Broadside Radiation From a Planar 2-D Leaky-Wave Antenna by Practical Surface-Wave Launching

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***Abstract*—A planar 2-D leaky-wave (LW) antenna, capable of broadside radiation, is presented for millimeter wave applications. A directive surface-wave launcher (SWL) is utilized as the antenna feed exciting cylindrical surface-waves (SWs) on a grounded dielectric slab (GDS). With the addition of a segmented circular strip grating, cylindrical LWs can be excited on the antenna aperture. Measurements illustrate maximum gain at broadside at 19.48 GHz in both the E and H planes with a 10° half power beamwidth. Specifically, a directive pencil beam is observed just at the edge of the TE_1 SW mode cuttoff frequency of the slab (19.47 GHz), suggesting maximum radiation at the edge of a *TE* stopband.**

***Index Terms*—Leaky-wave (LW), leaky-wave antenna (LWA), surface-wave (SW), surface-wave launcher (SWL).**

I. Introduction

THE fundamental properties and optimization for maximum leaky-wave (LW) radiation at broadside is a challenging topic and one with considerable interest within the electromagnetics community [1], [2]. In particular, planar leaky-wave antennas (LWAs) are attractive due to their low cost, ease of fabrication and compatibility with other planar devices and monolithic technologies. In general, these types of antennas consist of a planar guiding structure that can support the propagation of cylindrical LWs, i.e., cylindrical waves which leak energy into free space during their radial propagation along the guiding surface. With appropriate design, such planar 2-D LWAs can generate highly directive pencil beam patterns at broadside [2]–[4].

A new planar 2-D LWA is realized in this work for millimeter wave applications. The presented design can be characterized by an appropriate feed and 2-D antenna aperture, as shown in Fig. 1. To the authors knowledge this is the first time such a LWA has been fabricated and measured, providing experimental verification of [1]–[4]. Specifically, by utilizing cylindrical surface-waves (SWs) on a grounded dielectric slab (GDS) and by the addition of a segmented circular strip grating, defining a capacitive partially reflecting surface (PRS), conditions can be suitable for cylindrical LW excitation and thus pencil beam radiation at broadside [4].

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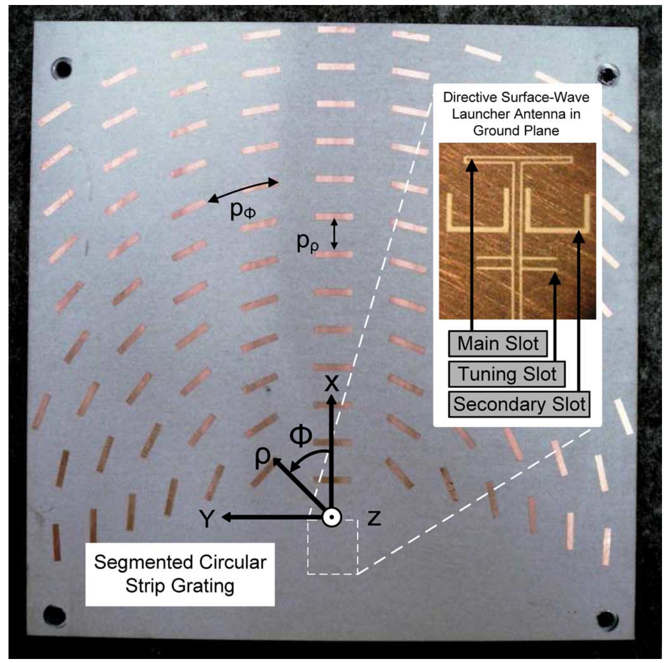

Fig. 1. Realized planar 2-D LWA. The antenna feed defined by a SWL is described by a main radiating driven slot (length of 1.92 mm) with two secondary folded reflector (individual length of 2.75 mm) and four tunning slots (individual length of 0.65 mm). A PRS is realized on top of the GDS (at $z = 0$) by the addition of a segmented circular strip grating described by the periodicities, p_ρ and p_ϕ, in the $\hat{\rho}$ and $\hat{\phi}$ directions, respectively.

