Multilayer Antennas for Directive Beam Steering Broadside Radiation and Circular Polarization

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***Abstract*—Multilayer antennas that utilize surface-waves launchers (SWLs) for leaky wave (LW) excitation are presented for microwave and millimeter-wave applications. Specifically, by placing two superstrate dielectric layers on top of a base grounded dielectric slab, a resonant cavity structure can be realized, and the bound field distributions can be transformed into LWs for radiation into the far field. For verification of the multilayer designs a single antenna structure is fabricated using commercially available substrates. A pencil beam can be observed at 17.4 GHz with measured gain values of >10.5 dBi at broadside. In addition, by using an array of such SWL sources, beam steering can be achieved as well as circular polarization.**

I. Introduction

High gain leaky-wave antennas (LWAs) have been utilized in the design of many radar and satellite communication systems. In particular, 2D LWAs are advantageous for their compatibility with monolithic devices, low cost and pencil-like beam patterns. These antennas are characterized by a suitable aperture and source configuration exciting cylindrical leaky-waves (LWs) which can leak energy into free space during their radial propagation along the guiding surface [1]. With appropriate design multilayer LWA configurations can be realized with reduced size, improved gain values and increased radiation efficiencies for microwave and millimeter-wave frequencies of operation. Theoretical concepts have been reported in [1]-[4] demonstrating radiation at broadside as well as conical-sector beam patterns in the far field.

This work investigates practical and low cost multilayer LWA designs using printed surface-wave launcher (SWL) antenna sources [5]-[8] for pencil beam radiation, broadside beam steering and circular polarization (CP). Measurements and simulation results are presented examining the functionality of a three-layer stackup of dielectric slabs with a bottom antenna ground plane as shown in Figs. 1-3. In addition, two particular source configurations (Fig. 4) are examined for broadside and one-sided beam patterns in the far field. By the appropriate frequency of operation, material thicknesses, dielectric constants, and SWL source configurations, LWs can be excited on the top guiding surface realizing the aforementioned pencil beam patterns. To the authors' knowledge this is the first practical implementation of such low cost multilayered LWAs using SWLs for single frequency beam steering and CP.

By placing a non-directive SWL, Fig. 4(a), in the ground plane of a base grounded dielectric slab (GDS), defined by ϵ_{r_1} and h_1, and covering this bottom slab with two superstrate

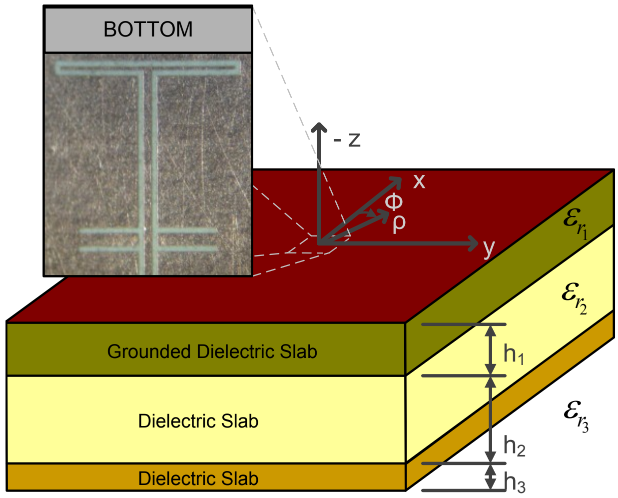

Fig. 1. Illustration of the compact LWA considered in this work defined by a base GDS (ϵ_{r_1} and h_1) covered by two superstrate dielectrics. A single SWL or an array of sources can be utilized as the printed antenna feed.

dielectrics (ϵ_{r_2}, h_2 and ϵ_{r_3}, h_3, respectively) a leaky, parallel-plate guiding structure can be realized [3],[4]. The bound bi-directional surface wave (SW) field distribution, excited by the central non-directive SWL source [6] is perturbed, realizing far field pencil beam patterns at broadside (Figs. 5-7). Moreover, by placement of a directive SWL source, Fig. 4(b), at the edge of the bottom ground plane a directional SW field distribution can be generated [7] for one-sided beam patterns off broadside (Fig. 8). Physically, the dielectric coverings define an effective partially reflecting surface (PRS) achieving new boundary conditions for energy leakage (Fig. 9) and the transformation from a bound to a radiated mode.

