A Simple Technique for Surface-Wave Power Routing and Application to Power Directing Circuits

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***Abstract*— Electromagnetic surface-waves (SWs) on planar dielectric substrates are generally considered an adverse effect that can degrade the performance of printed circuits, antennas, and arrays. However, with appropriate boundary conditions, SWs can be harnessed as an efficient means of power transport achieving bound, guided-wave propagation along a grounded dielectric slab; surface-wave launchers have been shown to be a useful technique to excite such cylindrical-wave field distributions. Recent applications include printed leaky-wave antennas, lensing structures, and planar quasi-optical power combiners. Unfortunately, reduced through powers can be observed in such designs due to the radial propagation of SWs along the slab. But, by the inclusion of a simple parallel-plate waveguide medium to surround such structures, SWs can be confined, further directed, and routed for increased throughput. Concepts are extended to a fixed and tunable three port power divider for SW channeling. Additional applications include other dividing/combining systems and feeding structures for planar antennas and circuits at microwave and millimeter-wave frequencies of operation.**

I. INTRODUCTION

The emergence of new ubiquitous communication systems has increased the need for creative antenna solutions, novel sensors, and low-profile circuit configurations that can offer good performance at a low cost. Other emerging applications include automotive and airport tracking radar, phased array radars for security and defense, and satellite, terrestrial and space-based transceiver links for multimedia exchange. The microwave and millimeter-wave frequency ranges have shown much promise allowing for increased data transmission rates while also offering smaller and compact designs.

Printed or planar circuits can meet this cost-effective requirement. They are attractive due to their low profile, ease of fabrication, and compatibility with other planar devices and monolithic technologies. However, at these microwave and millimeter-wave frequencies of operation, substrates can become electrically thick and unwanted surface wave (SW) field distributions may be easily excited, reducing circuit efficiencies and thus diminishing system performance [1]. More specifically, power losses can be observed with undesired coupling between elements along with unwanted radiation into the far field. One strategy to minimize such SW excitations can be to reduce the height, h, of the utilized dielectric, but at the sacrifice of planar circuit strength and durability. Low dielectric constant substrates may also be used to lessen SW effects but at the cost of increased antenna and circuit size.

Generally these SWs were always looked upon as a parasitic and unwanted electromagnetic effect. Conversely however, SWs can actually be harnessed for efficient and bound propagation along a planar grounded dielectric slab (GDS) [1]-[3]. For example, printed surface-wave launchers (SWLs) have been shown to be useful as an efficient means to excite SWs in such planar devices [3]-[8]. Typically these SWLs are fed by coplanar-waveguide (CPW) transmission lines (TLs) (as shown in the inset of Fig. 1) allowing for simple integration with other printed circuit designs and monolithic technologies. Moreover, these SWL sources can couple energy into the dominant TM_0 SW mode of a grounded slab with radial propagation along the air-dielectric interface [4]. Such SWLs can also be used to feed planar antennas for far field beam steering [5], radiation at end-fire [6], and at broadside [7],[8].

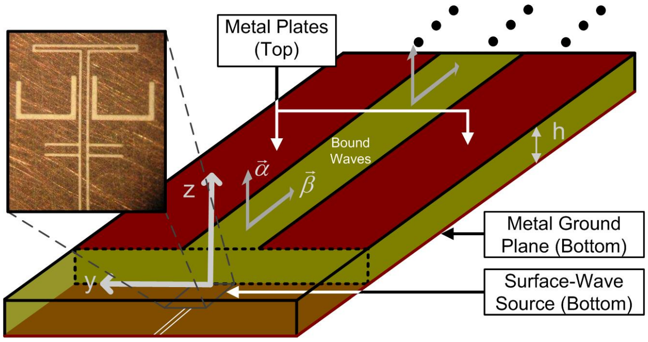

Fig. 1. Illustration of the considered SW source and planar wave-guiding structure. The SWL (embedded in the bottom ground plane) can generate cylindrical SWs with radial propagation along the air-dielectric interface. By the addition of metallic plates on top of the slab, bound SWs can be channeled for unidirectional propagation along the x-axis. Applications include planar dividing/combining circuits and SW power routing for planar antennas.

This work investigates new planar power routing circuits for microwave and millimeter-wave frequencies of operation using such SWLs (as shown in Figs. 1-4). Applications include antenna control circuits and high speed networks. These simple structures can be used to distribute or route power in a planar circuit system (Fig. 3). In addition, such power dividing circuits can be made tunable by inclusion of phase shifters and multiple sources as shown in Fig. 4; ie. by using an appropriately phased array of transmit SWLs, power can be routed to desired antenna elements or secondary circuits.

