Optimum Excitation of Surface waves on a Planar Structure

S.F. Mahmoud[*], Y.M.M.Antar[**] and H.F.Hammad[***]

[*]*Kuwait* University
[**]Royal Military College of Canada
[***]*Queen's* University

Introduction

Excitation of surface waves on planar integrated microwave circuits is often considered as an adversary effect. However there exist situations when the main objective is to efficiently excite a surface wave with least possible leakage, or radiated power. Examples of these situations include the design of surface wave antennas. A recent application is the implementation of quasi-optical slab beam power combiners, which offer several advantages over transmission-based combiners [1,2]. These combiners depend on the efficient excitation of the dominant surface wave mode inside a dielectric slab. Accordingly we seek, in this paper, to maximize the surface wave excited by a slot dipole on the ground plane of a grounded dielectric slab. Next we consider the design of a *Yagi* slot array that maximizes the front to back ratio of excited surface waves. First, we present a rigorous theory for the prediction of surface wave and leakage powers on a grounded planar dielectric slab due to a single slot dipole or an array of slot dipoles. Numerical simulations to verify the theory are then presented.

Theory

We start by considering a two-dimensional model of the problem where a grounded dielectric slab of uniform thickness d is assumed to extend infinitely parallel to the y-z plane. A y directed slot of width "w" (along z) in the ground plane, is used to excite the slab. The slot itself is excited by a uniform z-oriented electric field E_{zs} and therefore, acts as an infinite magnetic line source of magnetic current given by $m_y = E_{zs}w$ (volts). To limit the problem to the two dimensional model, we assume that the slot is infinite in the y direction. Later we can consider the finite slot length, but the infinite length assumption has shown strikingly good agreement with simulations and experiment with finite slot length. The slot excites a discrete set of (say M) surface waves traveling along $\pm z$ as well as a continuous spectrum of pseudomodes that account for radiated fields. The excited fields are obviously of TM type with magnetic field; H_y and electric field components E_z and E_x (x is orthogonal to the dielectric slab). Assuming a time harmonic excitation of the form $\exp(jwt)$, general expressions for the total fields are:

$$H_y(x,z) = \sum_{m=1}^{M} A_m\, h_m(x)\exp(-jb_m z) + \int_0^{\infty} C(l)\; h(l;x)\exp(-jb\; z)\,dl \tag{1}$$

$$\vec{E}(x,z) = \sum_{m=1}^{M} A_m\, \vec{e}_m(x)\exp(-jb_m z) + \int_0^{\infty} C(l)\,\vec{e}(l;x)\exp(-jb\; z)\,dl \tag{2}$$

where $h_m(x)$ is the magnetic y-field component of the m^{th} surface wave mode which must be oscillatory within the slab ($0\leq x\leq d$) and exponentially decaying in the air ($d\leq x<inf.$). On the other hand, $h(l;x)$ is a pseudomode with a transverse (x) wavenumber l and is composed of an incident

plane wave onto the slab; exp($j\,l x$-$j b\, z$), and a reflected plane wave; $R(l)$exp($-j\,l x$-$j b\, z$). Obviously the range of the spectrum $0 \leq l \leq k_0$ represents fields with active radiation power while the range $k_0 \leq l < inf.$ corresponds to the evanescent part of the field. While a pseudomode does not satisfy the radiation condition on its own, the sum of pseudomodes making up the radiated and evanescent fields does satisfy the radiation condition, as it should [3,4]. In (1), A_m and $C(l)$ are amplitude coefficients to be determined by the source of excitation. In (2), $\vec{e}_m(x)$ is the electric field vector of the m^{th} surface wave mode and $\vec{e}(l, x)$ is that of the pseudomode with transverse wavenumber l.The first is given by: $\vec{e}_m(x) = (1/we)(b_m\hat{x} - j\hat{z}\,\partial/\partial x)\,h_m(x)$ with a similar expression for $\vec{e}(l, x)$, while $b = \sqrt{k_0^2 - l^2}$, for $z>0$ and $b = -\sqrt{k_0^2 - l^2}$, for $z<0$.