Recently a two element linear array of directive SWLs was presented for steering and control of SWs [8]. Such a feeding technique is advanced in this work by implementing a new arrayed configuration of four non-directive SWLs placed at the center of the antenna ground plane as shown in Fig. 10(a). By the appropriate element power weighting (in magnitude and phase) broadside beam steering (Figs. 10-11) and/or left-handed (LH) or right-handed (RH) CP can be achieved at a single frequency (Fig. 12). Essentially, a constructive and tunable standing SW field distribution is generated on the guiding surface allowing for advanced beam control in the far field. It should be noted that the following convention is used to describe the substrate and superstrate dielectric

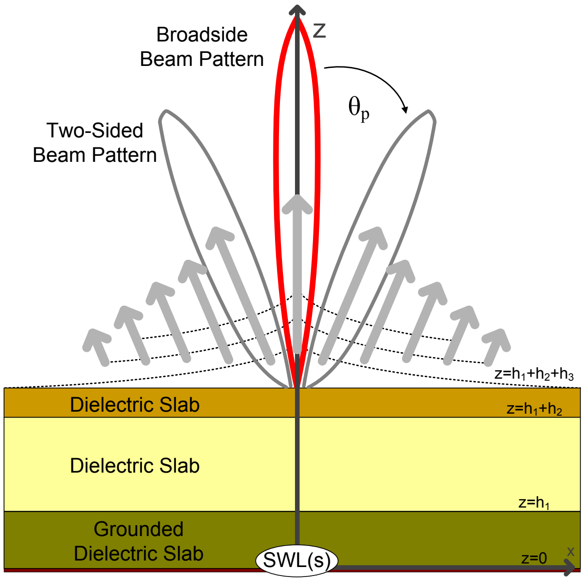

Fig. 2. Stackup configuration of the proposed multilayer LWA fed by SWL(s). By the appropriate source configuration and dielectric layers, one-sided or two-sided beam patterns are possible along with CP and beam steering. In this work all substrate dimensions were held constant to 6 cm by 6 cm.

layers utilized in the investigated multilayer LWA structures: $\epsilon_{r_i} = [\epsilon_{r_1}, \epsilon_{r_2}, \epsilon_{r_3}]$ and $h_i = [h_1, h_2, h_3]$ mm. In addition, power feed ratios at the ith port are defined in magnitude and in phase angle as $P_i = [\text{MAG}_i \angle \text{PHASE}_i]$ for the four element non-directive SWL array.

II. Theoretical Considerations & Antenna Design

A three-layer dielectric LWA structure above a ground plane is considered in this work as shown in Figs. 1-3. High gain values may be achieved at a desired pointing angle, θ_p, if the base dielectric materials and superstrate thickness are chosen according to the following relation [2]-[4]:

$$h_i = \frac{\lambda_0}{4\sqrt{\epsilon_{r_1} - \sin^2\theta_p}}. \tag{1}$$

In addition, increased gain values can be achieved if the dielectric constant of the substrates meets the following conditions: $\epsilon_{r_1} >> \epsilon_{r_2}$ and $\epsilon_{r_3} >> \epsilon_{r_2}$. Thus, a high-low-high dielectric profile is required for increased radiation efficiencies [2]-[4].

