Efficiently Illuminated Broadside-Directed 1D and 2D Tapered Fabry-Perot Leaky-Wave Antennas

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Abstract—**The study of Fabry-Perot leaky-wave antennas which are properly tapered to optimize their directivity at broadside, is presented in this work. For this purpose, a careful synthesis of the complex aperture illumination (amplitude and phase) induced by the radiating leaky mode is for the first time employed in the synthesis of this type of antennas. The study commences from the one-dimensional (1D) fan-beam Fabry-Perot antennas and extends to two-dimensional (2D) pencil-beam Fabry-Perot antennas. Theoretical and simulated results are reported, illustrating an increase in the antenna directivity at broadside direction in the order of 2dBs for the 1D case, and of 4dBs for the 2D case.**

Keywords- Fabry-Perot antennas, tapered leaky-wave antennas, aperture illumination efficiency, directivity optimization

I. INTRODUCTION

Fabry-Perot leaky-wave antennas (FP LWAs) provide highly directive radiation patterns from a single low-directive source embedded inside the FP cavity [1-3]. Thus, FP LWAs become a very attractive solution when compared to externally fed antenna systems (such as reflector, lenses or reflectarrays), and also when compared to arrays, which need much more complicated feeding networks, such as phased arrays. The directivity of any large-aperture radiator can be maximized if the aperture efficiency is optimized; this aspect has been very much considered for all above antenna systems (reflectors, lenses, reflectarrays, and arrays) and several leaky wave antenna configurations. However, to the authors' knowledge, a detailed analysis and systematic synthesis of prescribed aperture distributions on FP LWAs designs has not been performed so far. Following the leaky-wave antenna (LWA) perspective of FP LWAs' radiation mechanism [4-6], here we propose the tapering of the leaky wave to increase the aperture efficiency. The proper tapering of the leaky propagation constant ($k = \beta - j\alpha$) along the FP cavity allows to tailor the amplitude and phase of the fields illuminating the radiating aperture, and hence, the synthesis of the corresponding radiation pattern. This technique has been successfully applied in one-dimensional (1D) [7,8] and two-dimensional (2D) [9] LWAs, but this is the first time that it is applied to optimize broadside radiation from FP LWAs. In order to have simultaneous and independent control over the leaky-mode phase constant (β) and leakage rate (α), we employ the FP structure with two periodic layers proposed in [2,4-6] (see Fig.1). The PCB located at the top of the FP cavity acts as partially-reflective surface (PRS) [3], and consists of a metallic sheet periodically perforated with slots (see Fig. 1). As explained in [5], this PRS provides the control over α by modifying the length of its resonant slots (L_{PRS}, shown in Fig. 1). A second grounded PCB is located at the bottom of the FP cavity, and consists of a dipole array printed on a thin substrate which acts as a high impedance surface (HIS) [2]. This HIS primarily controls β by modifying the length of its resonant dipoles L_{HIS} [5]. Both 1D and 2D topologies shown in Fig. 1 are analyzed and designed in this contribution.
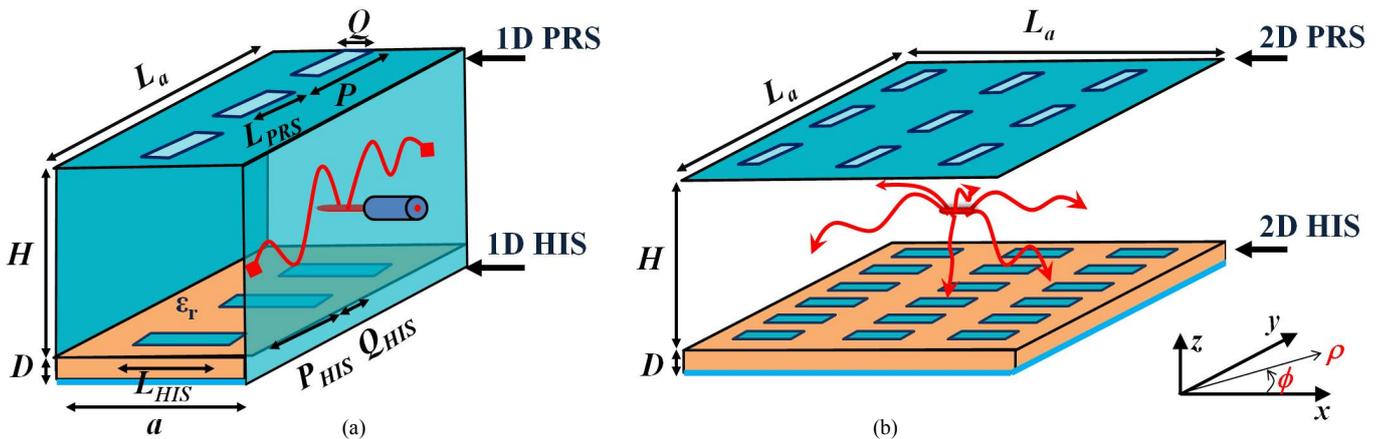

