A New Leaky-Wave Antenna Design using Simple Surface-Wave Power Routing Techniques

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***Abstract*—A planar antenna that uses surface waves (SWs) for leaky wave (LW) excitation is presented. Specifically, a surface-wave launcher (SWL) is employed to excite SWs for bound, guided-wave propagation along the utilized dielectric slab. By introducing simple techniques to route excited fields, guided waves can be confined for increased directivities and radiation performances. Concepts are first examined in simple test circuits and extended to the proposed LWA design. Simulations and measurements demonstrate one-sided beam scanning from back-to forward-fire with directive beam patterns in the far field from 17 to 25 GHz. Reported gain values are greater than 10 dBi. Such a low-cost and low-profile LWA may be advantageous for radar systems and satellite communications. Presented routing techniques are also applicable to other antennas and printed circuits operating at microwave and milliliter-wave frequencies.**

I. Introduction

Recently, surface-wave launchers (SWLs) have been shown to be a useful feeding technique for new high gain planar leaky-wave antennas (LWAs). In these designs slotted configurations in the ground plane of the slab act as the antenna source [1],[2] where energy is efficiently coupled into the dominant TM_0 surface wave (SW) mode [3]. Bound cylindrical-waves can be excited with radial propagation along the 2-D antenna aperture [4]. Conical-sector and pencil beam patterns can be observed in the far field. In addition, these types of LWA structures are desirable for their low cost and compatibility with other planar devices and monolithic topologies.

Relatively large 2-D antenna apertures may be required in these designs to leak out the power contained within the slab. But, by the inclusion of a new and simple medium to surround such structures, SWs can be confined, further directed, and routed achieving smaller apertures with antenna gain values similar to those of [1] and [2]. The presented LWA structure is shown in Figs. 1 and 2. Essentially, an inverted ground plane design is studied with an integrated SWL feed for excitation of a hybrid SW, slot-line mode. Similar propagation characteristics to that of the TM_0 SW can be observed. Routing concepts are first examined using simple testing circuits (Figs. 3 and 4) and results are compared in Figs. 5 and 6. Measurements and simulations of the proposed LWA design are also shown in Figs. 7 - 9. Good radiation efficiencies can be observed along with fan-beam scanning in the far field from the backward to the forward direction as a function of frequency. To the authors' knowledge this is the first time that such an LWA has been designed and measured, offering good radiation performances and one-sided beam scanning.

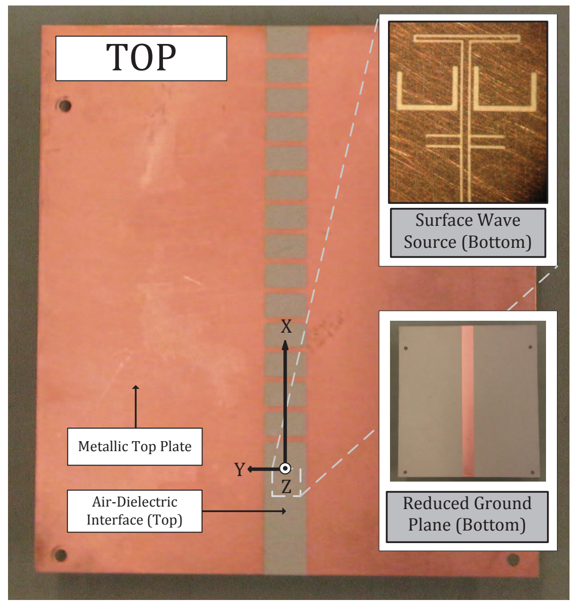

Fig. 1. Realized planar antenna structure. Guided waves are routed or channeled by the reduced ground plane and top plate configurations. Leaky wave excitation can occur due to the metallic strips between the top plates.