A. Radiation into the Far Field by Leaky Wave Excitation

The resonant gain of such multilayer antenna structures can be described by LW phenomena. Radiation can occur with far field beam patterns at a particular angle, θ_p, due to the presence of LW field distributions on the top guiding surface. More specifically, cylindrical TE_z and TM_z LW field distributions can be excited [1] on the top dielectric aperture at $z = h_1 + h_2 + h_3$. The TE_z LW mode determines the E_ϕ component of the far field pattern, while the TM_z mode dictates E_θ. Thus the TE_z $[TM_z]$ LWs determine the H-plane [E-plane] pattern in the y-z $[x$-$z]$ plane. Also, as the dielectric constant of the top superstrate layer increases the leakage rate decreases and thus the antenna gain can approach maximum values, but at the cost of reduced radiation bandwidths [1]-[4].

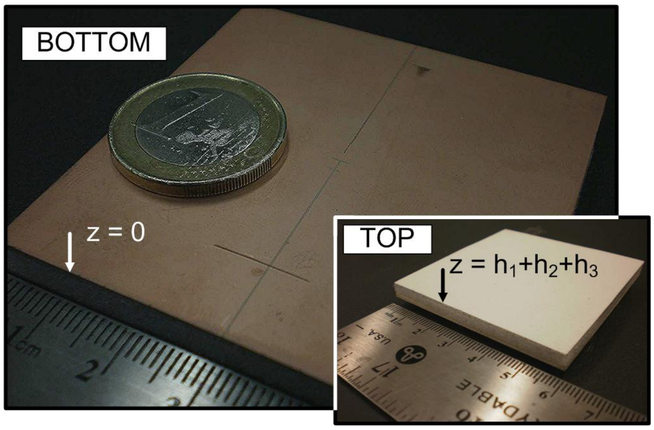

Fig. 3. Measured 6 cm by 6 cm multilayer LWA (ϵ_{r_i}=[10.2, 1, 30] and h_i=[1.27, 3, 0.7874] mm) with a non-directive SWL in the ground plane.

B. Non-Directive and Directive Surface-Wave Launchers

Two different slotted SWL antenna sources are utilized in this work for the purposed multilayer LWA structures. Physically, the non-directive and directive SWL source configurations (Fig 4 (a) and (b), respectively) can efficiently couple energy into the dielectric layers generating bidirectional and unidirectional field distributions for radiation into the far field. Essentially, the input signal is coupled into the dominant TM_0 SW mode of the bottom slab and the half wavelength slots in the ground plane define the main element for SW excitation.

The non-directive SWL directs energy in both the forward and backward directions ($\pm\hat{x}$) and this type of source is useful for broadside radiation and two-sided antenna beam patterns in the far field. Conversely, a unidirectional field distribution can be produced by a directive SWL where the majority of the energy is directed along the $+\hat{x}$ direction only; this type of source is useful for one-sided antenna beam patterns in the far field. In addition, the printed SWLs were fed by coplanar waveguide transmission lines allowing for simple integration with other printed designs and circuit topologies.

C. Comparison With and Without the Superstrate Layers

By observing the magnitude and phase of the field distribution throughout the dielectric layers (in a x-z cutting plane

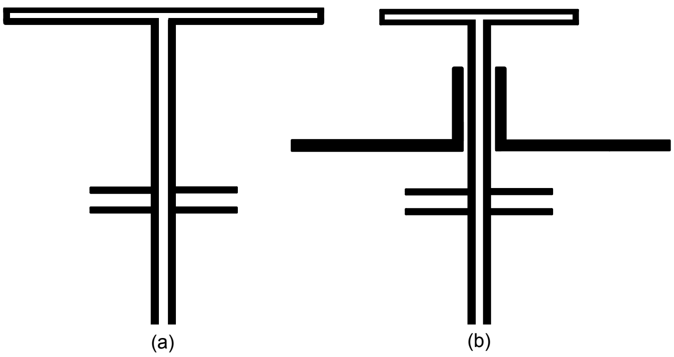

Fig. 4. Ground plane trace of the utilized (a): non-directive [8] and (b): directive [10] SWL sources; realized by ground plane slots in the base slab (ϵ_{r_1}, h_1). Main top 'T' slot lengths are 2.5 mm and 2.0 mm, respectively.

