Printed-Circuit Leaky-Wave Antenna With Pointing and Illumination Flexibility

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***Abstract*—A novel leaky-wave antenna, based on a periodic set of slots printed on a rectangular dielectric waveguide is conceived in this work. The antenna presents the ability to independently control the aperture illumination and the pointing direction, by only modifying the photoetched printed-circuit layout. The working mechanism is described using a leaky-mode dispersion analysis, and cosine-tapered designs are performed at 50 GHz. The radiation patterns are obtained using HFSS analysis to check the reduction of sidelobes levels, and the capacity to tune the pointing direction over a wide range of elevation angles.**

***Index Terms*—Leaky-wave antennas, millimeter-wave antennas.**

I. Introduction

RECENTLY, a hybrid printed-circuit dielectric-waveguide technology has been proposed to conceive tapered leaky-wave antennas (LWA) for millimeter waveband applications [1]. In this technology, the originally nonradiative host dielectric guide becomes a leaky structure when a printed circuit is asymmetrically added in the dielectric-air interface. This technology also allows to taper the aperture illumination by modulating the planar circuit dimensions, leading to a reduction of the sidelobes level. A scheme of a slot-circuit tapered LWA is shown in Fig. 1(a). This type of antennas is mechanically easy to realize, since the slot dimensions are the only responsible for the antenna illumination. By interchanging different layouts over the same host guide, one can design a specified low-sidelobes radiation pattern, as demonstrated in [1]. However, the pointing direction of the LWA is mainly controlled by the dispersive frequency response of the TE_{10} mode of the host dielectric guide [1]. The only way to control the pointing angle of the LWA at a fixed frequency is by modifying the host guide dimensions [basically, the dielectric slab width a, see Fig. 1(a)]. In this work, a modification of this antenna is proposed. The new antenna makes use of a periodic set of slots printed on the dielectric guide [see Fig. 1(b)]. By adjusting the periodicity P of the printed layout, the pointing direction of the antenna can be adjusted, without losing the ability to taper the aperture illumination.

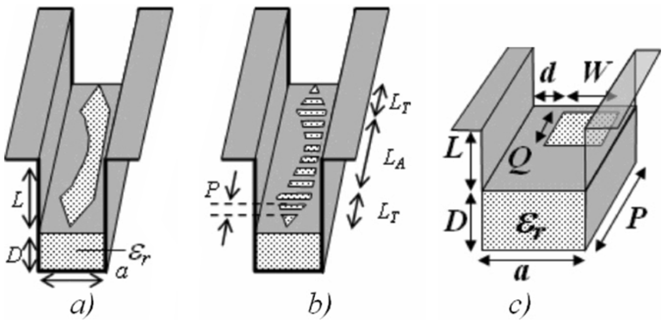

Fig. 1. Hybrid printed-circuit dielectric-waveguide leaky-wave antennas (a) uniform, (b) periodic, and (c) unit cell.

II. Theory and Results

When the printed slot is modified from the uniform [Fig. 1(a)] to the periodic layout [Fig. 1(b)], the set of space-harmonics are excited in the periodic structure [2]. The propagation constant of the $m = -1$ space-harmonic can be described in complex form if this harmonic is radiating, as it corresponds to a leaky-wave

$$k_{-1} = \beta_{-1} - j\alpha = \left\{\beta_0 - \frac{2\pi}{P}\right\} - j\alpha \quad (m^{-1}) \tag{1}$$

where β_0 is the bloch-wave phase constant and α is the leakage rate. For the antennas shown in Fig. 1, β_0 is mainly determined by the waveguide width a, since the bloch-wave is the perturbation of the TE_{10} mode of the host dielectric waveguide. Conversely, the phase constant of the $m = -1$ space-harmonic, β_{-1}, can be modified by changing the printed-circuit periodicity P $(\beta_{-1} = \beta_0 - 2\pi/P)$. The $m = -1$ harmonic radiates if its phase constant satisfies the radiation condition [2], given by

$$\left|\frac{\beta_{-1}}{k_0}\right| < 1 \tag{2}$$

where k_0 stands for the free-space wavenumber. In this case, the angle of maximum radiation θ_m is given by the next equation

$$\theta_m = \arcsin\frac{\beta_{-1}}{k_0}. \tag{3}$$

The elevation pointing angle θ_m is measured from the broadside direction, and it can have either positive or negative values, depending on the frequency of operation. As the frequency is increased, θ_m moves from the backward to the forward quadrant, leading to the well-known backward to forward frequency

