Rigorous Analysis of an Aperture-Coupled Microstrip Antenna Fed by a Microstrip Line on a Perpendicular Substrate

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Abstract— **A rigorous analysis of an aperture-coupled microstrip antenna fed from a perpendicular microstrip line has been developed. A hybrid spectral/space-domain method is used, along with a general reciprocity formulation, to model the perpendicular microstrip feeding. Experimental results for a prototype model are compared with computed results, showing good agreements.**

I. Introduction

A METHOD of feeding an aperture-coupled microstrip antenna from a microstrip line on a perpendicular substrate (Fig. 1) was proposed in [1]. This method of feeding is attractive for integrated phased arrays, because the perpendicular feed substrate provides significantly increased space for integration of active devices and feed network. In addition, as it is always desirable, the spurious radiation from the feed circuitry on the perpendicular substrate is completely isolated from main antenna radiation in the front side. This is important for array designs with a low-sidelobe and/or low-cross-polarization level. However, as it may be evident, the printed antenna elements and the feed circuitry have to be separately fabricated on two different substrates. The two substrates then have to be aligned with respect to each other, establishing the necessary electrical and mechanical connectivity between them (see Fig. 1). This can sometimes be inaccurate for millimeter wave frequencies. For microwave frequencies, when the design dimensions are relatively larger, the accuracy achievable through the mechanical alignment would be adequate for practical designs.

Due to the significant complexity of the feeding geometry, accurate CAD models would be essential. No analysis of this perpendicularly-fed microstrip antenna has been published to date. Rigorous modelling of the perpendicular feeding, and the effect of the perpendicular substrate on slot-fields pose the main difficulty in modelling the geometry. In this letter we discuss a rigorous analysis of the perpendicularly-fed geometry, and compare the computed results with a prototype experiment. We have applied the general reciprocity modelling of [2], [3] in order to characterize the coupling to the perpendicular microstrip line. The standard spectral-domain techniques used for microstrip antenna analyses cannot be directly applicable here to model the effect of the perpendicular substrate on the feed-coupling and slot-radiation. Instead, hybrid spectral/space-domain integrations, along with the generalized spectral-domain Green's functions of [3], [4] (that handles any arbitrary source and multilayering), have been used to accurately account for the effect of the perpendicular substrate.

Manuscript received February 24, 1994.

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IEEE Log Number 9402183.

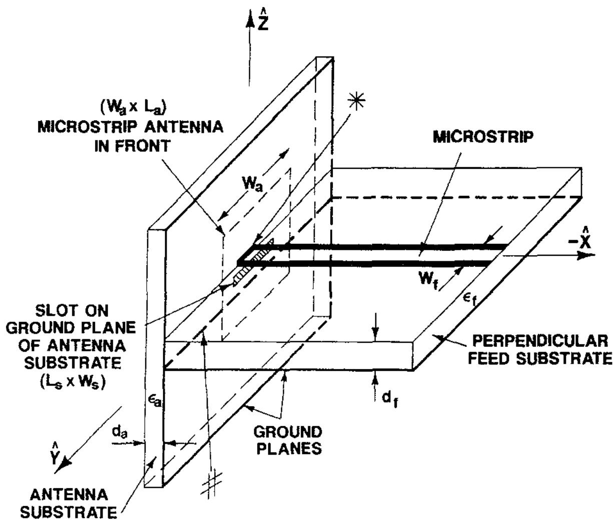

Fig. 1. Geometry of an aperture-coupled microstrip antenna fed by a microstrip line on a perpendicular substrate. *: Microstrip line soldered to the ground plane of the antenna substrate. #: Ground plane of the antenna substrate soldered to the ground plane of the perpendicular feed substrate. Metal T-supports may be used to connect the two ground planes, in order to achieve significant mechanical strength.

