Continuous One-Sided Beam Scanning Through Broadside from Backfire to Forward Fire by Efficient Surface-Wave Excitation

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***Abstract*—A planar leaky-wave antenna (LWA) defined by a circular configuration of strips that utilizes surface waves (SWs) for leaky wave (LW) excitation is presented for continuous beam scanning and broadside radiation. Specifically, a printed directive surface-wave launcher (SWL) source is employed as the antenna feed, generating unidirectional SW field distributions on a grounded dielectric slab (GDS). Measured maximum gain with a 6° pattern beamwidth was observed at 22.3 GHz $+12^\circ$ away from the broadside direction. Beam scanning is also realized over a large radiating bandwidth (18.0 to 26 GHz) with pointing angles ranging from -55° to $+47^\circ$ in the $E(x\text{-}z)$ plane.**

I. Introduction

The emergence of new and innovative wireless communication systems has increased the demand for creative antenna solutions that can offer high gain at a low cost. The microwave and millimeter-wave frequency ranges have shown much promise allowing for increased data transmission rates while offering smaller and compact designs. These new antenna configurations also need to be easily integrated with modern microwave and millimeter-wave circuits for increased versatility and ease of design at the system level.

Printed or planar leaky-wave antennas (LWAs) can meet this high gain and low cost requirement. They are attractive due to their low profile, ease of fabrication and compatibility with other planar devices and monolithic technologies [1]-[3]. But dielectric slab selection and optimal feed configuration can be challenging at microwave and millimeter-wave frequencies. Multilayered aperture coupled slot configurations (defined by microstrip feed lines) may be considered, but unfortunately, air gaps between layers can increase losses and broadband matching may be troublesome. Thus single-layer topologies may be favorable when low-loss designs are of interest.

In addition, at these microwave and millimeter-wave operating frequencies substrates can become electrically thick and thus unwanted surface wave (SW) field distributions may be excited on the antenna aperture. Significant power losses can be observed with undesired coupling between metallic elements. Unwanted parasitic radiation and spoiling of the desired antenna beam pattern is also possible [4]. One design strategy is to minimize such SW excitations by reducing the height, h, of the utilized dielectric, but at the sacrifice of antenna durability and strength. Furthermore, low dielectric substrates ($\epsilon_r < 3$) may also be used to lessen SW effects but at the cost of increased antenna size.

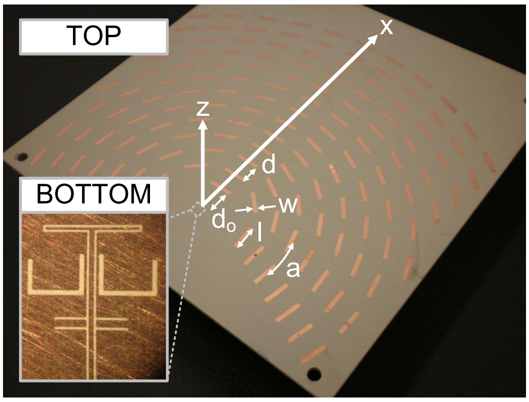

Fig. 1. Investigated LWA defined by a segmented circular strip grating (strip width and length: $w = 1.25$ mm, $l = 7.25$ mm) printed on top of a GDS ($\epsilon_r = 10.2, h = 50$ mil). A directive SWL in the ground plane defines the antenna feed. For the realized metallic configuration $d_0 = 9.3$ mm with radial and azimuthal periodicities, $d = 6$ mm and $a = 12$ mm, respectively.

On the other hand there has been (and continues to be) a significant research initiative by the electromagnetics community to minimize SW excitations. By developing new electromagnetic band gap (EBG) structures or high impedance surfaces (HISs) the unwanted effects of SWs on planar devices can be minimized. Essentially, these new structures are designed for operation within a SW stop band regime [5]. With the utilization of such EBGs or HISs, fabrication costs can escalate and design procedures can be numerically exhaustive.

