Periodic Leaky-Wave Antenna on Planar Goubau Line at Millimeter-Wave Frequencies

Daniel Sánchez-Escuderos, *Member, IEEE*, Miguel Ferrando-Bataller, *Member, IEEE*, Jose I. Herranz, *Member, IEEE*, and Marta Cabedo-Fabrés, *Member, IEEE*

***Abstract*—A periodic leaky-wave antenna on a planar Goubau line is presented. This transmission line is formed by a planar single-wire waveguide on a thin dielectric substrate. Leakage is produced by adding dipoles along the line on the bottom face of the substrate. A coplanar waveguide is used to feed the antenna, which acts as a smooth transition between the input coaxial cable and the planar Goubau line. The advantage of using this line lies on its losses, lower than those of typical microstrip lines due to the absence of a ground plane. As a result, a higher radiation efficiency than in microstrip-fed antennas can be obtained while keeping similar advantages, e.g., low profile or low production cost. A prototype of the antenna at 40 GHz has been fabricated. Measurements of this prototype are presented in this letter.**

***Index Terms*—Leaky-wave antennas, low-loss waveguides, microstrip antennas, millimeter-wave antennas, planar Goubau line.**

I. Introduction

MICROSTRIP antennas present interesting features—e.g., low profile, light weight, or low production cost [1]—and can be integrated with the feeding network on the same substrate. Resulting structures are compact and, hence, very useful in practical applications. This fact has made microstrip antennas one of the most studied structures both in books [1], [2] and papers [3].

An important drawback of microstrip antennas is their potential low radiation efficiency [1], [2], mainly caused by the high concentration of field in the dielectric substrate, which adds both dielectric and ohmic losses. This problem becomes worse in microstrip-array antennas, either in resonant or in traveling-wave designs, since losses are also present in the feeding microstrip line.

If the ground plane is eliminated, the confinement of field in the dielectric substrate is reduced and, hence, a large reduction of both dielectric and ohmic losses is achieved. The resulting transmission line, known as planar Goubau line (PGL) [4], [5], presents a slow fundamental mode with a lower attenuation than a microstrip line with the same dimensions and materials.

Since the fundamental mode of the PGL propagates bounded to the line, radiation can only be achieved by exciting a high-order mode or including periodic perturbations along the line. This letter proposes the use of capacitively coupled dipoles to excite a radiating space harmonic. The resulting low-profile periodic leaky-wave antenna presents lower losses than similar designs, e.g., in microstrip [3] or substrate integrated waveguide (SIW) technologies [6], due to the lower confinement of field in the dielectric substrate. The feeding of the proposed antenna is made by a coplanar waveguide, which smoothly adapts the input coaxial cable impedance to the PGL impedance.

The resulting structure radiates in two symmetric directions due to the absence of a ground plane. To confine the energy in one direction, the use of a reflector plane, not connected to the ground plane of the coplanar waveguide, is proposed. Radiation patterns of both configurations, with and without reflector plane, present the expected steering behavior with frequency. A prototype has been manufactured and measured to confirm this behavior and the high radiation efficiency.

The letter is organized as follows. First, the planar Goubau line is studied, and its main parameters are analyzed. Then, the periodic leaky-wave antenna on the planar Goubau line is presented in both cases, with and without reflector plane. Finally, the prototype and measured results are shown, and main conclusions are highlighted.

II. Planar Goubau Line

The *Goubau line* is a classical transmission line formed by a metallic rod (the *Sommerfeld line*) coated by a dielectric layer [7]. Although a metallic shielding is not present in these transmission lines, the fundamental mode is bounded and, hence, does not radiate along the line.

Recently, the Sommerfeld line has been proposed, and experimentally validated, for low-loss transmission in the Terahertz and submillimeter-wave band [8]. Unfortunately, the Goubau line cannot be used in such applications due to the higher losses caused by the dielectric coating. Nevertheless, the use of this transmission line cannot be dismissed for lower frequency bands. Specially useful is the planar version of the Goubau line, the PGL. In [4], the PGL is analyzed and compared to other waveguides, and in [9], the PGL is used in to connect two points in a short path.

