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A New Configuration of Printed Non-Directive Surface-Wave Sources for Advanced Beam Control

Symon K. Podilchak [1,2], Al. P. Freundorfer [2], Yahia M. M. Antar [1,2]

[1] *Department of Electrical and Computer Engineering, Royal Military College of Canada*
13 General Crerar Crescent, Kingston, Ontario, Canada, K7K 7B4

[2] *Department of Electrical and Computer Engineering, Queen's University at Kingston*
19 Union Street, Walter Light Hall, Kingston, Ontario, Canada, K7L 3N6

E-mail: antar-y@rmc.ca

***Abstract*—An array of surface-wave launcher (SWL) sources is presented for surface-wave (SW) control and beam steering on a grounded dielectric slab (GDS). Specifically, a four element array configuration of non-directive SWLs is investigated. By varying the relative phase difference and magnitude between SWL elements, the excited SW field distribution on the guiding surface can be steered and controlled. Simulations and measurements of a single SWL element are provided along with simulations of the proposed array. If metallic gratings or strips, or additional dielectric layers are placed on top of the GDS, the bound SWs can be transformed into radiated leaky-waves (LWs) and directive beam patterns can be generated in the far field. Examples are provided illustrating that broadside beam steering and circular polarization can be achieved at a single frequency. These slotted SWL arrays can be useful for novel SW beam scanning designs and other LW or cavity based antennas.**

I. Introduction

High gain planar antennas and arrays are attractive for their compatibility with other printed technologies, low cost and ease of fabrication. Applications include automotive and airport tracking radar, phased arrayed systems for security and defense, circular polarization (CP), and satellite communications. Unfortunately, conventional corporate feeding schemes for these beam steering designs can be problematic at high frequencies. More specifically, power losses may be observed at microwave and millimeter-wave frequencies due to unwanted surface wave (SW) excitations. This can lead to reduced antennae and circuit efficiencies, and thus diminished system performances.

These SWs were typically looked upon as an adverse and parasitic effect causing undesired electromagnetic coupling between metallic elements and unwanted radiation into the far field. An alternative approach is to try and efficiently excite such SWs using surface-wave launchers (SWLs). By the selection of electrically thick substrates with relatively high dielectric constant values ($\epsilon_r \approx 10$), SWs can be efficiently excited [1] on a ground dielectric slab (GDS). Essentially by the appropriate configuration of slots in the ground plane of a GDS energy can be coupled into the dominant TM_0 SW mode of the utilized slab. Both directive [2]-[4] and non-directive SWL source configurations [5], [6] have been investigated in the literature for the realization of both unidirectional and bidirectional SW field distributions. In addition, these SW launching techniques have been shown to be useful for exciting leaky waves (LWs) on such guiding structures [2]-[6]. Thus in these designs SWs were deemed helpful for feeding planar leaky-wave antennas (LWAs).

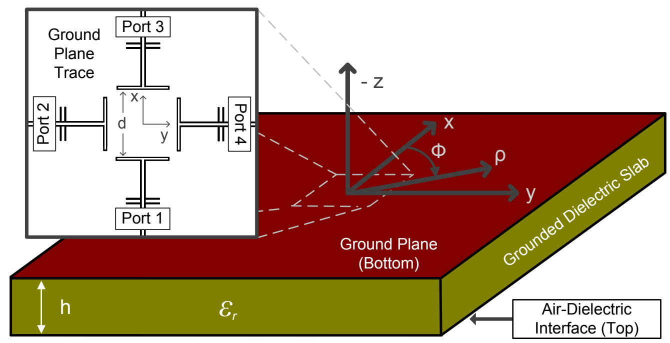

Fig. 1. Illustration of the considered source configuration and antenna structure. The four non-directive SWLs define the SW feed array (ports defined 1 to 4 as in the figure inset) embedded in the ground plane of the slab. With placement of grating, strips or multiple dielectric layers on top of the slab, LWs can be excited along the 2-D aperture and by the appropriate SWL port excitation far field beam steering is possible as well as CP.

