Planar Leaky-Wave Antenna with Flexible Control of the Complex Propagation Constant

Alejandro Javier Martínez-Ros, Student Member, IEEE, José Luis Gómez-Tornero, Member, IEEE, and George Goussetis, Member, IEEE

Abstract—This paper demonstrates for the first time the capability to independently control the real and imaginary parts of the complex propagation constant in planar, printed circuit board compatible leaky-wave antennas. The structure is based on a half-mode microstrip line which is loaded with an additional row of periodic metallic posts, resulting in a substrate integrated waveguide SIW with one of its lateral electric walls replaced by a partially reflective wall. The radiation mechanism is similar to the conventional microstrip leaky-wave antenna operating in its first higher-order mode, with the novelty that the leaky-mode leakage rate can be controlled by virtue of a sparse row of metallic vias. For this topology it is demonstrated that it is possible to independently control the antenna pointing angle and main lobe beamwidth while achieving high radiation efficiencies, thus providing low-cost, low-profile, simply fed, and easily integrable leaky-wave solutions for high-gain frequency beam-scanning applications. Several prototypes operating at 15 GHz have been designed, simulated, manufactured and tested, to show the operation principle and design flexibility of this one dimensional leaky-wave antenna.

Index Terms—Complex propagation constant, leaky-wave antenna (LWA), microstrip antennas, planar antennas, substrate integrated waveguide (SIW).

I. INTRODUCTION

PLANAR leaky-wave antennas (PLWAs) have been the object of study over the past decades due to their inherent capability to combine the characteristics of planar antennas (low profile, low-cost, and simplicity of integration with other planar circuits), with the performances of the LWA (simple feeding, high directivity and frequency beam scanning capability) [1]–[15]. The first attempts to achieve PLWA were proposed in 1979 by Ermert [1] and Menzel [2] based on the radiation of the first higher order mode of the microstrip line. However, almost a decade passed until Oliner and Lee explained in detail the radiation mechanism of the microstrip LWA (MLWA) [3]–[5]. Fig. 1a shows the layout of a conventional MLWA, which is asymmetrically fed to excite the first higher order leaky-mode [6]. The electric field distribution of this mode at the microstrip cross section ($E$) is plotted with continuous blue lines, and the equivalent magnetic currents radiating in the form of a space-wave from the microstrip line edges discontinuity are plotted with dotted red lines ($M$).

Thiele et al. proposed a variation of the MLWA, called the half-mode MLWA (HMLWA) [7], [8] which is shown in Fig. 1b. As it can be seen, the width of the microstrip is reduced to half ($W/2$ in Fig. 1b), by using close shorting pins at one side of the microstrip line, which act as a perfect electric conductor (PEC) wall. Moreover, since the leaky-mode is the fundamental mode in the HMLWA, the excitation becomes easier, and complicated feeding structures [6] are not needed anymore. Recently, a periodic version of the HMLWA has been proposed to achieve backward-to-forward scanning [9]. Composite right-left handed microstrip lines (CRLH) have also been engineered to conceive “metamaterial” MLWAs [10]–[12]. These CRLH-MLWAs are based on much more complicated periodic unit-cells to make the dominant microstrip mode become leaky, providing full scanning capability, including radiation at broadside. Nevertheless, the main drawback of all previous MLWAs is that the leaky-mode leakage rate $\alpha$ and phase constant $\beta$ cannot be independently controlled. For this reason, the radiation efficiency $\eta_{RAD}$ cannot be optimized for a given scanning angle and radiating length, resulting in low efficiency designs and in the generation of an unwanted reflected lobe (overall for short MLWA) that must be reduced by using alternative configurations [13]–[15].

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**Fig. 1.** Planar leaky-wave antennas (PLWAs) together with their equivalent magnetic currents (dotted line) and electric fields (continuous line): a) Menzel antenna. b) Thiele half-mode antenna. c) PLWA studied in this paper.
The scheme of the novel PLWA is shown in Fig. 1c. This configuration is similar to the HMLWA with the addition of a second row of conducting vias separated a distance \( P \), which behaves as an inductive partially reflective surface (PRS) [16] and allows the propagation of the fundamental mode in a substrate integrated waveguide (SIW) [17]. The space between PRS posts permits the control over the leakage level, as demonstrated in [18], [19]. Although the antenna proposed in this paper presents similarities with the SIW LWA introduced by Deslandes and Wu in [19], there a lateral wave radiates from the open-end of the truncated substrate. This radiation mechanism was well described by the authors, and was the basis for identifying additional limitations originating from Snell’s law at the dielectric-air interface. On the contrary, the LWA studied in this paper radiates in the form of a space leaky-wave created in the discontinuity between the grounded microstrip lateral edge and the extended dielectric-filled ground plane. This radiation mechanism is the same that in conventional MLWA [1]–[5] and HMLWA [7]–[9], and it is preferred when compared with [19] since it allows to arrange in parallel several PLWAs in a one dimensional array using a single substrate, as done in conventional MLWAs [4], [8], [14], [20]. Another type of SIW LWA is the presented in [21], in which backward-to-forward scanning is obtained by using a dominant slow-wave non radiative SIW mode which excites a fast-wave higher-order \((n = -1)\) space harmonic. This different radiating mechanism is obtained by using periodic metallic posts separated at a distance \( P \) in the order of half-wavelength, while in the case of our LWA and in [19], a dominant fast-wave radiative SIW mode is used and \( P \ll \lambda/2 \). Nevertheless, the ability to independently control the leaky-mode phase velocity and leakage rate was not proven in [19] or [21], and it is theoretically and experimentally demonstrated in this paper. To the authors’ knowledge, this is the first time that this flexible control over the leaky-mode is demonstrated in pure planar technology, avoiding the use of bulky waveguides [20], [22].