A. *Efficient and Bound Cylindrical Surface-Wave Propagation*

By the selection of an appropriate GDS for efficient SW excitation [1], and by using the aforementioned directive SWLs, bound cylindrical-wave field distributions can be generated with radial propagation along the air-dielectric interface.

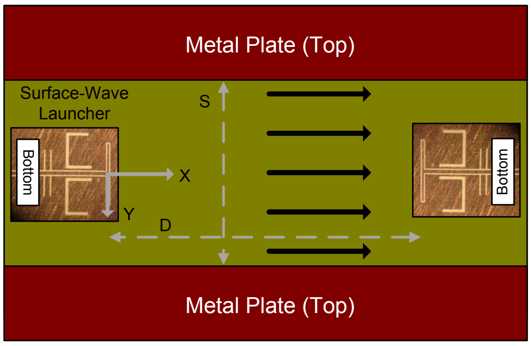

Fig. 2. With the proposed metallic plates on top of the slab (separated by a distance S) through powers can be increased between two SWLs (D apart).

Unfortunately, if SWs are to be used as the main method of power transport, field strength values can be diminished (due to the radial electric field, $E_\rho \approx E_o/\sqrt{\rho}$) with consequently reduced through powers for such routing structures.

B. Test Circuit Analysis for Improved Power Routing

To overcome these challenges a new design technique is examined in this work. In particular, by inclusion of a medium to surround such wave guiding circuits, SW propagation can be controlled and TM field strength values can be increased within desired regions along the slab. Hence, improved through powers can be observed between SWL elements and thus increased system performances may be possible. One strategy to accomplish this design goal can be the utilization of a SW stopband region to surround the proposed wave guiding circuits. In this work such a medium is achieved by placing appropriately configured metallic plates on top of the slab; ie. a parallel-plate waveguide (PPW) is realized below cutoff. Physically, if SWs approach such a medium, reflections can occur and SWs can be routed away from that medium achieving the required channeling. Other methods for realizing such SW stopbands regions are also possible (such as high impedance surfaces or a periodic arrangement of via elements), but the parallel-plates were employed for their simplicity and low cost.

Initially, these design techniques were utilized to optimize the separation distance, S, between two top plates and to minimize insertion losses between two SWLs. Essentially SW propagation can be confined to a specific region for efficient and directive power routing as illustrated in Figs. 1 and 2. Results are compared to measurements using a simple test circuit. Insertion losses can be decreased by 7 dB at 23 GHz (Fig. 5) with reflection losses below 20 dB (Fig. 6(a)). In addition, field strength comparisons with and without the top metallic plates are shown in Figs. 6(b), 7, and 8 for S=10 mm. Concepts are extended to a power divider and increased throughputs of 5 dB can be observed by the addition of the simple top metallic plates (Fig. 9). To the authors' knowledge these structures are the first planar routing circuits to utilize SWs as the main method of power transport.

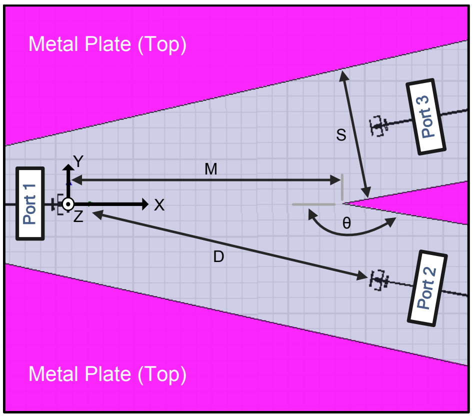

Fig. 3. Investigated power divider using the top metallic plates for SW confinement ($D = 40$ mm, $S = 18$ mm, $M = 35.5$ mm, and $\theta = 170°$).

C. Benefits of Low Cost Surface-Wave Power Routing

It should be noted that simple 3-Port TL segments (made by the appropriate 'T' section in the CPW feeding TL) or surface-mount components could also be used for power dividing. But unfortunately simple bends in CPW TLs can excite unwanted slot-line modes at microwave and millimeter-wave frequencies and thus increased losses may be observed. Thus one benefit of the proposed SWL power routing circuit configurations is that such radiative modes may not be easily excited. Furthermore, these simple designs are completely printed and may reduce the need for additional surface-mount components.