A. Planar Antenna Feed by Practical Surface-Wave Launching

The LWA feed is defined by a planar surface-wave launcher (SWL) embedded in the ground plane and fed by a coplanar waveguide transmission line [4]–[6]. The directive SWL is characterized by a main radiating slot with two secondary reflector and four tunning slots as shown in the inset of Fig. 1. Thus the slot configurations act as magnetic dipole sources for the investigated 2-D LWA. Essentially, the main radiating slot couples energy into the dominant TM_0 mode of the slab while the two secondary folded reflector slots increase forward directivity achieving unidirectional SW propagation.

B. Broadside Radiation by Cylindrical Leaky-Waves

With the propagation of cylindrical SWs on the guiding surface (generated by the planar SWL feed) and by the addition of the segmented circular strip grating (on top of the GDS) cylindrical LWs can be excited on the 2-D antenna aperture with TM and/or TE field configurations [2]–[5]. Specifically, as theoretically described in [2], for realization of directive radiation at broadside both TM and TE radiated components, E_θ and E_ϕ,

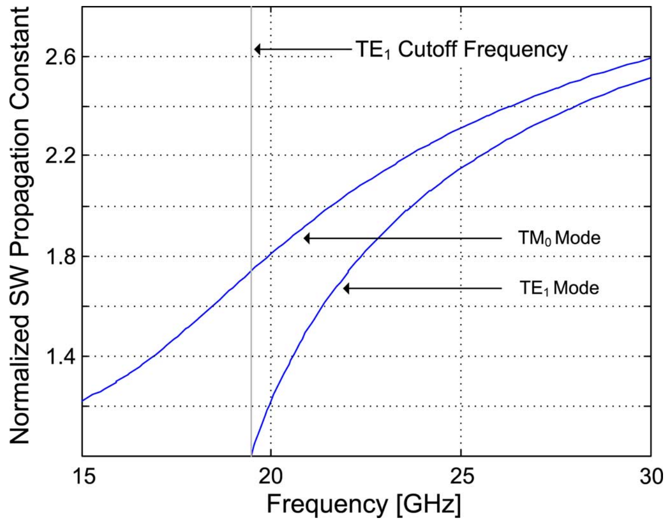

Fig. 2. SW propagation constants of the TM_0 and TE_1 SW modes (normalization with respect to k_0) for the utilized GDS (with no strips). The main radiating slot [secondary reflector slots] of the SWL feed can couple power into the TM_0 [TE_1] SW mode of the slab since the TM_0 SW mode has a zero cutoff frequency [TE_1 SW mode can exist for $f \geq 19.47$ GHz].

should combine and be approximately equal in both the E and H planes in the far field.

II. Practical 2-D Leaky-Wave Antenna Feed by Planar Surface-Wave Launching

For SW excitation a directive Yagi–Uda like SWL was used with half wavelength slots and secondary reflector slots in the ground plane [4], [5]. Substrate properties ($\epsilon_r = 10.2$, $h = 1.27$ mm and $\tan\delta = 0.0023$) were properly chosen such that approximately 85% of the input power was coupled into the dominant TM_0 SW mode of the slab [6]. By folding of the secondary reflector slots, cross polarization beam patterns can be observed in the far field [7] suggesting the existance of a TE field distribution on the slab.

A. Surface-Waves Modes Supported by the Slab

The theoretical TM_0 and TE_1 SW mode propagation constants for the utilized GDS were determined by the transverse resonance technique [8]. Results are shown in Fig. 2 suggesting that both field configurations can exist on the guiding surface after the TE_1 SW mode cutoff frequency of the slab.

