Planar Leaky-Wave Antenna Designs Offering Conical-Sector Beam Scanning and Broadside Radiation Using Surface-Wave Launchers

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***Abstract*—Two planar antenna designs that utilize surface-waves for leaky-wave excitation are investigated. Specifically, a surface-wave launcher is implemented to excite cylindrical surface-waves, which are bound to a grounded dielectric slab. By the addition of circular metallic strip gratings, a partially reflecting surface is realized, providing appropriate conditions for 2-D leaky-wave radiation. In particular, two designs are investigated: a continuous circular strip and a segmented circular strip grating. Results illustrate conical-sector beam scanning for the continuous circular strip grating between 20–22 GHz, while broadside radiation is observed at 21.2 GHz by the segmented circular strip design.**

***Index Terms*—Grounded dielectric slab (GDS), leaky-wave antenna (LWA), leaky-wave (LW), partially reflecting surface (PRS), surface-wave (SW), surface-wave launcher (SWL).**

I. Introduction

LEAKY-WAVE antennas (LWAs) have sustained much interest and attention in the electromagnetics community [1]–[6]. In particular, planar 2-D LWAs are desirable for their compatibility with other planar devices, low cost, and directive beam patterns, thus making them attractive for radar systems and satellite communications. Generally, a 2-D LWA consists of a planar structure that can support cylindrical leaky waves (LWs), i.e., cylindrical waves with a complex wavenumber which leak energy into free space during their propagation; the interface between air and the guiding planar structure defines the 2-D antenna aperture [1], [7], and [8].

Specifically, this work investigates planar 2-D LWAs defined by a grounded dielectric slab (GDS) covered with circular metallic strip gratings defining an effective partially reflecting surface (PRS). With appropriate boundary conditions and substrate characteristics, cylindrical surface-waves (SWs) can be contained to a GDS [9], [10]. By utilizing SWs and by the addition of metallic strip gratings, LWs can be excited which propagate along the perturbed structure [2], [7], [8]. Using this excitation technique, SWs and thus LWs can exist on a planar GDS, respectively defining the antenna feeding network and

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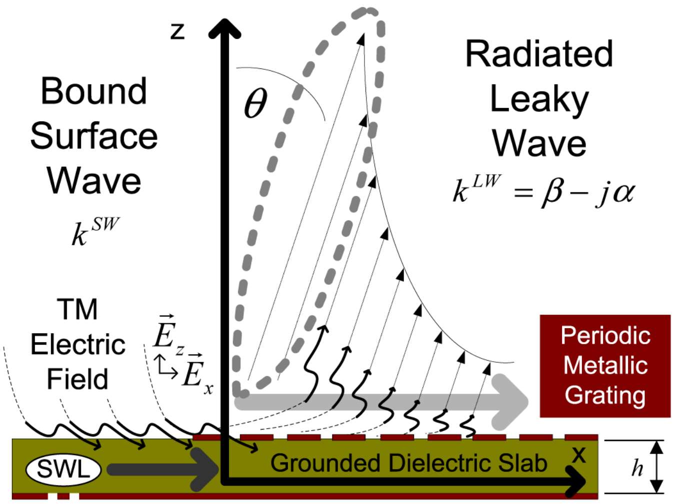

Fig. 1. Antenna structure considered in this work. A slotted magnetic dipole source (with a coplanar waveguide feed) acts as a surface wave launcher (SWL) antenna generating a TM_0 SW mode that is bound to a GDS. The addition of periodic metallic gratings (defining an effective PRS) can excite leaky waves.

radiation mechanism as shown in Fig. 1. Furthermore, with knowledge of the complex LW wavenumber, $k^{\rm LW} = \beta - j\alpha$, the nature of the far field beam pattern can be determined. With correctly designed gratings, LWAs with pencil and conical-sector beam patterns are realizable [1], [4]–[6].

II. Theoretical Considerations

A. Surface-Wave Excitation

Practically, a surface-wave launcher (SWL) antenna is realized with slots embedded within a ground plane fed by a coplanar waveguide transmission line [9], [10]. A bound TM_0 SW mode is excited and characterized by k^{SW}. Essentially, the slots act as magnetic dipole sources for the 2-D LWA [5]. The printed SWL antenna is shown in Fig. 2 and thus allows for simple integration with other planar devices.