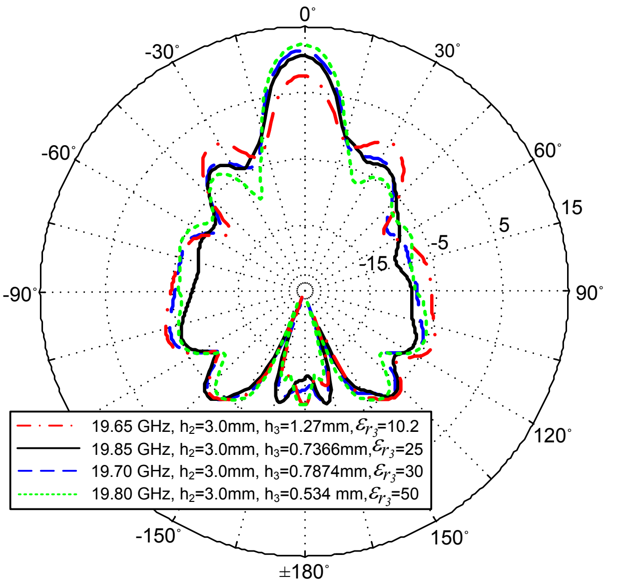

Fig. 5. Simulated $E_\theta(\phi = 0°)$ gain patterns in the $E(x\text{-}z)$ plane (in dBi) using a single non-directive SWL. Observed maximum gain values are shown. Improved gain is possible by increasing ϵ_r of the top dielectric layer.

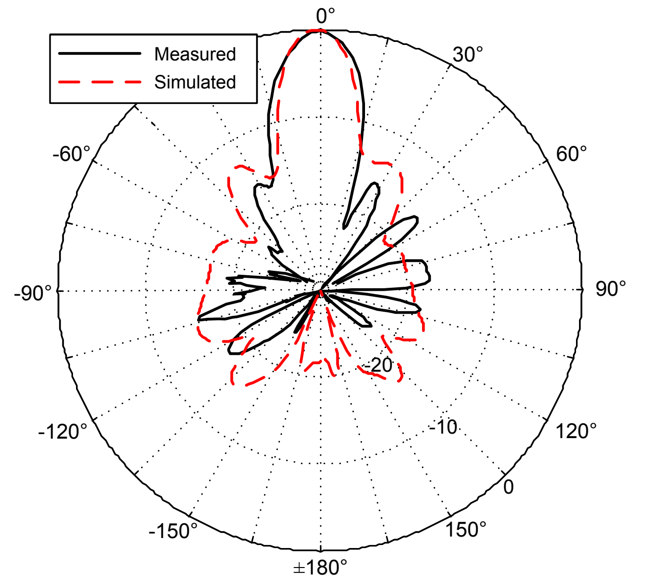

Fig. 7. Measured beam patterns in the $E(x\text{-}z)$ at 17.4 GHz and normalized to observed maximum gain. Values shown in dB. Agreement can be observed with the simulated beam pattern; ϵ_{r_3}=30 and h_3=0.7874 mm, as in Fig. 5.

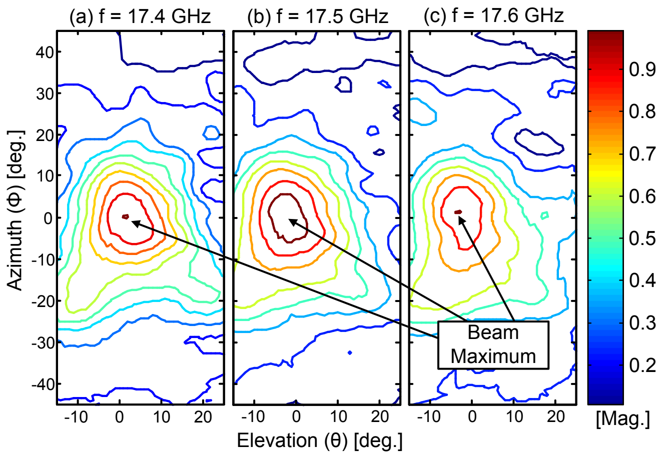

Fig. 6. Measured 2D gain patterns in the azimuth and elevation. Values have been normalized to observed maximum and results are shown in linear units.

