Leaky-Wave Antenna in Planar Technology with High Directivity in the Transverse Plane

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***Abstract*—A leaky-wave antenna (LWA) designed in substrate integrated waveguide (SIW) technology and showing high directivity in its transverse plane is presented. In addition, the proposed SIW LWA allows for the flexible control of its complex propagation constant, and thus of its radiation properties. For this purpose, the width of the SIW is used for the control of the phase constant and the separation between posts for the leakage rate. Moreover, the proposed structure works with the TE_{20} mode of the SIW, which makes it possible the radiated electric fields be added in phase at the center of the SIW, providing higher directivity in the transverse plane compared to single line-source antennas. Full-wave simulations are given to support the theoretical concepts exposed along the work. Furthermore, several prototypes have been designed at the frequency of 15 GHz to validate this work.**

***Index Terms*— Leaky-wave antenna (LWA), planar antennas, substrate integrated waveguide (SIW), complex propagation constant.**

I. Introduction

Planar devices have continually received a lot of interest due to their appealing characteristics of low-profile, low-weight, low-cost, and easiness of integration with other devices. As a result of it, several technologies have been developed, e.g., microstrip, coplanar waveguide, stripline, etc. [1], and more recently the substrate integrated waveguide (SIW) technology, which combines some of the advantages of conventional rectangular waveguides (RWG) as low-losses and high performances into a planar structure [2]–[5]. These interesting properties have made possible that a huge variety of devices, including filters, antennas, dividers, multiplexers, etc. were designed into SIW [6]. Leaky-wave antennas (LWA) have not been an exception and multiple designs have been proposed to date [7]–[13]. Commonly, planar LWAs only exhibit directivity along its longitudinal plane, due to the radiation is generated by a single-line source. In order to obtain a high directivity at the transverse plane, several antennas can be arranged as in [2], [10] or a single LWA with two line-sources can be used. Based on this second approach, the microstrip LWA proposed by Menzel [14] or the periodic SIW LWA by Xu [9] can be found. Although both designs show more directivity at the transverse plane compared to single-line-sources LWA, no control over the complex propagation constant of the leaky mode is obtained. This limitation can be overcome with the SIW LWA proposed in this work. In particular, the SIW is designed to operate with its TE_{20} mode and, due to the large

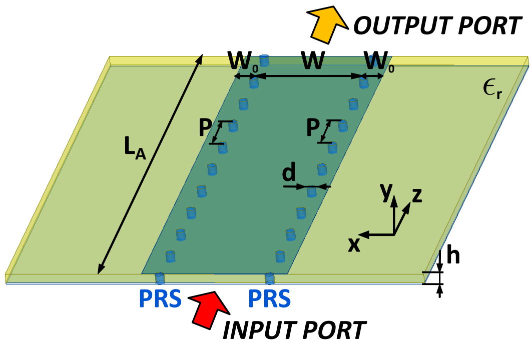

Fig. 1. Scheme of the SIW LWA and main geometrical parameters.

separation between posts, the leakage is generated at both sides of the SIW. Thus, by varying the width W of the line and the separation P between posts, a flexible control of the complex propagation constant is obtained.

A scheme of the proposed structure with its main geometrical parameters is plotted in Fig. 1. In particular, it can be seen the SIW with the truncated top layer of width $W + 2W_0$ and the two rows of metallic posts of diameter d separated a distance P. The rest of the work is organized as follows. Section II describes the main radiation properties of the proposed SIW LWA and the control of the leaky mode as function of the geometrical parameters W and P. In Section III three antennas radiating at different pointing angles and constant beamwidth have been designed and simulated with commercial full-wave software, results have been validated with theoretical ones for both H- and E-planes. Finally, the conclusions of the work have been summarized in Section IV.

II. Analysis of the LWA in SIW Technology

Radiation properties in LWAs are mainly determined by the complex propagation constant of the leaky mode. In this way, the complex propagation constant of this TE_{20} mode can be expressed as

$$k_z(z) = \beta_z(z) - \mathrm{j}\alpha_z(z) \tag{1}$$

where β_z stands for the phase constant and α_z for the leakage rate. Moreover, the radiated pointing angle $\theta_{\mathrm{RAD}}(z)$ can approximately be determined by the ratio of β_z to the free-space wavenumber $k_0 = 2\pi/\lambda_0$ [15]

$$\sin\theta_{\mathrm{RAD}}(z) \approx \beta_z(z)/k_0 \; . \tag{2}$$

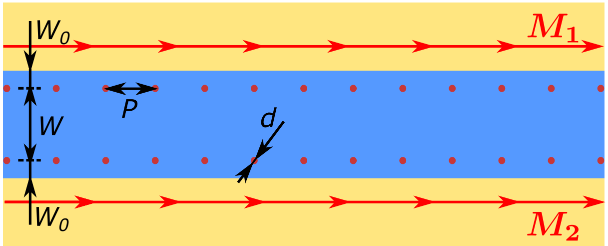

Fig. 2. Top view of the double-sided SIW LWA and its two equivalent magnetic currents lines $\boldsymbol{M}$.

