A Dual-Layer Planar Leaky-Wave Antenna Designed for Linear Scanning Through Broadside

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***Abstract*—A low-cost planar leaky-wave antenna (LWA) offering directive antenna beam patterns as well as linear beam scanning through broadside is proposed. The design is based on a one-sided annular slot grating placed on a dual-layer grounded dielectric slab with an integrated TM_0 antenna feed system in the bottom ground plane. By appropriate selection of the width and the period of the top radiating annular slots, as well as the substrates, the structure is optimized to excite and perturb the dominant TM mode for the generation of directive beam patterns that can scan with frequency in the far field. In particular, the antenna parameters are chosen to obtain a narrow open stopband frequency range at broadside as well as control the dispersive scanning behavior. A method-of-moments dispersion analysis has also been developed to assist in the design and fully characterize the proposed antenna. These results are complemented by full-wave simulations and measurements of a LWA prototype offering realized gain values in excess of 14 dBi with scanning through broadside at 23.5 GHz.**

***Index Terms*—Annular slot grating, dual-layer substrate, leaky-wave antenna (LWA), planar antennas, surface waves (SWs).**

I. Introduction

PLANAR antennas, in particular microstrip patch antennas, are low-cost and low-profile structures that have received considerable interest and attention in recent decades because of their versatility and compatibility with other planar technologies. Typical applications include radar and remote sensing as well as communication applications.

These microstrip patches can provide a high-gain pencil beam when arranged in an array configuration, but feeding and radiation efficiency can be troublesome at microwave and millimeter-wave frequencies due to unwanted surface-wave (SW) excitations. Alternatively, high-gain planar antennas of the leaky-wave type (planar leaky-wave antennas, LWAs) can be designed to leak and exploit these SWs by the transformation from a slow guided wave to a fast wave. In this case, radiation is characterized by means of a complex leaky-wave (LW) mode, i.e., a wave propagating along the antenna structure, seen as an open waveguide, with a certain amount of attenuation, α, due to radiation.

However, to generate and support a LW with the required phase and attenuation constants, β and α, respectively, and hence radiation features such as the main beam pointing angle θ_p and beamwidth, the planar structure should be properly designed. In addition, the LW should be dominant, in the sense that the excitation of the LW fields should be large in comparison to those of any other guided modes and that of the space wave [1]–[3]. These types of low-profile LWAs can generate conical and directive pencil-beam patterns that scan with frequency. Recently, planar configurations based on metallic strip patternings have been introduced using SWs [4]–[7], and, in particular, a new kind of circular two-dimensional (2-D) LWA, a so-called bull-eye, was presented in [8]. It was constituted by a radial and periodic metallic strip grating (MSG) printed on a grounded dielectric slab (GDS).

In this letter, we propose a new design of a *one-sided* planar LWA of the "bull-eye" type [8]–[10], optimized for broadside radiation and low-cost fabrication (see Fig. 1). To the best of the authors' knowledge, no similar antenna with a directional and integrated feed system has been reported that can offer continuous frequency, *one-sided* pencil-beam scanning through broadside with realized gain values above 16 dBi. In particular, we report the design of an annular slot grating placed on top of a dual-layer GDS. The directional feed system and bottom layer are designed to efficiently support the dominant TM mode of the slab. The second dielectric layer (superstrate) and slot grating enable the control of α for the excited LW mode and define the radiation mechanism, i.e., a partially reflecting surface (PRS) to transform the radial, guided-wave mode contained within the dual-layer GDS to a radiating LW mode. More importantly, the proposed structure is optimized to display a very narrow open stopband at broadside as well as linear scanning behavior with frequency through broadside [11], [12]. To this aim, the thickness and permittivity of the dielectrics have been properly designed to generate an evanescent TM field in the superstrate that radially propagates within the bottom guide at the h_1 and h_2 interface, similar to a TM_0 SW mode that radially propagates at the air–dielectric interface of a GDS with an evanescent field component in the air region.