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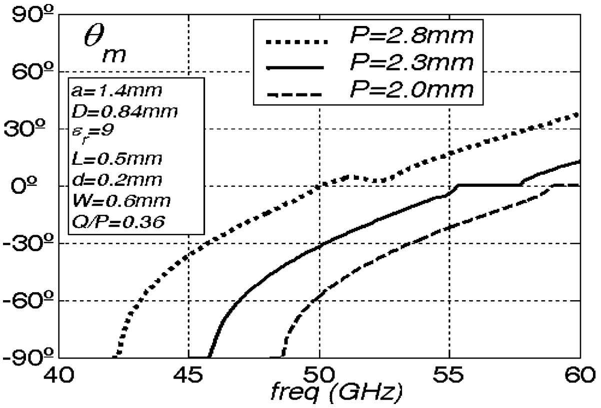

Fig. 2. Slitted PLWA millimeter waveband frequency-scanning response for different periodicities.

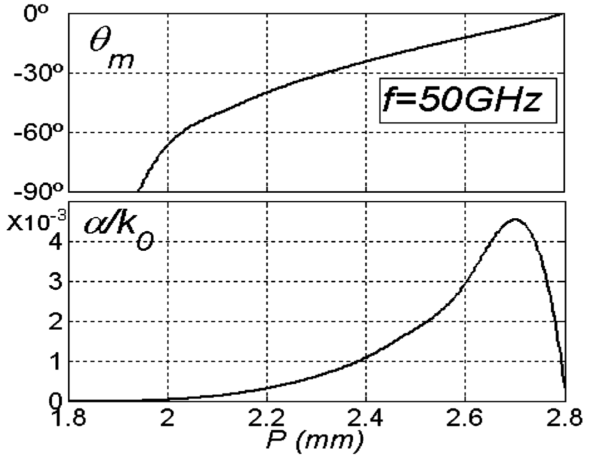

Fig. 3. Dependence of θ_m and α/k_0 at 50 GHz with P for the slitted PLWA (Q/P =0.36).

scanning response inherent to any periodic leaky-wave antenna (PLWA) [2].

A moment method accurate leaky-mode analysis method [3], specifically conceived for the type of structures shown in Fig. 1, has been applied to obtain the complex leaky-wave propagation constants. By applying periodic boundary conditions, the unit cell shown in Fig. 1(c) is analyzed to obtain the dependence of θ_m and α with the frequency, and with the different geometrical parameters.

Fig. 2 shows the frequency response of θ_m for the proposed slitted PLWA shown in Fig. 1(b), and for different values of P. The values of the rest of geometrical parameters, according to Fig. 1(c), are summarized in the inset of Fig. 2. It can be seen how the response is shifted to lower frequencies as the periodicity is increased. This phenomenon explains how, at a fixed frequency, the pointing angle can be increased by using a larger value of P. As an example, Fig. 3 shows the variation of θ_m at 50 GHz for the same dimensions of the PLWA in Fig. 2, as a function of P. In this analysis we use a constant normalized slot length ($Q/P = 0.36$), and a linear dependence is obtained from $\theta_m = -60^\circ$ to $\theta_m = 0^\circ$. The backward quadrant has been chosen to avoid the interference of higher-order radiating space-harmonic, which commonly occurs in the forward quadrant [2]. Also the variation of the normalized leakage rate, α/k_0, is plotted. As it is well-known, α/k_0 decreases as the leaky-mode reaches the endfire direction ($\theta_m = -90^\circ$).

