Directive Surface-Wave Launchers and Application to Planar Quasi-Optical Power Combining using a Metallic Grating Lens

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***Abstract*— Guided surface-waves (SWs) on planar substrates are generally an adverse effect that can degrade the performance of millimeter-wave circuits and antenna arrays. However, with appropriate boundary conditions, such SWs can be harnessed as an efficient means of power transport achieving bound propagation along a grounded dielectric slab (GDS). Specifically, this work investigates SWs generated from a planar directive surface-wave launcher (SWL). By the addition of printed metallic grating configurations (placed on top of the GDS), cylindrical SWs can be refracted for bound plane-wave propagation. Concepts are extended to a new quasi-optical power combiner circuit for millimeter-wave frequencies of operation. To the authors' knowledge this is the first time such a monolithic quasi-optical power combiner has been presented using directive SWLs and planar metallic grating lenses.**

***Index Terms*— Planar Millimeter-Wave Circuits, Quasi-Optical Power Combining, Surface-Waves, Surface-Wave Launchers.**

I. Introduction

Directive surface-wave launchers (SWLs) have been shown to be a practical feeding technique for quasi-optical power combining circuits [1], [2] and new leaky-wave antennas [3]-[6]. In these designs, slotted configurations in the ground plane of a dielectric slab are used to efficiently excite cylindrical TM_0 surface-waves (SWs) for propagation along a planar guiding surface [7], [8].

In such guided and radiated-wave applications a dielectric lens can be used to control the field distributions generated from a central SWL source. Essentially two different materials are required to achieve refraction and hence control of SWs. For instance in [2], a dielectric lens (or air gap) within a grounded dielectric slab (GDS) was investigated for cylindrical TM_0 SW focusing from a network of SWLs. That proposed power combiner was novel, but practical fabrication of such a design would be difficult since a finely-shaped dielectric lens would be required within a main GDS.

In an effort to ease fabrication in such complex circuit systems a novel planar metallic grating lens is investigated for bound plane-wave generation. Design concepts are extended to a new quasi-optical power combining circuit for millimeter-wave frequencies of operation (Figs. 1 and 2); the metallic grating lens alters the propagating cylindrical SW phase front on the GDS [9] for in phase power collection at the input of the SWL receiver array. Physically, the radial electric field of the excited TM_0 SW mode couples to the metallic gratings and the electric field (near each strip segment) is confined between the strip and the ground plane suggesting the excitation of a hybrid microstrip mode [10]. Such phase compensation (achieved by the passive metallic grating lens) allows for constructive interference and thus may be required for efficient power combining in the proposed quasi-optical planar circuit.

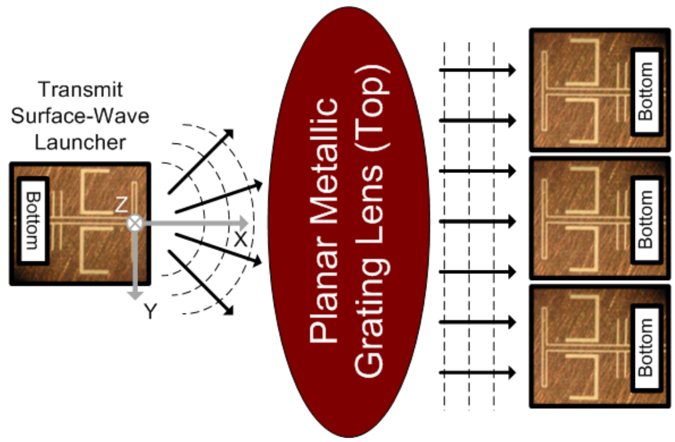

Fig. 1. Illustration of the planar quasi-optical power combiner. The transmit SWL (embedded in the ground plane of a GDS) excites a bound cylindrical SW along the guiding surface. The addition of the grating lens (on top of the GDS) generates a guided plane-wave for in phase power collection at the input of the receiver SWL array.

II. Printed Surface-Wave Launchers for Bound and Guided-Wave Propagation

The SWLs were realized by slots in the ground plane of a dielectric slab and the slotted configurations were fed by coplanar waveguide (CPW) transmission lines (TLs). Essentially, the main radiating slot of an individual SWL excites a cylindrical TM_0 SW mode and unidirectional SW propagation can be achieved by the addition of two secondary reflector slots. The substrate properties ($\epsilon_r = 10.2$, $h = 1.27$ mm, $\tan\delta = 0.0023$) were properly chosen such that approximately 85% of the input power was coupled into the dominant TM_0 SW mode of the slab [8]. In addition, two CPW shorted stubs act as tuning slots and match the SWLs to the 50 Ω TL feeds.