for $z > 0$) further insight into the operation of the proposed LWA antenna structures (with a single non-directive SWL source) can be understood. Simulated field values are shown (in magnitude and phase) with and without the superstrate dielectric layers (Fig. 9 for ϵ_{r_i}=[10.2, 1, 25] and h_i=[1.27, 3.0, 0.7366]); by covering the bottom GDS with two superstrate layers a leaky, parallel-plate guiding structure can be observed. The bound field distributions excited by the non-directive SWL source are perturbed at $z = h_1 + h_2 + h_3$, new boundary conditions exist, and the transformation from a bound mode to a radiated mode can be examined.

This can also be observed in the phase distribution throughout the layers. With no added superstrates bound SWs propagate away from the source and toward the periphery along the $\pm x$ axis. With the addition of the top superstrate layer field propagation occurs away from the slab in the $\pm x$ and $+z$ directions, for $z > h_1 + h_2 + h_3$, and thus is representative of a bi-directional LW field distribution on the antenna aperture. The radiated space waves combine in the far field realizing the observed broadside beam patterns.

D. An Arrayed Configuration of Four Non-Directive Sources

The non-directive SWL sources can be placed in a four element array (Fig. 10) and by modifying the relative magnitude and phase difference between elements, P_i, the generated field distributions within the dielectric layers can be steered and controlled. Specifically, by placing four non-directive SWLs at the center of the ground plane, field distributions can be

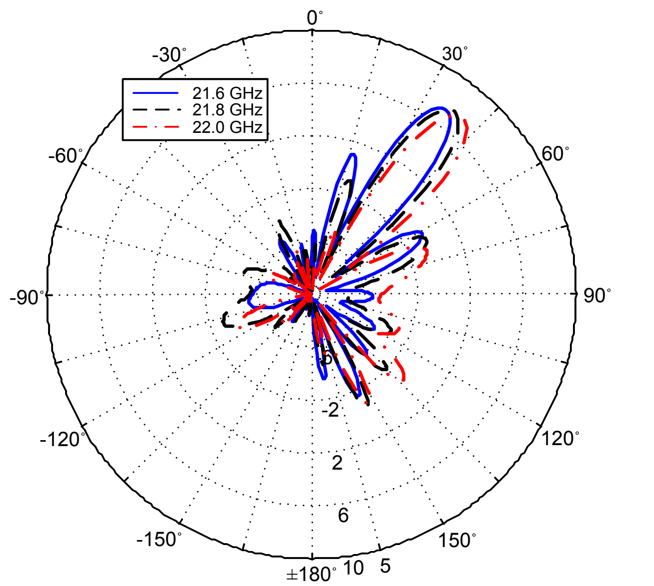

Fig. 8. $E_\theta(\phi = 0°)$ gain patterns (in the x-z plane) in dBi for the investigated LWA using a directive SWL source. A maximum of 7.15 dBi is observed at $\theta = 40°$ for ϵ_{r_i}=[10.2, 1, 25], h_i=[1.27, 2.786, 1.27] mm.