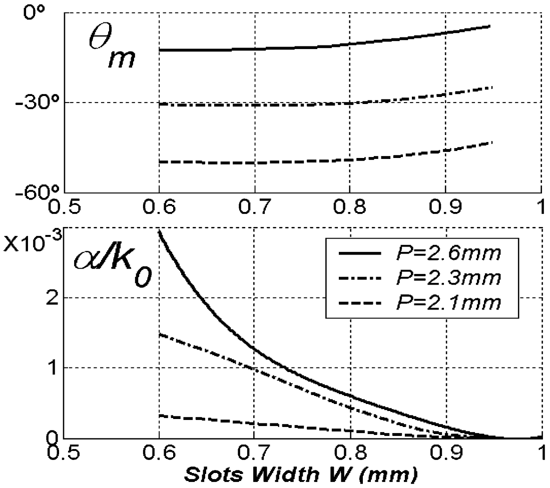

Fig. 4. Dependence of θ_m and α/k_0 at 50 GHz with the slot width for different values of P ($Q/P = 0.36$), with d =0.2 mm.

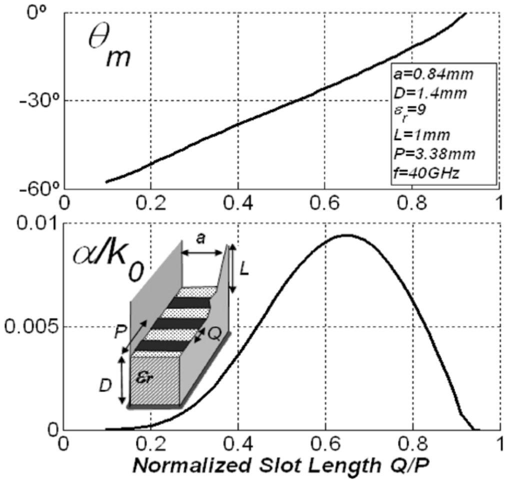

Fig. 5. Control of the leakage rate in conventional PLWA.

Different technologies have been applied to conceive PLWA which present the same pointing-control behavior, as the microstrip [4], the dielectric grating [5], the strip-loaded dielectric slab [6] and the dielectric-inset waveguide [7]. However, the main contribution of the proposed antenna is that the leakage rate can also be controlled by using the same asymmetry radiation principle demonstrated in [1] for nonperiodic LWA. This control is performed by adjusting the asymmetry level, and it can be done for any value of P. Fig. 4 shows how α/k_0 is varied from zero to a maximum value, when the slots width W is modified. Analogous responses can be obtained by modifying the slot position d. Three values of P have been selected, which result in three different pointing directions at 50 GHz according to Fig. 3. In this way, α/k_0 can be controlled without affecting the pointing direction θ_m.

This leakage control mechanism is the main novelty with respect to other PLWA [6], [7] which were based on slots printed along the whole width of the host dielectric waveguide ($W = a$). An example is given in Fig. 5, where the control of α/k_0 for the dielectric-inset PLWA proposed in [7] is illustrated.

