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***Abstract*—A fully metallic sectorial leaky-wave antenna (LWA) is proposed to perform passive two-dimensional direction-of-arrival (DoA) estimation. The LWA consists of a sectorial waveguide with radial glide-symmetric corrugations on the bottom plate and periodic slots on the top plate. The sectorial geometry and the slots allow for a 2-D directional pattern in azimuth (ϕ) and elevation (θ) planes. The antenna, designed without active components and fed by a single port, ensures a simple and cost-effective design. The performance of the LWA for 2-D DoA estimation is evaluated using the multiple signal classification (MUSIC) algorithm. The proposed passive LWA enables accurate elevation and azimuth DoA estimation with a single-port setup.**

***Index Terms*—Direction-of-arrival (DoA) estimation, leaky-wave antennas (LWA), multiple signal classification (MUSIC), metasurfaces, periodic structures, higher symmetry.**

I. Introduction

Accurate 2-D direction-of-arrival (DoA) estimation is crucial for modern sensing technologies and mmWave communication systems. Traditional DoA estimation systems often use phased antenna arrays. Although effective, these configurations are generally large, costly, and can lead to high power consumption due to their reliance on active components [1]. As a promising alternative, passive metasurfaces provide a compact and cost-efficient solution by enabling spatial manipulation of phase and amplitude distributions in guided and radiated waves. This property is exploited in metasurface-based leaky-wave antennas (LWAs) [2]–[6], which enable frequency-dependent beam scanning through controlled radiation leakage. To exploit this potential, the multiple signal classification (MUSIC) algorithm has been used for 2-D DoA estimation of signals received by suitably designed LWA. However, the front-end complexity and the detection capability in a wide field of view still need to be addressed. On one hand, [4] uses a multiport configuration, which involves a complex front-end architecture, and, moreover, the proposed solution leads to ambiguity in the detection of azimuth angle ϕ. On the other hand, as an alternative, a passive LWA based on sectorial corrugated waveguide with single-port feeding was proposed in [5], but the azimuthal mirror-symmetry of the radiation pattern leads to ambiguity in the ϕ angle estimation. In [6], a single-port LWA with radial glide-symmetric corrugations on the bottom plate and periodic slots etched on the top plate was proposed to break the azimuthal mirror-symmetry of the radiation pattern.

This work proposes a simplified front-end design that resolves azimuthal ambiguity with a single-port antenna. The paper is organized as follows. Section II describes the LWA with radial glide-symmetric corrugations on the bottom plate and periodic slots etched on the top plate, and the simulated results are shown. Section III performs DoA estimation using the proposed LWA with MUSIC algorithm. Conclusions are drawn in Section IV.

II. Radial glide-symmetric corrugated LWA

Based on the approach presented in [5], this work proposes a sectorial waveguide with corrugations on the bottom plate and periodic slots on the top plate for 2-D direction-of-arrival (DoA) estimation. The concept of radial glide-symmetry was proposed for the first time in [6]. To resolve the ambiguity in estimating the angle ϕ reported in [5], arising from the azimuthal mirror-symmetry of the radiation pattern, this work employs a sectorial leaky-wave antenna featuring radial glide-symmetric corrugations and non-mirror-symmetric slots with respect to the xz (or $\phi = 0$) glide plane [6].

A. LWA geometry

The geometry of the corrugated leaky-wave antenna is shown in Fig. 1a and Fig. 1b. The angular aperture ϕ_0, along with corrugation and slot parameters, follows the design detailed in [5], [6] and are summarized in the caption of Fig. 1. Different from [6], a radial length $L = 210\,\text{mm}$ was selected to ensure that most of the power is radiated before the termination of the antenna [5].