Recently a two element linear array of directive SWLs was presented for steering and controlling SWs along a planar guiding surface [3]. In that work bound SWs were directed from the origin of the SWL array along a single axis. Field strength maxima were steered $\pm 18°$ away from that main axis by varying the relative phase difference between SWL elements. Concepts were extended to one-sided beam steering in the far field by the addition of an elliptical [3] and circular grating configuration [4] on top of the slab.

In an effort to increase the tunability range and versatility for such beam steering designs a new four element SWL array configuration (Fig. 1) is investigated in this work. More specifically, by placing four non-directive SWLs at the center of a large ground plane SW field distributions can be directed along the $\pm\hat{x}$ or $\pm\hat{y}$ axis for bound propagation along the air-dielectric interface of a GDS. Physically, a constructive and tunable SW field distribution is generated on the guiding surface. Bound field maxima can also be steered off the main axis for advanced SW control along the azimuth. By the addition of an appropriate configuration of metallic gratings or strips, leaky waves (LWs) can be excited on the guiding surface (as

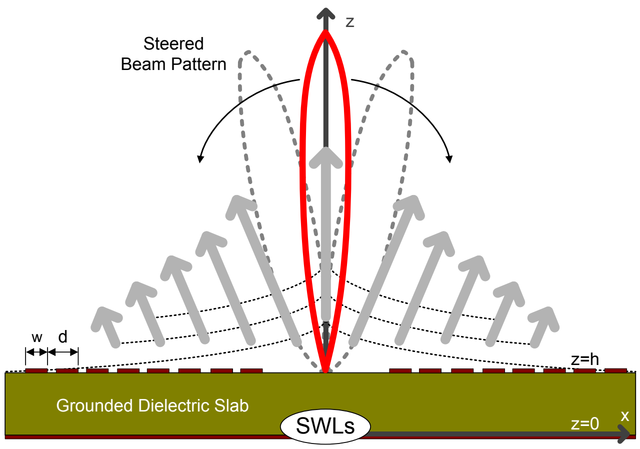

Fig. 2. By the addition of metallic gratings or strips (width w and periodicity d) LWs can be excited on the planar guiding surface. By the appropriate source excitation beam patterns can be steered or controlled at a single frequency.

illustrated in Fig. 2) realizing one-sided or two-sided directive beam patterns in the far field. Measurement and simulation results of the utilized single element non-directive SWL source (Fig. 3) are provided in Figs. 4 and 5 while simulation results for the proposed array (and resultant beam patterns) are shown in Figs. 6-10; field distributions generated on the guiding surface are varied offering advanced antenna beam control at a single frequency. In addition, both left-handed (LH) or right-handed (RH) CP bound field distributions are also possible along with broadside beam steering.

II. Surface-Wave Launchers for Beam Control

To excite the dominant SW mode on the utilized GDS ($\varepsilon_r = 10.2$, $h = 1.27$ mm, $\tan\delta = 0.0023$), coplanar waveguide fed non-directive SWLs were utilized [5], [6]. These sources can be described by slots in the ground plane with a main SW radiating slot (length of 1.92 mm) and four tuning elements (individual length of 0.65 mm), as shown in Fig. 3. Essentially, the main slots can excite cylindrical TM field distributions with backward and forward propagation along the guiding surface. In addition, substrate properties and frequencies of operation were chosen for efficient coupling into the dominant TM_0 SW mode of the slab [1].

A. Bound Field Distributions Generated by a Single Source

Measured and simulated SW field distributions generated by the non-directive SWL source are shown in Figs. 4 and 5. Measured evanescent field strength readings (and analogous simulated values) were collected using a near field probe traversed (0.5 mm above the air-dielectric interface) on an arc centered (radius, $r_0 = 4.5$ cm and $r_0 >> \lambda^{SW}$) at the main slot. The measured fields along this arc represent the SW field distributions at a significant distance from the SWL source and thus can represent the SW beam pattern on the GDS [3]. It should be noted that no gratings or strips were included in theses measurements and simulations. Increased SW field strengths values were observed in the backward direction and are likely a result of secondary SW excitation due to the tuning slots and coplanar waveguide feeding line transition.