II. Antenna Design Principles

These SWLs for efficient SW excitation have been shown to be advantageous for new LWA designs [1]-[3]. Typical structures use 2-D guiding surfaces to support the excited cylindrical LW fields [4]. Essentially, the slotted configurations in the antenna ground plane can act as a magnetic dipole source and cylindrical SWs ($E_\rho \approx E_o/\sqrt{\rho}$) are generated with radial propagation along the air-dielectric interface. Consequently, reduced powers are observed as the guided SW is converted to a LW along the 2-D antenna aperture. Moreover, the completely planar SWL designs are typically fed by 50-Ω coplanar-waveguide transmission line as shown in the inset of Fig. 1. By the appropriate substrate selection ($\varepsilon_r = 10.2$, $h = 1.27$ mm, and $\tan\delta = 0.0023$) energy can be efficiently coupled into the dominant TM_0 SW mode of the slab [3]. By the addition of two secondary reflector slots, unidirectional SW propagation can be achieved for one-sided beam scanning.

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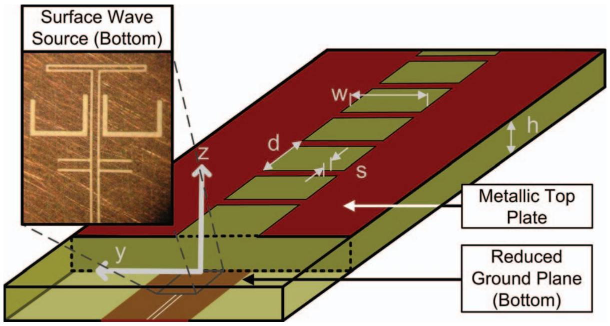

Fig. 2. Planar LWA considered in this work. The SWL (embedded in the bottom ground plane) can generate cylindrical SWs with radial propagation along the air-dielectric interface. By the added metallic plates on top of the slab and the reduced ground plane (bottom), bound SWs can be channeled for unidirectional propagation. Antenna leakage is ensured by addition of the periodic linear array of metallic strips of width s on top of the slab.

A. Reduced Aperture Size By Improved Power Routing

To overcome the requirement of a relatively large aperture new design techniques are examined in this work. In particular, by inclusion of a medium to confine the excited SW fields, propagation can be controlled and TM field strength values can be increased as desired within the dielectric, but at the cost of a fan-beam pattern in the far field (as apposed to a pencil or conical-sector beams for 2-D LWA configurations, [1]-[4]). Depending on the application this fan-beam pattern may be more favorable.

The proposed strategy for SW confinement can be explained by the addition of two stopband regions. In this work such a medium is achieved by placing appropriately configured metallic plates near the x-axis on top of the slab while also reducing the width, w (=10 mm), of the bottom ground plane. Physically, if SWs approach such a medium, reflections can occur and be routed away from that medium achieving the required channeling. Other techniques for realizing these stop-bands regions are possible (such as high impedance surfaces or a periodic arrangement of via elements), but the top parallel-plates and reduced ground plane configurations were employed for their simplicity and low cost implementation.

B. Test Circuit Analysis for Improved Power Routing

Initially, these design techniques were investigated using two tests circuits with no gratings: a full ground plane configuration for cylindrical SW propagation along the planar structure, and a reduced ground plane with the added top plates for SW confinement near the x-axis (Fig. 4). Through powers between two SWLs were investigated in each circuit. Thus propagation along the channel was compared to the more classic configuration of a simple grounded dielectric slab and SW source. The distance between the two top plates and the width of the ground plane was also optimized in a commercial solver while minimizing insertion losses. A fixed distance between the SWLs of $D = 40$ mm was maintained and S-parameters were observed. In addition, simulated currents are compared at 23 GHz on all metal surfaces encapsulating the slabs for the two test circuits as shown in Fig. 5.

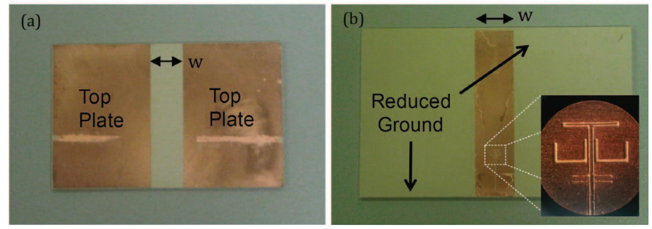

Fig. 4. Realized test circuit. (a): Top side, the two metallic plates are shown. (b): Bottom side with the reduced ground plane for SW confinement. Results in Fig. 6 are also compared to a similar test circuit (not shown) with a full ground plane extending to the edge of the board and no top metallic plates. No gratings were included in these investigated circuit designs.