II. Feed Modelling

The coupling slot on the ground plane of the microstrip antenna (see Fig. 1) can be equivalently modelled as two magnetic current distributions, $\pm\overline{M}_s$, oppositely directed with respect to each other, placed on the two sides of the infinite ground plane ($-\overline{M}_s$ on the antenna side).

$$\overline{M}_s(y, z) = \hat{x} \times \overline{E}_s(y, z) = V_s\hat{x} \times \overline{f}_s(y, z), \qquad (1)$$

where $\overline{E}_s = V_s\overline{f}_s(y, z)$ is the electrical field distribution across the slot, V_s is the voltage (unknown) at the center of the slot, and $\overline{f}_s(y, z)$ is the field distribution across the slot normalized to unit voltage across the slot center. Now, concentrating on the feed side of the antenna geometry, we have a magnetic current distribution, $+\overline{M}_s$, placed on an infinite ground plane (ground plane of the antenna) coupled to a perpendicular microstrip line. We decompose this problem into two parts [2], [3]. In part A of the problem, remove the magnetic curmet, $+\overline{M}_s$, and then we just have a microstrip line short circuited by the perpendicular ground plane. If one unit of signal is incident from the input microstrip port, we will have a reflected signal, $R_A = -1$, due to the short circuit. In part B of the problem, allow the magnetic current $+\overline{M}_s$ to independently radiate and couple to the output microstrip port. Let the resulting outgoing signal at the microstrip port be R_B. Now, the original problem can be treated as a superposition of the two individual parts (A& B). Thus, the actual reflection coefficient, R, at the microstrip port can be written as:

$$R = R_A + R_B = R_B - 1. \tag{2}$$

Using the general reciprocity modelling of [2], [3], where we apply reciprocity between the separate fields of parts A and B, we have:

$$\begin{aligned} R_B &= \frac{1}{2}(1 - R_A) \iint_{slot} \overline{h}(y, z) \cdot \overline{M}_s(y, z) dy dz \\ &= V_s \iint_{slot} \overline{h}(y, z) \cdot (\hat{x} \times \overline{f}_s(y, z)) dy dz = V_s \Delta v, \end{aligned} \tag{3}$$

$$\Delta v = \iint_{slot} \overline{h}(y, z) \cdot (\hat{x} \times \overline{f}_s(y, z)) dy dz, \tag{4}$$

or,

$$R = R_B - 1 = V_s \Delta v - 1. \tag{5}$$

In (3) and (4) $\overline{h}(y, z)$ is the transverse modal magnetic field distribution of the microstrip line and is assumed known *a priori*. Thus, assuming a known slot-field distribution, $\overline{f}_s$, such that Δv can be computed from (4), the reflection coefficient at the microstrip port, R, is directly related to the unknown slot voltage, V_s, via (5). The y-integration of Δv in (4) can be evaluated in spectral-domain using spectral-domain Green's function of [3], [4], and the known propagation constant and strip-current distribution of the microstrip, whereas the z-integration of Δv can be evaluated in space-domain. Using the simple z-variation of the spectral-domain Green's functions of [3], [4], however, the z-integration of Δv can be implemented analytically.

III. Moment Method Analysis

If the slot is excited by a unit voltage across its center point, with the same electric field distribution $\overline{f}_s$, as before, and the microstrip line is removed, the current induced on the microstrip patch can be solved by a spectral-domain moment method. The standard procedure is to expand the patch current by a set of known basis functions with unknown amplitudes, and then to solve for these unknown amplitudes using a Galerkin's testing procedure. Now, from the knowledge of the antenna current and the slot electric field distribution, $\overline{f}_s$, the admittance seen across the center of the slot are calculated as:

$$Y_s = Y_{sf} + Y_{sa} + Y_{sp}, \tag{6}$$

where Y_{sf} is the admittance of the slot in the feed side, and Y_{sa} is the admittance of the slot in the antenna side obtained from the computation of the self reaction of the slot in the respective sides. The other term, Y_{sp}, in (6) is the equivalent admittance of the patch as seen at the slot center and is computed from the mutual reaction between the patch current and the slot. The admittances, Y_{sa} and Y_{sp}, are due to coupling in a transversely uniform layered medium, and can be computed without any special treatment due to the perpendicular substrate. Therefore, Y_{sa} and Y_{sp} are similarly computed as in [5] using appropriate spectral Green's functions [3], [4]. However, the slot admittance, Y_{sf}, in the feed side cannot be directly implemented in the spectral domain, due to the presence of the perpendicular substrate.