Figure 1. Scheme of (a) 1D and (b) 2D Fabry-Perot Leaky-Wave Antennas with planar PRS and HIS (Dimensions: H = 10mm, $a = P$ = 8.5 mm, D =1.13mm, Q = 3mm, P_{HIS} = 1.7mm, Q_{HIS} = 0.5mm, ε_r = 2.2).

II. 1D Fabry-Perot LWA

Although most of 1D LWAs have been used to scan in the elevation plane [5,7,8], recently there is an increased interest on the study of 1D LWAs which are symmetrically fed from its center position, and which present optimized broadside radiation when the leaky-mode satisfies the *splitting condition* ($\beta = \alpha$) [10-16].
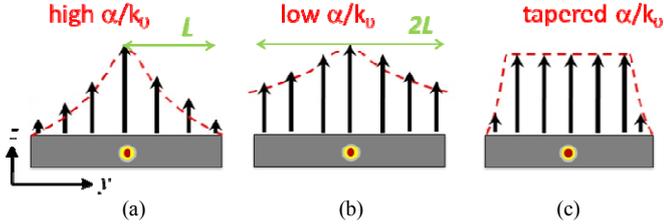

Figure 2. Aperture illumination for 1D LWAs, (a) and (b) are non tapered, (c) is tapered.

In non-tapered antenna designs, one can only choose a higher or a lower value of α/k_0 which is kept constant along the whole LWA length, as sketched in Fig. 2(a) and 2(b). These non-tapered examples clearly show that the illumination of the radiating aperture becomes more uniform when α/k_0 is lowered [Fig. 2(b)]. Therefore, the reduction of α/k_0 could be considered as a first approach to improve the aperture efficiency (η_{AP}) of a FP LWA. However, when α/k_0 is decreased, more guided energy reaches the LWA far ends, as it can be seen in Fig. 2(b). Two possible solutions have been proposed to deal with this non-radiated power: *1)* to place matched loads at the antenna's edges to absorb it [12-15], or *2)* to use open or short circuited terminations [10,11]. In the first case, the radiation efficiency ($\eta_{RAD} = 1 - e^{-2\alpha L}$) falls as η_{AP} is increased (*i.e.*, as α/k_0 is decreased). As demonstrated in [15], the theoretical compromise gives an ideal maximum normalized gain factor $\eta_{RAD} \times \eta_{AP} = 0.73$ when $\eta_{RAD} = 0.87$ and $\eta_{AP} = 0.84$. If the second solution if employed, the open or short circuits may create a standing leaky-wave [10,11], which further reduces the aperture efficiency (as it corresponds to a cosine-type illumination), and it also creates diffraction lobes due to the strong discontinuity at the edges. This compromise between radiation and aperture efficiency can be overcome if the leakage rate is tapered along the LWA length, so that uniform illumination with ideal $\eta_{AP} = 1$ can be theoretically achieved whilst keeping radiation efficiency as high as possible, as depicted in Fig. 2(c). Typically $\eta_{RAD} \leq 0.9$ is pursued, to avoid too high values of α at the last sections of the tapered LWA [7]. The value of $\alpha(y)$ at any longitudinal position of the antenna that provides the desired field distribution along the LWA aperture can be found using the well-known expressions in [7,16]. The same tapering function is applied to the leaky wave phase constant $\beta(y)$, so that the *splitting condition* $\beta(y) = \alpha(y)$ [10-16] is satisfied at any longitudinal position z of the antenna and broadside radiation is optimized along the whole LWA with length L in each one of the two directions. The red dashed line in Fig. 3 shows the tapered value of $\beta/k_0 = \alpha/k_0$ obtained for a symmetric 1D LWA with $L = 3\lambda_0$ and $\eta_{RAD} = 0.85$, together with three different cases of non-tapered antennas. As the red dashed line in Fig. 3 shows, low leakage is required at the centre of the