One challenge with the proposed SW power routing circuits is to achieve compact topologies that are more efficient and that can provide improved performances when compared to other commercially available circuits having equivalent functionality. Thus losses should be minimized in the presented structures while maintaining compactness. Cumbersome Rotmann Lens feeding systems and optical star couplers, for example, have similar functions to the proposed SWL power routing circuits. Costs can escalate with these off-the-shelf commercial systems, and thus one advantage of the presented planar designs is that simple printed circuits can be realized

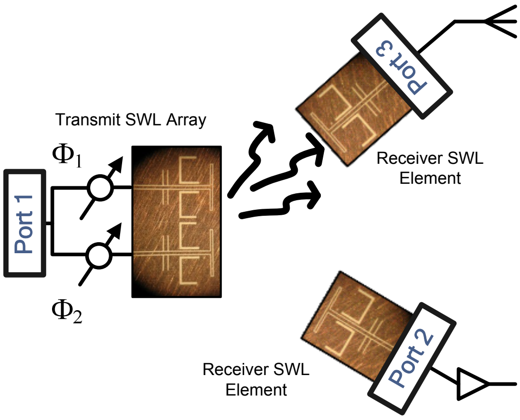

Fig. 4. Illustration of a tunable power routing circuit. An array of transmit SWLs can steer guided-waves to specific receiver SWLs by changing the relative phase difference between transmit elements. Secondary circuits such as amplifiers, antennas, filters and/or other passive and active circuit can be connected to the receiver SWL elements at Ports 2 and 3. In this example, SWs are routed to the Port 3 receiver element (and the secondary antenna).

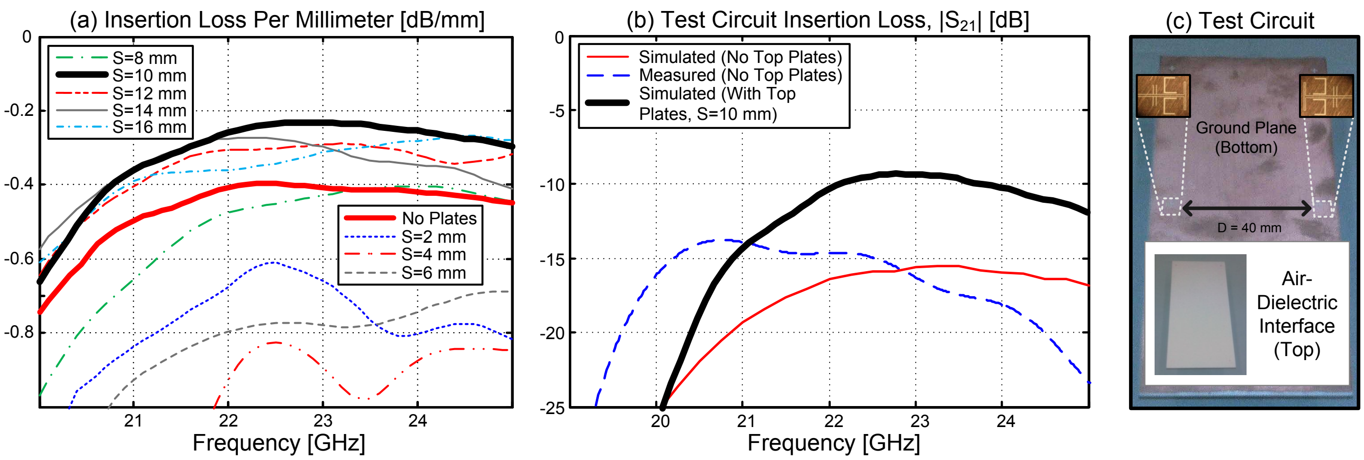

Fig. 5. Test circuit investigations. (a): Insertion loss per mm between two SWLs (Fig. 2) with $D = 40$ mm. (b): $|S_{21}|$ dB. (c): Realized test circuit.