B. Surface-Waves Modes Excited by the Launcher

To confirm the excitation of both TM_0 and TE_1 SW modes a simulation was performed by placing the SWL in the center of a large GDS (with no strips) and sampling the near field along the air dielectric interface. Results are shown in Fig. 3 illustrating that the majority of the TM SW power (E_z, generated by the main slot), propagates in the forward $+\hat{x}$ direction achieving unidirectional SW propagation. A TE field distribution (E_ϕ) is also observed in the $\pm\hat{y}$ directions (generated by the folded secondary slots [7]) with reduced field strength levels when compared to the TM field distribution.

Thus, the two folded secondary slot segments achieve unidirectional TM SW propagation while simultaneously exciting TE SWs. A null is also observed at the origin, near the coplanar

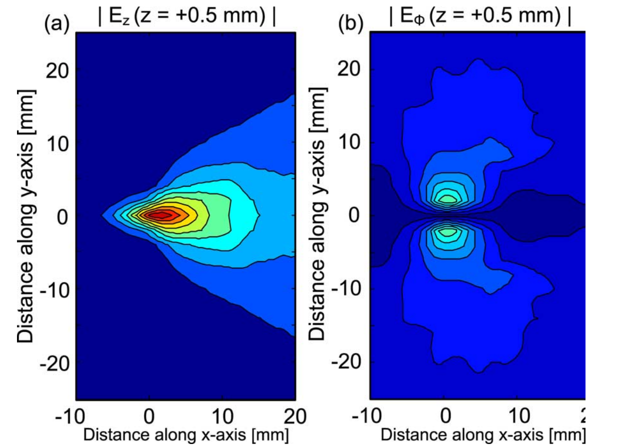

Fig. 3. Simulated TM and TE SW field distributions 0.5 mm above the guiding surface at 24 GHz: (a) $|E_z(x,y)|$ and (b) $|E_\phi(x,y)|$. The majority of the TM [TE] field distribution is directed in the $+\hat{x}$ [$\pm\hat{y}$] direction[s].

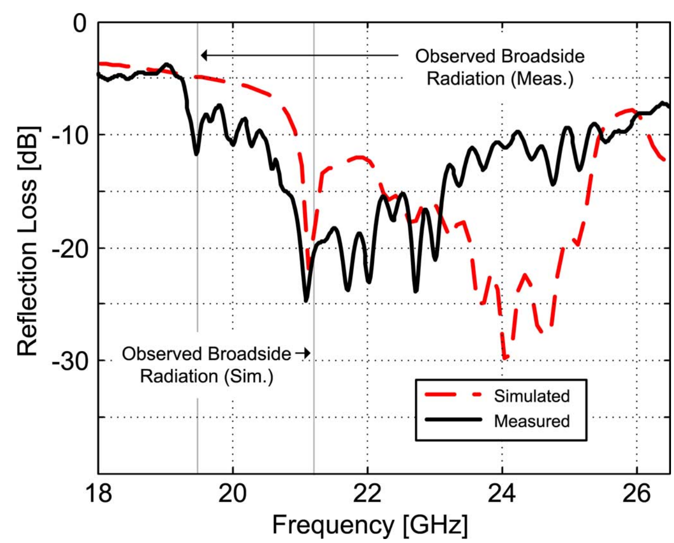

Fig. 4. Reflection loss values for the proposed LWA design with the directive SWL feed. Maximum radiation at broadside is measured [simulated] at 19.48 [21.2] GHz with loss values below 10 dB.

waveguide transmission line, since the TE field distribution propagating from each folded secondary slot cancels at $y = 0$ [7].

III. Segmented Circular Strip Grating for Maximum Leaky-Wave Radiation at Broadside

By the addition of an appropriately designed segmented circular strip grating (realizing a capacitive PRS) on top of the GDS a pencil beam at broadside is possible [4]. Simulated and measured reflection loss values for the realized LWA (with the aforementioned SWL feed) are shown in Fig. 4 while beam patterns are illustrated in Figs. 5–8.