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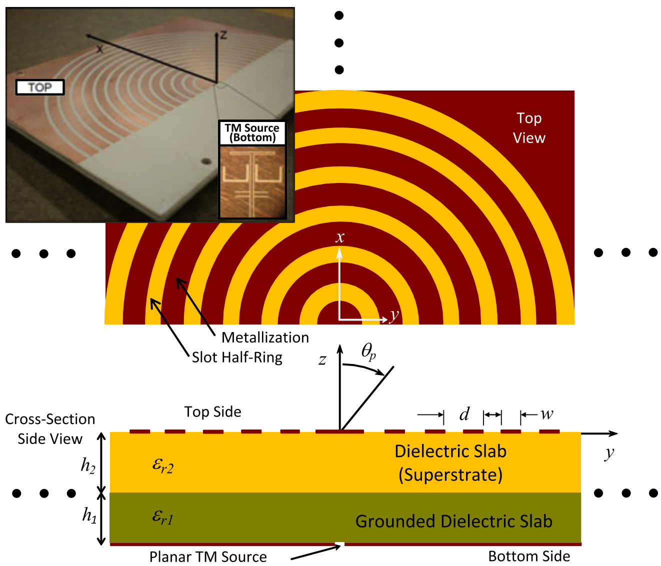

Fig. 1. Top and cross-sectional views of the considered planar antenna defined by a slot grating on a dual-layer GDS. The measured *one-sided* antenna prototype (see the inset) has 14 annular slots ($w = 1.4$ mm and $d = 5$ mm) defining the top PRS. An arrangement of printed slots in the bottom ground plane acts as the antenna feed with a 50-Ω coplanar waveguide feeding transmission line for excitation of the dominant TM_0 mode.

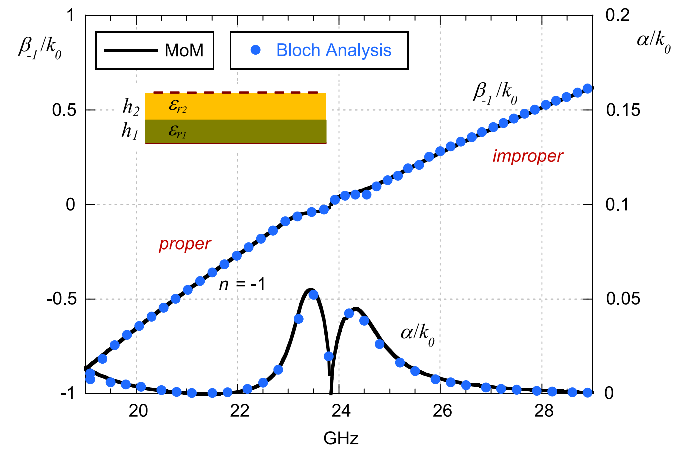

Fig. 2. LW phase and attenuation constants, obtained by MoM dispersion analysis on the linearized 1-D unit cell of the dual-layer structure. Results are also compared to the Bloch analysis technique reported in [17], which uses a commercial full-wave solver and 15 unit cells for the proposed dual-layer LWA. Structure parameters: $d = 5$ mm, $w = 1.4$ mm, $\varepsilon_{r1} = 10.2$, $h_1 = 1.27$ mm, $\varepsilon_{r2} = 3$, and $h_2 = 1.524$ mm.

Our proposed structure is also relatively compact, 80 × 160 mm^2 (or $6.4\lambda_0 \times 12.8\lambda_0$ when compared to the free-space wavelength at the center design frequency of 24 GHz), which may be a feature of interest in most practical cases where planar antennas of the traveling-wave type are employed. It should also be mentioned that the proposed LWA could be particularly suitable for some applications such as wireless power transmission, tracking radar, security, and surveillance [4]–[7] due to its frequency beam scanning and broadside radiation characteristics with high gain.

We note that other "bull-eye" LWAs defined on a single-layer GDS with a top MSG have been proposed recently, but in a *two-sided* configuration and with complete microstrip annular rings [13]. These structures offered gain values at broadside of about 13 dBi with dimensions $11.3\lambda_0 \times 11.3\lambda_0$, however, by the combination of two far-field beam patterns [14]. Finally, it should be mentioned that some initial findings were reported in [15] on the proposed dual-layer LWA, but only preliminary simulation and experimental results were presented for a larger *two-sided* implementation. In addition, the theoretical details describing the fundamental antenna operation were limited.

