A Novel Leaky-Wave Antenna Combining an Image NRD Guide and a Strip Circuit

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***Abstract*—This letter presents a novel leaky-wave antenna which combines an image NRD (nonradiative dielectric) guide and a printed strip circuit. The proposed structure allows for an easier, cheaper and more flexible tapering mechanism than all previous leaky-wave antennas in NRD technology. The working mechanism is explained, and two different tapering strip-circuit topologies are proposed. Cosine tapered illuminations are designed using a two-dimensional leaky-mode analysis technique. Simulations with high-frequency structure simulator (HFSS) three-dimensional analysis are presented for validation purposes. Also, the influence of the feeding transitions for each printed-circuit design is studied. Results show the feasibility of one of the proposed designs, leading to a tapered radiation pattern with sidelobes level below -20 dB.**

***Index Terms*—Leaky-wave antennas (LWAs), millimeter wave antennas, NRD (nonradiative dielectric) guide, printed-circuit technology, tapered antennas.**

I. INTRODUCTION

SEVERAL leaky-wave antennas (LWAs) based on the nonradiative dielectric (NRD) guide have been proposed in the last decades for use in millimeter-wave applications [1]–[8]. These antennas are illustrated in Fig. 1. NRD waveguides are good candidates to overcome the losses and manufacturing difficulties associated to high frequencies components [1]. The original bounded mode of the NRD guide is made leaky if a suitable perturbation is added. In some of these designs, the parallel-plates height L is shortened to allow the radiation from the evanescent fields outside the dielectric slab [3], [5], [7] as illustrated in Fig. 1(a). By adjusting the parallel-plate height L appropriately, the leakage rate of the leaky-mode can be controlled. Alternatively, one can introduce an asymmetry in the transverse direction of the NRD guide to excite the parallel-plate propagating TEM leaky-wave [2], [4], [6], [8]. By controlling the asymmetry level, one can modify the leakage rate of the antenna. A gap in the NRD structure was used in [2], as shown in Fig. 1(b), and more complicated trapezoidal asymmetric NRD guides were proposed in [8] to conceive LWAs in NRD technology, as shown in Fig. 1(c). In [4], a slot in one of the parallel-plates was added to induce radiation, as sketched in Fig. 1(d), and an asymmetric groove NRD, shown in Fig. 1(e), was used in [6]. In any case, it is necessary in a practical design to taper the LWAs' illumination to reduce the sidelobes level [9] by controlling the leaky-mode radiation rate (α). All the aforementioned NRD LWA technologies do not allow for a flexible tapering mechanism, since the NRD or parallel-plates structure itself must be modified along the antenna length to obtain the taper.

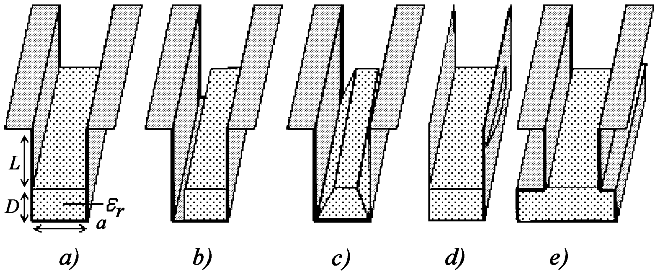

Fig. 1. Different leaky-wave antennas in NRD technology.

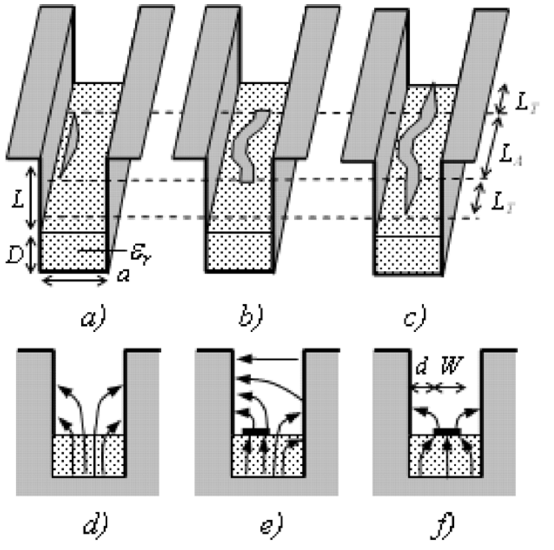

Fig. 2. Novel leaky-wave antennas in hybrid NRD-strip technology.