An alternative approach [3], [4] is to try and efficiently excite such SWs by the selection of electrically thick substrates with relatively high dielectric constant values ($\epsilon_r \approx 10$). Planar surface-wave launchers (SWLs) offer a simple solution to these problems at millimeter-wave frequencies by avoiding the implementation and design of EBGs or HISs. Specifically, by utilizing the appropriate configurations of printed slots in the ground plane of a grounded dielectric slab (GDS), the negative effects of SWs can be mitigated. Such a novel technique for SW excitation has shown to be advantageous for new LWA designs [2],[3]. These completely printed antennas are fed by a coplanar wave guide (CPW) transmission (TL) allowing for simple integration with other planar structures

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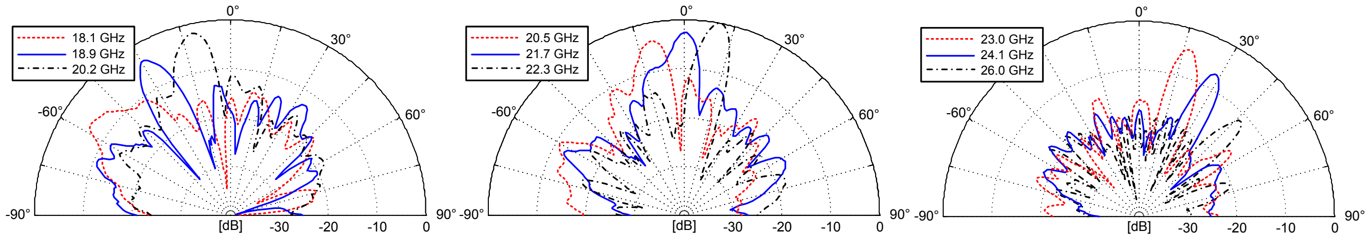

Fig. 2. Measured beam patterns, $E_\theta(\phi = 0°)$, in the $E(x$-$z)$ plane. Results shown in dB and normalized to observed maximum at 22.3 GHz.

and monolithic technologies. Essentially, the input signal is efficiently coupled into the dominant TM_0 SW mode of the slab, wave confinement can be realized [4], and the unwanted and parasitic effects that are typically associated with SWs are utilized to the advantage of the planar antenna designer.

New results for such a SW fed planar LWA are presented in this work for microwave and millimeter-wave frequencies. Applications include automotive and airport tracking radar. The design can be characterized by a directive SWL feed and a 2-D antenna aperture (as shown in Fig. 1). Specifically, by efficient excitation of cylindrical SWs on a GDS and by the addition of a segmented circular strip grating [3], conditions can be made suitable for cylindrical leaky wave (LW) radiation with pencil beam and conical-sector beam patterns in the far field [1]. Numerical results, simulations and measurements are provided in Figs. 2 - 7. As illustrated this antenna can generate one-sided beam patterns in the far-field with beam scanning from backfire through broadside, followed by beam scanning towards end-fire. Maximum gain values are observed at 22.3 GHz in the forward direction with a near broadside pointing angle ($\theta_p = +12°$) and a pattern beamwidth of $6°$. In addition, beam scanning is observed over a large radiating bandwidth (18.0 GHz to 26 GHz) with pointing angles ranging from $-55°$ to $+47°$ with a reduction in gain of at worst of 12 dB at 26 GHz. To the authors' knowledge this is the first time that such a wide angle one-sided backfire to forward fire beam scanning LWA, driven by SWs, has been designed and measured.

II. Antenna Feed for Surface Wave Excitation

An important consideration in the design of these of LWAs is the planar GDS selection [4]. More specifically, proper slab characteristics should be chosen to achieve efficient power

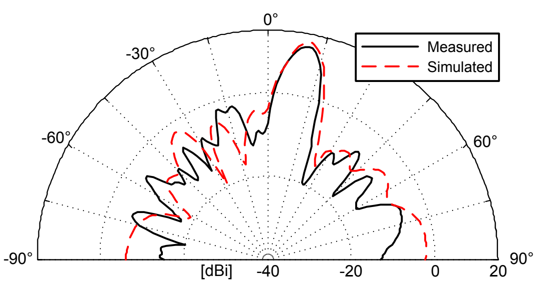

Fig. 3. Realized gain pattern at 22.3 GHz (E plane referenced to the main slot of the directive SWL). Good agreement is observed with the simulations.