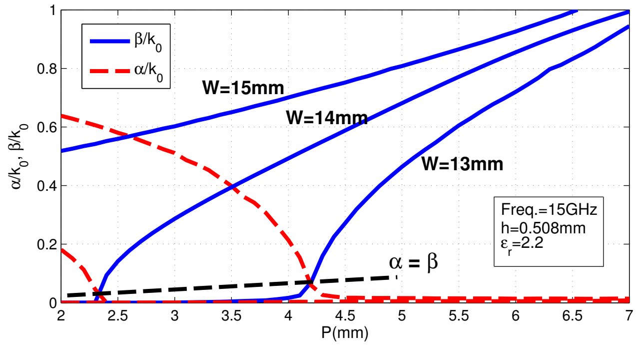

Fig. 3. Control of the complex propagation constant as function of P and several widths of the SIW ($W = 13$ mm, 14 mm and 15 mm).

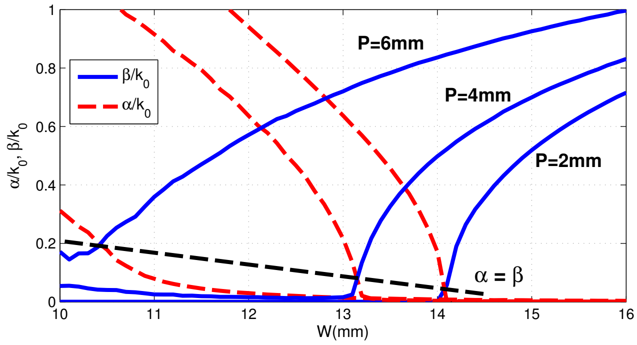

Fig. 4. Control of the complex propagation constant as function of W and several separation of posts ($P = 2$ mm, 4 mm and 6 mm).

As a result of this relation, the radiation angle can be determined by controlling the phase constant. On the other hand, the beamwidth $\Delta\theta$ can also be expressed as

$$\Delta\theta \approx \frac{1}{\frac{L_A}{\lambda_0}\cos\theta_{\text{RAD}}} \tag{3}$$

with L_A being the length of the LWA.

As shown in Fig. 1, the proposed structure consists of a SIW working with its TE_{20}-like mode, which is controlled to radiate according to a prescribed specification. Due to the field distribution of the TE_{20} mode, the antenna can count with two radiating sides that can be modelled as two magnetic current lines, $\boldsymbol{M}$, along the edges of the SIW LWA, as illustrated in Fig. 2. These magnetic current lines act as radiating sources that are added in phase at the center of the antenna due to the opposite polarization of the electric field at each radiating side, thus giving rise to a higher directivity at the transverse plane when compared to single line-source antennas [11]. Therefore, it is obtained a radiation pattern similar to the microstrip radiating with its first higher-order mode [16] or the periodic LWA [9], but with the additional advantage of adding control over both β and α.

The flexibility to control the leaky mode as function of the main geometrical parameters (W, P) of the SIW LWA is shown in Figs. 3 and 4. To this aim, the complex propagation constant of the structure is obtained from the computed ABCD parameters [1]. In particular, the variation of the normalized values of the phase constant (β/k_0) and leakage rate (α/k_0) are plotted in Fig. 3 for a range of values of P from 2 mm to 7 mm and several SIW widths ($W = 13$ mm, 14 mm and 15 mm). It can be observed that α/k_0 increases with P due to the higher radiation losses of the SIW, as illustrated by the higher cut-off point ($\alpha = \beta$). Furthermore, it is seen that α decreases for larger values of W and a fixed value of P, due to the higher β/k_0 that corresponds to a larger pointing angle θ_{RAD} (2), and provides smaller radiation losses [11].

In Fig. 4 it is shown the behavior of the leaky mode as the width W of the SIW is varied from 10 mm to 16 mm for several values of $P = 2$ mm, 4 mm and 6 mm. It can be observed that β/k_0 increases with W for a fixed value of P due to the increase of the phase constant of the SIW, which is associated with a higher radiation angle according to (2). This increase of β/k_0 can also be observed for larger separation between posts P and a fixed value of W, as a result of a larger effective width of the SIW that gives rise to a larger phase constant. Moreover, it can be seen how α decreases for larger values of W, because of the larger θ_{RAD} which corresponds to a more grazing incidence, thus reducing the leakage rate [15].