A. Directive Surface-Wave Launcher Operation

As the name implies the directive SWL achieves forward directivity using a reflector-based Yagi-Uda concept [2]-[8].

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The reflector is positioned so that the magnetic current on the reflector slots leads the current on the main driven slot with a 90° phase shift. Thus the SW field distributions add constructively at the main slot, while at the secondary reflector slots, the field distributions cancel. This results in a SW propagating in the $+\hat{x}$ direction. Thus, the directive SWL utilizes the secondary reflector slots to constructively add SWs in the forward direction for unidirectional SW propagation.

B. Forward Surface-Wave Power Relative to the Backward Surface-Wave Power

The directivity of a SWL can be defined as the ratio between the forward and backward SW field components. A measure of this forward to backward SW power can be defined as the front to back ratio [1], [2], [7], [8]. This ratio was investigated in this work using the test circuit of Fig. 3 (a). The main launcher (port 1) was placed near two other launchers: behind (by 6.5 mm), port 2, and in the front (by 4.8 mm), port 3. In addition, all SWLs were connected to CPW TLs matched to 50 Ω.

The directive SWL in front was positioned to accept forward power as a receiver element. A SWL was also placed behind to accept backward directed (and perhaps unwanted) power. Thus the forward [backward] power represents S_{31} [S_{21}].

1) Directive Surface-Wave Launching: Measured and simulated results for the forward and backward SW powers generated by the directive SWL are shown in Figs. 4 and 5. Measured results show the maximum forward radiated power occurs at 22 GHz while the simulated maximum occurs at 24 GHz. This observation is consistent with the shift in minimum reflection loss as further described in [5] and [6]. Minor deviations can be observed and are likely a result of substrate surface roughness, reflections from the edge of the finite substrate, dielectric thickness variations and difficulty in modeling the SWLs due to microfabrication.

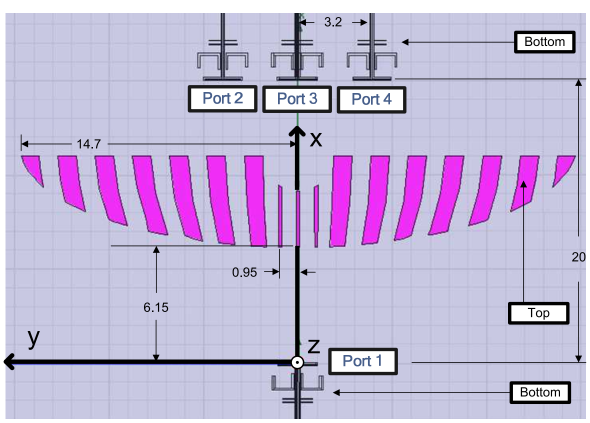

Fig. 2. Simulation model for the proposed quasi-optical power combiner (dimensions in mm) using a single SWL source and a receiver array of 3 SWL elements. Dimensions for the utilized grating lens are shown (periodicity for the outer gratings 2 mm, width of three inner strips 0.16 mm and remaining strips 0.97 mm).