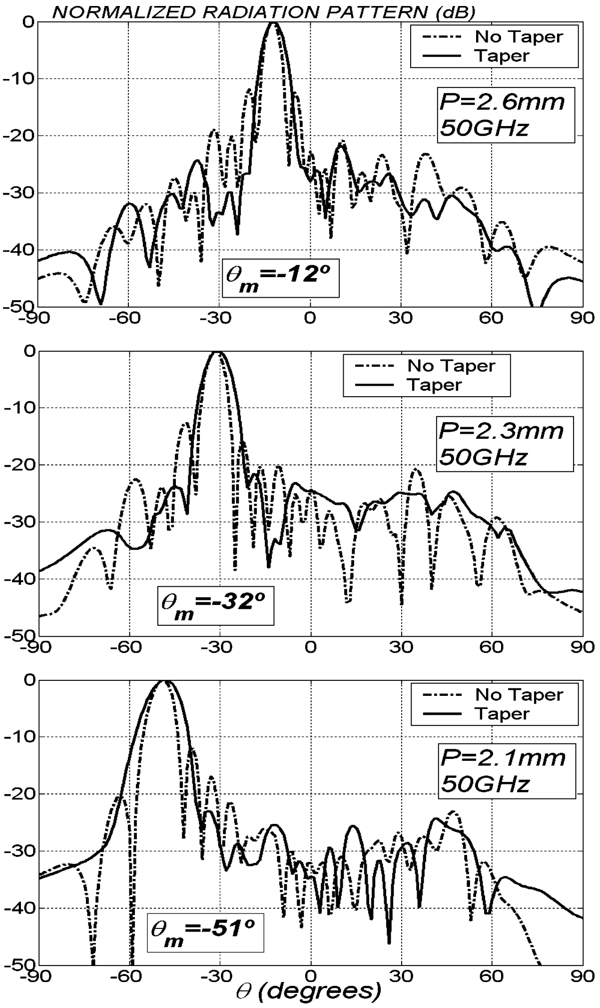

Fig. 6. Normalized radiation patterns obtained with HFSS, demonstrating the ability to control θ_m and the sidelobes level.

In all previously proposed tapered printed-circuit PLWA, α/k_0 could only be controlled by modifying the slot length Q. As it can be seen in Fig. 5, this process has a strong effect in the pointing direction of the PLWA. In order to keep θ_m constant for all the values of α/k_0, the period P must also be varied for the different values of Q. This tapering procedure is much more complicated than in the case of the new printed-circuit PLWA, where P need not be modified to make the taper.

To validate the mentioned ability to independently and easily control the pointing direction and the aperture illumination, three different designs have been performed. All of them work at 50 GHz and use the same host dielectric waveguide than in previous figures ($a = 1.4$ mm, $D = 0.84$ mm, $\varepsilon r = 9$, $L = 5$ mm). The length of the antennas is $L_A = 10\lambda_0$. The periodicity P has been selected to radiate at three different θ_m, which cover a wide range of pointing directions. As it was illustrated in the leaky-mode dispersion curves of Fig. 4, the slots widths can be modified along the antenna length to vary the leakage rate α/k_0 while barely affecting θ_m. The small phase aberrations in θ_m which can be seen in Fig. 4 are corrected by readjusting the slots position [parameter d in Fig. 1(c)] [1]. In this way, one can obtain the variation of the layout dimensions (W and d) along the antenna length to obtain a tapered cosine illumination in the antenna aperture for any pointing direction (selected with P).

The layouts designed with the leaky-mode analysis approach were introduced in a commercial electromagnetic analysis tool (*HFSS*). The results obtained for the normalized radiation patterns are plotted in Fig. 6. The control of the pointing direction is confirmed, obtaining the values predicted by the leaky-mode analysis ($\theta_m = -12^\circ$, -32° and -51° for $P = 2.6$ mm, 2.3 mm, and 2.1 mm, according to Fig. 3). Both the tapered and the nontapered antennas were analyzed to check the reduction of the sidelobes level due to the cosine illumination. It can be seen in Fig. 6 that the sidelobes are reduced from 13 dB to below 20 dB in all cases. Tapered transitions of length $L_T = 2\lambda_0$ [see Fig. 1(b)] were added at the edges of the printed-circuit to reduce reflections.

III. CONCLUSION

The proposed antenna allows to control both θ_m and α/k_0 by only modifying the periodic slot layout, while the host dielectric waveguide dimensions do not need to be altered. This antenna presents important advantages with respect to the nonperiodic counterpart (in which θ_m could only be controlled by varying the frequency or the host guide geometry), and also as compared to previous printed periodic antennas (in which α could not be controlled without affecting θ_m). This design flexibility has been checked with HFSS results. This technology also offers interesting manufacturing advantages, since different slots masks can be designed to obtain different desired electrical specifications (pointing direction and illumination), and lately incorporated to the same host waveguide.

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