antenna (where the source is placed). The value of α/k_0 increases as the edges of the LWA are reached, compensating the natural exponential decay of the leaky-wave. This tapered value of $\beta/k_0 = \alpha/k_0$ is provided along the LWA length by modifying the length of the resonant elements in the periodic layers, as shown in Fig. 4. The blue dotted line in Fig. 4 shows that the slots in the PRS are short in the centre of the antenna, providing the required low leakage close to the feed. Their lengths increase as we move towards the edges, allowing the requested increase of α. In order to satisfy the splitting condition at each point of the LWA length (*i.e.*, to achieve the corresponding variation of $\beta = \alpha$), the lengths of the dipoles in the HIS must also be varied, as the red continuous line in Fig. 4 shows. The tapered design with the central coaxial feeding is shown in Fig. 5. The lengths of the slots in Fig. 5(b) and the dipoles in Fig. 5(c) correspond to the synthesized dimensions depicted in Fig. 4.
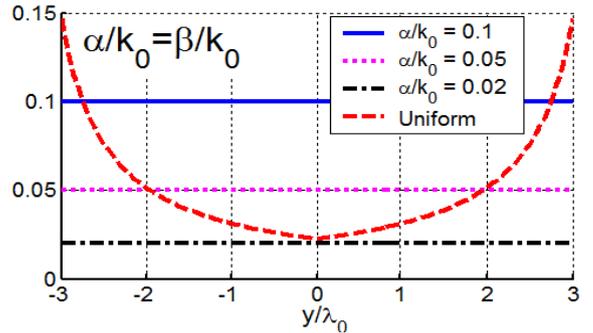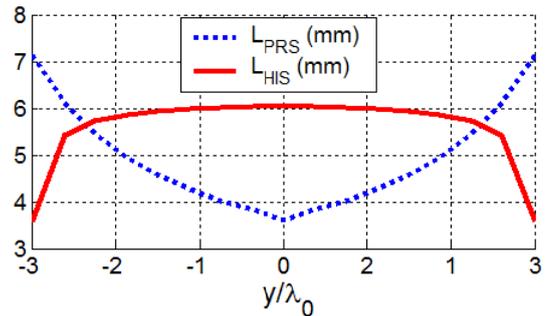

Figure 3. Tapering function for 1D LWAs.

Figure 4. Synthesized length of the slots in the PRS (L_{PRS}) and length of the dipoles in the HIS (L_{HIS}) which provides the tapered illumination of Fig. 3.

The normalized radiation patterns obtained with *HFSS* for the cases exposed in Fig. 3 are plotted in Fig. 6. As it corresponds to 1D LWAs, the patterns in Fig. 6 characterize fan-beams; the main beam is narrow in the H-plane [Fig. 6(a)] and wider in the E-plane [Fig. 6(b)]. The main differences between the four cases under study can be clearly identified in Fig. 6(a), regarding beamwidth, sidelobe level and diffraction level [measured at ±90º from the broadside direction in the H-plane of Fig. 6(a)]. The main concluding results are summarized in Table I. As previously explained, the case of lowest leakage rate ($\alpha/k_0 = 0.02$) provides the highest aperture efficiency $\eta_{AP} = 99.6\%$. However, this is at the expense of the lowest radiation efficiency ($\eta_{RAD} = 53\%$) and the highest diffraction level (-21dB) when compared to higher constant values of $\alpha/k_0 = 0.05, 0.1$ (which are worse in the sense of