It should be noted that a pencil beam at broadside (with maximum gain) was measured [simulated] at $f_b = 19.48$ [21.2] GHz. Deviations may be attributed to fabrication tolerances and modeling of the metal thicknesses near the SWL and strip segments. In addition, variations may also be observed given the precision of the commercial simulator, HFSS; results were analyzed after two consecutive iterations with a 2% convergence

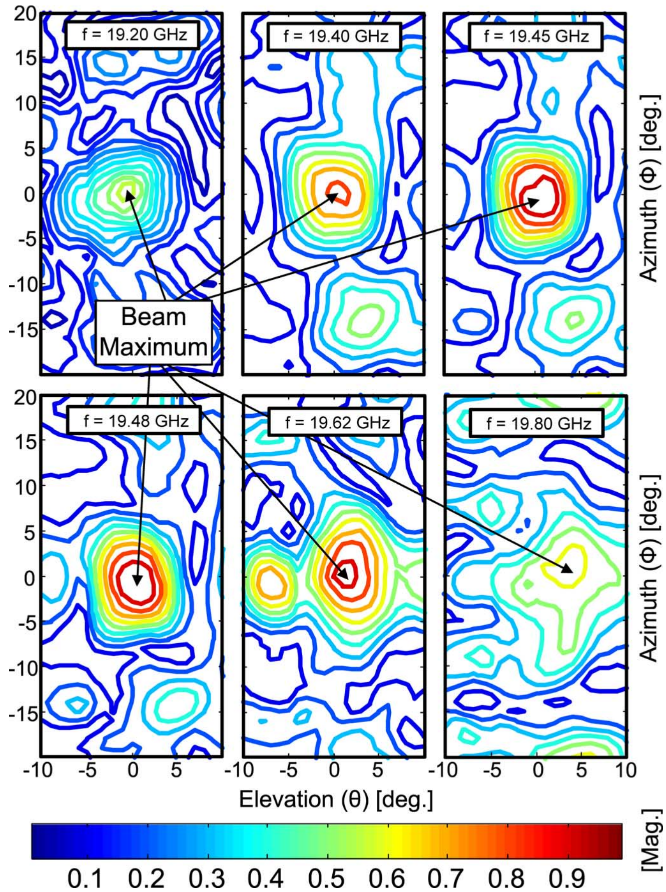

Fig. 5. Measured 2–D gain pattern in linear units and normalized to maximum gain at broadside at $f_b = 19.48$ GHz. The pencil beam is only observed between 19.20 and 19.80 GHz and at its maximum ($f = f_b$) the 3_{dB} beam width is approximately 10° in both the azimuth and elevation.

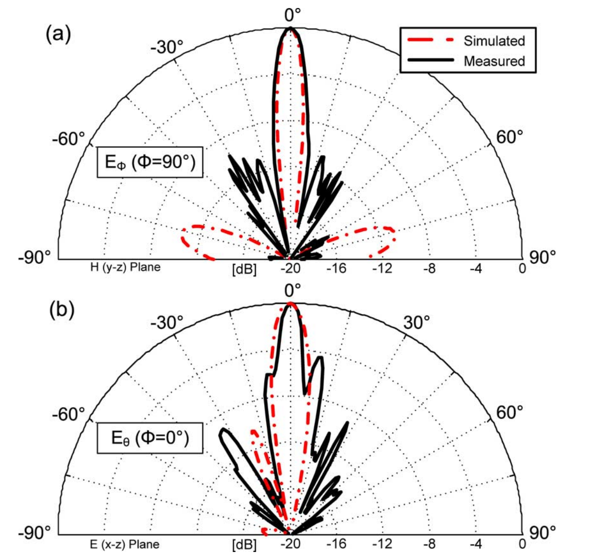

Fig. 6. Broadside beam patterns normalized and shown in dB (H/E planes referenced to main slot of SWL). (a) $|E_\phi(\phi = 90^\circ)|$. (b) $|E_\theta(\phi = 0^\circ)|$. Measured [simulated] beam patterns shown at $f_b = 19.48$ [21.2] GHz.