This letter is organized as follows. In Section II, the modal analyses of a linearized version of this "*one-sided*, half bull-eye antenna" are developed by using the method of moments (MoM) for accurate predictions of the relevant leaky modes supported by the structure. These theoretical analyses and design approaches are confirmed through full-wave simulations. In Section III, experimental validation and a performance assessment of the measured planar LWA prototype are compared against the MoM results. Conclusions follow in Section IV.

II. Theoretical Modal Analysis

We exploit here LW theory to provide first insight on the performance of the proposed dual-layer, "bull-eye" LWA. The design of the considered radial structure can be based on the modal analysis of an equivalent one-dimensional (1-D) linearized (lossless) structure, as was previously done for similar annular configurations in [16] and [17]. Consequently, the antenna design can start by the analysis of an infinite 2-D structure with propagation normal to the strips. To this aim, a MoM code developed and presented for the first time in [18] for the analysis of single-layer, phased-array microstrip LWAs has been suitably modified in this work to account for the presence of the superstrate and PRS.

As is well known, radiation is usually described in terms of space harmonics (i.e., Floquet waves) for these LWAs generated by the presence of the periodic structure. Given the direction of propagation to be along the x-axis, the nth harmonic has a wavenumber defined by $k_{xn} = k_{x0} + 2\pi n/d$, where d is the period and $k_{x0} = \beta_0 - j\alpha$ is the wavenumber of the fundamental harmonic [1]–[3]. Typically, the structure is designed to radiate through the $n = -1$ spatial harmonic.

Starting from the design of the single-layer structure as discussed in [16] for efficient SW excitation, where a GDS with $\varepsilon_{r_1} = 10.2$ and thickness $h_1 = 1.27$ mm were chosen, the superstrate and PRS were added to provide a further degree of freedom in controlling α and the scanning behavior. Dispersion curves β_{-1}/k_0 and α/k_0 for the linearized version of the LWA in Fig. 1, with a superstrate having permittivity $\varepsilon_{r_2} = 3$ and thickness $h_2 = 1.524$ mm, are shown in Fig. 2. It can be observed that the normalized phase constant for the considered spatial harmonic increases *linearly* with frequency passing through broadside, i.e., $\beta_{-1}/k_0 = 0$, at a frequency value f_c equal to about 24 GHz. This defines a *proper* LW, $\Im\{k_{zn}\} < 0$, with a pointing angle θ_p that will scan from backward endfire to broadside (for frequencies lower than f_c) and an *improper* LW, $\Im\{k_{zn}\} > 0$, from broadside to forward endfire (for frequencies greater than f_c) where k_{zn} defines the wavenumber in the vertical direction.

In Fig. 2, results obtained with the modal Bloch approach based on the full-wave simulation of the truncated structure are also reported. Typically, the number of unit cells simulated depends on the complexity of the structure. However, results have been obtained with 15 unit cells [17]. Good agreement between the MoM and the hybrid Bloch-wave approach for both the *proper* and *improper* branches can be observed.

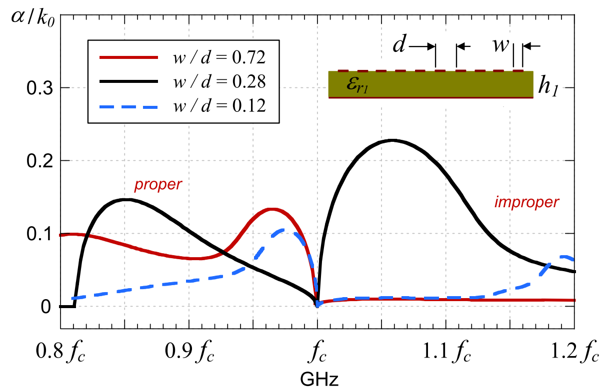

Fig. 3. Numerically calculated MoM LW attenuation constants for a single-layer structure as shown in the inset for different top strip widths, w, while all other structure parameters were held constant ($d = 5$ mm, $\varepsilon_{r1} = 10.2$, and $h_1 = 1.27$ mm). Values are shown versus the normalized open stopband frequency, f_c, around which a *double bump* is not observed.