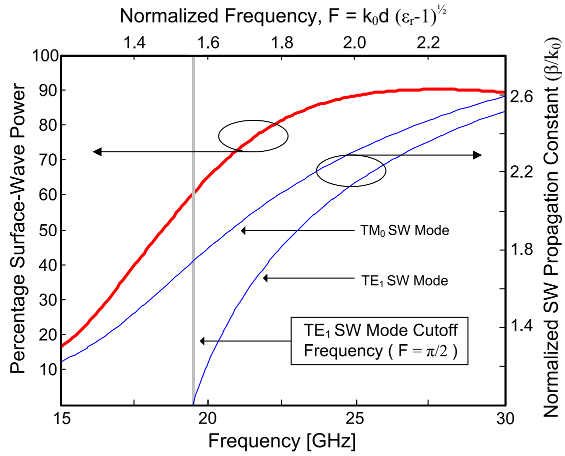

Fig. 4. Percentage of SW power (non-reflected) that can be coupled into the slab by an ideal slot [4], superimposed with the normalized propagation constants of the first two SW modes (TM_0 and TE_1) that can be excited on the utilized GDS. Efficiencies of 90 % can be achieved after the TE_1 SW mode cutoff frequency of the slab ($F = \frac{\pi}{2}$ or 19.47 GHz) .

coupling from the CPW TL feeding line into the dominant TM_0 SW mode. Thus the amount of bound SW power (P^{SW}) relative to any power losses (P^{LOSS}, or parasitically radiated power), should be maximized. A measure of this comparison (or percentage SW power) can be related to SWL efficiency

$$\eta^{SWL} \propto \frac{P^{SW}}{P^{SW} + P^{LOSS}} = \frac{P^{SW}}{P^{TOTAL}}. \quad (1)$$

This equation can compare the amount of power coupled into bound SWs, to the amount of power lost due to radiation into free space. Thus the frequency of operation of the SWL and antenna should occur where the bound SW power, P^{SW}, achieves maximum values; ie. $\eta^{SWL} \approx 90\%$. It should be noted that this analysis assumes an ideal slotted source and does not include any reflection losses due to the 50Ω CPW TL and slot transition.

The percentage of SW power excited by an ideal slot versus frequency is shown in Fig. 4. The normalized SW propagation constants for the first two SW modes of the slab (TM_0 and TE_1) are also shown. Numerical results suggest that maximum SW coupling efficiencies can occur after the TE_1 SW mode cutoff frequency of a slab [4]. Moreover, a GDS should be chosen to simultaneously support both TM_0 and TE_1 SW modes as a large radiation bandwidth can be achieved.