The PGL, shown in Fig. 1(a), is formed by a metallic strip over a dielectric substrate. Note that no ground plane is present in this transmission line. As in the classical Goubau line, the

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The authors are with the Instituto de Telecomunicaciones y Aplicaciones Multimedia (ITEAM), Universitat Politècnica de València (UPV), 46022 Valencia, Spain (e-mail: dasanes1@iteam.upv.es; mferrand@dcom.upv.es; jiherhe@upvnet.upv.es; marcafab@dcom.upv.es).

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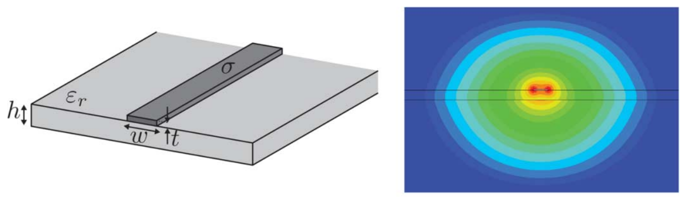
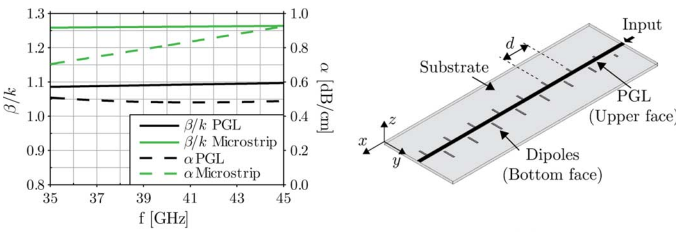


(a) (b)

Fig. 1. Planar Goubau line: (a) 3-D structure and (b) electric field of fundamental mode TM_{01} on a transverse cross section.



(a) (b)

Fig. 2. (a) Dispersion diagram and attenuation of a microstrip line and a PGL. (b) Structure of the simulated periodic leaky-wave antenna on PGL.

fundamental mode (TM_{01}) of the PGL is bounded. To illustrate this behavior, Fig. 2(a) shows the dispersion diagram of the fundamental mode of a PGL and a microstrip line with dimensions $t = 35\ \mu$m, $w = 0.75$ mm, and $h = 508\ \mu$m; copper in the metallic strip; and a dielectric substrate with $\varepsilon_r = 1.8$ and $\tan\delta = 0.02$. As can be observed, $\beta > k$ at all frequencies, and hence the mode is slow compared to the free-space velocity and does not radiate.

The electric field of mode TM_{01} is confined around the metallic strip as shown in Fig. 1(b) and presents radial polarization. The absence of a ground plane reduces the confinement of field in the dielectric substrate compared to a microstrip line. Consequently, the attenuation of the PGL is lower than the attenuation of an equivalent microstrip line, as shown in Fig. 2(a).

The above reduction in attenuation enables the PGL to be used in the design of planar antennas with a high efficiency in the millimeter-wave band. In order to produce the desired radiation, perturbations may be added along the line. The result is the periodic leaky-wave antenna presented in Section III.

III. Periodic Leaky-Wave Antenna

The inclusion of periodic perturbations along the planar Goubau line excites an infinite number of space harmonics in the line [2]. These harmonics are all tied together and comprise the fundamental mode. Hence, if one harmonic is fast, i.e., $\beta_n/k_0 \leq 1$, the whole structure radiates. The propagation constant of each harmonic (β_n) depends on the free-space wavenumber (k_0), the distance between perturbations (d), and, in case of small perturbations, the propagation constant in the isolated transmission line (β_0) as follows:

$$\frac{\beta_n}{k_0} = \frac{\beta_0}{k_0} + \frac{2n\pi}{k_0 d}. \tag{1}$$

The direction of the main beam in the resulting periodic leaky-wave antenna depends on the distance d. By suitably choosing this distance, a forward or backward pattern may be obtained. If a broadside pattern is chosen, the beam is located in the so-called *open stopband* region [2], and hence the gain of the antenna decreases considerably. To avoid this problem, the distance d in the proposed periodic leaky-wave antenna is chosen to have a nonbroadside radiation pattern.

For a single-beam operation, mode $n = -1$ is selected. In this case, the beam's pointing (θ_m) and the distance d are related as

$$\sin\theta_m \approx \frac{\beta_{-1}}{k_0}. \tag{2}$$

According to (1) and the dispersion diagram shown in Fig. 2(a), the distance between perturbations must be within the margin $d \in [0.48\lambda_0, 0.95\lambda_0]$ to have a single-mode $(n = -1)$ operation. In this letter, a separation of 5.25 mm ($0.79\lambda_0$ at 40 GHz) is chosen so that the beam direction is, approximately, $-19°$.