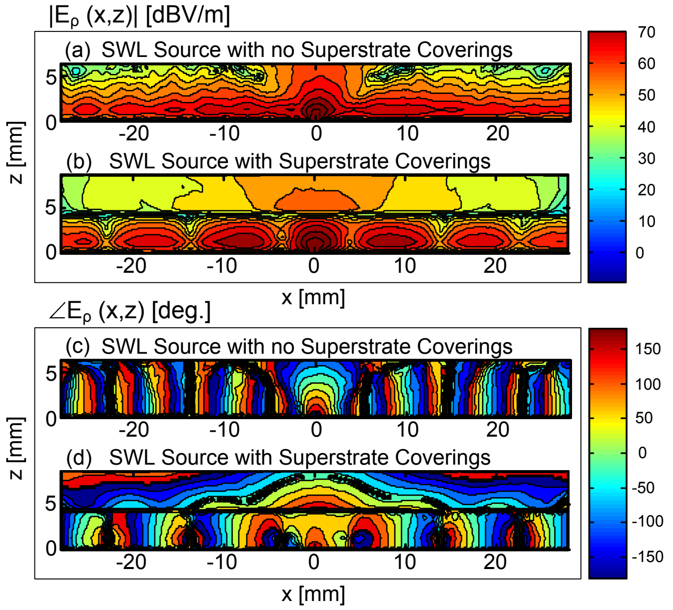

Fig. 9. Field distribution generated by the non-directive SWL source at 19.85 GHz. A comparison is made with and without the superstrate coverings. Substrate parameters ϵ_{r_i}=[10.2, 1, 25] and h_i=[1.27, 3.0, 0.7366] mm.

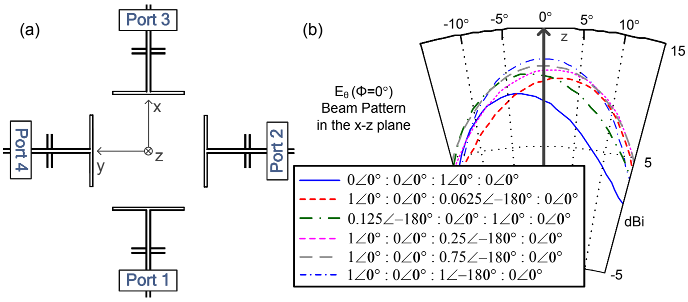

Fig. 10. (a): Investigated SWL array for broadside beam steering and CP. (b): By the appropriate feeding the main far field beam can be steered $\pm 4.5°$. Substrate parameters ϵ_{r_i}=[10.2, 1, 25] and h_i=[1.27, 3.0, 0.7366] mm.

directed along the $\pm\hat{x}$ or $\pm\hat{y}$ axis dictating the region of LW field excitation on the top guiding surface. Physically, a constructive and tunable field distribution is generated within the layers and field maxima can also be steered off the main axis for control along the azimuth. Applications include single frequency beam steering in the far field and CP.

III. Multilayer Leaky-Wave Antenna Designs

For optimal radiation performances and increased antenna gain values at microwave and millimeter wave frequencies of operation, relatively high dielectric constant values are required for the top layer with very particular thickness requirements for the entire structure. For example, high gain values may be achieved at a desired pointing angle, θ_p, if the dielectric material thicknesses are chosen according to Eq. 1. But in practice acquiring such exact substrate characteristics (for a particular design frequency) can be very challenging. Furthermore, high precision tooling or milling may be required to achieve the required layer thicknesses and fabrication costs can escalate. Thus for the realization of low cost designs, the use of commercially available materials may be advantageous.

A. Multilayer Designs Using a Single Surface-Wave Source

For the proposed LWA and SWL feeding technique commercially available dielectric materials were acquired from Rogers Corporation and Emerson & Cuming; dielectric values of ϵ_{r_i} = [10.2, 1, 30] with corresponding thicknesses of h_i=[1.27, 3.0, 0.7874] mm. These materials were utilized for the compact LWA design (Fig. 3). Initially, the single non-directive SWL source was etched in the centre of the bottom ground plane and the top superstrate layers were bonded to the base GDS using an adhesive spray (3M Fastbond 77).