In order to compute Y_{sf}, we first image the magnetic current of the slot against the antenna ground plane, resulting in a geometry with a magnetic current, $2V_s(\hat{x} \times \overline{f}_s(y, z))$, distributed on a plane (yz plane) perpendicular to the infinite feed substrate (xy plane) (see Fig. 1). The feed substrate is now of infinite lateral extent because of the imaging across antenna ground plane. Note that in this equivalent problem of the slot in the feed side, the equivalent magnetic current is placed freely inside the dielectric, not immediately over the ground plane of the feed substrate. This problem is handled by use of the general set of Green's functions of [3], [4], that can account for a magnetic source placed anywhere inside the dielectric layer of a grounded substrate. The y-integration for the computation of Y_{sf} is easily implemented in the spectral-domain, but the z-integration is performed in space-domain using the z-dependence of the generalized Green's function of [3], [4], and the z-dependence of slot electric field, $\overline{f}_s(y, z)$.

When the excitation is provided from the perpendicular microstrip line, instead of an ideal delta-gap excitation at the center of the slot, the Galerkin testing of the magnetic field boundary condition across the slot can be written in terms of the unknown center voltage, V_s, and the admittances of (6) [5]:

$$-V_s(Y_{sf} + Y_{sa} + Y_{sp}) + (1 - R)\Delta v = 0 \tag{7}$$

or,

$$V_s = \frac{(1 - R)\Delta v}{Y_s}. \tag{8}$$

Solving (5) and (8), the equivalent impedance seen by the microstrip line can be written as:

$$Z_{eq} = \frac{1 + R}{1 - R} = \frac{\Delta v^2}{Y_s} = \frac{\Delta v^2}{Y_{sa} + Y_{sp} + Y_{sf}}. \tag{9}$$

Equation (9) is equivalent to a parallel combination of the three admittances, Y_{sa}, Y_{sp} and Y_{sf}, coupled to the microstrip line through a transformer of turns ratio $n = \Delta v$, as shown in Fig. 2(b).

IV. Results

A prototype aperture-coupled microstrip antenna with a perpendicular microstripline feeding was built and tested. The results of the experiment are compared with the computation in Fig. 2(a), showing good agreement. Three entire basis sinusoid