This letter presents a novel type of NRD LWA, in which the image NRD guide is combined with a strip circuit, as shown in Fig. 2. The strip-circuit is printed on the dielectric-air interface to induce the asymmetry radiation mechanism, and to control the leakage rate. By modulating the strip width and position [W and d, see Fig. 2(f)] one can design a tapered illumination, while taking advantage of the electrical performances of the NRD transmission medium. In order to obtain different illumination designs, one must only replace the printed-circuit with the appropriated mask, while keeping unchanged the host image

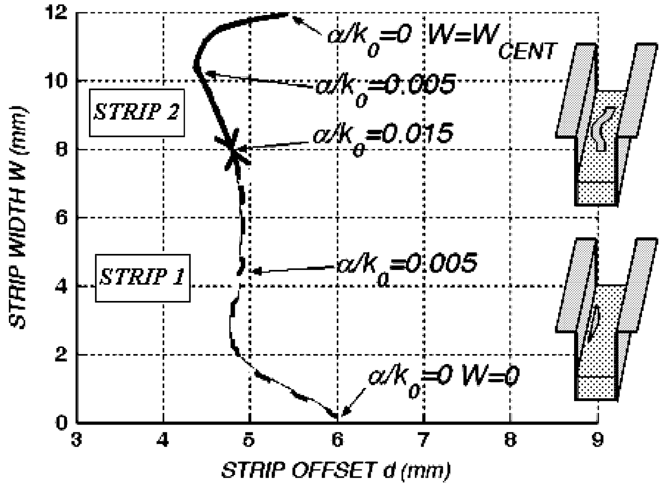

Fig. 3. Constant $\theta_m = 40^\circ$ contour curve for the strip dimensions.

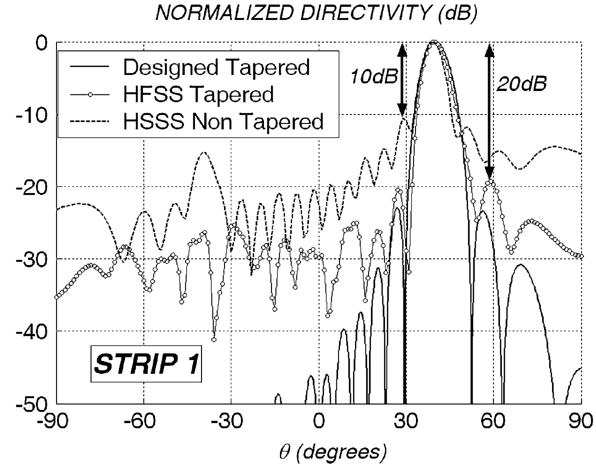

Fig. 4. Normalized radiation diagram for the *STRIP-1* LWA design.

NRD waveguide and the parallel-plates. This hybrid technology is much more flexible and cheaper than previous NRD-based LWAs, since common photolithographic processes can be used to fabricate the antenna, avoiding the complicated mechanization of the waveguide. This hybrid printed-circuit waveguide technology was proposed for the case of a slitted dielectric rectangular waveguide (RWG) LWA [10], but it has never been applied to the NRD guide.

II. THEORY

A full-wave, accurate method of moment technique [11] is used to obtain the complex propagation constant ($k = \beta - j\alpha$) of the leaky-wave mode in the perturbed NRD guide. A tapered illumination function $F(z)$ can be obtained if the leaky-mode leakage rate is varied along the antenna length (z-axis), while keeping its phase constant unchanged, according to the next expressions [9]

$$\alpha(z) = \frac{1}{2} \frac{F(z)}{\frac{1}{\eta}\int\limits_{z=0}^{L_A} F(z)\partial z - \int\limits_{z=0}^{z} F(z)\partial z} \tag{1}$$

$$\beta(z) = k_0 \sin\theta_m \tag{2}$$

being L_A the aperture length, η the LWA efficiency, k_0 the free-space wavenumber and θ_m the LWA elevation pointing direction (with respect to the broadside direction). Therefore, it is essential to determine which dimensions of the printed strip-circuit allow to change α without changing β. Fig. 3 presents a constant $\theta_m = 40^\circ$ contour curve for the TE $_{10}$ leaky-mode in the novel strip-loaded NRD LWA. An X-band rectangular waveguide ($a = 22.86$ mm, $D = 10.16$ mm) filled with PTFE ($\varepsilon_r = 2.2$), with parallel-plates of height $L = 40$ mm is used at the frequency of 6.5 GHz. Using this contour curve, one can obtain the variation of the dimensions of the strip-circuit (W and d) to synthesize the desired leaky-mode leakage function (1) with constant pointing direction θ_m.