aperture efficiency but present higher radiation efficiency and lower diffraction level). As explained before, the highest diffraction is due to higher energy reaching the LWA edges discontinuity (in this case it is a radiating open end), as a result of the lower radiation efficiency η_{RAD}. All these facts affect the directivity, which reaches a maximum value of $D = 11.63$dBi for the non-tapered design with constant $\alpha/k_0 = 0.05$. On the contrary, the 1D FP LWA with tapered $\alpha(y)$ makes available a directivity of $D = 13.15$dBi. This is possible thanks to very high aperture efficiency $\eta_{AP} = 0.98$ as a result of the more uniform illumination, while it is kept very high radiation efficiency ($\eta_{RAD} = 0.85$). Also, the simulated sidelobe level (SLL) is reported in Table I for each case, observing how the SLL increases as the aperture is more uniformly illuminated, tending to theoretical -13dB for perfect uniform illumination.
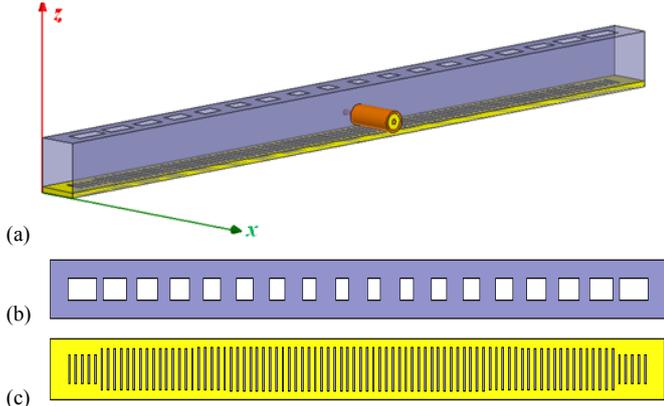
TABLE I.   DIRECTIVITY ENHANCEMENT IN H-PLANE OF 1D FP LWAs

CASE	D(dBi)	η_{AP}	η_{RAD}	Diffraction	Sidelobe
$\alpha/k_0 = 0.1$	11.15	60.8%	97.7%	-40 dB	-29 dB
$\alpha/k_0 = 0.05$	11.63	88.4%	85%	-30 dB	-25 dB
$\alpha/k_0 = 0.02$	11.02	99.6%	53%	-21 dB	-15 dB
Tapered α/k_0	13.15	98%	85%	-25 dB	-14 dB

III. 2D FABRY-PEROT LWA

Two-dimensional FP LWAs have recently become increasingly popular for the high-directive pencil beams radiating at broadside. These can be attributed to a cylindrical leaky wave from a single point source [17]. However, they usually present very narrow bandwidth and low aperture efficiency due to the high quality factor of the resonator. Improved bandwidth is obtained when the PRS reflectivity is decreased at the cost of reducing the illumination efficiency [18]. Multiple fed FP LWAs have also been proposed to increase the bandwidth and illumination efficiency at the expense of a much more complex array feeding network [19,20], losing one of the most interesting features of FP LWAs which is their simple feeding scheme. The use of double-layer PRS with slightly different resonant frequencies can extend the bandwidth; however, the reported gain and aperture efficiency were deficient [21,22]. The use of step-sized HIS (also known as compound FP LWAs [23,24], or tapered AMC LWAs [25]) has been proposed to increase the gain-bandwidth product and the associated aperture efficiency. However, the tapered designs presented in [23-25] relied on full-wave simulations of the whole antenna, and an efficient technique to design the tapered dimensions of the HIS has not been proposed so far. Recently, a design procedure has been suggested for spiral circularly polarized LWAs based on modulated surface impedance [26]. In this contribution, we present for the first time a systematic approach to design tapered 2D FP LWAs, in which both periodic layers (PRS and HIS) are modulated to obtain high aperture efficiency while assuring pencil-beam broadside radiation.

The approximate expression given in [9] is employed to obtain the requested tapering of the cylindrical leaky-wave leakage rate as a function of the radial distance ρ, imposing again the *splitting condition* $\beta(\rho) = \alpha(\rho)$. As it was proceeded in the 1D case, the geometry of both periodic PRS and HIS layers is now synthesized in order to achieve the desired leaky-mode complex propagation constant at each point of the antenna (Fig. 7 shows the dimensions of the PRS slots and the HIS dipoles for a tapered $10\lambda_0 \times 10\lambda_0$ LWA). As the blue dotted line in Fig. 7 shows for $L_{PRS}(\rho)$, the PRS slots are widened as we move far from the antenna center feed. This is needed to exponentially increase the leakage rate, so that both the cylindrical dispersion and the exponential energy drop are compensated, and quasi-uniform illumination is obtained across the whole antenna aperture. At the same time, the HIS dipoles lengths $L_{HIS}(\rho)$ must be complementarily tapered, so that the phase variations introduced by the PRS modulation are compensated, and the *splitting condition* is satisfied at any antenna aperture position. The modulation of the HIS dipoles lengths is plotted with red continuous line in Fig. 7.