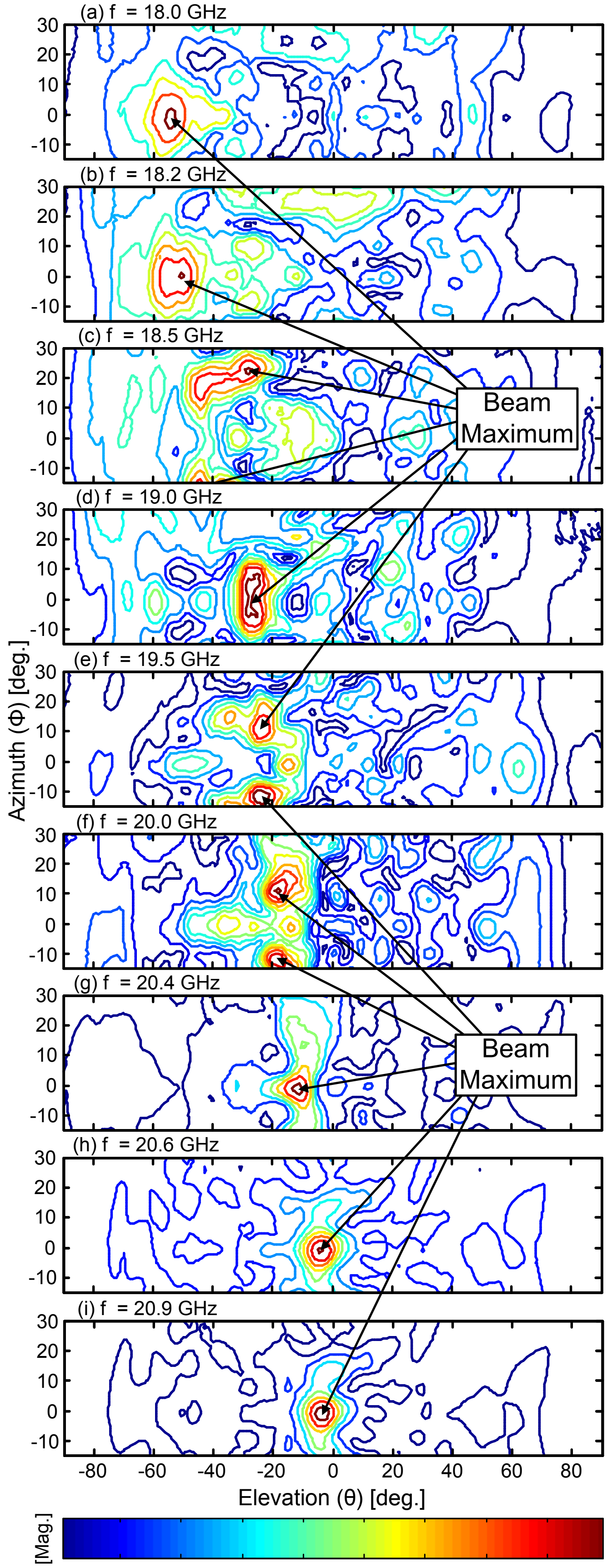

Fig. 5. Measured backfire to broadside 2D beam patterns as a function of θ and ϕ. Values are normalised to observed maxima and shown in linear units.

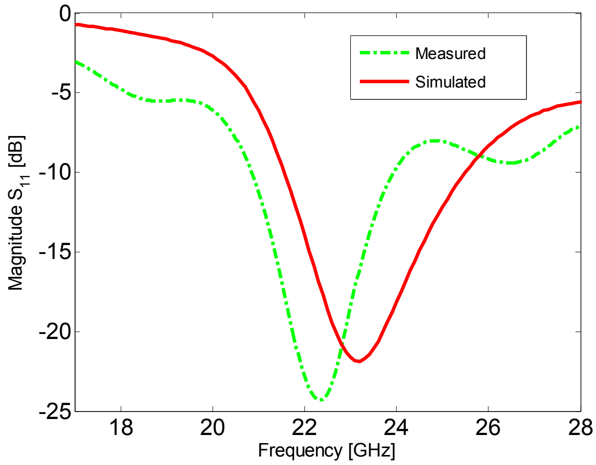

Fig. 6. Reflection loss of the SWL with no strips on top of the GDS. Simulation and measured results are in good agreement. Measured results illustrate that minimum reflection losses are observed at 22.3 GHz. Maximum antenna gain is also achieved at this same frequency as shown in Fig. 3, suggesting that a good SW coupling efficiency may be realized, $\eta \approx 85\%$.

Coplanar TL fed Yagi-Uda like slot configurations have been recognized as an efficient means for coupling into the dominant TM_0 SW mode of a GDS. Moreover, these slotted configurations can be thought to act as magnetic dipole sources for new planar LWAs [2],[3]. Depending on the antenna application one source configuration may be favorable. For instance, directive and non-directive SWL designs can generate both unidirectional and bidirectional field distributions on the guiding surface, respectively realizing one-sided [3],[4] and two-sided beam patterns in the far field.

In this work one-sided beam scanning was of interest and thus a directive SWL source was employed. As shown in the inset of Fig.1 the directive SWL can be defined by a main radiating slot with two secondary reflector and four tunning slots for good reflection loss values (Fig. 6). The main radiating slot couples energy into the dominant TM_0 SW mode of the slab while the two secondary folded reflector slots increase forward directivity achieving the desired unidirectional SW propagation. In addition, these slotted configurations can be thought to act as integrated planar sources for efficient SW excitation and bound propagation along the air-dielectric interface.

III. Antenna Design, Results and Discussion

The segmented circular strip grating on top of the GDS defines a capacitive partially reflecting surface (PRS) for LW radiation over a broad frequency scan range (18 to 26 GHz). Physically, the feedless array of strips can radiate energy with decreasing amplitude away from the directive SWL source; ie. the cylindrical SWs propagating along the guiding surface from the origin inductively couple to the strip segments, energy leakage occurs along the antenna aperture, and the generated space waves combine in the far field realizing the observed beam patterns. In effect a typical corporate feeding network is replaced by a SWL source achieving efficient SW excitation.

A pencil beam at $\theta_p = -55°$ is observed at 18.0 GHz as shown in Fig. 5. Gradual beam scanning towards broadside continues with an increase in frequency. Near the TE_1 SW mode of the slab (19.47 GHz) beam splitting is observed (18.5 GHz) followed by beam combining (19.0 GHz) and further beam splitting. At 20.4 GHz a single directive beam is realized with continued pencil beam scanning through broadside to 23.1 GHz as shown in Figs. 5 and 7. At 23.8 GHz beam scanning continues toward end-fire but with a conical-sector far field beam configuration.