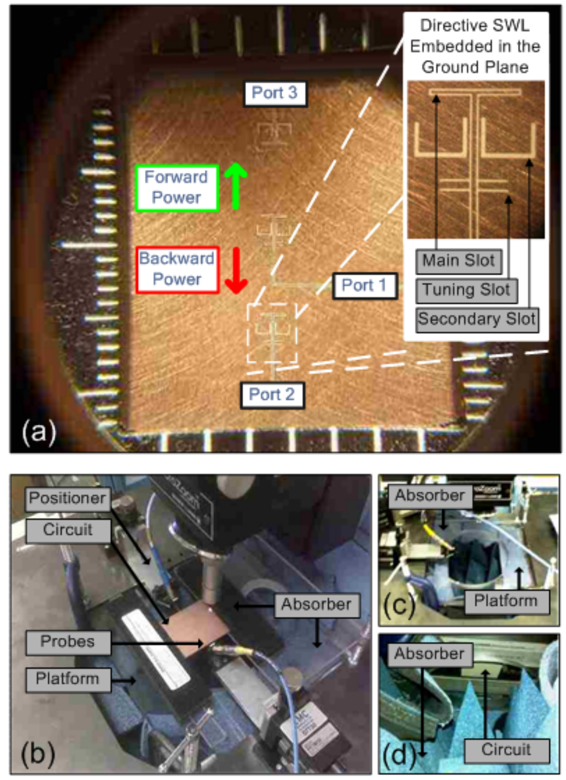

Fig. 3. Circuit and measurement system used to observe the forward and backward SW power. (a): Realized SWL layout. (b): SWLs were measured using integrated circuit probes (PICO model 40A-GSG-150-P), $x-y-z$ positioners and a probing station. Absorber was placed at the edge of the slab to minimize any edge reflections. (c) and (d): To ensure a suitable air-dielectric interface for SW excitation and propagation along the slab, a hole was cut in the plexiglass probing station platform. Cone absorbers were also placed below the slab to eliminate any interference from the metal probing station thus providing isolation for the device under test.

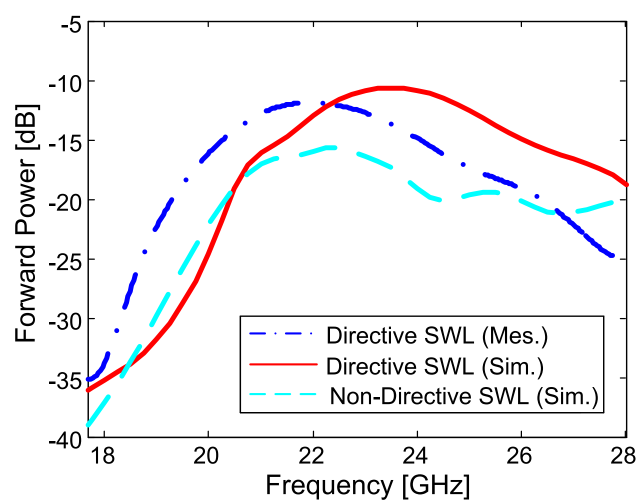

Fig. 4. Measured and simulated forward directed $(+\hat{x})$ SW power generated by the directive SWL. A comparison is made to a non-directive SWL (no secondary reflector slots).

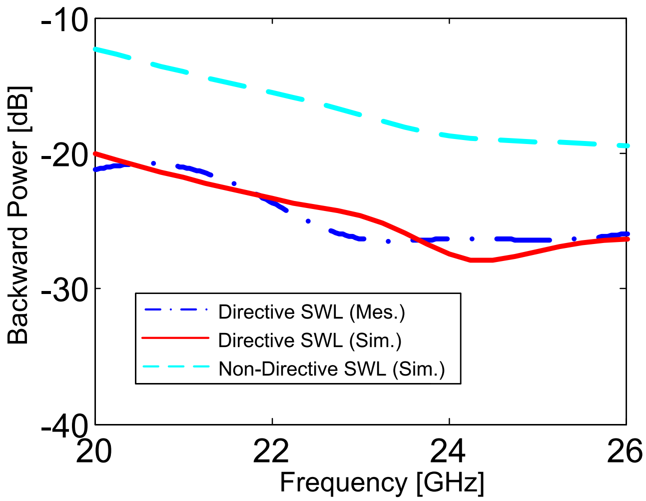

Fig. 5. Measured and simulated backward SW power ($-\hat{x}$) generated by the directive SWL. A comparison is made to a non-directive SWL (no secondary reflector slots).

2) Non-Directive Surface-Wave Launching: An interesting comparison can be made by removing the secondary-reflector slots defining a non-directive SWL. As expected, the non-directive SWL does not generate as much SW power in the forward direction when compared to the directive SWL (by approximately 5 dB).

C. Front to Back Ratios for the Surface-Wave Launchers

The front to back power ratios (forward power minus backward power) for the two SWLs are shown in Fig. 6. As expected the directive SWL generated more power in the forward direction when compared to the non-directive SWL by approximately 7 dB at 23 GHz. It is interesting to note that the

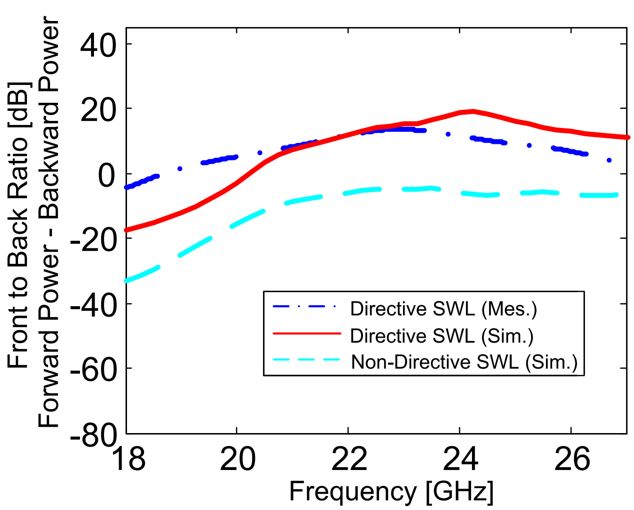

Fig. 6. Forward power to backward power ratios.