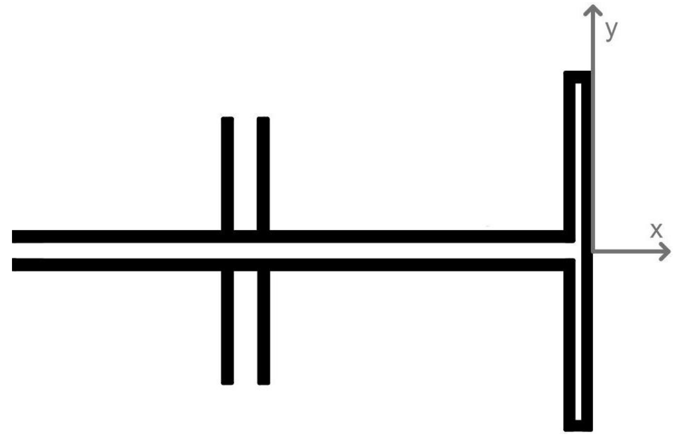

Fig. 3. Ground plane trace of a single non-directive SWL source.

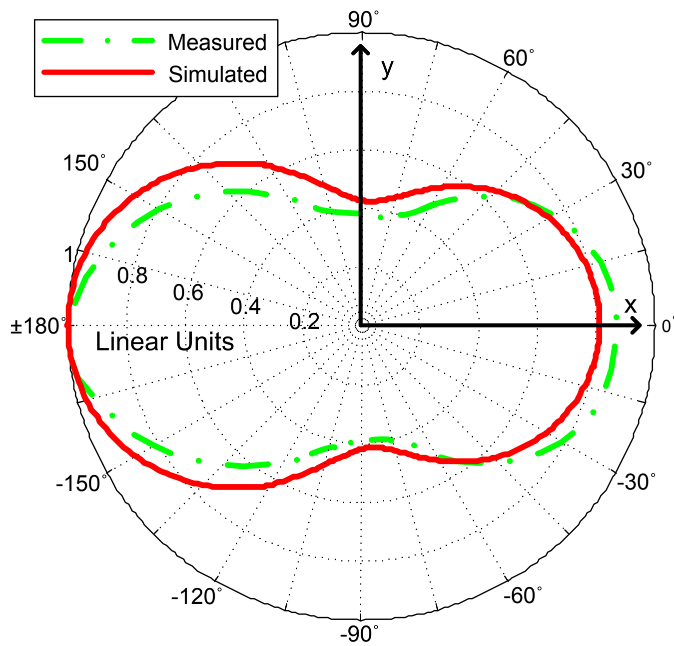

Fig. 4. Normalized SW beam pattern generated by a single non-directive SWL source [5] placed at the origin (as in Fig. 7).

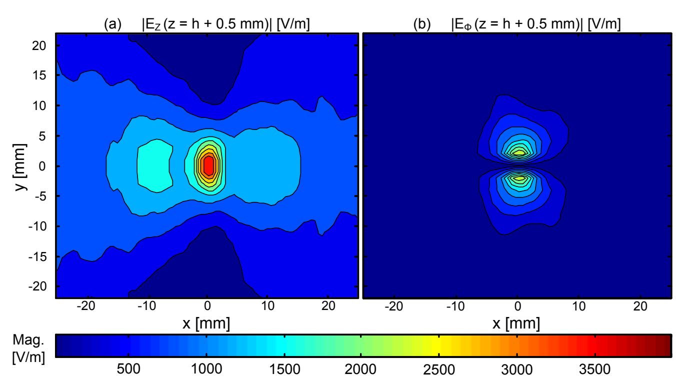

Fig. 5. TM and TE field distributions, $|E_z|$ and $|E_\phi|$, 0.5 mm above the air-dielectric interface at 23 GHz generated by a single non-directive SWL at the origin (as in Fig. 3). No gratings or strips (or other SWLs) were included in the simulation. A TM bi-directional field distribution can be observed.