The proposed design uses transverse dipoles as periodic perturbations in the PGL. The unit cell is formed by two dipoles separated $d/2$, placed on each side of the metallic strip to compensate the phase difference. Taking advantage of the absence of a ground plane, dipoles are located on the bottom face of the dielectric substrate. Excitation of dipoles is done capacitively through the dielectric. This configuration allows a higher degree of freedom in the optimization process since contact of dipoles and metallic strip of PGL is avoided.

A 16-element periodic leaky-wave antenna (eight cells of two dipoles) with a cosine distribution has been designed at 40 GHz using the same PGL as in Section II. An eight-step optimization, one for each cell, has been carried out. On each step, two new dipoles have been added to the preceding structure, keeping the dimensions and positions of previously added dipoles. Thus, only the new dipoles had to be optimized adjusting their length and offset with regard to the metallic strip.

The resulting periodic leaky-wave antenna has been optimized and simulated with ANSYS HFSS [10] at 40 GHz. Fig. 2(b) shows the simulated structure, where an ideal port has been assumed at this stage of the design. Color of substrate has been set to semi-transparent to be able to observe the dipoles on the bottom face of the substrate. The radiation pattern on the H-plane at 40 GHz is depicted in Fig. 3(a) with a colored line. The presence of two main lobes is caused by the absence of a ground plane.

If a single main beam is required, a metallic plane must be used. In order to keep low losses, an air gap must be included between this plane and the antenna. The separation (s) of the antenna to the metallic plane must be optimized so that the radiated power toward the metallic plane is completely reflected and added in phase to the direct beam. Fig. 3(b) depicts a diagram of this behavior. By adding both rays in phase, the directivity of the radiation pattern is maximized. In the proposed antenna, the maximum directivity is given for $s = 5$ mm.

The radiation pattern of the structure with a reflector plane is shown in Fig. 3(a) (see black line). A single beam with a higher directivity on the opposite side of the reflector plane is obtained, as it was expected. The small lobe at 190° is caused by the finite dimensions of the reflector plane in the HFSS model. In Fig. 4(a), the typical beam steering on the H-plane of the

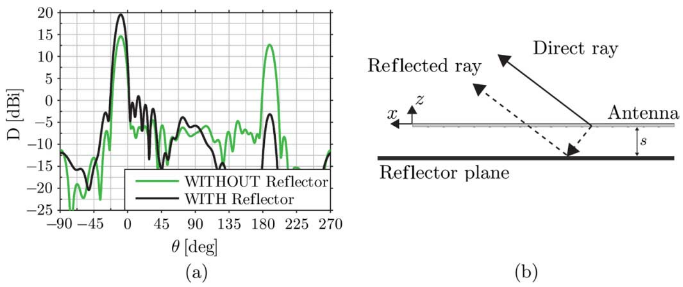


Fig. 3. (a) Comparison of the H-plane radiation pattern with and without reflector plane at 40 GHz. (b) Rays in the periodic leaky-wave antenna with reflector plane.

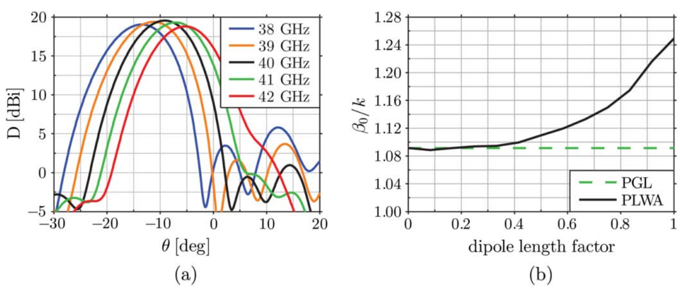


Fig. 4. Pointing of the periodic leaky-wave antenna. (a) Directivity on the H-plane at several frequencies. (b) β_0/k with different dipole lengths.