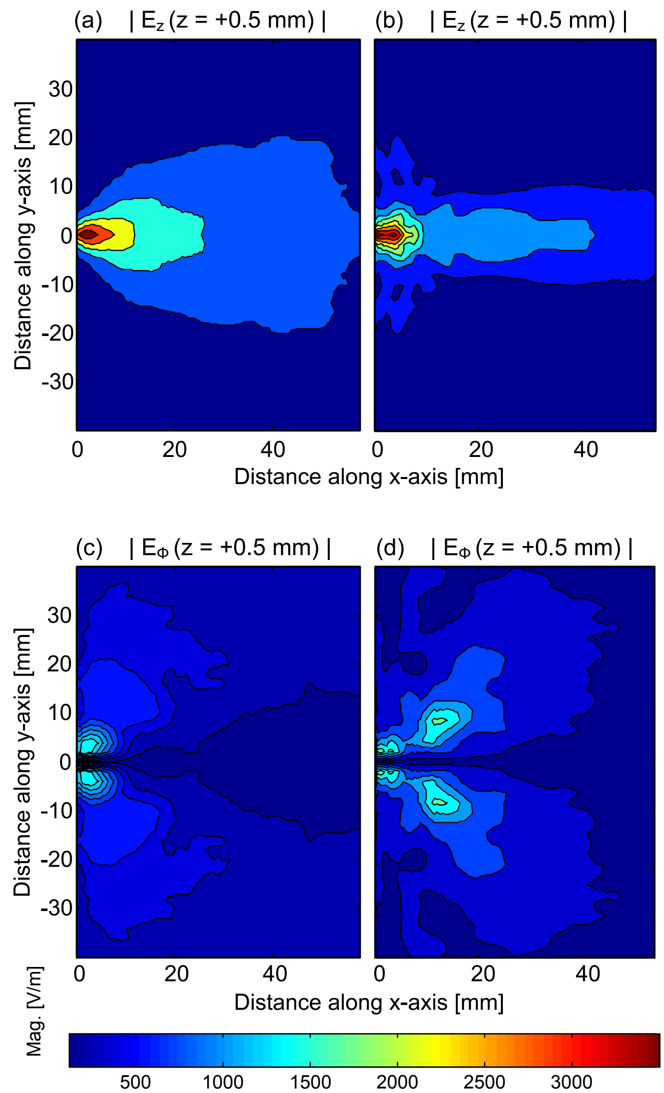

Fig. 7. Simulated TM and TE field distributions generated at 23 GHz on the guiding surface (by a single SWL placed at the origin with and without the grating lens): (a) $|E_z|$ without lens, (b) $|E_z|$ with lens, (c) $|E_\phi|$ without lens and (d) $|E_\phi|$ with lens.

non-directive SWL's front to back ratio is approximately -3 dB suggesting that the non-directive SWL excited SWs in both the $\pm\hat{x}$ directions (with slightly more power directed in the backward direction) defining a bidirectional field distribution.

III. Quasi-Optical Power Combining Using a Planar Grating Lens and Surface-Wave Launchers

The metallic grating lens (layout as shown in Fig. 2) was designed for bound plane-wave propagation along the GDS. Essentially, by the addition of the planar grating lens, the TM SW field components (generated by the SWL transmit source) can capacitively couple to the metallic segments altering the phase velocity of the guided-wave and hence achieving refraction. The resultant field distributions in magnitude and phase excited on the GDS (generated by the SW source, with

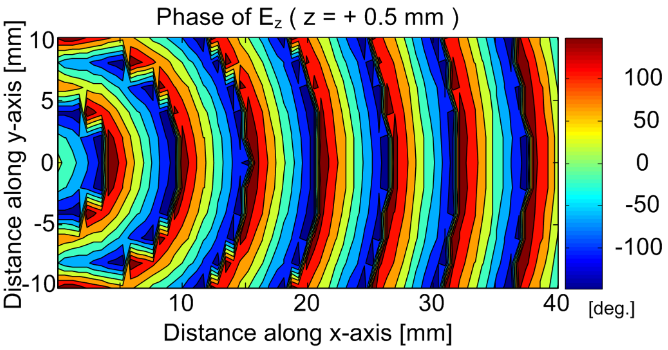

Fig. 8. Simulated TM field distribution ($\angle E_z$) generated at 23 GHz on the guiding surface without the grating lens by a single SWL placed at the origin. The cylindrical SW phase front is illustrated.

