

$$\Delta\theta \cong \frac{1}{\frac{L_A}{\lambda_0}\cos\theta_m} \approx \frac{\alpha_y / k_0}{0.183\cdot\cos\theta_m} \tag{3}$$

Therefore, the control of the leaky-mode radiation-rate in a wide range is of key importance to design a LWA with high radiation efficiency and any desired beamwidth or directivity [9]. With the proposed 1D-LWA, this can be easily done by properly designing the length of the dipoles of the top FSS. However, as it can be seen in the curves of θ_m in Fig.2-b, a second-order effect happens when the top FSS varies: the pointing angle is shifted from $\theta_m=27^o$ to $\theta_m=21^o$ (at the design frequency of *15GHz*) as W_{FSS} is decreased. This change in θ_m is due to the variation of the reflection phase of the FSS (θ_{FSS}) when W_{FSS} is modified, which is also illustrated in the curve of θ_{FSS} plotted in Fig.2-d.

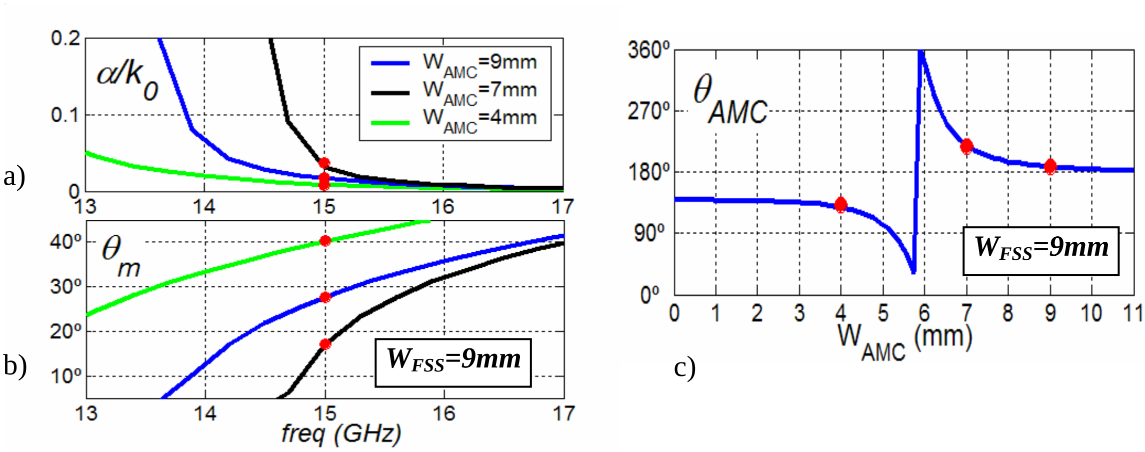

Fig.4- a-b) Frequency dispersion curves for different AMC c) Variation of the AMC response at *15GHz* as a function of its dipoles length, showing how the reflection phase of the AMC is controlled

In order to control and tune the pointing angle of the TE leaky-mode, one can modify the AMC dipoles' length, W_{AMC}. Fig.4-a and Fig.4-b show the frequency dispersion curves for three different values of W_{AMC} (*9mm*, *7mm* and *4mm*), while keeping W_{FSS} constant *(9mm)*. It is illustrated how α/k_0 is barely modified at the design frequency (*15GHz*), while the pointing angle can be tuned from $\theta_m=17^o$ to $\theta_m=40^o$ as W_{FSS} is varied. This change in θ_m is due to the dependence of the reflection phase of the AMC (θ_{AMC}) with W_{AMC}, as it is shown in Fig.4-c. The AMC behaves very similar as a perfect conductor ($\theta_{AMC}\approx180^o$) when $W_{AMC}=9mm$. In the case $W_{AMC}=7mm$, the AMC has a higher reflection phase ($\theta_{AMC}=218^o$, see Fig.4-c), making the resonant cavity be smaller and therefore reducing the pointing angle from $\theta_m=27^o$ to $\theta_m=17^o$ (see Fig.4-b). On the contrary, for $W_{AMC}=4mm$, the AMC presents a lower reflection phase ($\theta_{AMC}=135^o$, Fig.4-c), thus increasing the radiation angle to $\theta_m=40^o$ (Fig.4-b). For all these cases, it is seen in Fig.4-a how the leakage rate is barely affected. A deeper discussion on how to independently control θ_m and α/k_0 will be given in the presentation.

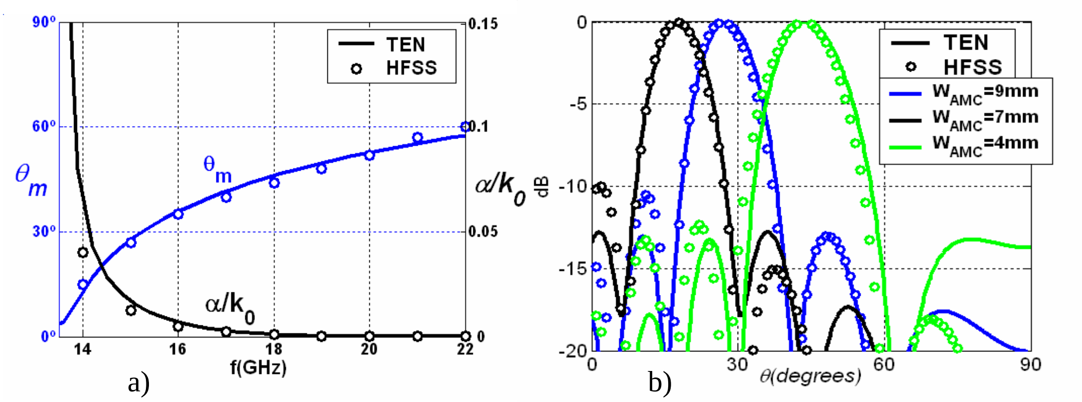

Fig.5- a) Validation of frequency dispersion curves for $W_{FSS}=9mm$ and $W_{AMC}=9mm$ b) Normalized radiation patterns in the elevation plane of the LWA with $L_A=4\lambda_0$ at *15GHz* for different AMC

Finally, the frequency dispersion of the proposed LWA with $L_A=4\lambda_0$, $W_{FSS}=9mm$ and $W_{AMC}=9mm$ is validated by comparing with HFSS results in Fig.5-a. Excellent agreement is observed, thus validating the results obtained with the simple TEN shown in Fig.1-b. The common frequency-beam steering response of a LWA is observed in Fig.5-a [9]. For the fixed design frequency of *15GHz*, the AMC dipoles lengths are given three different values (*9mm*, *7mm* and *4mm*) as it was described in the previous section, obtaining the radiation patterns in the elevation plane shown in Fig.5-b. As it was predicted by the leaky-mode, the pointing angle θ_m of the proposed LWA can be easily controlled in a wide range of scanning angles by only varying the AMC dipoles lengths. Very good agreement is again obtained when comparing with full-wave FEM results obtained with HFSS. This structure offers an original mechanism to control the radiation pattern of the PPW leaky-wave when compared to the one proposed in [4-5] and it is directly extensible to 2D PRS-LWA [1-3]. In addition, the proposed technology has the advantage that this flexible control of the radiation pattern might be electronically performed by just inserting varactor diodes in the two metallodielectric FSS, in order to modify the effective length of the constituent dipoles.

Acknowledgments

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