There are two different ways to vary the leakage rate while keeping θ_m constant, by only modifying the strip dimensions. The first is by varying the strip width from zero [in which case the NRD mode is bounded, $\alpha = 0$, as illustrated in Fig. 2(d)], to the required strip widths, which provide radiation due to the asymmetry principle [see the leaky-mode field lines in Fig. 2(e)]. The second taper topology provides zero leakage by using a symmetrically located strip [Fig. 2(f)], and increase α by displacing the strip along the antenna length [changing d in Fig. 2(f)]. The first taper mechanism will be referred as "*STRIP-1*", and it is represented in Fig. 2(a). The second taper topology will be referred as "*STRIP-2*", and it is illustrated in Fig. 2(b). These two types of strip designs correspond to the lower and uppers segments, respectively, of the contour curve shown in Fig. 3.

III. RESULTS

To check this theory, two cosine illuminated LWAs (-23 dB sidelobes level) with $L_A = 10\lambda_0$ (9° beamwidth) are designed in strip-loaded NRD technology. The $\theta_m = 40^\circ$ contour curves plotted in Fig. 3 are used in the design of the printed-circuit dimensions to synthesize the desired leakage function $\alpha(z)$. From these dimensions, the evolution of the leaky-mode along the antenna length can be described in terms of its evolving complex propagation constant, $k(z) = \beta(z) - j\alpha(z)$, and the expected radiation pattern can be obtained from the theoretical leaky-mode aperture illumination. This modal design will be contrasted with full-wave simulations of the three-dimensional LWA structure, performed with a commercial FEM solver [high-frequency structure simulator (HFSS)].

Fig. 4 shows the radiation patterns obtained for the *STRIP-1* LWA (continuous line), together with comparisons with the results obtained from HFSS analysis (circles). Very good agreement is observed, thus validating the *STRIP-1* design [Fig. 1(a)]. It can be seen that all the sidelobes are at least -20 dB below the main lobe, which points at the designed elevation angle ($\theta_m = -40^\circ$). Also, results obtained from HFSS for the non-tapered antenna ($W = 5$ mm, $d = 3$ mm) are shown with a dashed line, to illustrate the 10 dB sidelobes level reduction introduced by tapering the LWA. Therefore, it is confirmed the ability of this technology to obtain a tapered antenna design, by only adding a strip to the interface of the image NRD guide.

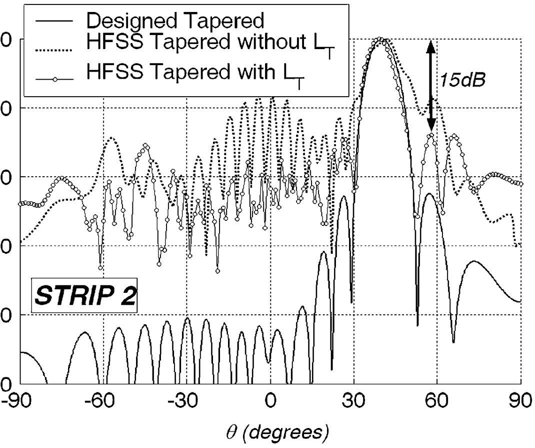

Fig. 5. Normalized radiation diagram for the *STRIP-2* LWA design.