The slots are etched on the top plate in the positive ϕ region (region 1) with a radial period $p_{s,1} = 6.3\,\text{mm}$, and in the negative ϕ region (region 2) with a radial period $p_{s,2} = 5.4\,\text{mm}$. The slot periods and shapes are chosen to radiate a single beam and to yield a directional pattern in the E-plane (xz plane), while the angular aperture of the sector grants to a lesser extent some directivity on the H-plane

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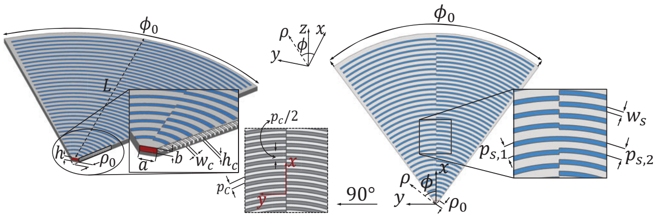
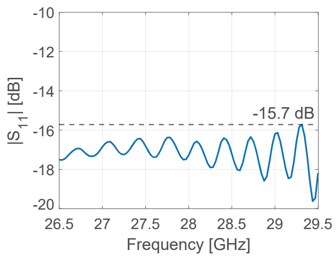


(a) (b)



(c)

Fig. 1: Radial glide-symmetric corrugated sectorial LWA with feeding in red: a) isometric view, b) top view. The geometric parameters are $\phi_0 = 73°$, $L = 210\,\text{mm}$, $\rho_0 = 4.8\,\text{mm}$, $p_{s,1} = 6.3\,\text{mm}$, $p_{s,2} = 5.4\,\text{mm}$, $w_s = 2.14\,\text{mm}$, $h_c = 1.6\,\text{mm}$, $p_c = 2\,\text{mm}$, $w_c = 1\,\text{mm}$, $a = 7.112\,\text{mm}$, $b = 2.556\,\text{mm}$, $h = h_c + b$. (c) $|S_{11}|$ of the LWA proposed.

(yz plane). A different frequency- and azimuthal-scanning behavior is achieved in each one of the regions 1 and 2 thanks to the different slot parameters. This increases the diversity in the radiation pattern with respect to the xz plane [6]. 32 and 38 concentric slots are etched on the top plate in the two regions, all with the same radial width $w_s = \lambda_0/5$, where λ_0 is the free-space wavelength at a central frequency of 28 GHz.

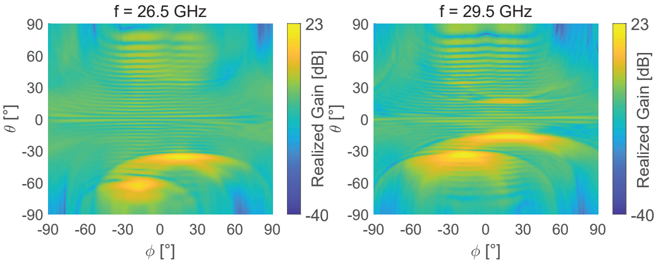
B. LWA radiation properties

In this subsection, the radiation features of the radial glide-symmetric corrugated sectorial leaky-wave antenna are discussed. The structure exhibits good impedance matching across the considered bandwidth $[26.5, 29.5]\,\text{GHz}$, as confirmed by the reflection coefficient $|S_{11}| < -15\,\text{dB}$ (Fig. 1c), achieved without requiring initial corrugation or slot tapering. The 2-D realized gain of the antenna is shown in Fig. 2 at the lower and upper frequency of the considered bandwidth. As expected, the two regions of the antenna are responsible for the radiation of two distinct beams. They exhibit frequency- and azimuthal-dependent scanning asymmetric with respect to the glide plane at $\phi = 0$. This asymmetry is exploited in the next section to enable unambiguous simultaneous θ/ϕ detection.

III. Direction-of-Arrival Estimation

A. LWA-based MUSIC algorithm

Direction-of-arrival (DoA) estimation is performed through the multiple signal classification (MUSIC) algorithm applied to the proposed LWA. The system model assumes D sources using a multicarrier modulation scheme, impinging on the



(a) (b)

Fig. 2: Realized gain of the LWA in the xy plane for the lower and upper frequency of the considered bandwidth: (a) 26.5 GHz (b) 29.5 GHz.