The rest of the paper is distributed as follows. Section II describes the working mechanism of the novel PLWA. Several designs are performed, manufactured and tested in section III to illustrate the flexibility to control the pointing angle and the beamwidth with the proposed PLWA, while keeping high radiation efficiency. Finally, the conclusions of this work are summarized in section IV.

II. ANALYSIS OF A LWA IN PLANAR TECHNOLOGY

The PLWA proposed in this work is formed by a combination of printed circuit and via-holes, providing a completely planar structure integrated in a single substrate layer (see Fig. 2a). The structure has been designed to operate with the perturbed \( TE_{10} \) leaky-mode of the SIW [18] which is created between the PEC posts and the PRS posts separated a distance \( W \). The radiation mechanism of a LWA is mainly defined by the leaky-mode complex longitudinal propagation constant [20]:

\[
k_z = \beta - j\alpha
\]  

Concretely, the equivalent magnetic currents \( M \) created at the microstrip lateral edge, act as a line source in the \( z \)-axis (see Fig. 1c), and they are responsible for the high directivity in the \( H \)-plane \((y-z \text{ plane})\) while for the \( E \)-plane \((x-y \text{ plane})\) a typical fan beam is achieved [20]. In Fig. 2b the distribution of the electric field lines for a cross section of the LWA is represented. The amount of radiated power directly depends on the leakage rate \( \alpha \) and the LWA length \( L_A \), and it determines the antenna radiation efficiency:

\[
\eta_{RAD} = 1 - e^{-2\alpha L_A} = 1 - e^{-4\pi \frac{\alpha L_A}{\lambda_0}}
\]  

Typically \( \eta_{RAD} = 90\% \) is selected to allow a feasible control of the antenna illumination [20]. On the other hand, the efficiently illuminated LWA radiating length \( L_A \) and the pointing angle \( \theta_{RAD} \) determine the main beam width:

\[
\Delta \theta \approx \frac{1}{L_A \cos \theta_{RAD}}
\]  

where the scanning angle \( \theta_{RAD} \) is measured from the \( y \)-axis, and it depends on the leaky-mode phase constant \( \beta \):

\[
\sin \theta_{RAD} \approx \frac{\beta}{k_0}
\]  

For the proposed antenna, the control of \( \alpha \) and \( \beta \) can be easily performed by modifying the printed circuit parameters \( P \) and \( W \). Once the substrate and the SIW width \( W \) have been chosen to set the leaky-wave regime in the desired frequency band, the period between posts \( P \) must be designed. For large values of \( P \), the losses become non negligible.
and the transmission line suffers from radiation leakage [18]. In this case, the periodic conducting posts can be viewed as an inductive impedance [23, pp. 285–289], acting as a partially reflective surface (PRS) whose transparency can be controlled by the distance between posts $P$. On the contrary, the period $P_0$ of the other row of via-holes must be chosen small enough to consider it like a perfect electric conductor (PEC) [18]. Fig. 3 and Fig. 4 shows the behavior of $\alpha/k_0$ and $\theta_{RAD}$ when $P$ and $W$ are varied. These results have been obtained for a frequency of 15 GHz in a lossless substrate with $h = 1.57 \text{mm}$ and $\epsilon_r = 2.2$, by using commercial full-wave simulator HFSS [24]. The rest of the printed-circuit parameters are kept constant to $W_0 = 1.5 \text{ mm}$, $P_0 = 2 \text{ mm}$ and $d = 1 \text{ mm}$ for all the designs. It must be highlighted that the width $W_0$ of the edge microstrip section has to be less than $\lambda/4$ in order to avoid the appearance of unwanted channel modes [20].

![Fig. 3](image)

**Fig. 3.** Curves for $\alpha/k_0$ and $\theta_{RAD}$ varying the distance between posts $P$ for several values of $W$ at 15 GHz.