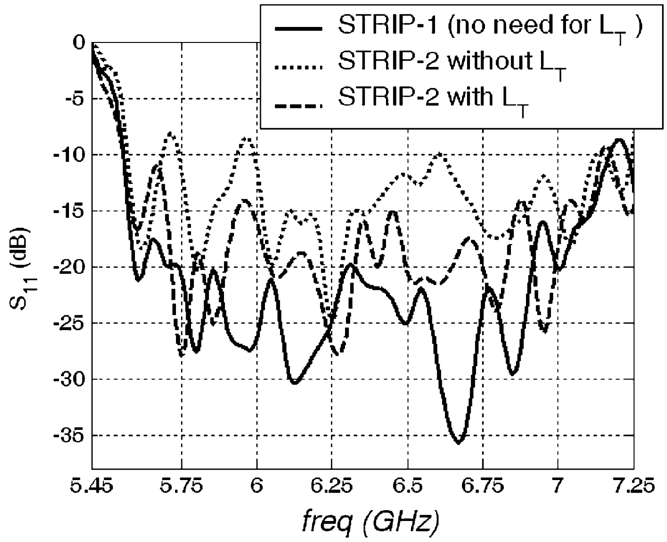

Fig. 6. Comparison for the input matching of each antenna design.

Following the same procedure, the *STRIP-2* LWA is designed, and the results are presented in Fig. 5. This time, the HFSS simulations (dotted line) do not match the low sidelobes radiation pattern expected from the modal design (continuous line). Interferences are created due to reflections and diffractions at the discontinuity between the naked NRD guide and the strip-loaded NRD radiation section [see Fig. 2(b)], spoiling the leaky-mode tapered radiation pattern. A triangular transition of length $L_T = \lambda_0$ must be added to the antenna length L_A, as illustrated in Fig. 2(c). Fig. 5 also shows the results obtained with this triangular transition of length L_T (line with circles). The radiation diagram is improved, reducing the nondesired sources of radiation. However, it can be seen that the response is not as good as expected, obtaining -10 dB sidelobes level. The investigation of the structure has revealed that this is due to diffraction from the sharp wedge of the triangular transition, which is located at the middle of the waveguide, where the TE_{10} leaky-mode carries the maximum of energy. In the case of the *STRIP-1* design, the diffraction is much lower due to the fact that the wedge of the printed circuit is located on the side of the NRD guide [see Fig. 2(a)], where the energy carried by the TE_{10} mode is minimum.

Therefore, the *STRIP-2* LWA presents a worse response than the *STRIP-1* antenna in any case. Moreover, the *STRIP-1* NRD LWA does not require the addition of a transition of length L_T from the original NRD guide to the strip radiating section. This is because the *STRIP-1* geometry does not introduce any discontinuity, since the strip edges (at the beginning and at the end of the printed circuit) start from zero width. As a result, the total antenna length is reduced for the case of the STRIP-1 antenna [L_A, see Fig. 2(a)] as compared to the STRIP-2 antenna [$L_A + 2L_T$, see Fig. 2(c)]. In addition, Fig. 6 shows a comparison of the input matching (S_{11}), obtained with HFSS simulations, for the three antenna designs shown in Fig. 2. Waveguide port excited with the main mode of the NRD guide (TE_{10} mode) was used to feed the antennas and compute the S-parameters. It can be seen that the transition of length L_T is needed in the *STRIP-2* design to reduce the reflections. On the other hand, the *STRIP-1* antenna presents a better matching than the *STRIP-2* counterpart. This is again due to the position of the strip, which creates a greater discontinuity for the case of the *STRIP-2* circuit [wedge of the strip in the middle of the NRD guide, see Fig. 1(c)]. All these aspects make the *STRIP-1* antenna a better topology to design tapered LWAs in the proposed hybrid NRD-strip technology.

IV. CONCLUSION

This letter has presented a novel leaky-wave antenna, which makes use of an image NRD guide with a strip printed in the air-dielectric interface. The proposed technology is more flexible than previous NRD LWAs, where the NRD guide or the parallel-plates should be modified using complicated mechanization processes to obtain a taper design. It has been demonstrated that the printed strip circuit dimensions can control the aperture illumination, thus reducing the sidelobes level, while keeping unchanged the NRD guide structure. This taper mechanism is much more flexible and cheaper, since the strip circuit can be fabricated using standard planar-circuit techniques. Comparisons between the leaky-mode design and HFSS full-wave three-dimensional simulations have been shown to validate the taper ability of the proposed antenna. Two different types of strip-tapering topologies have been proposed to control the leaky-mode leakage rate, showing the differences between them. A better radiation diagram (lower sidelobes level) and better input matching can be obtained with the *STRIP-1* circuit, and with the advantage of needing a shorter antenna than in the case of the *STRIP-2* circuit.

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