III. Simulated Radiation Patterns

As previously shown in Fig. 3 and Fig. 4, an independent control of the leaky mode can be achieved by means of the proper variation of the geometrical parameters of the antenna (W, P). Consequently, it is possible to obtain a prescribed radiation diagram of the leaky mode along its longitudinal plane. In order to prove this, three antennas with different pointing angles ($\theta_{\text{RAD}} = 10°$, $30°$ and $50°$) and same beamwidth ($\Delta\theta = 10°$) have been simulated in HFSS and compared with theory for a design frequency of 15 GHz. A commercial substrate Taconic TLY-5 ($h = 0.508$ mm, $\epsilon_r = 2.2$, $\tan\delta = 0.0009$) has been used. Fig. 5 shows the radiation patterns at the H-plane for the three designed antennas. Full-wave results (in solid line) are compared with theoretical ones (in dashed line) obtained from the leaky mode. It can be observed a good agreement between results and how both pointing angles and beamwidth have been correctly obtained.

Nonetheless, Eqs. (2) and (3) only allow us to determine the main radiation properties of a line-source LWA along its longitudinal plane (yz-plane), since a fan-beam radiation pattern [15] is expected in the transverse plane (xy-plane).

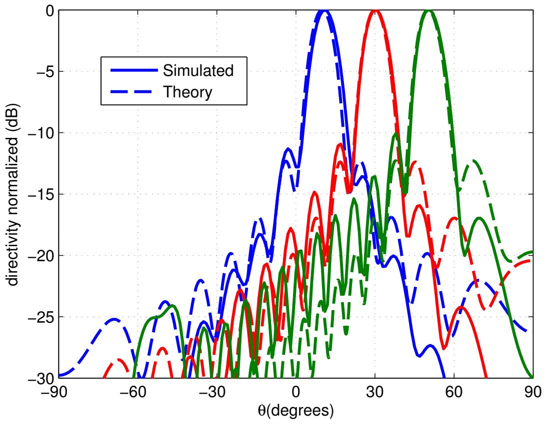

Fig. 5. Simulated and theoretical H-plane radiation patterns for the antennas radiating at $\theta_{\mathrm{RAD}} = 10°$, $30°$ and $50°$ with $\Delta\theta = 10°$.

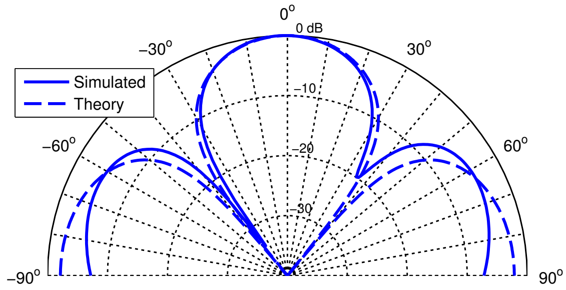

Fig. 6. Simulated and theoretical E-plane radiation pattern for the antenna radiating at $\theta_{\mathrm{RAD}} = 30°$ at the H-plane.

Here it is convenient to remind that the radiation pattern of a single line-source can be seen as the sum of multiple point sources, which provides directivity along the H-plane but a fan-beam pattern at the E-plane because of its behavior as a single point source. However, for the proposed antenna, there are two radiating sides separated at a distance $W+2W_0$, which can be defined as two equivalent magnetic currents lines. In this case, the E-plane is the result of the sum of two point sources separated a distance $x_{\mathrm{d}} = W + 2W_0$, and its array factor [17] at the E-plane is then given by

$$\mathrm{AF}(\theta,\phi) = a_0 \mathrm{e}^{-\mathrm{j}k_0(x_{\mathrm{d}}/2)\sin\theta\cos\phi} + a_1 \mathrm{e}^{\mathrm{j}k_0(x_{\mathrm{d}}/2)\sin\theta\cos\phi} . \tag{4}$$

To validate this theoretical approach, the radiation pattern at the E-plane for the antenna pointing with $\theta_{\mathrm{RAD}} = 30°$ and $\Delta\theta = 10°$ at the H-plane is shown in Fig. 6. Full-wave simulated results (in solid line) are compared with the theoretical ones (in dashed line) obtained from the array factor of (4). The polar diagram shows good agreement between both results, although, as expected, some differences are observed because the considered array factor does not take into account the effect of the dielectric ground plane and the fringing fields at the radiating sides. However, it still can be used as a good approximation for obtaining the radiation pattern as shown in Fig. 6.

IV. Conclusion

A planar leaky-wave antenna designed in substrate integrated waveguide technology and with capability to radiate from both sides of the SIW line has been presented. The proposed SIW LWA uses the TE_{20} mode of the SIW as the fundamental one, which allows for the radiated electric field be added in phase at the center of SIW thus providing higher directivity at the transverse plane compared to single line-source antennas. Moreover, by means of the geometrical parameters (W, P) of the SIW, an effective control of the complex propagation constant ($k = \beta - \mathrm{j}\alpha$) is obtained. To demonstrate this control, three antennas radiating with three different pointing angles ($\theta_{\mathrm{RAD}} = 10°$, $30°$ and $50°$) and same beamwidth ($\Delta\theta = 10°$) at 15 GHz have been designed. Results obtained with commercial full-wave software have been compared with theoretical ones and good agreement is found.

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