1) Design for Broadside Radiation: Maximum gain values of 12.5 dBi can be observed at broadside at 19.80 GHz using a non-directive SWL source with a top superstrate layer with a dielectric constant of 50. Results are shown in Fig. 5 for other top slab layers (also designed to achieve broadside radiation). Measured 2D gain patterns in the azimuth and elevation are shown in Fig. 6 for the fabricated LWA design and results are compared to the simulations in the $E(x\text{-}z)$ plane (Fig. 7). Side lobe levels are $\leq$15 dB below the observed beam maximum. Furthermore, the presented LWA design can radiate a single pencil beam at broadside ($\theta_p = 0°$) from 17.26 GHz to 17.65 GHz (offering a fractional bandwidth of 2.24%) with a 3 dB radiating bandwidth of 0.32 GHz (from 17.31 GHz - 17.63 GHz) and pattern beamwidths $\leq 8°$. Measured maximum gain values are 10.68 dBi at 17.4 GHz. Thus with increased dielectric constant values (ϵ_{r3}>30) and particular thicknesses for the dielectric layers, improved gain values may be observed, but with a resultant decrease in radiating bandwidth. If increased radiation bandwidths are desired, lower ϵ_{r3} values for the top layer may be optimal.

It should be noted that a pencil beam at broadside (with maximum gain) was measured [simulated] at 17.4 [19.7] GHz. Deviations are a likely result of dielectric substrate variations, fabrication tolerances and difficulty in modeling the metal thicknesses near the slots due to microfabrication. In addition, the two adhesive layers (between $\epsilon_{r1}/\epsilon_{r2}$ and $\epsilon_{r2}/\epsilon_{r3}$) were not included in the simulations for simplicity. Regardless, maximum gain values were observed for these two particular frequencies and beam pattern shapes are in good agreement.

2) Design for One-Sided Antenna Beam Patterns: A directive SWL source was utilized for one-sided antenna beam patterns ($\theta_p = 40°$) as shown in Fig. 8. Commercially available substrates were utilized in the simulations with one-sided maximums observed for off broadside beam angles. Results suggest that by proper selection of the substrate parameters increased gain values may be observed for this pointing angle.

B. Single Frequency Beam Steering at Broadside

Broadside beam steering is also possible at a single frequency by using the four element array of SWLs. Simulations results are shown in Figs. 10 and 11 at 19.85 GHz. Since the controlled field distributions from the SWL array are

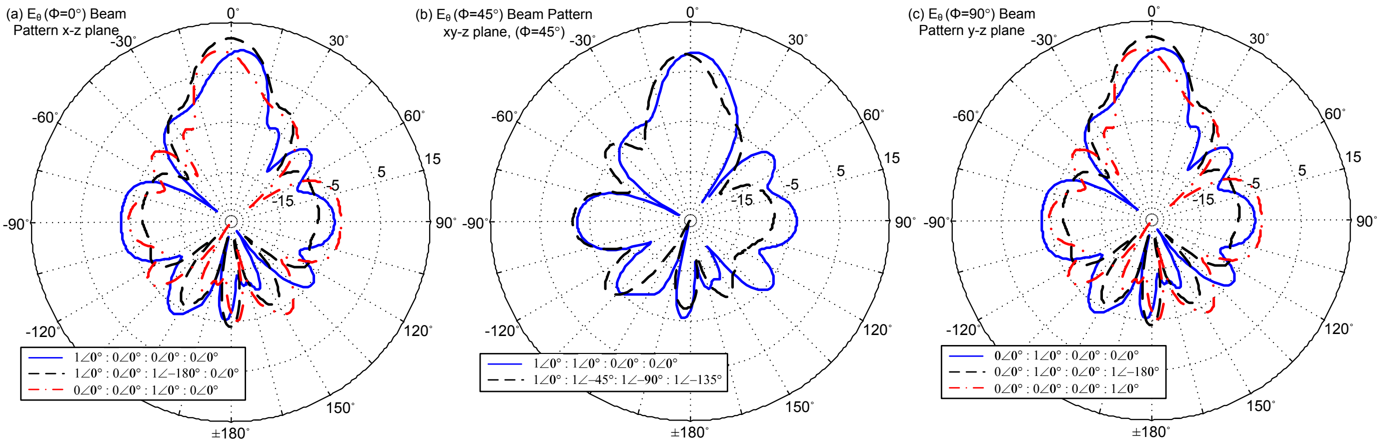

Fig. 11. Broadside beam steering at 19.85 GHz by tuning the feeding array distribution. The main pencil beam can be contained and controlled within a small cone defined by $\theta \in \pm 4.5°$ and $\phi \in \pm 180°$. Simulated results are shown in dBi in the x-z ($\phi = 0°$), xy-z ($\phi = 45°$), and y-z ($\phi = 90°$) planes.