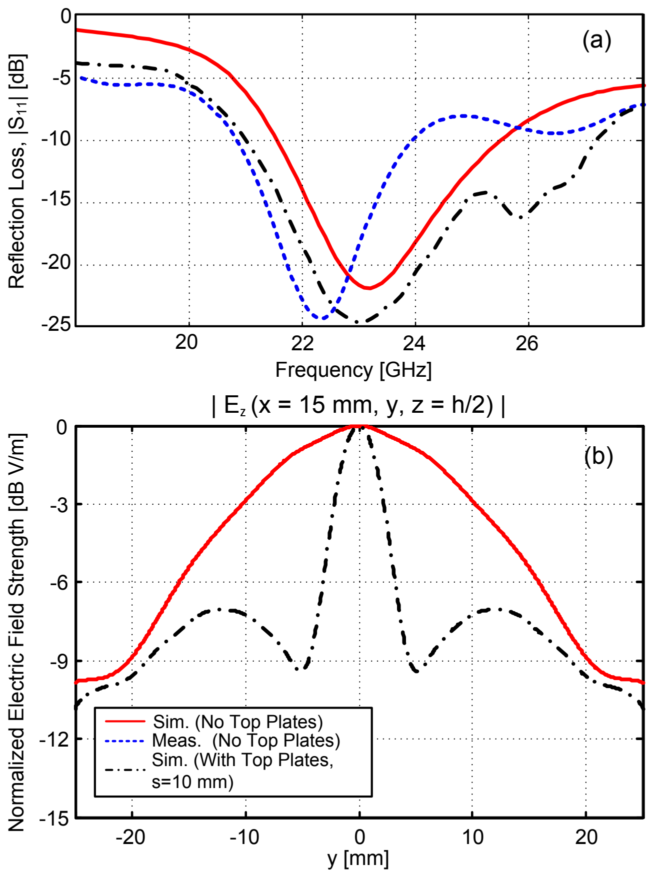

Fig. 6. (a): Test circuit $|S_{11}|$. (b): $|E_z|$ with/without the top metal plates.

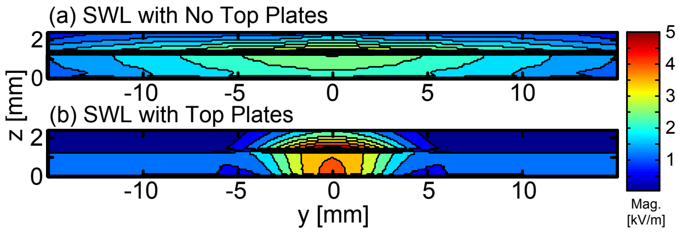

Fig. 7. Magnitude of the total electric field, $|E(x = 15\text{mm}, y, z)|$, in the air and dielectric regions at 23 GHz without [with] the top plates (a) [(b)].

offering similar utility. Thus such low-cost designs may be more favorable when compared to expensive and bulky system circuit topologies that are currently commercially available.

II. DIRECTIVE SURFACE-WAVE LAUNCHER SOURCES FOR EFFICIENT SURFACE-WAVE EXCITATION

Planar SWL excitation techniques have shown to be advantageous for many guided [4] and radiative-wave applications [5]-[8]. Essentially, the slotted configurations in the ground plane of the slab can act as magnetic dipole sources and the completely printed SWL designs are typically fed by 50Ω CPW TLs 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 [1] and theoretical coupling efficiencies of 90% have been observed in the literature for this range of operating frequencies and substrate specifications.

Cylindrical TM SW field distributions are generated from the main slot and unidirectional propagation can be achieved by the addition of two secondary reflector slots [4] with CPW shorted stubs acting as tuning elements for measured reflection losses below 20 dB at 23 GHz as shown in Fig. 6(a). Normalized electric field strength values, $|E_z(x{=}15\text{ mm}, y, z{=}\frac{h}{2})|$, are observed within the middle of the slab (– red) as a function of y as shown in Fig. 6(b) with 50% of the field distribution contained within $y \leq |10|$ mm.

In addition, a two element linear array of SWLs has also been used to dynamically control SW field distributions on a GDS [5]. Essentially, SWs can be steered at a single frequency by varying the relative phase difference between SWL elements ($\delta = \Phi_2 - \Phi_1$) and such a planar feeding network may be advantageous for adaptive and tunable power handling circuits as illustrated in Fig. 4. Practically, power can be directed to the desired circuits and/or antenna elements.

III. DECREASED INSERTION LOSSES FOR SURFACE-WAVE CONFINEMENT BY USING TOP METALLIC PLATES

Initially a simple test circuit was realized for comparisons with and without the top metallic plates as shown in Fig. 5(c).

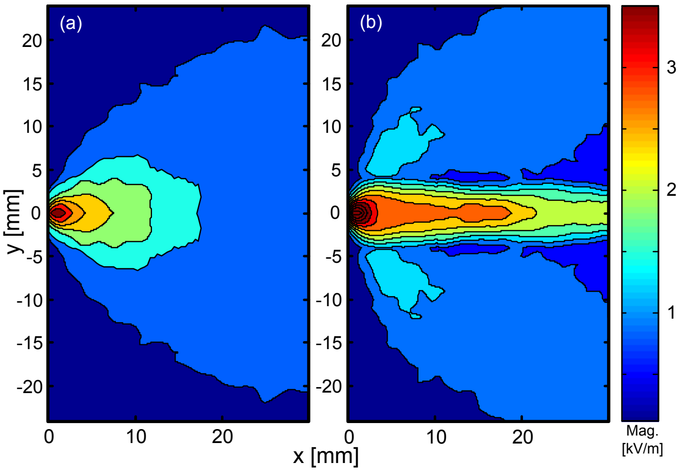

Fig. 8. TM field strength, $|E_z(x, y, z{=}\frac{h}{2})|$, at 23 GHz without [with] the top plates (a) [(b); bounds SWs are channeled by the surrounding PPW mediums].