Unfortunately, it is challenging to obtain a beam exactly at broadside (i.e., $\beta_{-1} = 0$) for a unidirectional periodic LWA structure, where a so-called open stopband is present (i.e., $\alpha = 0$). However, special techniques can be adopted to mitigate [11] or suppress [12] the open stopband. In our design, the superstrate, the periodicity d and the strip width w have been properly chosen to obtain moderately high values for the attenuation constant, i.e., $\alpha/k_0 > 0.02$, below and above f_c, and, in particular, to control the frequency-dependent attenuation constant that can be characterized by a double symmetric bump around f_c. Similar LW dispersion behavior was also obtained in [11] but with a different approach, which employed two strips within a unit cell for controlled leakage. In our work, a simpler, dual-layer planar structure for low-cost implementation is designed with a single slot within each unit cell, classically defining the structure periodicity and perturbation mechanism for LW excitation and radiation.

As a comparison to our proposed dual-layer LWA and its desired dispersion features (see Fig. 2), the attenuation constant for three other single-layer structures having different top strip widths is shown in Fig. 3. It can be observed that the values are shown versus the normalized open stopband frequency f_c. As expected, a nonsymmetric shape for α with respect to f_c is obtained in all cases along with larger open stopband intervals.

It should be stressed that the presence of the superstrate and PRS can considerably mitigate this open stopband behavior (see Figs. 2 and 3); this could permit radiation at broadside when considering a practical and truncated planar LWA that supports a radial cylindrical LW mode [2]. For example, as reported in [13]–[16], a well-defined conical-sector and pencil-beam pattern were observed in the far field with frequency scanning through broadside with moderately high gain.

Once the dispersion analyses of the proposed structure have been performed for the desired LW excitation, the main features of the far-field beam pattern generated by the LWA can be further characterized [1]. Even though the dispersion analysis reported in Fig. 2 presents a linearized 1-D version for the proposed planar LWA, the results are still informative for the radial implementation. For example, the dominant TM leaky mode supported by the structure shows a relatively high value for the normalized leakage constant around the open stopband frequency. This has been taken into account in the fabrication of the LWA prototype, whose total radial length has been fixed to

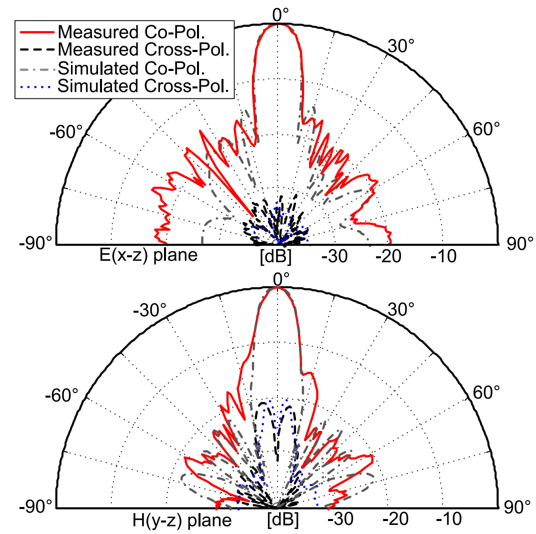

Fig. 4. Measured radiation patterns in both the $E(x\text{–}z)$ and $H(y\text{–}z)$ planes at 23.5 GHz (referenced to main slot of the TM antenna feed). Measured results are normalized to the observed realized gain maximum of 14 dBi at broadside and compared to the simulations.

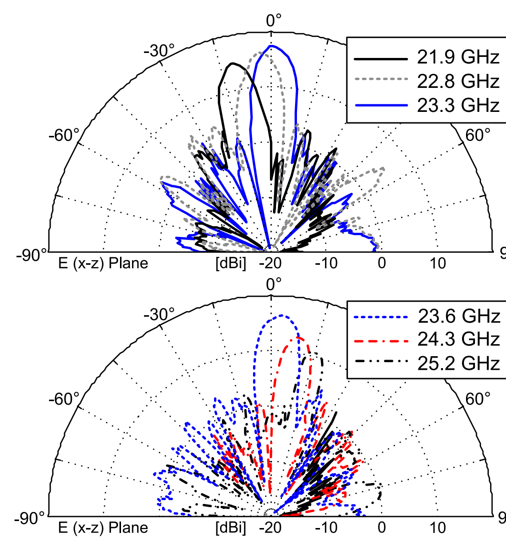

Fig. 5. Measured beam patterns at different frequencies. The observed maximum realized gain is greater than 16 dBi. Top: endfire to broadside scanning; bottom: broadside to endfire.

achieve a 90% radiation efficiency or more when $\alpha/k_0 \geq 0.03$. Following this design approach, experimental results for the proposed LWA are described in Section III.