B. Leaky-Wave Radiation by Guided Surface-Waves

If a 2-D metallic grating is placed a suitable distance from the SWL (and on top of the GDS) cylindrical LWs can be excited [1]. The printed metallic grating, defines an effective PRS. Radiation is achieved by a fast $n = -1$ spatial harmonic [6],

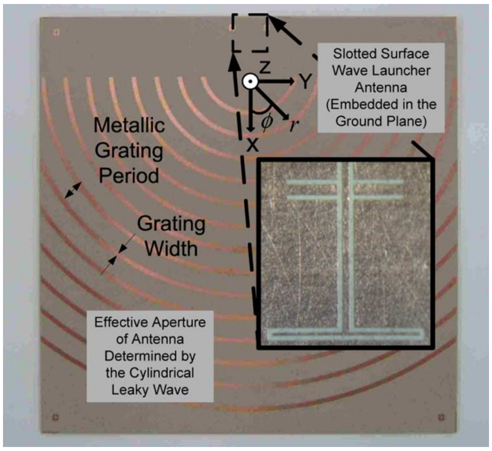

Fig. 2. Realized antenna structure. The utilized SWL, further described in [9] and [10], excites a cylindrical TM_0 SW mode on a GDS ($\epsilon_r = 10.2$, $h = 1.27$ mm, $\tan\delta = 0.0023$ and board size: 15×15 cm). A PRS is realized by a continuous circular strip grating (periodicity p_r).

defined by an elevation beam angle, θ, that is well known for off broadside angles [2]

$$\theta \approx \sin^{-1}\left(\frac{\beta}{k_0}\right) = \sin^{-1}\left(\frac{\beta_0}{k_0} - \frac{\lambda_0}{p_r}\right) \tag{1}$$

where β is the LW phase constant, β_0 is the phase constant of the $n = 0$ spatial harmonic (which is approximated by the phase constant of the guided TM_0 SW mode), p_r is the period of the metallic grating in the radial direction and the free space wavelength defines the free space wavenumber ($\lambda_0 = (2\pi/k_0)$). Such a 2-D LWA can excite backward or forward cylindrical LWs generating pencil and conical beam patterns for specified scan angles [1], [4]–[6].

III. Design Principles and Implementation

Given a specific frequency (λ_0), grating period (p_r) and guided SW phase constant (β_0) the radiation pattern can be steered to a desired beam angle as described by (1). The beamwidth is related to the LW attenuation constant (α) and can be controlled by the grating width [12]–[14]. Using these design principles, two LWA designs are suggested. They offer pencil and conical-sector beam patterns that scan as a function of frequency. Both designs utilize the aforementioned SWLs [9], [10] to excite a TM_0 SW mode on a high permittivity substrate ($\epsilon_r = 10.2$, $h = 1.27$ mm and $\tan\delta = 0.0023$). The PRSs were implemented using thin periodic metallic strips (of width 1.25 mm) conformal to the $+\hat{x}$ directed cylindrical SW phase front generated by the SWL antenna.

A. Continuous Circular Strip Grating for Conical-Sector Leaky-Wave Radiation

If the metallic strips are continuous, a LW mode can be excited and pencil-like or conical-sector beam patterns are possible for frequency dependent beam angles. The investigated 2-D LWA is shown in Fig. 2. The radius of the mth concentric ring, $r(m)$, can be defined by

$$r(m) = r_0 + p_r(m-1) \tag{2}$$

where $r_0 = 10$ mm and $p_r = 6$ mm for the fabricated design. With these design parameters the main beam angle can be estimated by (1). Furthermore, the behavior of the circular strip grating is comparable to the 1-D counterpart [12]–[14] excited by a magnetic line source.

With such a 2-D planar LWA, radiation at broadside can be challenging [1], [5], [6]. Physically, the LW fields on the guiding surface diminish and the main radiating harmonic ($n = -1$) enters into a LW stopband ($|\beta| < \alpha$) with reactive character. Thus, maximum radiation will likely be observed at the edges of this LW stopband [6]. Furthermore, a conical-sector beam pattern can be observed in the LW passband ($|\beta| > \alpha$) since the SWL directs the SW into a cylindrical sector along the guiding surface [9].

