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Analysis and Design of a Circularly-Polarized Planar Leaky-Wave Antenna

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***Abstract*—We present the design and analysis of a K-band radially-periodic leaky-wave antenna radiating a circularly polarized broadside pencil beam. The structure is constituted by a metallic strip grating printed on top of a single-layer grounded dielectric slab, and is fed on the bottom by means of a square array of printed surface-wave launchers. The structure is optimized to support the fast $n = -1$ spatial harmonic, whose behavior has been accurately characterized through a full-wave dispersive analysis developed by means of an in-house method-of-moments (MoM) code. By proper phasing the four independent feeding points, linear or circularly polarized pencil beams can be obtained by exciting a dominant but weakly-attenuated, cylindrical TM leaky-wave mode. In this way, highly-directional broadside pencil beams showing good polarization purity can be obtained. The proposed design is of interest for modern satellite and terrestrial point-to-point communications.**

I. Introduction

Planar leaky-wave antennas (LWAs) are a class of low-cost and low-profile guiding structure and can represent an attractive alternative to more common array configurations of resonant microstrip patches [1]. Thanks to their traveling-wave nature, simple and efficient feeding structures are typically used to launch a slow-wave for radiation. Power leakage into the far-field can be obtained by some perturbation mechanism to generate highly-directional beam patterns and thus defines the transformation of the slow, guided-waves into fast-waves. This allows for characterizing the radiation in terms of complex leaky-wave (LW) modes [1, Ch. 7], that in turn effectively represent waves propagating along the air-dielectric interface. A radially periodic LWA is made by a grounded dielectric slab (GDS) loaded with a metal strip grating having an annular geometry (typically referred as bull-eye, see, e.g., [2] and refs. therein) as shown in Fig. 1.

As is well-known, to effectively design this class of LWA, the relevant structure has to be properly designed in order to support a weakly-attenuated cylindrical leaky wave (CLW) mode of order m [3]; i.e., a traveling-wave with an azimuthal dependency of the kind $e^{-jm\phi}$, whose contribution to the aperture field should be made dominant with respect to other guided modes and the space-wave (see, e.g., [1, Ch. 7]).

In this contribution, we propose the design of an annular LWA driven with four feed points for the generation of a highly-directional circularly-polarized (CP) pencil beam at

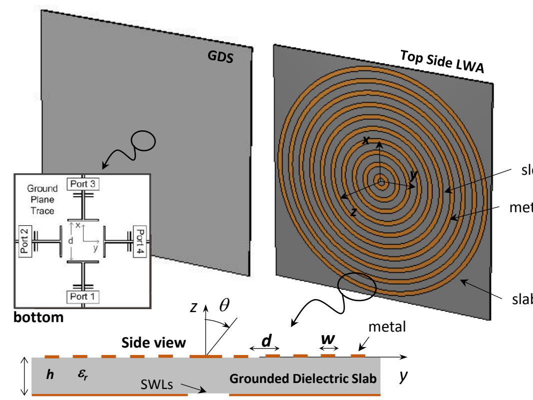

Fig. 1. Bottom view of the GDS and of the LWA (left and right panel, respectively). A proper arrangement of printed slots in the bottom ground plane of the GDS (see inset), practically realized using an array of SWLs, acts as the antenna feed for excitation of the dominant TM_0 SW mode. A side view for the bull-eye antenna is also presented in the bottom panel.

broadside. To this aim, a new square arrangement of planar surface-wave launchers (SWLs) integrated into the ground plane [2] are considered and properly phased to radiate a CP beam with high polarization purity. It should be mentioned that typically, to obtain a CP far-field pattern, an array of linearly polarized elements can be considered [4]-[6]. This can be comprised of patches or microstrip antennas, however, at millimeter-wave frequencies reduced antenna radiation efficiency can be observed. Moreover, this more conventional solution can require the design of a bulky feed system which can reduce the total antenna gain and total antenna efficiency.

As an alternative approach to employing printed patch arrays for the generation of CP beam patterns, LWAs can represent a low-cost and simple antenna for implementation. For example, in the last decade, both 1-D periodic and 2-D LWA design have been proposed to support CP beams (see, e.g., [7]–[9], and refs. therein). However, by using four feed elements in a square configuration it is possible to obtain low cross-polarization levels over a wider beamwidth and frequency bandwidth and thus such a topology was utilized in our proposed K-band LWA design (see Fig. 1).