LWA as $D\,(d = 1, ..., D)$ plane waves. The received signal in the frequency domain is expressed as:

$$\mathbf{x}[k] = \mathbf{A}\mathbf{s}[k] + \mathbf{z}[k]\ , \tag{1}$$

where $\mathbf{x} \in \mathbb{C}^{M\times 1}$ is the received vector with M frequency samples, $k = 1, ..., K$ is the k-th snapshot among K, $\mathbf{A} \in \mathbb{C}^{M\times D}$ is the LWA response matrix, $\mathbf{s} \in \mathbb{C}^{D\times 1}$ is the source vector, representing the complex amplitudes of the D sources, and $\mathbf{z} \in \mathbb{C}^{M\times 1}$ is a complex additive white gaussian noise (AWGN) vector with uncorrelated components. Each column of $\mathbf{A}$, expressed as $\mathbf{a}(\theta_d, \phi_d)$, corresponds to the LWA frequency response for an incoming plane wave with direction-of-arrival (θ_d, ϕ_d), and is extracted through full-wave HFSS simulations. Crucially in this framework, M refers to the number of frequency-domain samples (subcarriers), replacing the role of array elements in conventional MUSIC approaches. The sample covariance matrix is estimated as:

$$\hat{\mathbf{R}} = \frac{1}{K}\sum_{k=1}^{K} \mathbf{x}[k]\,\mathbf{x}^H[k]\ , \tag{2}$$

and its noise subspace is used to construct the MUSIC pseudospectrum:

$$P(\theta, \phi) = \frac{1}{\mathbf{a}^H(\theta_d, \phi_d)\mathbf{E}_N\mathbf{E}_N^H\mathbf{a}(\theta_d, \phi_d)}\ , \tag{3}$$

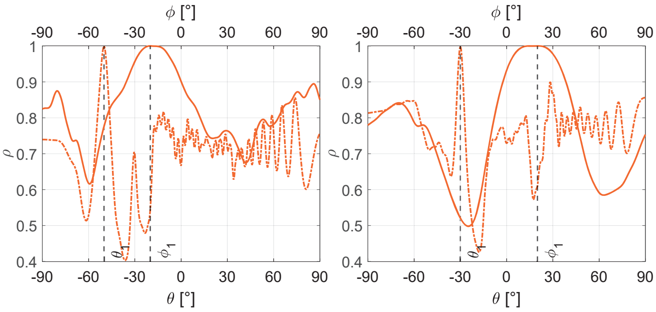
where $\mathbf{a}(\theta_d, \phi_d)$ is the steering vector, $\mathbf{E}_N$ is the noise subspace of $\hat{\mathbf{R}}$, and $(\cdot)^H$ denotes the Hermitian transpose. The DoAs are estimated by identifying the peaks of $P(\theta, \phi)$.

B. Results

The autocorrelation function for the LWA is defined as:

$$\rho = \frac{|\mathbf{a}^H(\theta_d, \phi_d)\,\mathbf{a}(\theta_d + d\theta, \phi_d + d\phi)|}{\|\mathbf{a}(\theta_d, \phi_d)\|\,\|\mathbf{a}(\theta_d + d\theta, \phi_d + d\phi)\|}. \tag{4}$$

The results are shown in Fig. 3. We analyze two cases: plane waves (sources) with a direction-of-arrival lying in the field of view of the beam produced by region 1 (Fig. 3a) and direction-of-arrival lying in the field of view of the beam produced by region 2 (Fig. 3b). The corresponding values are provided



(a) (b)

Fig. 3: Autocorrelation function ρ for a direction-of-arrival in the field of view of the beam produced in each region of the radial glide-symmetric corrugated LWA at: a) $\theta_1 = -50°, \phi_1 = -20°$, b) $\theta_1 = -30°, \phi_1 = 20°$.

in the caption of Fig. 3. The autocorrelation reveals sharp elevation peaks, enabling robust θ estimation in both cases. Although the wider radiation pattern in the azimuthal direction produces an almost flat azimuthal response, which limits the estimation accuracy in ϕ, the performance is nevertheless improved compared to [5] thanks to the suppression of the ambiguity related to an xz symmetry plane.