B. Segmented Circular Strip Grating for Directive Radiation at Broadside

By periodic segmentation of the continuous circular strip PRS, directive broadside radiation can be achieved. The orientation of such a 2-D LWA is shown in Fig. 5. The radius of the m-th ring is defined as in (2) with $r_0 = 10$ mm and $p_r = 7$ mm, while the periodicity of each segment (p_ϕ) is 14 mm (defined on the arc of each ring) in the $\hat{\phi}$-direction.

Essentially, suitable boundary conditions are employed for strip resonance at a specific frequency [11]. Maximum current excitation occurs at the edges of the strip segments defining an effective array of Hertzian dipoles on a high dielectric half-space. If strip placement and separation is appropriate ($p_\phi \approx \lambda$), resonance can be in phase. Furthermore, the broad radiation pattern of such elemental sources is well known for broadside angles [15]. In addition, the effective array of Hertzian dipoles can be modeled as circular grid array of elemental sources [16], suggesting that broadside radiation is indeed realizable.

Essentially, a LW is excited along the guiding surface as the strip elements are poor radiators ($\eta_{\text{dipole}} = (3/2\epsilon_r) \ll 1$) [15], and the magnitude of their excitation decreases exponentially in the radial direction along the guiding surface. This suggests that the normalized LW propagation and attenuation constants, $\widehat{\beta} = (\beta/k_0)$ and $\widehat{\alpha} = (\alpha/k_0)$, of the proposed LWA are equal at broadside [5]. Similar to the continuous circular strip design, by variation in the PRS, controlled directive beam patterns are realizable within a desired frequency range.

IV. Results and Discussion

A. Continuous Circular Strip Leaky Wave Antenna

Measured conical-sector beam patterns for the continuous circular strip LWA are shown in Fig. 3. The maximum gain, $+4^\circ$ away from broadside, is observed at 21.12 GHz. Furthermore, forward conical-sector [and backward pencil beam] radiation is

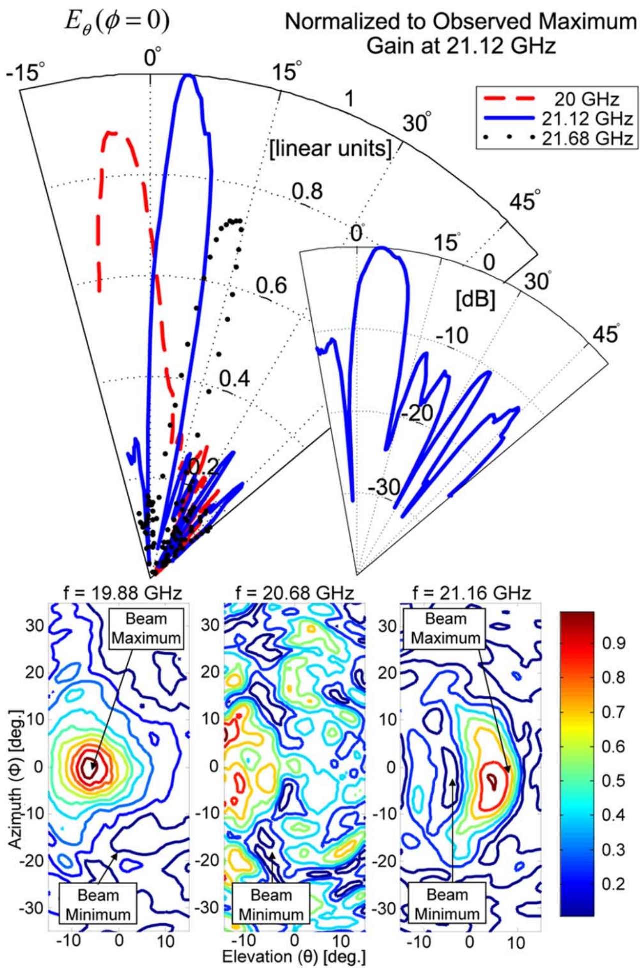

Fig. 3. Measured gain, E_θ, in linear units and dB for the continuous circular strip PRS (normalized to observed maximum at 21.2 GHz). A broadside null is observed at 20.68 GHz illustrating the LW stopband, with maximum radiation occurring at the edges of this LW bandgap, $f \in [20\ \mathrm{GHz}, 21.12\ \mathrm{GHz}]$. At 19.88 and 21.16 GHz, a distinct pencil-like and conical sector beam are observed, respectively.