III. Antenna Design and Measurements

Measurements were completed in a calibrated anechoic chamber, and the prototyped structure is presented in the inset of Fig. 1. Some details regarding the layout of the employed TM planar antenna source are also shown in the inset and [5], which have been shown to offer efficient TM_0 excitation for similar planar LWAs. However, for the present LWA, unlike the *two-sided*, single-layer structures proposed in [13] and [16], a *one-sided* beam pattern is desired and generated by the unidirectional source.

The simulated and measured co- and cross-pol components of the radiation pattern for the proposed *one-sided* dual-layer

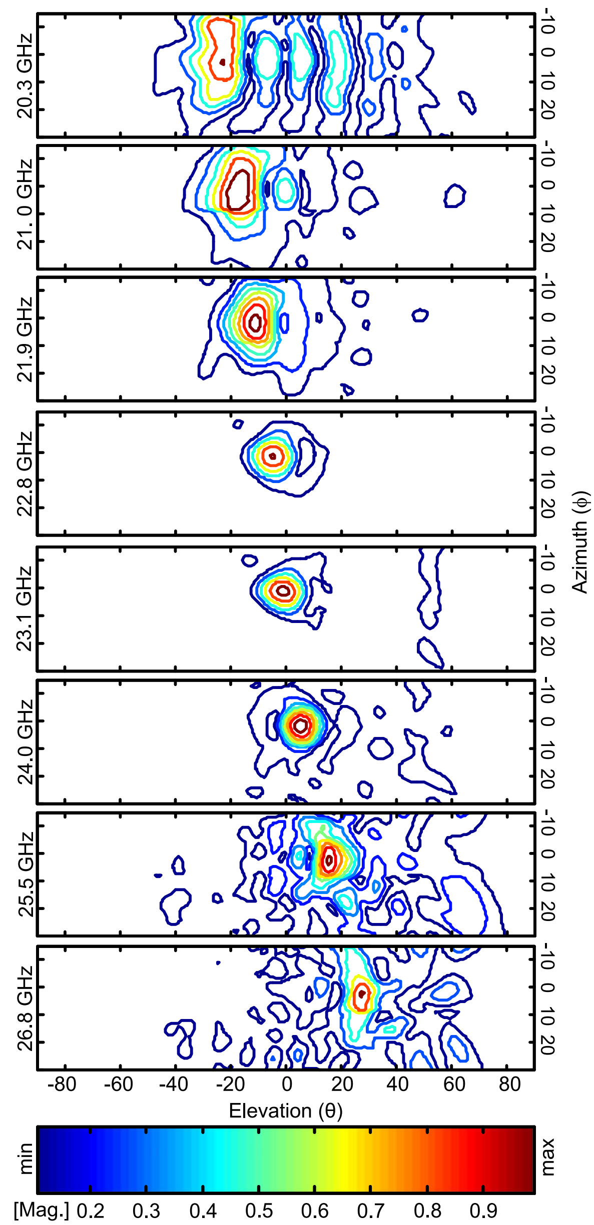

Fig. 6. Measured 2-D patterns. A single pencil beam from 20.3 to 26.8 GHz is observed. Values have been normalized to observed maxima, and results are shown in linear units. The frequency values increase from the top to the bottom in the subfigure panels.