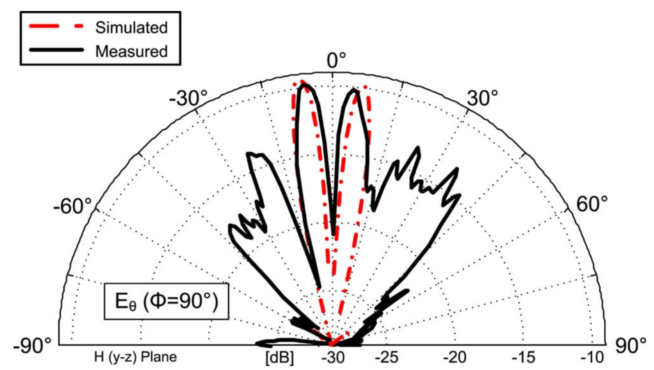

Fig. 7. Cross-polarization beam pattern at broadside: $|E_\theta(\phi = 90^\circ)|$. Normalized to maximum copolarization gain (Fig. 6). Values are 10 dB below the main pencil beam with a null at broadside.

error or less. Increased accuracy was not feasible due to the computational requirements of such an electrically large and complex structure. In addition, nine rings (or less) of the segmented design could be simulated. Larger structures could not be simulated. Thus, to ensure that the majority of the LWs were radiated, thirteen rings were fabricated increasing the effective aperture (and possibly gain) of the realized LWA.

A. Segmented Circular Strip Grating Design and Operation

The fabricated 2-D LWA is shown in Fig. 1 and the radius, $\rho(m)$, of each segmented concentric ring, m, can be defined by $\rho(m) = \rho_0 + p_\rho(m-1)$ where $\rho_0 = 10$ mm and $p_\rho = 7$ mm. The periodicity of each segment in the $\hat{\phi}$ direction (p_ϕ) is 14 mm. Such an arrayed configuration of strips can leak or radiate energy into free space with decreasing amplitude away from the SWL source [4]. Physically, the magnetic field component of the cylindrical TM SW mode propagating along the guiding surface inductively couples to the strip segments (individual strip length of $0.471\lambda_0$ at 19.48 GHz) with decreasing current amplitude along the aperture. Essentially, suitable boundary conditions are employed for maximum strip resonance at the TE_1 SW mode cuttoff frequency as illustrated in Fig. 9. In addition, strips are placed and appropriately orientated for in phase resonance.

B. Measured 2-D Leaky-Wave Radiation at Broadside

A pencil beam with maximum gain was observed at broadside at 19.48 GHz just after the TE_1 SW mode cutoff frequency (19.47 GHz) of the slab suggesting maximum radiation at the edge of a TE LW stopband (similar to the 1-D case as presented in [1]). In addition, these results also imply that both TM and TE cylindrical LWs were excited on the aperture and that the radiated far-field components, E_θ and E_ϕ, combined at broadside with approximately equal value in both principal planes (E and H planes referenced to main slot of SWL) [2].

Side lobe levels were difficult to observe since measurements were completed in the K band and near the noise floor of the anechoic chamber as shown in Figs. 6 and 7. In addition, a comparison of simulated gain (18.55 dB) and directivity values in the H and E planes suggest a radiation efficiency of 57.6%. Also, simulated endfire radiation in Fig. 6(a) is reduced (when compared to measured) due to the increased antenna size.

Low cross-pol levels are also observed in the far field and 10 dB below the main pencil (Figs. 7 and 8). A null at broadside is seen due to the TE field cancellation at the center of the SWL