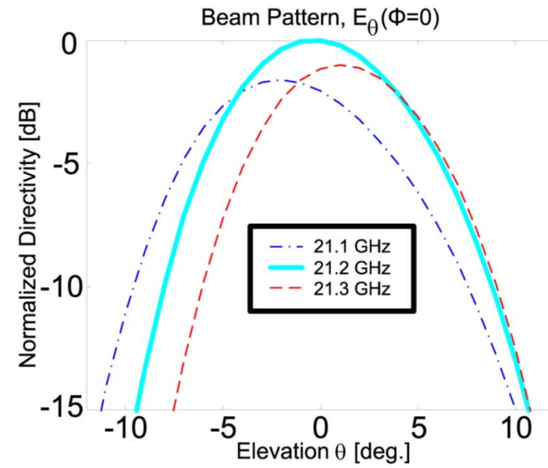

Fig. 4. Backward, broadside and forward pencil beams are observed for the segmented circular strip PRS with maximum directivity observed at broadside.

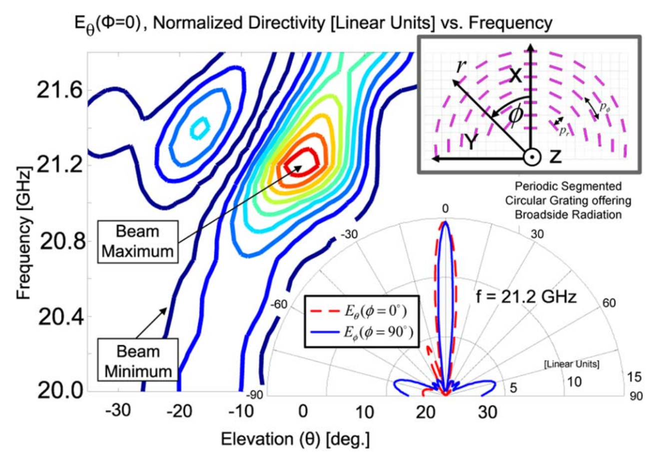

Fig. 5. $E_\theta(\theta, f)$ beam pattern normalized to maximum directivity at 21.2 GHz, shown in linear units for the segmented circular strip PRS. A polar plot of the directive beam pattern is also shown at broadside.

observed for $f > 21.12$ GHz [and $f < 20.0$ GHz]. These results can be described as follows. In the forward region a conical-sector beam pattern is observed since the SWL directs the cylindrical SW into a confined region [9]. Conversely, in the backward region the far field components are focused, generating a confined pencil beam. Furthermore, a reduced gain is observed in the backward region when compared to the forward region as shown in the polar plot of Fig. 3. This suggests the LW attenuation constant $(\widehat{\alpha})$ is larger in the backward region defining a smaller effective aperture and hence reduced gain when compared to the forward region.

A broadside null is observed at $f = 20.68$ GHz, suggesting a LW stopband. The broad beam with no observable maximum implies that the attenuation constant is greater than the phase constant $\left(\widehat{\alpha} > |\widehat{\beta}|\right)$. Essentially the main radiating harmonic enters into a LW stopband with negligible radiation.

Since beam maximums are observed in both the backward and forward directions, the edges of this stopband region can be approximated at 20.0 and 21.12 GHz. This also suggests that the attenuation and phase constants are equivalent $\left(\widehat{\alpha} \approx |\widehat{\beta}|\right)$ at 20.0 and 21.12 GHz, respectively [5], [6].

B. Segmented Circular Strip Grating Design

By periodic segmentation of the circular strips, broadside radiation is achieved. Initial Finite Element simulation results display a 23.5 dB directive gain at broadside, when the frequency of operation is 21.2 GHz as shown in Figs. 4–8. In addition, forward [and backward] pencil beam radiation is observed for $f > 21.2$ GHz [and $f < 21.2$ GHz] as illustrated in Fig. 4. For clarity, a polar plot of the beam pattern is also shown at broadside in Fig. 5. Low cross polarization levels in dB, are also shown in Fig. 6. These results suggest that the normalized phase and attenuation constants are equal $\left(|\widehat{\beta}| = \widehat{\alpha}\right)$ when the broadside beam is observed at 21.2 GHz.