Results are compared to measurements and simulations of the simple test circuits in Fig. 6. It can be observed that good performances are achieved in the operating frequency range of the investigated LWA. In addition, insertion losses can be decreased by 10 dB from 18 - 28 GHz (and 15 dB from 21 - 25 GHz) for the circuit design using the power routing techniques. These results suggest SW propagation can be confined to the desired region within the slab for efficient and directive power routing. To the authors' knowledge these circuits are the first studies of a simple planar wave guide, defined by a reduced ground plane and top metallic plates, for SW channeling.

III. Antenna Simulations and Measurements

Initially numerical simulations were completed by modeling the entire LWA structure (14 grating periods, with strip periodicity, d = 7 mm, and width s = 1.25 mm). Good

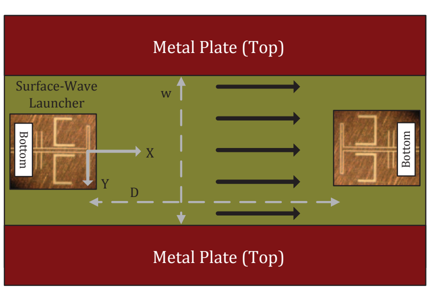

Fig. 3. Test circuit illustration. With the metallic plates on top of the slab (separated by a distance w = 10 mm) and reduced ground planes, through powers can increase between two SWLs (D = 40 mm apart, with no gratings).

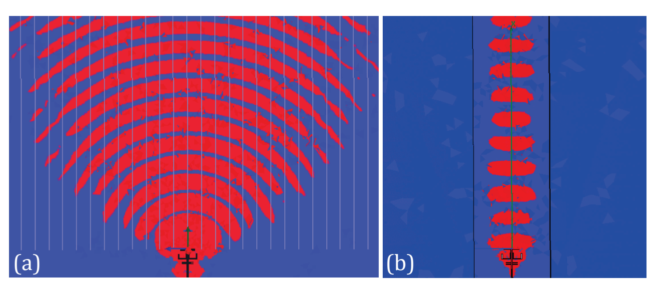

Fig. 5. Simulated currents generated on all metal surfaces for the test circuits. (a): With the full and extended ground plane configuration a forward directed and radial distribution can be observed. (b): Reduced ground plane and added top plate design. Currents are routed and confined.

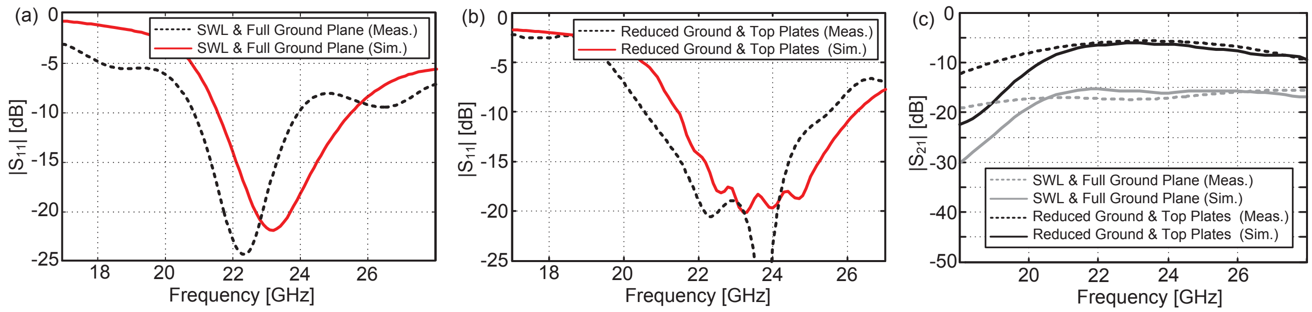

Fig. 6. Test circuit measurements and simulations. No gratings were included in the analysis to ensure bound, guided-wave operation. (a): $|S_{11}|$ of the circuit with a full ground plane. (b): $|S_{11}|$ of the test circuit with the reduced ground plane and additional top plates for SW power routing. (c): $|S_{21}|$ comparison.