Orthogonality relationships exist among the surface wave modes and pseudomodes and can be expressed, for a lossless structure, by [4]

$$
\begin{aligned}
&\int_{x=0}^{\infty} [\vec{e}_m(x) \mathrm{x}\, h_n^*(x)\vec{y}].\vec{z}\; dx = N_m\, d_{nm} \\
&\int_{x=0}^{\infty} [\vec{e}(l;x) \mathrm{x}\, h^*(l';x)\vec{y}].\vec{z}\; dx = N(l)\; d(l - l')
\end{aligned}
\tag{3}
$$

where the d_{nm}=0 unless $n=m$ whence it is equal to unity, while $d(.)$ is the usual delta function. The factors N_m *and* $N(l)$ can be derived explicitly in terms of the modal fields.

Now we consider a y directed infinite slot of width w, and a uniform E_{zs}, acting as a magnetic line source of magnetic current $m_y = E_{zs} w$. The fields generated by this source take the general form in (1) and (2) and the coefficients A_m and $C(l)$ are determined from the reciprocity theorem along with the orthogonality relations in (3). These result simply in:

$$
\begin{aligned}
A_m &= -m_y / 2N_m \\
C(l) &= -m_y / 2N(l)
\end{aligned}
\tag{4}
$$

Now that we have determined the fields of the slot as given by (1),(2) and (4), we are able to determine the surface wave power and radiation power in simple summation and integral forms. In addition, the slot admittance (per unit length along y) is given by:

$$
Y_{slot} = G_s + jB_s = -\int_{slot} E_{zs} H_y{}^*(0, z)\, dz / m_y^2 \tag{5}
$$

which is also obtained in similar forms. The results obtained so far allow us also to determine the mutual admittance between two parallel slots of given widths and given spacing.

Numerical results

The percentage power launched in surface waves relative to the total power delivered by the source is computed versus normalized frequency for different values of the relative permittivity e_r. The frequency is limited to a single surface wave mode propagating, which means that $k_0 d\sqrt{e_r - 1} \equiv V < p$. Results show a monotonic increase of the percentage surface wave power with V up to about $V=2.5$ where there is a broad maximum, whose value increases with the substrate ε_r. For example a peak value of *88*% is attained for $e_r = 9.8$, and *68*% for $e_r=3.0$.

The slot conductance (G) and susceptance (B) per unit free space wavelength l_0 along y are plotted versus V. The conductance displays a peak around $V=1.6$ and the peak value depends on the substrate relative dielectric constant, while B has a maximum slope near to the peak of G. Moreover and as expected, the results indicate that the slot conductance is almost independent of the slot width w as long as width is narrow enough to support the assumption of uniform E_z field across the slot. On the other hand, the slot susceptance changes considerably with the slot width. We can conclude that an optimum value of V that maximizes the surface wave power must lie somewhere between $V=1.6$ (for maximum G) and $V=2.5$ (for maximum percentage surface wave power. This agrees with experimental work conducted in [2].

Design of a Yagi slot array

A three-element *Yagi* slot array, composed of a fed slot and a director and reflector parasitic slots, is designed. The array is optimized with respect to the slot widths and the spacing between the elements for a maximum front to back ratio of surface wave power. It was possible to achieve a front to back ratio better than *20* dB over a bandwidth of ~*4*% around the normalized frequency $V=1.9$.

Conclusions

Rigorous analysis of Radiation and surface wave excitation on a grounded dielectric slab driven by a slot antenna has been considered. The full wave fields excited by the slot are derived. As a result, both surface wave and radiation powers, as well as the slot admittance are obtained in simple forms. The mutual admittance between parallel slots is also derived. This facilitates the design of a *Yagi* slot array for achieving maximum front to back ratio of excited surface waves. Results of this analysis are supported by previously published experimental work.

References:

[1] J. Harvey, E.R. Brown, D.B. Rutledge, and R.A. York, "Spatial power combining for high-power transmitters", *IEEE Microwave Magazine*, Dec. 2000, pp. 48-59.

[2] H.F. Hammad, A.P. Freundorfer, and Y. M.M. Antar, "*CPW* slot antenna for *TM* slab mode excitation", *IEEE Antenna and Propagation and URSI International Symposium, Boston, USA*, July 2001.

[3] S. F. Mahmoud and J. C. Beal, "Scattering of surface waves at a dielectric discontinuity on a planar waveguide", *IEEE Trans., MTT-23*, 1975, pp.193-198.

[4] S. F. Mahmoud, "Electromagnetic Waveguides;theory and applications", *IEE Electromagnetic aves Series 32, Peter Peregrinus Ltd*, 1991, sec. 4.3.

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