Figure 5. Tapered 1D FP LWA (a) 3D model with central coaxial feeding (b) Tapered 1D slotted-based PRS, (c) Tapered 1D dipole-basded HIS.
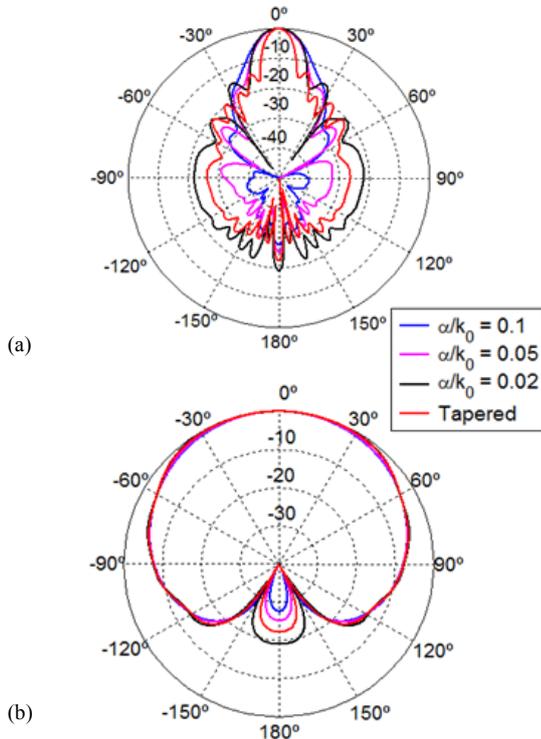
Figure 6. Normalized radiation patterns in dB of 1D FP LWAs (a) H-plane (b) E-plane.

It must be noticed that the tapering of 2D LWAs is a much more complicated task than the one performed for the 1D case, not only due to the cylindrical nature of the leaky-wave, but also due to the hybrid polarization of the radiating leaky-wave. Certainly, the *y*-polarized field can be considered as a TE wave when propagating in one of the main transverse axis [*x*-axis, ϕ = 0º in Fig. 1(b)], a TM wave when propagating in the complementary axis [*y*-axis, ϕ = 90º in Fig. 1(b)], and a combination of both polarizations for any other transverse direction and azimuthal angle ϕ [17].
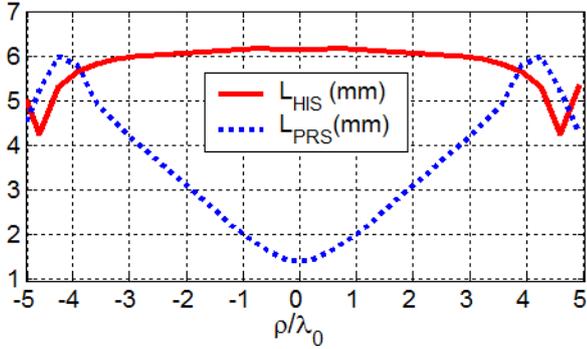

Figure 7. Synthesized length of the slots in the PRS (L_{PRS}) and length of the dipoles in the HIS (L_{HIS}) which provides a tapered quasi-uniform illumination in a 2D FP LWA.
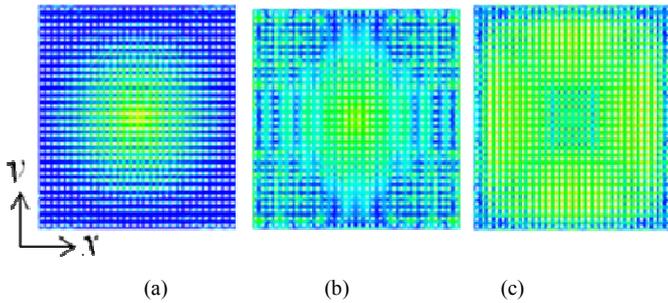

(a) (b) (c)

Figure 8. Aperture illumination in 2D FP LWAs (a) α/k_0 = 0.07 (b) α/k_0 = 0.015 (c) tapered $\alpha(\rho)$

Fig. 8 illustrates the near-field aperture illumination for three cases of 2D FP LWA with dimensions $10\lambda_0 \times 10\lambda_0$: the first case is a non-tapered LWA with high leakage-rate (α/k_0 = 0.07), the second non-tapered case presents lower rate (α/k_0 = 0.015), and the third case is a tapered design with quasi-uniform illumination and η_{RAD} = 90%. As it can be easily seen from the aperture fields, the most uniform distribution is obtained for the tapered case. The non-tapered case with leakage rate 0.07 provides simple exponential illumination with very poor aperture efficiency (η_{AP} = 24.3%) and therefore low directivity (D = 23.8dBi while the maximum achievable directivity is 29.9dBi). Negligible diffraction lobes are obtained as a result of the high η_{RAD} = 98%. The non-tapered scenario with leakage rate 0.015 illuminates better the antenna surface, but it suffers from distortion of the aperture field as a consequence of the standing waves created by the low amount of radiated energy (η_{RAD} = 61%), and therefore high amount of guided energy reaching the edges of the antennas [27,28]. The nulls and maxima associated to the standing wave can be clearly appreciated surrounding the