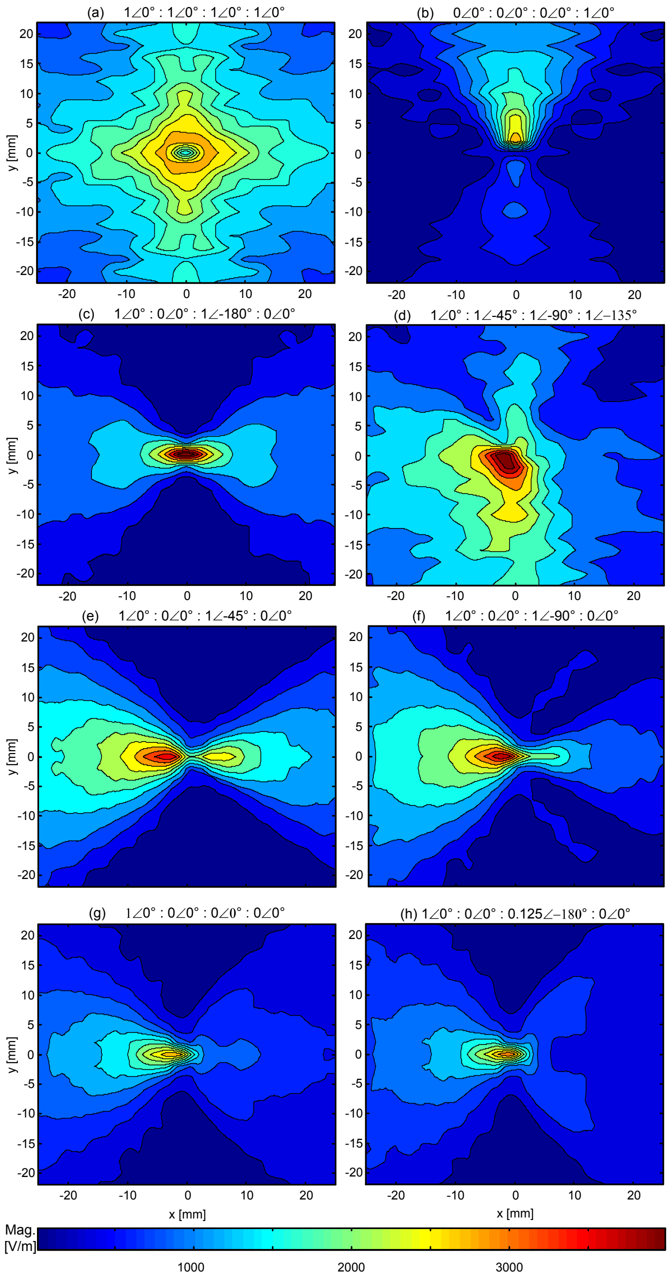

Fig. 6. TM field distribution magnitude, $|E_z(z = h + 0.5 \text{ mm})|$, generated above the air-dielectric interface at 23 GHz using the four element array of SWLs. No gratings or strips were included in the simulation. By varying the SWL port excitation ratios the SW field distribution can be controlled.

To further illustrate the TM field distribution (E_z) along the x-y guiding surface a simulation was performed by placing the non-directive SWL in the center of a large GDS and the near field along the air dielectric interface was sampled. Results are shown in Fig. 5 illustrating that the majority of the TM SWs generated by the main slot propagate in the both the forward and backward directions achieving unidirectional SW propagation (with also a slight field strength increase in the backward direction). A TE field distribution (E_ϕ) is also observed with propagation in the $\pm\hat{y}$ directions but with reduced field strength when compared to the E_z distribution.