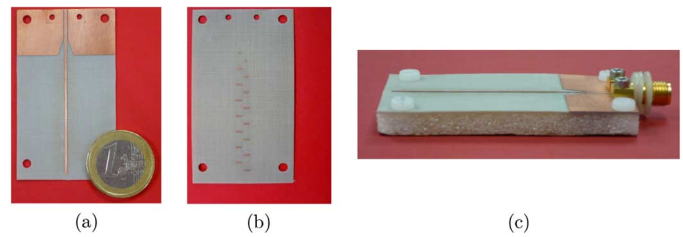


Fig. 5. Image of the manufactured periodic leaky-wave antenna: (a) upper face of the substrate, (b) bottom face of the substrate, and (c) lateral view of the complete structure.

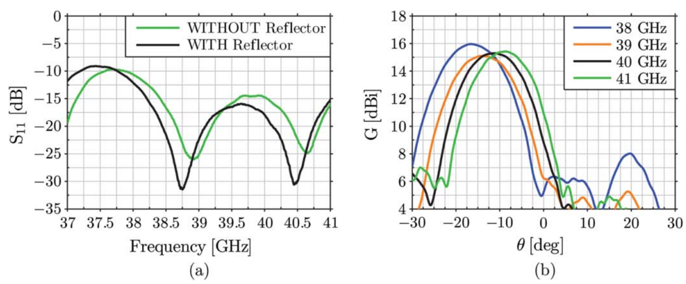


Fig. 6. Measurements of the manufactured antenna. (a) Matching with and without reflector plane. (b) Measured gain on the H-plane with reflector plane at several frequencies.

proposed antenna can be observed. A quite similar beamwidth and sidelobe level are kept at all frequencies.

The shift of the main beam's direction (-10°) with regard to the predicted direction (-19°) is caused by the use of strong perturbations, which severely modify β_0. An exact pointing approximation can only be achieved by considering the effect of dipoles in β_0 [11]–[13]. However, since the lengths of the different dipoles are optimized to obtain a cosine distribution, the exact pointing cannot be predicted from a single cell, but only considering the whole antenna.

Fig. 4(b) shows β_0/k at 40 GHz in the PGL (reference) and in the proposed periodic leaky-wave antenna (PLWA) as a function of a *dipole-length* factor that multiplies the length of all dipoles. If $\text{factor} = 0$, no dipoles are present, and β_0/k coincides with the propagation constant of the PGL. The larger the factor, the bigger the difference with regard to the reference value. If the complete antenna is considered $(\text{factor} = 1)$, $\beta_0/k = 1.25$ and, from (1), $\beta_{-1}/k = -0.17$. Hence, $\theta_m = -9.80^\circ$, which coincides with the value obtained in Figs. 3 and 4

It is worth noting that the antenna with the reflector plane does not confine the field between the metallic plane and the dielectric substrate, as in a microstrip line, and hence the transmission line losses are the same as in the PGL. Consequently, a radiation efficiency around 70% is obtained in both designs, with and without a reflector. If a microstrip-array antenna, with 16 transverse dipoles on the same plane as the metallic strip, is optimized on the same substrate as the proposed antenna, the efficiency decays below 30%.

IV. Prototype and Measurements

The periodic leaky-wave antenna has been manufactured to prove the validity of the above simulations. A photograph of the resulting structure is shown in Fig. 5. As previously explained, the PGL and the dipoles are on opposite sides of the dielectric substrate. The metallic strip of the PGL, located on the upper face of the substrate, may be observed in Fig. 5(a), and the dipoles, placed on the bottom face of the substrate, may be seen in Fig. 5(b). In Fig. 5(c), the lateral view shows the foam introduced in the bottom part of the antenna to keep the required distance between the reflector plane (when inserted) and the subtrate. This foam is only present on edges, but not in the middle of the antenna, in order not to increase losses.

A coplanar waveguide has been used to feed the antenna (from the 50-Ω connector to the PGL). The smooth transition allows a good matching of the antenna, as shown in Fig. 6(a). In this comparison, it can be seen that, for both cases, with and without reflector plane, a low S_{11} parameter is obtained in all the bands. There is a small shift between responses due to the presence of the reflector plane, but the matching is kept below -10 dB from 37 to 41 GHz in both cases.

The radiation pattern of the antenna with the proposed configurations has been measured at different frequencies. Fig. 7(a) shows the directivity on the H-plane at 40 GHz. As expected, the design without a reflector plane presents two main lobes on the H-plane, and when a reflector plane is introduced, just a single beam is obtained. The sidelobe level is lower than -16 dB, which coincides with the simulated result [see Fig. 3(a)].