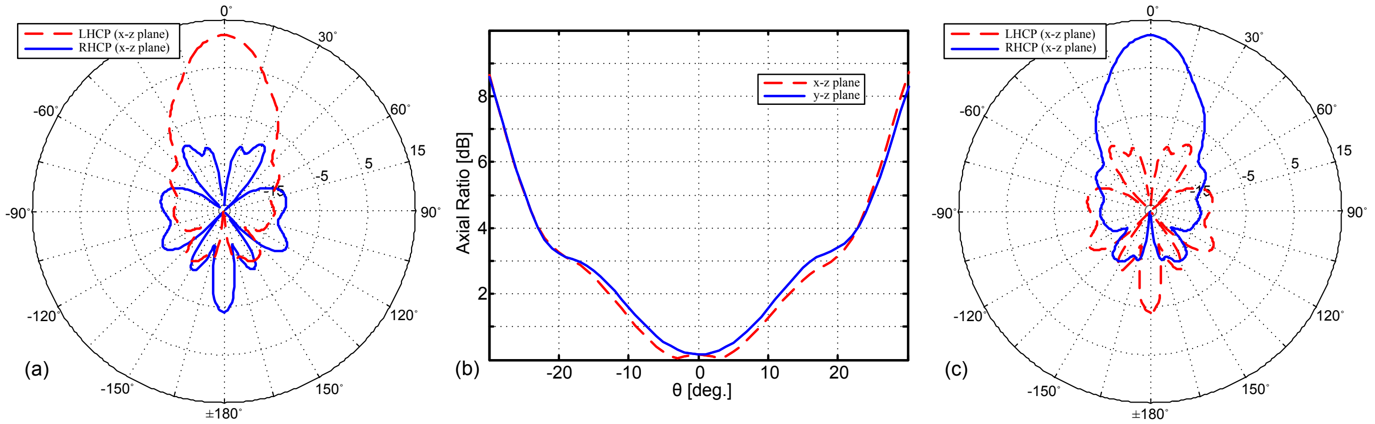

Fig. 12. Circularly polarized beam patterns at 19.85 GHz by the appropriate complex weighting distribution: (a),(b) LH CP ($1\angle 0° : 1\angle{+90°} : 1\angle{+180°} : 1\angle{+270°}$) and (c) RH CP ($1\angle 0° : 1\angle{-90°} : 1\angle{-180°} : 1\angle{-270°}$). Results are shown in dBic in for investigated LWA structure (ϵ_{r_i}=[10.2, 1, 25] and h_i=[1.27, 3.0, 0.7366] mm) with four SWL sources. The axial ratio (b) for the LH CP design is shown (similar results are expected for a RH configuration).

directed within the slab layers, LWs are also contained within a specified region as well on the top guiding surface realizing the controlled broadside beam steering in the far field.

C. Left- or Right-Hand Circular Polarization

Using the four element array of non-directive SWLs both LH and RH CP can be realized by quadrature feeding. Simulation results are shown in Figs. 12. Axial ratios below 3 dB are observed from $\theta = -17.5°$ to $+16.0°$ at 19.85 GHz in both the x-z and y-z planes for the LH CP design. Applications include satellite communications, space and radar tracking systems.

IV. Conclusions

By placing SWL antenna sources within the ground plane of a base GDS, and by covering this bottom slab with two top dielectric layers, a leaky, parallel-plate guiding structure can be realized; the top superstrate covering realizes an effective PRS for directive beam patterns in the far field. In addition, by inclusion of a four element array of SWLs, single frequency broadside beam steering as well as CP is also possible.

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