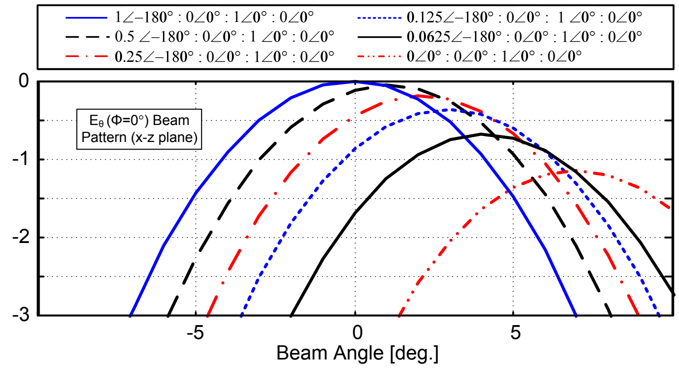

Fig. 7. By the addition of an annular ‘bull-eye’ grating and by fine tuning the SWL feeding distribution the main beam can be steered $+7°$ off broadside with a reduction in gain (of at most 1.2 dB). Simulated beam patterns (in the x-z plane) normalized to observed maximum at broadside (for $1\angle{-180°}$:$0\angle0°$:$1\angle0°$:$0\angle0°$) and shown in dB. Similar results are expected for a reverse weighting distribution but steering to the left of broadside. In addition, beam steering can occur in other planes as shown in Fig. 8.

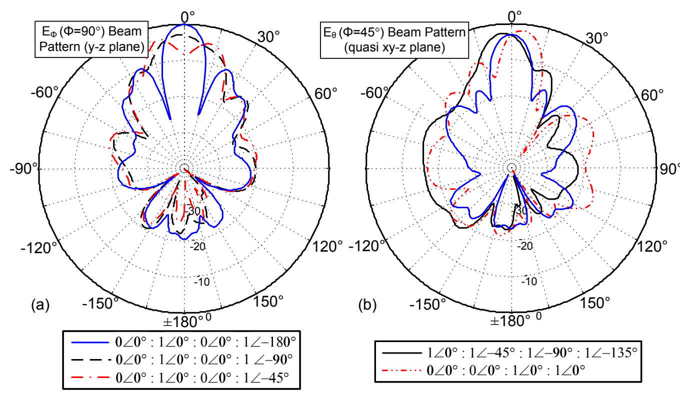

Fig. 8. Beam steering, one-sided and two-sided beam patterns are also possible in the y-z and xy-z planes by the appropriate SWL feeding.

B. Arrayed Configurations of Four Surface-Wave Sources

The non-directive SWL sources were closely packed ($d = \frac{\lambda^{SW}}{2} = 2.971$ mm) and placed in a four element array at the center of the ground plane (as shown in Fig. 1) for SW control on the guiding surface. Essentially, by modifying the relative power feed ratios (in magnitude and phase difference) between the non-directive SWLs, the generated field distribution on the GDS can be steered and controlled. Results are shown in Figs. 6 for various complex power ratios. For example, bound field strength maxima can be directed along the $-\hat{x}$ and $-\hat{y}$ axis with the following SWL feeding configuration: $1\angle0°$:$1\angle{-45°}$:$1\angle{-90°}$:$1\angle{-135°}$, Fig. 6(d). While SW field maximums can be directed along the $+\hat{y}$ [$-\hat{x}$] axis by excitation of the 4^{th} [1^{st}] port only as shown in Fig. 6(b) [(g)]. In addition, a weighted [equally weighted] bi-directional field distribution can also be achieved if opposing elements are $-45°$ or $-90°$ [$-180°$] out of phase as observed in Fig. 6(e) and (f) [(c)]. Field strength minimums are also observed for a uniform weighting, Fig. 6(a). A diverse number of other