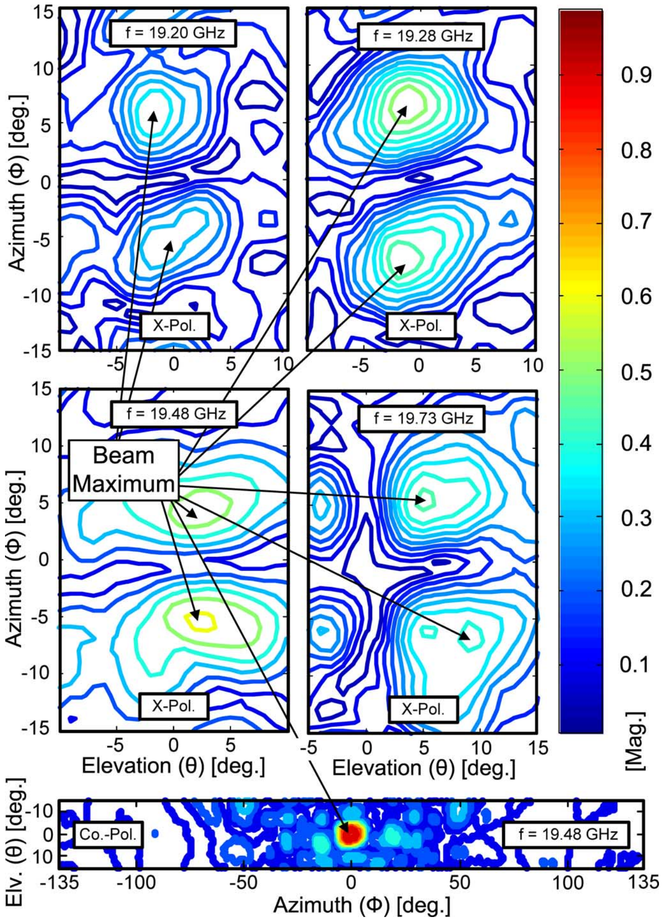

Fig. 8. Measured 2-D X-Pol gain patterns in linear units, normalized and compared to measured Co-Pol gain value ($f_b = 19.48$ GHz at broadside).

feed. Similar Yagi–Uda like slot antennas were investigated in [7] and with such secondary slots increased cross-pol radiation can be observed with cancellation at broadside.

IV. Conclusion

A planar 2-D LWA with maximum radiation at broadside was presented. By the design of a cylindrical SW feed and segmented circular strip PRS, TM and TE cylindrical LWs can be excited on the antenna aperture. Physically, the magnetic field distribution from the propagating SWs couples to the resonant strips. These results suggest that both TM and TE radiated far field components combined at broadside achieving maximum gain near the TE_1 SW mode cutoff frequency of the slab. In addition, the secondary slots of the SWL feed assist in achieving

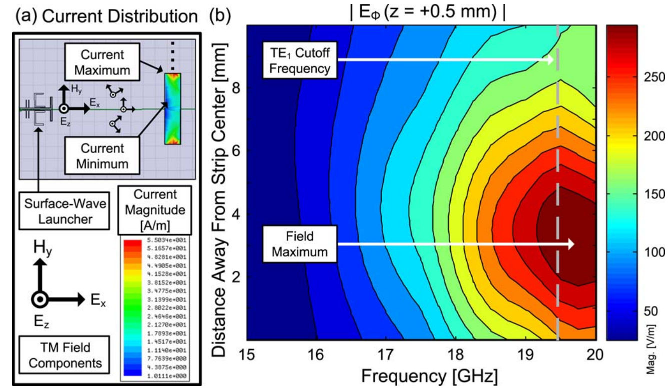

Fig. 9. (a) The TM SW mode (from the SWL) inductively couples to the first strip illustrating resonance. (b) Simulated $|E_\phi(y, f)|$ field distribution (along $\hat{y}$, shown as $\cdots\cdot$ in (a) with plot origin defined at the strip edge center) generated at first strip element. Field strength increases away from the strip with maximum occurring above the TE_1 SW mode cutoff frequency of the slab. Thus the current distribution on the strips can radiate or leak energy into free space with decreasing amplitude along the radial aperture. Realized strip length 7.25 mm or $0.471\lambda_0$ at 19.48 GHz. Strip width 1.25 mm.

unidirectional SW propagation but at the cost of cross-pol radiation in the far field. Thus, the segmented circular strip grating, frequency of operation and substrate properties are all central in attaining broadside radiation.

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