![Fig. 4](image)

**Fig. 4.** Curves for $\alpha/k_0$ and $\theta_{RAD}$ varying the width of the SIW $W$ for several values of $P$ at 15 GHz.

As it is shown in Fig. 3, higher values of $P$ make the PRS more transparent, thus increasing the leakage rate $\alpha/k_0$ from almost zero for $P = 2 \text{ mm}$ to $\alpha/k_0 = 0.04$ for $P = 5 \text{ mm}$. On the other side, $W$ mainly controls the cutoff frequency of the perturbed $TE_{10}$ mode of the SIW [18], therefore determining the leaky-mode phase constant $\beta$ and the associated $\theta_{RAD}$ (4) at a fixed frequency. As it can be seen in Fig. 4, as $W$ is increased from $W = 6.9 \text{ mm}$ to $W = 8.8 \text{ mm}$, $\theta_{RAD}$ is swept from $0^\circ$ to $60^\circ$ at 15 GHz. From Fig. 3 and Fig. 4 it is observed how both values of the leaky-mode propagation constant are affected mutually and therefore a simultaneous variation of $P$ and $W$ must be performed in order to achieve the desired values for $\alpha$ and $\theta_{RAD}$. It must be highlighted that the antenna proposed in [19] shows similar flexible control, being the geometrical parameters $L_1, L_2$ and $p$ in [19, Fig. 2] equivalent to $W_0, W_1$ and $P$ of the antenna presented in this paper. However, in [19] it was not demonstrated this versatility to simultaneously tailor the leaky-mode phase velocity and leakage rate.

### III. DESIGNS AND MEASUREMENTS

In order to validate the theoretical concepts shown in the previous sections and to demonstrate the ability to tailor the radiation pattern, several designs have been simulated and fabricated in commercial substrate RT/Duroid 5880 ($h = 1.57 \text{ mm}$, $\epsilon_r = 2.2$, $\tan \delta = 0.0009$). A scheme of the complete structure and its main geometrical parameters is represented in Fig. 5. The design can be divided in three well differentiated parts:

1) Transition from a microstrip to a SIW ($L_0$)
2) Transition from a SIW to the LWA ($L_1$)
3) Radiating Leaky-Wave Antenna ($L_A$)

The PLWA is excited by means of a microstrip line at port 1. On the other hand, the transitions $L_0$ and $L_1$ compensate and reduce the mismatch between propagation constants in both microstrip and SIW transmission lines, as proposed in [17], [25]. For all prototypes the following transition lengths have been used: $L_0 = 15 \text{ mm}$ and $L_1 = 46 \text{ mm}$.

![Fig. 5](image)

**Fig. 5.** Scheme of the novel PLWA including feeding lines.

By processing dispersion curves of $\theta_{RAD}$ and $\alpha/k_0$ as a function of the physical parameters $W$ and $P$, five LWAs have been designed. Three designs with same pointing angle (4) $\theta_{RAD} = 30^\circ$ and variable beamwidth (3) from $\Delta \theta = 5^\circ$ to $\Delta \theta = 20^\circ$ were performed for the design frequency of 15 GHz.
obtaining the requested values of $L_A$, $W$ and $P$ summarized in Table I. On the other hand, in Table II the physical dimensions for other three designs where the beamwidth is kept constant to $\Delta \theta = 10^\circ$ and the pointing angle is varied from $\theta_{RAD} = 10^\circ$ to $\theta_{RAD} = 50^\circ$ are represented. All the LWAs of Table I and Table II are designed to provide $\eta_{RAD} = 90\%$ (2) at the design frequency of 15 GHz, independently of the variation in the scanning angle and the beamwidth. The fabricated prototypes are shown in the picture of Fig. 6.

The measured $H$-plane radiation patterns at 15 GHz for the prototype designs of Table I and Table II are plotted in Fig. 7a and Fig. 7b, respectively. As it can be seen, the desired variation in $\theta_{RAD}$ and $\Delta \theta$ are successfully obtained, experimentally confirming the proposed design flexibility. On the other hand, the $E$-plane radiation pattern is characterized by a typical fan beam [20], as it can be seen in Fig. 8 for the case of the antenna with $\theta_{RAD} = 30^\circ$ and $\Delta \theta = 10^\circ$. As commented in the Introduction, a one dimensional array of LWAs might be used to increase the directivity in the $E$-plane [20]. The measured cross-polarization fields are also shown in Fig. 8, observing a maximum cross-polarization level of $-8$ dB.