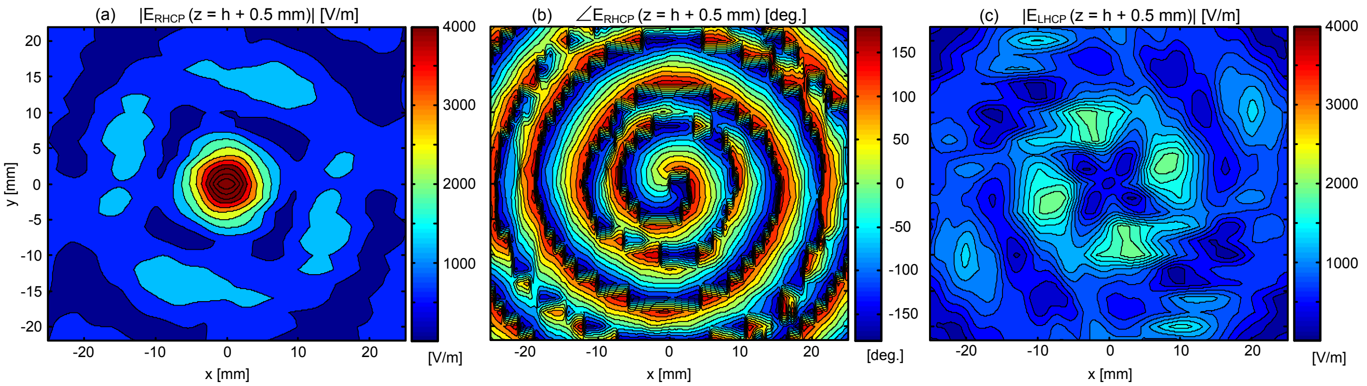

Fig. 9. Simulated RH and LH CP field distributions in magnitude and phase generated 0.5 mm above the guiding surface (with no gratings or strips) with the following port ratios: $1\angle 0° : 1\angle{-90°} : 1\angle{-180°} : 1\angle{-270°}$. If LWs were excited on this guiding surface RH CP beam patterns could be observed in the far field. Similar results are expected for a LH feeding configuration (Fig. 10) but with an opposite field orientation.

feeding configurations are also possible for advanced control.

C. Leaky-Wave Antenna Applications

By the addition of annular gratings on top of the slab LWs can be excited on the guiding surface with directive beam patterns in the far field [6], [7]. Other strip, slot or multilayer designs could have also been used to achieve LW radiation, as illustrated in Fig. 2, but in this work directive broadside beam steering was investigated using 'bull-eye' grating rings. Moreover, by applying a suitable power weighting distribution to the four SWL source elements controlled far field beam steering at broadside is possible at a single frequency. For the investigated LWA structure ($d = 7$ mm, $w = 1.25$ mm) near broadside beam steering at 21.4 GHz is shown in the x-z ($\phi = 0°$) and y-z ($\phi = 90°$) planes, and the translated xy-z ($\phi = 45°$) plane (Figs. 7 and 8). Beam steering at other pointing angles, θ_p, can also be realized by the appropriate aperture and source configuration. Since the steered SW fields from the SWL array are directed along the slab, LWs are also contained within a specified region as well [8] and the steered SW field distribution dictates the region of LW field excitation on the guiding surface, realizing the controlled far field beam patterns that are steered at a single frequency [3], [4].

D. Left- or Right-Handed Circular Polarization

By quadrature feeding of the SWL array RH or LH CP can be realized. Many modern satellite and terrestrial point-to-point communication systems use CP antennas and field distributions to maximize polarization efficiency. Essentially CP operation removes the need to continuously align the transmit and receiver antenna apertures. Simulation results are shown in Fig. 9 and 10 at 23 GHz illustrating a RH and LH CP field distribution on the guiding surface. In addition, LH or RH CP beam patterns in the far field are possible by a suitable antenna aperture for LW excitation.

III. Conclusion

A planar guiding structure defined by a GDS with a four element array of non-directive SWL sources was presented for single frequency beam steering applications. By the addition of an annular 'bull-eye' grating and by fine tuning the SWL

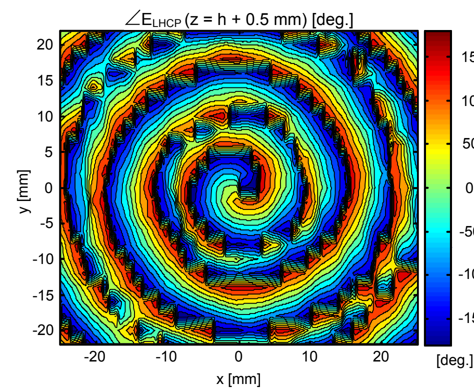

Fig. 10. Phase of a LH CP field distribution generated 0.5 mm above the guiding surface for $1\angle 0° : 1\angle{+90°} : 1\angle{+180°} : 1\angle{+270°}$.

feeding distribution broadside beam steering is possible at a single frequency in the far field. Concepts can be extended to LH or RH CP by a quadrature source feeding.

References

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