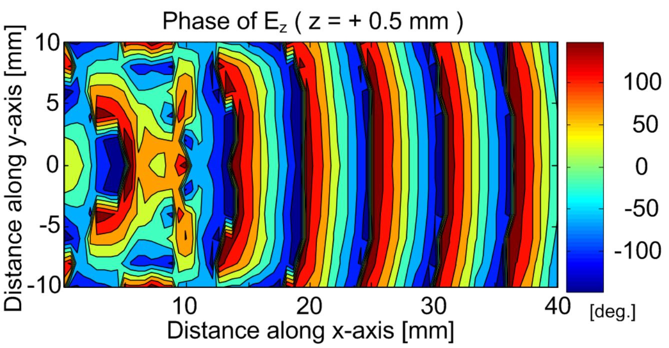

Fig. 9. Simulated TM field distribution ($\angle E_z$) generated at 23 GHz on the guiding surface by a single SWL placed at the origin with the grating lens. A bound plane-wave distribution is generated for $x \geq 14$ mm and $y \leq |5|$ mm.

and without the grating lens and no SWL receivers) is shown in Figs. 7 - 9.

Simulation results are also presented for the proposed quasi-optical power combiner circuit. Fig. 10 illustrates that, by the addition of the grating lens, the phase of the transmitted SW powers (S_{21}, S_{31}, S_{41}) at the receiver elements can be in phase achieving constructive interference and hence offering efficient power combining. For instance, with the additional gratings [no gratings] the unwrapped phase difference between SWLs receivers $(|\angle S_{31} - \angle S_{21}|$ or $|\angle S_{31} - \angle S_{41}|)$ is at most $12°$ [$200°$]. Since a good agreement between the measured and simulated results is observed for the presented directive SWL analysis (Figs. 4 - 6), additional investigations of such novel planar metallic grating lenses and new power combining circuits may be of interest for millimeter-wave applications.

IV. Conclusion

Control of cylindrical surface-waves (SWs) excited from a directive surface-wave launcher (SWL) source have been investigated using a planar metallic grating lens for millimeter-wave frequencies of operation. Specifically, by the design of appropriate metallic strip gratings, cylindrical SWs can be refracted for bound plane-wave propagation along the guiding surface. Design concepts are extended to a new quasi-optical

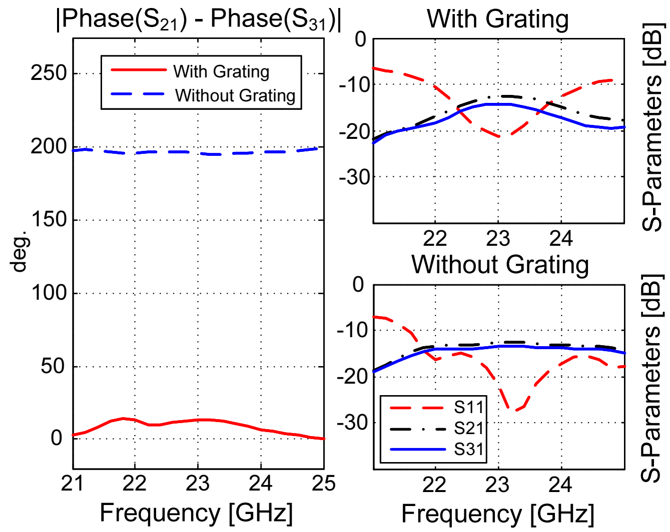

Fig. 10. Results of the quasi-optical power combiner. By the addition of the grating lens the relative unwrapped phase difference between receiver elements, $|\angle S_{31} - \angle S_{21}|$, is minimized (analogous results are obtained for $|\angle S_{31} - \angle S_{41}|$). Similar through powers, $|S_{21}|, |S_{31}|$ and $|S_{41}|$, are observed for the combiner with and without the planar metallic grating lens.

power combiner circuit. Results suggest that the grating lens can achieve in phase constructive interference at the SWL receiver elements ($|\angle S_{31} - \angle S_{21}|$ or $|\angle S_{31} - \angle S_{41}|$ is at most $12°$), without loss of through power, for efficient quasi-optical combining.

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