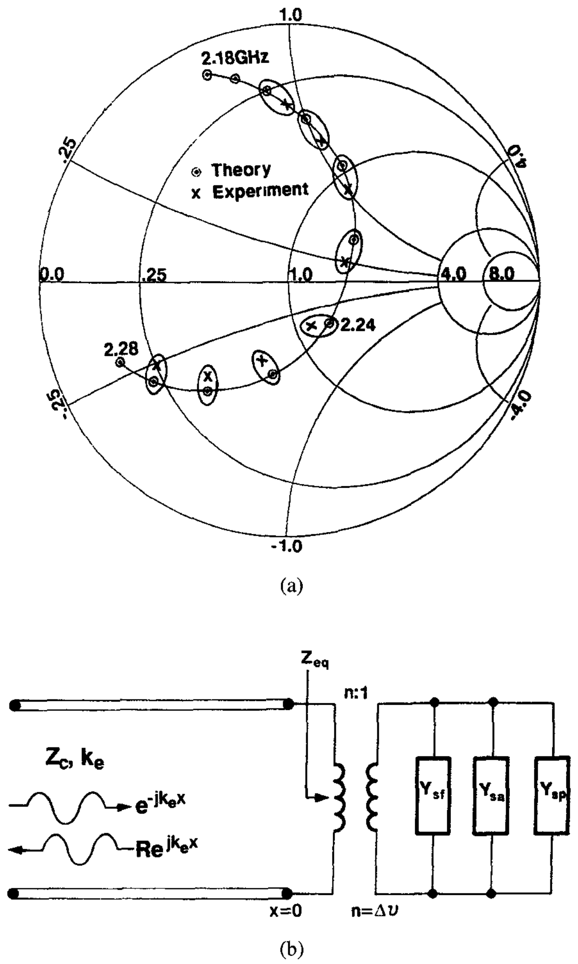

Fig. 2. (a) Theoretical and experimental results of equivalent normalized impedance, Z_{eq}/Z_c, of the perpendicularly fed antenna, with phase reference at the plane of the slot. $\epsilon_f = \epsilon_a = 2.36$, $d_f = d_a = 0.155$ cm, $W_a = 4.1$ cm, $L_a = 3.05$ cm, $L_s = 1.23$ cm, $W_s = 0.155$ cm, slot at the center of patch, $W_f = 0.47$ cm, $Z_c = 50\Omega$, $\epsilon_e = (k_e/k_0)^2 = 2.0$, $\Delta f = 10$ MHz. (b) Equivalent circuit using three parallel admittances coupled to the end of the microstrip feed line through a transformer.

(EBS) modes, uniform transversely, are used on the patch, whereas only one piecewise sinusoid (PWS) mode is used on the slot. The general performance (approximate impedance level, bandwidth, resonant frequency) of the perpendicularly fed geometry are similar to that of a parallel-fed geometry [5] with the same antenna, slot, and substrate parameters. As in parallel-fed geometries, the usual small bandwidth of a simple single-patch design can also be significantly increased by using two or more stacked patches in the front side. Unlike the parallel-feed geometry, however, the perpendicular-feed geometry does not have an additional stub for tuning [5]. Therefore, the slot dimensions have to be accurately designed in order to achieve the required matching condition. The slot admittance, Y_{sf}, in the feed side of a perpendicularly fed geometry and the relative levels of surface-wave excitation and back radiation from the slot can be significantly different from that of a parallel-fed geometry with the same slot dimensions. For a moderately matched design, the back radiation is found to be significantly lower (about 20 dB, or lower) than the front radiation, as desirable. This should be expected, because the small slot is used here as a nonresonant coupling element, that generates much weaker back-radiation than the resonant patch antenna in the front side. The airgap introduced while soldering the perpendicular substrate unto the backside of the aperture is a potential source of error, but is seen not to drastically affect the results. In addition, as mentioned before, it may be difficult to precisely align the microstrip line and the coupling aperture while soldering the perpendicular feed substrate unto the antenna ground plane. However, as has been verified theoretically as well as experimentally, the performance is relatively insensitive to this small error. This alignment problem may be critical for millimeter-wave designs.

References

[1] A. C. Buck and D. M. Pozar, "Aperture-Coupled Microstrip Antenna with a Perpendicular Feed," *Electron. Lett.*, vol. 22, no. 3, pp. 125–126, Jan. 1986.

[2] N. K. Das and D. M. Pozar, "Multiport Scattering Analysis of Multilayered Printed Antennas Fed by Multiple Feed Ports, Part I: Theory; Part II: Applications," *IEEE Trans. Antenn. Propagat.*, vol. 40, no. 5, pp. 469–491, May 1992.

[3] N. K. Das and D. M. Pozar, "A Generalized CAD Model for Printed Antennas and Arrays with Arbitrary Multilayer Geometries," L. Safai, Ed., in *Computer Physics Communication, Thematic Issue on Computational Electromagnetics.* Amsterdam: North-Holland Publications, 1991.

[4] N. K. Das, "A Study of Multilayered Printed Antenna Structures," Ph.D. thesis, Dept. of Electrical and Computer Engineering, Univ. of Massachusetts, Amherst, Sept. 1987.

[5] D. M. Pozar, "A Reciprocity Method of Analysis of Printed Slots and Slot-Coupled Microstrip Antennas," *IEEE Trans. Antenn. Propagat.*, vol. 34, no. 12, pp. 1439–1446, Dec. 1986.