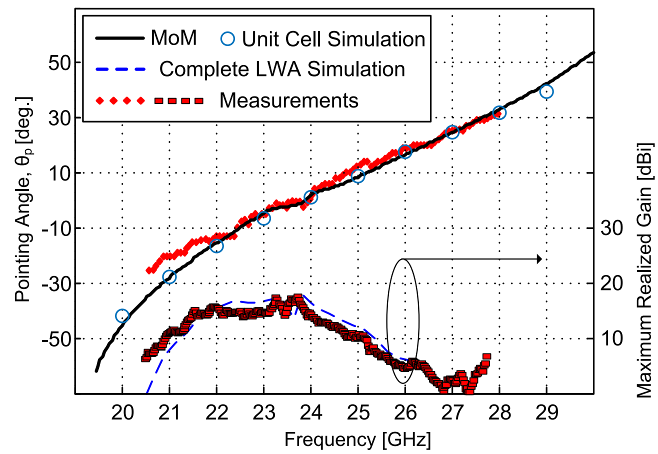

Fig. 7. Pointing angle θ_p for the "*one-sided* bull-eye" LWA in Fig. 1. Also shown is the maximum realized gain in the $E(x - z)$ plane.

structure are provided in Fig. 4 for a frequency where a broadside beam is observed ($f = 23.5$ GHz). Good agreement has been obtained as well as a very good polarization purity with a high gain at broadside. In addition, the sidelobe levels are 15 dB below the main beam patterns. The measured radiation patterns illustrating the scanning behavior through broadside are also presented in Fig. 5. Thanks to a very narrow open stopband frequency range, the antenna can radiate a single beam at broadside, with beam scanning from broadside to endfire from 23.3 to 21.9 GHz and in the forward direction from 23.6 to 25.2 GHz. It is also possible to appreciate the linear scanning features of the measured prototype by observing the 2-D patterns in the azimuth and elevation for different frequencies as shown in Fig. 6.

In Fig. 7, the scanning behavior of the fabricated prototype is reported, showing very good agreement between the pointing angles obtained by the measurements and the full-wave simulations based on a unit cell, as well as those predicted by LW theory ($\theta_p \simeq \sin^{-1}(\beta/k_0)$) through the MoM dispersion analysis (from Fig. 2). These results suggest that the LW field is dominant on the aperture generating the desired beam patterns in the far field. It should also be mentioned that there is slight disagreement between the numerical calculations and the measurements for θ_p below 22 GHz. As discussed in [13], this is related to the positioning of the first slot ring, $d_0 = 9.3$ mm as in this work. Moreover, full-wave simulations for the complete structure defined by the planar antenna and feed system (not reported here for brevity) show that when the position of the first ring is increased to about one wavelength ($d_0 \approx \lambda_0$), as in [13], the simulated and MoM beam pointing angles are in better agreement, i.e., -27° and -28°, respectively. This design choice, to position the first ring at a distance of 9.3 mm from the source, was selected to ensure a compact LWA implementation. Regardless of this fact, the desired *one-sided* linear beam scanning behavior is observed for the proposed LWA, where the slope of the pointing angle is equal to about 8°/GHz with scanning through broadside.

We finally note that the maximum realized gain shown in Fig. 7 has a quite stable behavior around broadside, with a negligible drop at the broadside frequency of 23.5 GHz. This suggests that the optimized scanning behaviors through broadside for the proposed *one-sided* LWA are achieved as per design. It should also be mentioned that a decrease in gain can be observed away from the broadside frequency, below 22 GHz for example, where the low values for α/k_0 (< 0.01 see Fig. 2) do not support significant leakage from the truncated and practically sized LWA structure.

IV. Conclusion

A dual-layer, radial slot-based planar antenna capable of providing linear one-sided beam scanning through broadside has been analyzed, designed, and measured. Dispersion analyses of the considered structure have been performed using a MoM full-wave approach, and results are further validated by a commercial numerical solver. Overall, through theoretical modeling, an optimized slot grating as well as the thicknesses and the permittivity of the dielectric layers have been selected to mitigate the open stopband and permit broadside radiation. The final design results in a compact, low-cost, and low-profile prototype showing attractive performance in terms of beam scanning through broadside with high gain.

In future work, modification to some of the antenna parameters may show to offer different radiation performances. In particular, by varying the top slot width w, as well as increasing the relative dielectric constant for the bottom layer ε_{r1}, the angular scan range can be enhanced along with a more constant leakage rate versus frequency. This would differ from the proposed feed and compact LWA implementation, which has been designed with a narrow open stopband frequency range at broadside, which can offer linear beam scanning through broadside with high gain.

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