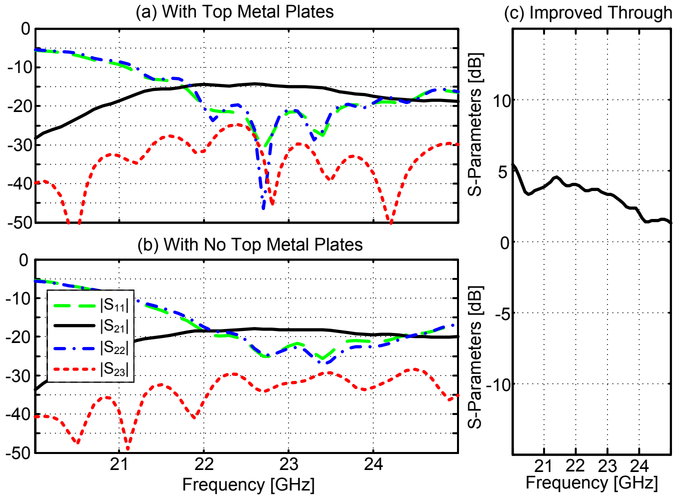

Fig. 9. Simulated S-Parameters of the power divider in Fig. 3. Good isolation values ($<$ 30 dB) with improved through powers of 3.2 dB ($|S_{21,a}|-|S_{21,b}|$) can be observed at 23 GHz by the addition of the top metallic plates. Similar results are observed for an analysis of $|S_{33}|$, $|S_{31}|$, and $|S_{32}|$, respectively.

This circuit can be defined by two directive SWLs separated by a distance $D = 40$ mm. Simulation and measurement results for this structure are shown in Figs. 5 and 6. Insertion losses of 0.40 dB/mm are observed as shown in Fig. 5(a) and agreement is achieved with the simulations and measurements (Fig. 5(b)). In addition, reflection losses are shown in Fig. 6(a). A frequency shift (≈1.5 GHz) is observed with the measurements and simulations and is likely due to substrate variations, fabrication tolerances and difficulty in modeling the metal thicknesses near the slots due to microfabrication [5].

To reduce insertion losses, metallic plates were placed on top of the air-dielectric interface. The separation distance, S, was varied to achieve increased throughputs. At a distance of $S{=}10$ mm insertion losses were decreased to 0.22 dB/mm, thus an improvement of 0.19 dB/mm can be observed when compared to the case of no metallic top plates. These results suggest that this simple wave guiding technique can minimize insertion losses while also offering low cost fabrication.

A. *Field Analysis of the Routed and Bound Surface-Waves*

Top plates were arranged to minimize SW coupling into the fundamental TM_0 (or equivalently the TEM mode) of the surrounding PPWs. In addition, the TM_1 and TE_1 PPW mode cutoff frequencies are $>$35 GHz, suggesting limited power losses into the surrounding medium. Since agreement between the measured and simulated values is observed for the realized test circuit, additional investigations may also be of interest.

The cylindrical TM SW field distribution generated from the main SW radiating slot is directed and channeled along the $\hat{x}$-axis as shown in Figs. 6(b), 7(b), and 8(b). Surface-wave confinement can be observed by inspection of the field distributions for the metallic top plate cases. Moreover, a significant portion of the field (50%) is contained within $y \leq |2.2|$ mm as shown in Fig. 6(b). Thus by adding the top metallic plates field strength values can be confined (by ≈4/5) to a narrow $\hat{x}$-directed section along the slab, when compared to the case of no top metallic plates.

B. *Application to Power Dividing and Combining Circuits*

Concepts are extended to a three port power divider circuit as shown in Fig. 3. Simulation results (Fig. 9) achieve increased through powers $>$3 dB at 23 GHz by addition of the top metallic plates. Such a novel circuit design can be made tunable by using an array of transmit SWL sources (Fig. 4).

IV. CONCLUSION

Confinement, power handling, and channeling of bound SWs was investigated. By using a new SW routing technique insertion losses can be reduced by 0.19 dB/mm when compared to a standard air-dielectric interface medium. Analysis was conducted by observing the insertion losses between two SWLs separated by a distance of 40 mm. Design strategies were also extended to a new power dividing/combining circuit.

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