It should be noted that a similar LWA design was presented by the authors in [3]. That work investigated a different strip configuration achieving maximum radiation at broadside. Minimal beam scanning (of high quality) was observed away from the broadside direction with limited radiation in the backward direction ($\theta_p < 0°$). Furthermore, a directive pencil beam was observed at the edge of the TE_1 SW mode cutoff frequency of the slab (19.47 GHz), suggesting maximum radiation at the edge of a TE LW stopband. At the cutoff transition TE LW excitation can be strongest; ie. $\alpha^{TE} \approx |\beta^{TE}|$, implying that both TM and TE cylindrical LW field distributions were excited on the aperture and that the radiated far field components appropriately combined together at broadside [1].

In contrast to [3], gradual beam scanning from backfire through broadside to forward fire was desired in this work. Thus by operating at higher frequencies of operation, where η^{SWL} can approach maximum values (while also modifying the strip aperture), improved beam scanning quality can be observed. Increased radiation performances (along with reduced beam splitting) may also be realized by operating at higher frequencies of operation (if the same slab is considered), while also altering the circular strip design and slotted SWL source.

IV. Conclusions

A printed LWA structure was presented for one-sided continuous beam scanning through broadside. Measured results at 22.3 GHz illustrate a directive pencil beam pattern off broadside ($\theta_p = 12°$) with a pattern beamwidth of 6°. Agreement is also observed between the simulations and measurements and wide-angle beam scanning is achieved from $-55°$ to $+47°$. In addition good SW coupling efficiencies can be realized by the appropriate substrate selection and frequency of operation.

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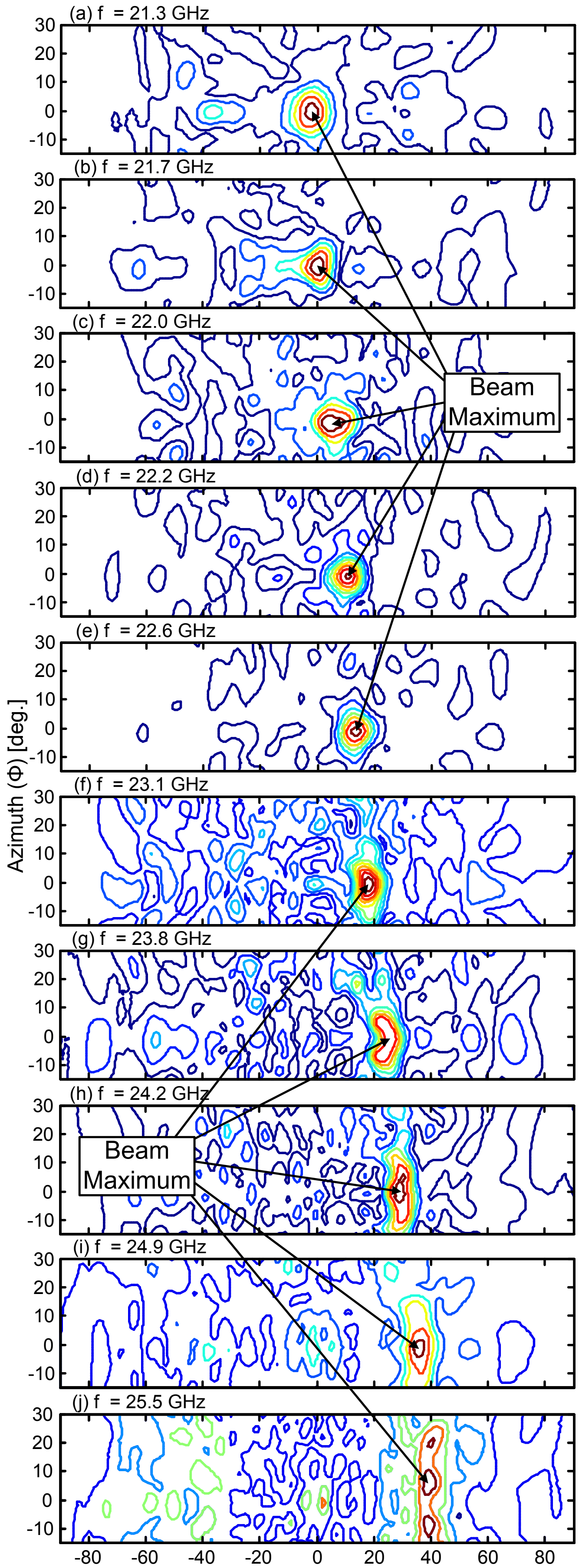

Fig. 7. Broadside to forward fire 2D beam pattern measurements.