II. Antenna Design and Dispersion Analysis

The design is based on a commercially available GDS, reported in Fig. 1 (top left panel), fed on the bottom by means

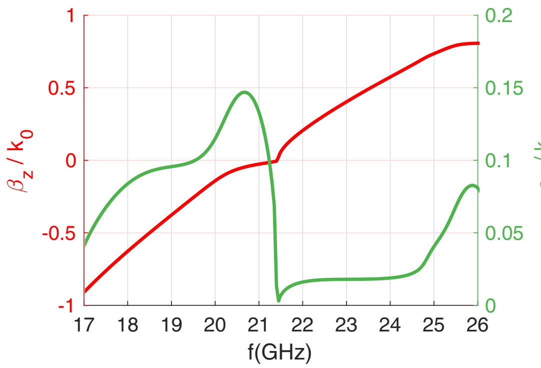

Fig. 2. Normalized LW phase (left axis) and attenuation (right axis) constants, obtained through the method-of-moments (MoM) by performing a dispersion analysis. Structure parameters: $d = 7$ mm and $w = 1.25$ mm.

of a square arrangement of SWLs at the origin. The four-port feeder is able to excite a surface-wave (SW) with an m-order azimuth harmonic, which is properly perturbed by the top annular MSG (see right panel in Fig. 1). A dispersive analysis of the considered annular structure has also been developed, considering the modal analysis of an equivalent 1-D linearized (lossless) structure (see Fig. 1 bottom panel), as done for similar annular configurations [2].

Thanks to the 2-D nature of the problem, the spectrum of Bloch modes propagating along the structure can be divided into both TM and TE modes, each mode being characterized by a Floquet representation in terms of an infinite number of space harmonics with wavenumbers $k_{yn} = \beta_0 + 2\pi n/p - j\alpha$. Typically, the structure is designed to radiate through the $n = -1$ space harmonic [1, Ch. 7]), [2]. By properly designing the MSG, low attenuation rates (i.e., $\alpha/k_0 \ll 1$) can be obtained, and a directive beam patterns can be observed. We consider here a laminate with $\varepsilon_r = 10.2$ and thickness $h = 1.27$ mm, and develop a dispersive analysis of the structure by means of an in-house MoM code previously developed by some of the authors (see [2] and refs. therein). The complex unknown of the problem, i.e., $k_{y0} = \beta_0 - j\alpha$ is determined by suitably selecting the proper or improper nature of the fast (i.e., radiating) space harmonics. We focus here on TM waves, excited by the SWL array in the ground plane.

The normalized dispersion curves of β_{-1}/k_0 and α/k_0 versus frequency for the LWA in Fig. 1 (right panel), are shown in Fig. 2. It can be observed that the phase constant for the considered space harmonic ($n = -1$) increases almost *linearly* with frequency, changing its sign passing through broadside, i.e., $\beta_{-1}/k_0 = 0$, at a frequency value f_c equal to about 21.5 GHz, and defining a *proper* LW with a pointing angle θ_p that will scan from backward endfire to broadside and an *improper* LW from broadside to forward endfire. Since we are interested in designing a CP polarized broadside pencil beam, we selected an operating frequency satisfying the well-known splitting condition; i.e. $\beta_{-1} \approx \alpha$. By inspection of Fig. 2 a good leakage rate (i.e., α/k_0 of the order of 0.05) is obtained around the cut-off of the LW mode for the proper branch, hence we have selected an operating frequency of about 20 GHz. This choice allows for dealing with a practically sized LWA while obtaining an efficiency of about 90%.

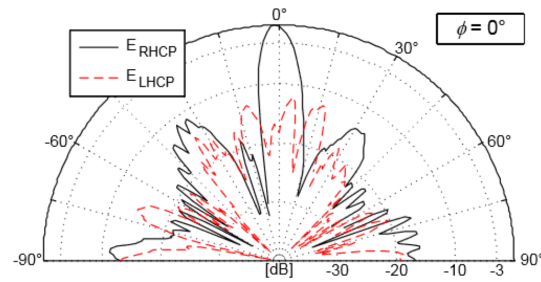

Fig. 3. Measured CP beam patterns at 19.9 GHz for the designed LWA (xz plane). A directive pattern with low cross-polarization levels are observed.

III. Radiation Features

Once the MSG is designed to support a fast spatial harmonic ($n = -1$ in this case), the four-port feeder can be suitably phased to generate an m-order azimuth harmonic, associated with the launched TM CLW mode for radiation. If a uniform amplitude and constant phasing is considered, both the structure and the feed arrangement are azimuth-symmetric, thus the antenna radiates an $m = 0$ CLW mode. Conversely, keeping constant the amplitude coefficients, and phasing of the four SWLs (see inset in Fig. 1) following a progressive phase pattern given by $\angle 0°$, $\angle -90°$, $\angle -180°$, and $\angle -270°$, an $m = 1$ CLW mode can be generated, and a RHCP polarized beam is obtained in the far-field.

Experimental validations have been completed on a manufactured prototype. Quadrature feeding of the SWLs was achieved using external couplers (one 180° and two 90°) and calibrated cables, defining a RHCP field distribution on the aperture. Measurements results for the radiation pattern are reported in Fig. 3, which shows a RCHP broadside pencil beam on the principal plane $\phi = 0$. The plot also reports the corresponding LHCP, showing a cross-polarization level of less than 10 dB. The realized gain values of the beam are greater than 10 dBic, with side lobe levels more than 10 dB below this maximum.

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