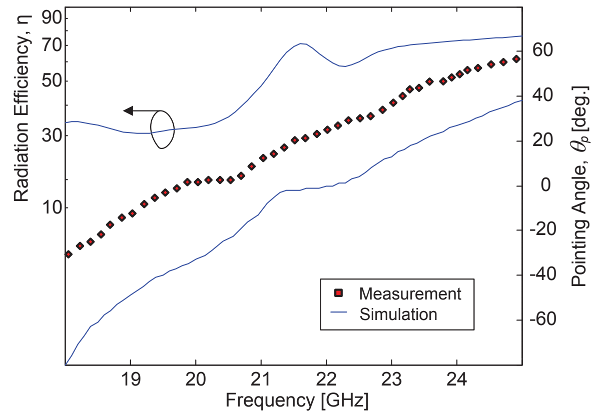

Fig. 7. Pointing angles and radiation efficiency. Deviations are observed (downward frequency shift of ≈1.2 GHz for the measurements when compared to the simulations) and are a likely result of substrate variations in ϵ_r.

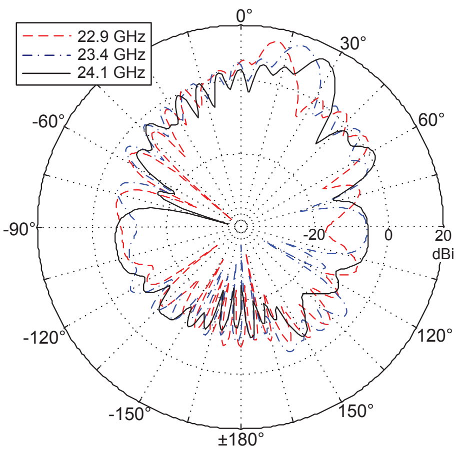

Fig. 8. Simulated gain patterns in the $E(x\text{-}z)$ plane for the LWA design.

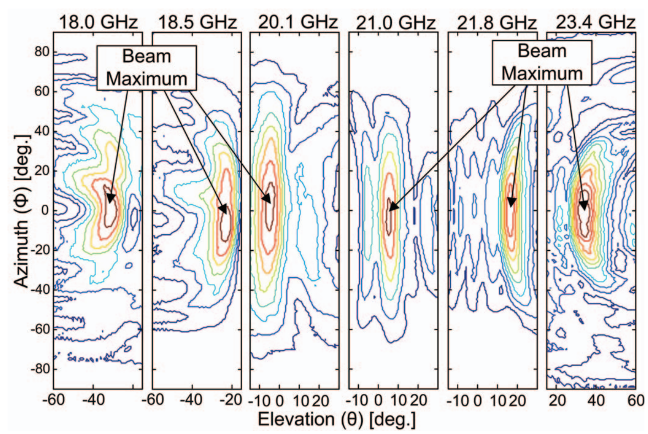

Fig. 9. Measured 2-D fan-beam patterns, E_θ, in linear units and normalized to the observed maximum. Measured results shown for $f = 18.0$, 18.5, 20.1, 21.0, 21.8, and 23.4 GHz. Gain values greater than 10 dBi are observed.

radiation efficiencies (defined as the ratio of the realized gain compared to antenna directivity) can be observed in Fig. 7. For near broadside radiating frequencies ($\theta_p \approx 0°$) radiation performance is reduced suggesting LW stopband behavior; this scanning behavior is typically observed for such one-sided LWA structures [2]. Measured and simulated beam patterns are plotted in polar form and as a function of azimuth and elevation, in Figs. 8 and Fig. 9, respectively. One-side beam scanning in the far field can be observed as a function of frequency. Reported gain values are greater than 10 dBi.

IV. Conclusion

A new planar LWA structure using SW power routing techniques is presented for one-sided beam scanning in the far field. Essentially, SWs are confined and channeled by the added top plates and ground plane reductions. To examine the effectiveness of the proposed technique, tests circuits were initially fabricated and measured. Concepts were then extended to the studied antenna configuration resulting in a novel and effective SW guidance mechanism. A new 1-D LWA design is the result offering fan-shaped beam patterns in far field. Presented design strategies are applicable to other antennas and circuits at microwave and milliliter-wave frequencies.

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