aperture centre in Fig. 8(b). As a result, the directivity is increased by only 2.3dB when compared to the nontapered case with higher leakage, obtaining D = 26.45dBi and η_A = 44.7%. However, the diffraction level strongly increases from below -40dB up to -18dB, as summarized in TableII. As in the 1D case, the tapered solution gives the best balance, providing η_{AP} = 73.2% and η_{RAD} = 90%, resulting in the highest directivity (D = 28.6dBi), and keeping low diffraction levels (below -30dB).

TABLE II.   DIRECTIVITY ENHANCEMENT IN 2D FP LWAs.

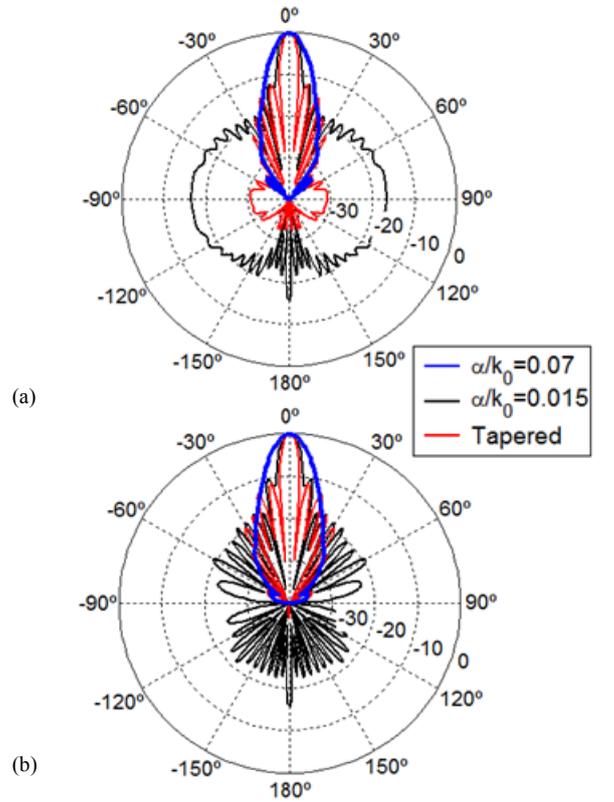| CASE	D(dBi)	η_{AP}	Diffraction
α/k_0 = 0.07	23.8	24.3%	-40dB
α/k_0 = 0.015	26.1	44.7%	-18dB
Tapered α/k_0	28.6	73.2%	-30dB

(a)

(b)

Figure 9. Normalized radiation patterns in dB of 2D FP LWAs (a) H-plane (b) E-plane.

The previous results are summarized in Table II, and the normalized radiation patterns in both H and E planes are plotted in Fig. 9. In contrast to the fan-beam patterns shown in Fig. 6, the main lobes in Fig. 9 are pencil beams, as it corresponds to a 2D FP LWAs. The previous numerical results are in coherence with these radiation patterns. It can be clearly checked in both Fig. 9(a) and (b) that among the three studied LWAs, the tapered case provides both narrow beamwidth and low diffraction, thus validating the validity of the proposed tapering technique.

IV. CONCLUSIONS

The optimization of the aperture illumination efficiency in 1D and 2D Fabry-Perot leaky-wave antennas, is studied in this paper. A quasi-uniform taper is proposed in order to achieve high aperture efficiency, while assuring high radiation efficiency to minimize diffraction and standing waves. Also, the splitting condition must be satisfied in all radiating sections of the LWA to obtain the highest directivity at broadside. In particular, the proposed technique is applied in the case of 1D and 2D LWAs loaded with a slotted-based partially-reflective surface (PRS) and a dipole-based high impedance surface (HIS). It has been illustrated with various numerical examples how the proper modulation of the PRS and HIS surfaces makes possible to increase the directivity of this type of resonant antennas in a totally novel manner, to the authors' knowledge. Study of the impact in the antenna bandwidth will be carried out in the near future.

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