In the region defined by $\theta \in [-35^\circ, -5^\circ]$ and $f \in [21\ \mathrm{GHz}, 21.8\ \mathrm{GHz}]$ noticeable back lobe radiation is observed due to unwanted scattering from the edges of the segmented metallic strips. Furthermore, the $E_\phi(\phi = \pi/2)$ beam pattern is nonzero at endfire as shown in Figs. 5 and 7. An explanation is provided by image theory and by analysis of the SW excitation

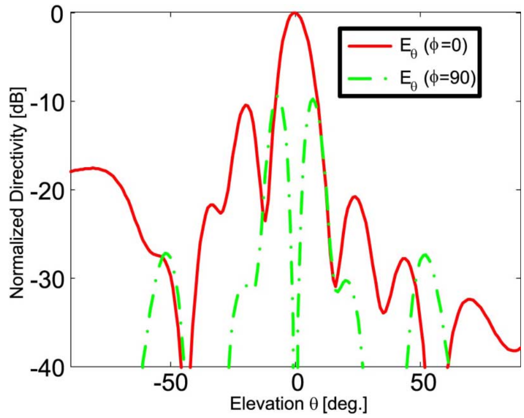

Fig. 6. Normalized $E_\theta(\phi = 0^\circ)$ and $E_\theta(\phi = 90^\circ)$ directive beam patterns at 21.2 GHz. A low cross polarization level (< -40 dB) is observed at broadside for the segmented circular strip PRS.

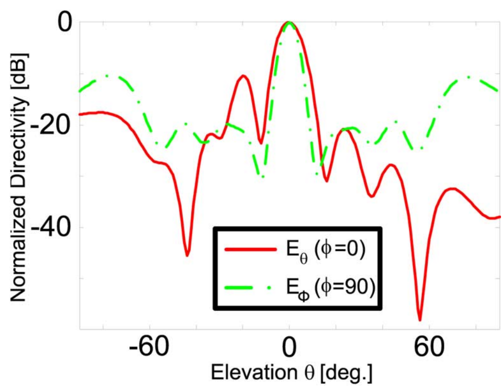

Fig. 7. Normalized $E_\theta(\phi = 0^\circ)$ and $E_\phi(\phi = 90^\circ)$ directive beam patterns at 21.2 GHz for the segmented circular strip PRS.

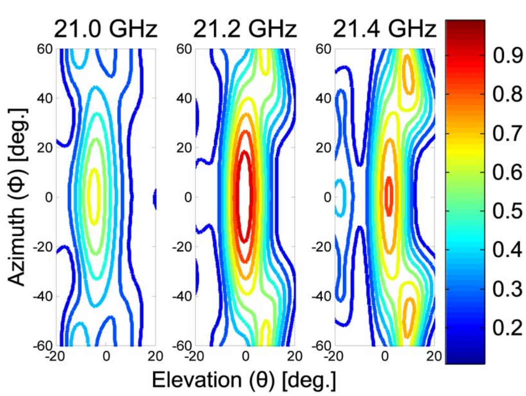

Fig. 8. Backward, broadside and forward 2-D beam patterns for the segmented circular strip PRS with a maximum observed at broadside (displayed in linear units and normalized to the beam maximum at 21.2 GHz).

mechanism. Since the SWL is a magnetic dipole source, an image magnetic source can be used to model the resultant ground plane reflections. The additional fields produced by the image magnetic dipole constructively add with the fields from the original SWL antenna in the far field.

V. Conclusion

Two leaky wave antennas have been suggested. By cylindrical surface-wave launching on a grounded dielectric slab and by the addition of appropriate period metallic gratings, leak-waves can be excited. A continuous metallic circular strip grating generated pencil-like and conical-sector beam patterns for specific beam angles. This design displayed a leaky-wave stopband at broadside. Conversely, directive broadside radiation is suggested with the segmented circular strip partially reflecting surface.

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