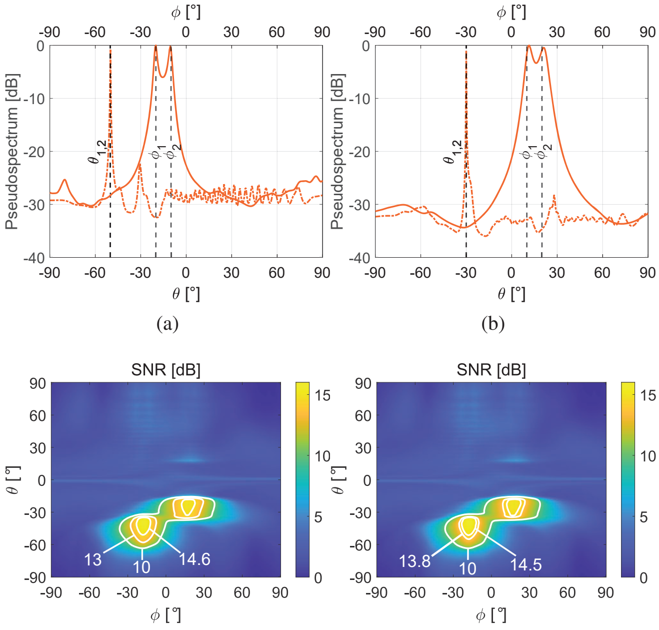
The MUSIC pseudospectrum validates these trends. The results are shown in Fig. 4. Similarly to the autocorrelation analysis, we investigate two scenarios: two sources (plane waves) with identical elevation and with ϕ angles in region 1 and in region 2. The sources are selected in the field of view of the beams produced by the antenna in the two regions. The corresponding values are reported in the caption of Fig. 4. Finally, the signal-to-noise ratio (SNR) employed in the MUSIC simulations is defined as follows:

$$\mathrm{SNR} = \|\mathbf{a}(\theta_d, \phi_d)\|^2 \, \mathbb{E}\left[\frac{|\mathbf{s}_d[k]|^2}{\|\mathbf{z}[k]\|^2}\right]. \tag{5}$$

As shown in (5), SNR is dependent by the incoming plane wave with DoA (θ_d, ϕ_d), and thus on the angles (θ_d, ϕ_d). Numerical results demonstrate that the LWA enables accurate estimation of both elevation (θ) and azimuth (ϕ), effectively eliminating the $\pm\hat{\phi}_d$ ambiguities reported in [5].

IV. Conclusions

A novel fully metallic periodic leaky-wave antenna for passive 2-D DoA estimation has been presented. The design employs a sectorial waveguide with radial glide-symmetric corrugated metasurface on the bottom plate and periodic slots on the top plate. The shapes of the corrugations and of the slots enable to break the azimuthal mirror-symmetry of the radiation pattern respect the glide plane at $\phi = 0$. The performance of the LWA for 2-D DoA estimation are evaluated using the MUSIC algorithm. The proposed single-port LWA leads to a correct estimation of both azimuth (ϕ) and elevation (θ) angles. This passive and low-cost structure is well suited for next-generation integrated systems where compactness and power



(a) (b) (c) (d)

Fig. 4: Pseudospectrum with two sources: a) $\theta_{1,2} = -50°, \phi_1 = -20°, \phi_2 = -10°$, b) $\theta_{1,2} = -30°, \phi_1 = 10°, \phi_2 = 20°$. SNR utilized is dependent by the incoming plane waves and with values c) $\mathrm{SNR}_{1,2} = [12.9, 14.6]$ dB, d) $\mathrm{SNR}_{1,2} = [13.8, 14.5]$ dB. For both cases $K = 100, M = 49$.

efficiency are critical. Future work will aim to experimentally validate the proposed design.

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