A comparative showing very good agreement between measured and simulated $H$-plane radiation diagrams is depicted for all the designed antennas in Fig. 9. As it can be seen, the $H$-plane scanning angle and main beamwidth can be flexible tailored as theoretically predicted. Moreover, the measured values of gain (G) and directivity (D) are reported for each prototype.
in the insets of Fig. 9, together with the deduced radiation efficiency ($\eta_{\text{RAD}} = G/D$). It is shown how the expected high efficiency ($\eta_{\text{RAD}} \approx 90\%$) has been obtained for all tailored designs, in spite of the pointing angle and beamwidth selected. Also, Fig. 9f represents the measured levels of co-polarization ($\phi$ polarization) and cross-polarization ($\theta$ polarization) at the $H$-plane for the case of the antenna radiating at $\theta_{\text{RAD}} = 30^\circ$ with $\Delta\theta = 10^\circ$. The rest of designs showed similar levels of cross-polarization.

Fig. 10 depicts the measured $S_{11}$ and $S_{21}$ parameters for the antennas with a fixed beamwidth (Fig. 10a), and with fixed pointing angle (Fig. 10b) at the center frequency. Good matching is obtained for all prototypes at the design frequency of 15 GHz ($S_{11}$ parameter around $-17\, \text{dB}$). Moreover, it can be observed how both $S_{11} \approx -17\, \text{dB}$ and $S_{21} \approx -13\, \text{dB}$ remain constant for all antennas at 15 GHz. As a consequence, the radiation efficiency extracted from the measured S parameters ($\eta_{\text{RAD}} = 1 - |S_{11}|^2 - |S_{21}|^2$) results in $\eta_{\text{RAD}} \approx 90\%$ for all the designs (independently on the values of $\theta_{\text{RAD}}$ and $\Delta\theta$), in coherence with the efficiency estimated from the measured gain. By using simulations for the antenna with and without material losses, and comparing them with the measured S parameters, a difference in $S_{21}$ parameter at 15 GHz from $-11.5\, \text{dB}$ (without losses) to $-13\, \text{dB}$ (with losses, in agreement with the measured results) was obtained. Thus, it can be claimed that the $1.5\, \text{dB}$ increase in the insertion losses is due to ohmic losses, resulting in less than 3\% reduction of the radiation efficiency.

Fig. 9. Measured and simulated $H$-plane radiation diagrams at 15 GHz for each antenna: a) $\theta_{\text{RAD}} = 30^\circ$ and $\Delta\theta = 20^\circ$. b) $\theta_{\text{RAD}} = 10^\circ$ and $\Delta\theta = 10^\circ$. c) $\theta_{\text{RAD}} = 30^\circ$ and $\Delta\theta = 10^\circ$. d) $\theta_{\text{RAD}} = 30^\circ$ and $\Delta\theta = 5^\circ$. e) $\theta_{\text{RAD}} = 50^\circ$ and $\Delta\theta = 10^\circ$. f) Levels of co-polarization and cross-polarization for $\theta_{\text{RAD}} = 30^\circ$ and $\Delta\theta = 10^\circ$.

Fig. 10. Measured S parameters: a) Variation of the pointing angle $\theta_{\text{RAD}}$ for a constant beamwidth $\Delta\theta = 10^\circ$. b) Variation of the beamwidth $\Delta\theta$ for a constant pointing angle $\theta_{\text{RAD}} = 30^\circ$. 
Finally, the frequency dispersion of $\theta_{RAD}$ and peak gain for the antenna with $\theta_{RAD} = 30^\circ$ and $\Delta \theta = 10^\circ$ is represented in Fig. 11. Very good agreement between simulations and measurements is observed, achieving a measured peak gain of 10.9 dB at $\theta_{RAD} = 30^\circ$ for the design frequency of 15 GHz. Moreover, it can be observed the typical frequency beam scanning capability inherent to LWAs, that makes them useful for scanning applications, such as frequency modulated continuous-wave (FMCW) radars [20].

Fig. 11. Measured and simulated frequency dispersion of $\theta_{RAD}$ and gain for the antenna with $\theta_{RAD} = 30^\circ$ and $\Delta \theta = 10^\circ$ at 15 GHz.

### IV. Conclusion

The ability to control the leaky-mode complex propagation constant in a PLWA has been shown in this paper. This antenna combines the feasibility to flexibly choose the pointing angle and the beamwidth while keeping optimum high radiation efficiency, and with the advantage of using a complete planar technology. The proposed design is based on a substrate integrated waveguide (SIW) which cavity width $W$ and periodicity between via-holes $P$ can be varied to simultaneously control the leaky-mode phase and leakage constant. In order to validate the theoretical results obtained with commercial full-wave software, five prototypes operating at 15 GHz have been built and measured, showing very good agreement between theory and experiments. In three designs the pointing angle was kept constant and the beamwidth was varied, whereas for the other two the beamwidth was fixed for different pointing angles. All prototypes showed 90% radiation efficiency, demonstrating for the first time the capability of a planar LWA to obtain a versatile radiation diagram with high radiation efficiency in a simple, low-cost and effective way.

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### REFERENCES