Fig. 7(b) shows the measured directivity on the E-plane at 40 GHz for both proposed configurations. The wider beam on this plane corresponds to the use of only two elements in the y-direction.

The beam steering on the H-plane can be observed in Fig. 6(b). Here, the attention is focused on the main beam of the periodic leaky-wave antenna with reflector plane. The gain in this lobe is represented to better quantify the losses at each

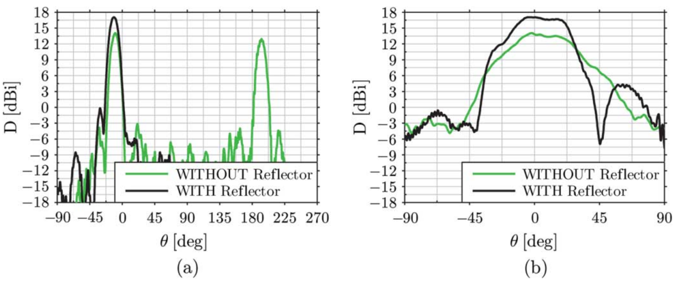


Fig. 7. Measured directivity of the periodic leaky-wave antenna with and without reflector plane at 40 GHz: (a) H-plane and (b) E-plane.

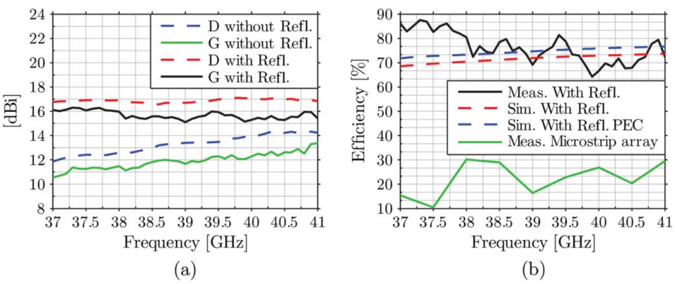


Fig. 8. Losses versus frequency. (a) Measured maximum gain and directivity with and without reflector (Refl.) plane. (b) Efficiency with reflector plane.

frequency. As can be observed, the direction of the main beam changes with the frequency, though the gain is quite uniform. Note that the stopband effect is not present because the pointing is still far from the broadside direction.

The maximum gain and directivity have been measured in the band 37–41 GHz using a spherical near-field measurement setup with a standard-gain horn as a probe. The gain was determined by substitution, as described in [14] for near-field measurements. The comparison for both, with and without reflector plane, is shown in Fig. 8(a). A high gain and directivity can be observed in both cases.

Fig. 8(b) compares the simulated and measured radiation efficiency of the array with reflector plane. The average efficiency in the upper part of the band (38–41 GHz) is 71%. The same comparison for the antenna without reflector plane gives similar values, with an average efficiency of 70% in the same band. Fig. 8(b) also shows the simulated efficiency in the proposed antenna with reflector plane considering perfect conductors. As can be observed, a low percentage of efficiency (5%) is lost by the effect of real conductors. From this comparison, it can also be concluded that a 25% of efficiency is lost by the dielectric due to its high loss tangent (0.02).

Fig. 8(b) also compares the above efficiencies with the measured efficiency in a microstrip-array antenna with 16 transverse dipoles on the same substrate as the proposed antennas. As it was expected, the high dielectric confinement decreases the radiation efficiency to values below 30%.

V. CONCLUSION

A periodic leaky-wave antenna in the millimeter-wave band has been proposed in this letter. A planar Goubau line has been used to distribute the energy to the different dipoles forming the array. This transmission line presents lower losses than common microstrip lines at high frequencies due to the absence of a ground plane.

To avoid the double-beam shape of the periodic leaky-wave antenna with planar Goubau line, the use of a reflector plane is proposed. The presence of this plane does not increase the losses of the antenna since the transmission line has the same attenuation as without this plane. This behavior has been confirmed in the measured results since a similar measured radiation efficiency 71% and 70%, with and without reflector plane, respectively, has been obtained.

Measured results also confirm the good sidelobe level, predicted in simulations, as well as the beam steering in frequency. This last feature may be especially important at higher frequencies (in the 60-GHz band) where automotive radar is being increasingly used. In this context, the high efficiency of the proposed design is very appealing, especially compared to other common technologies at these frequencies.

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