A Reduced Surface-Wave Twin Arc-Slot Antenna For Millimeter-Wave Applications

Michael A. Hickey, Meide Qiu and George V. Eleftheriades

Abstract— **A simple, uniplanar, reduced surface-wave twin arc-slot antenna element for millimeter-wave (mm-wave) integrated circuit antenna systems is presented. This design allows for almost complete surface-wave cancellation and resonance to be achieved simultaneously. Measured far-field radiation patterns on an electrically thick substrate are in very good agreement with theory and show little evidence of surface-wave propagation.**

I. Introduction

Printed slot antennas are useful at millimeter-wave frequencies because of their simplicity, low profile, low cost, light weight and their ease of integration with electronics. A single slot antenna element printed on a dielectric substrate at millimeter-wave frequencies suffers greatly from surface-wave losses because typical substrates become electrically thick at these frequencies. The surface-wave losses can be reduced by using broadside linear twin-slot elements to achieve phase-cancellation of the dominant TM_0 mode, but only in the broadside direction [1].

A novel twin arc-slot antenna element is proposed here that is shown to reduce the surface-wave fields over a wide angular range in the substrate. This work bears some similarity to the reduced surface-wave circular microstrip patch antennas proposed by Jackson, *et al.* in [2]. However, a microstrip patch that excites no surface-waves is larger than a resonant patch, and complex inhomogeneous substrates were proposed in [2] in order to allow complete surface-wave cancellation and the required resonance to be achieved simultaneously. With the proposed twin arc-slot element, achieving nearly complete surface-wave cancellation and resonance simultaneously is made simple by allowing the radius and length of the arc-slot apertures to be chosen independently.

II. Theory

The twin arc-slot element geometry is shown in Fig. 1. The arc-slots are printed on a substrate having relative permittivity ϵ_r and thickness h. To avoid excitation of higher-order surface-wave modes and to maximize the front-to-back radiated power ratio, the substrate thickness is made equal to a quarter dielectric wavelength (*i.e.* $h = \lambda_d/4$) [1]. As a result, only the dominant TM_0 surface-wave mode is allowed to propagate. The radius of the arc-slots is R. Each arc-slot is fed at its midpoint by a coplanar waveguide (CPW) feed-line, dividing each arc-slot into two branches of length $L/2$, corresponding to a branch arc angle of ϕ_B, as shown in Fig. 1.

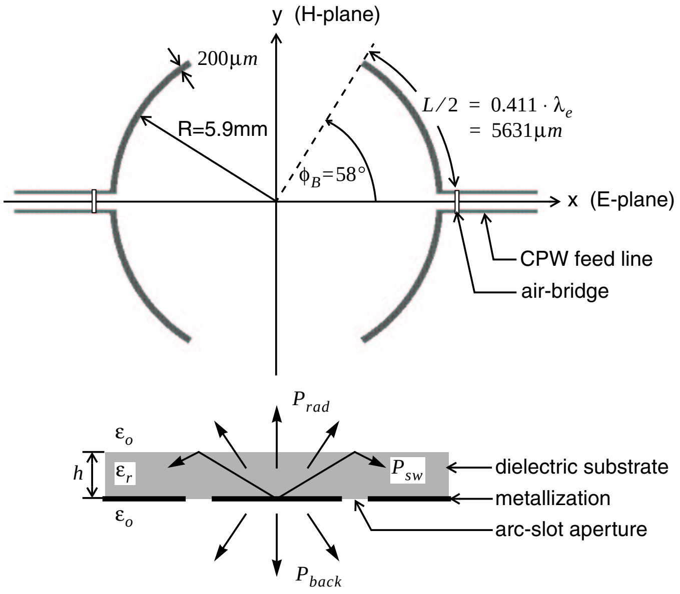

Fig. 1. Geometry of the twin arc-slot antenna

The radiation efficiency of a slot antenna is defined by

$$\eta_{rad} = \frac{P_{rad}}{P_{rad} + P_{sw} + P_{back}} \tag{1}$$

where P_{rad} is the useful power radiated into the air through the substrate, P_{sw} is the power coupled into the TM_0 mode (trapped in the substrate), and P_{back} is the power radiated directly into the air at the back side of the antenna.

The theoretical analysis of the radiation efficiency of a slot antenna having an arbitrary aperture current distribution has been presented in [3] and [4]. For the twin arc-slot antenna design shown in Fig. 1, the slot aperture is assumed to be very narrow and the magnetic current distribution is assumed to be a sinusoidal one given by,

$$\vec{M}(\phi') = \begin{cases} \hat{\phi}\, sin\big[k_e R(\phi_B - |\phi'|)\big] & 0 < |\phi'| < \phi_B, \\ -\hat{\phi}\, sin\big[k_e R(\phi_B - |\phi' - \pi|)\big] & 0 < |\phi' - \pi| < \phi_B \end{cases} \tag{2}$$

where $k_e = 2\pi/\lambda_e$, $\lambda_e = \lambda_0/\sqrt{\epsilon_{eff}}$ and ϵ_{eff} is the effective dielectric constant, which is approximately equal to $(\epsilon_r + 1)/2$ for a thick substrate.

The theoretical radiated space-wave power (P_{rad} and P_{back}) of the twin arc-slot element can be calculated according to the method shown in [3] and [4]. The power coupled to the TM_0 surface-wave mode can be expressed in terms of cylindrical TM_{0n} waves emanating from the center of the arc-slot element and the result is given ac-

The authors are with The Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, Ontario M5S 3G4, Canada.

cording to [3] as,

$$P_{sw} = P_{TM_0} = \frac{\omega \epsilon_0 \epsilon_r}{2 h_{eff}} \sum_{n=1}^{+\infty} |C_n|^2 \qquad (3)$$

where h_{eff} is the effective height of the grounded dielectric substrate corresponding to TM modes, and C_n is the coupling coefficient of the TM_{0n} mode given by,

$$\begin{aligned} C_n = & \frac{2\big[(-1)^n - 1\big] k_e R^2}{n^2 - (k_e R)^2} \\ & \big[\cos(k_e R \phi_B) - \cos(n\phi_B)\big] \big[J_n'(\beta_{TM_0} R)\big] \end{aligned} \qquad (4)$$

where $\beta_{TM_0} = 2\pi/\lambda_g$ is the propagation constant of the TM_0 mode and λ_g is the guide wavelength of the TM_0 mode.

Only the first few low-order terms in the summation of (3) are significant, and (4) vanishes for n=even. If R is chosen such that $J_1'(\beta_{TM_0} R) = 0$ (*i.e.* $R = x_1'/\beta_{TM_0} = 0.293\lambda_g$, $x_1' = 1.8412$, where $x_1' = 1.8412$ is the first root of $J_1'(x)$), then the most significant term $n = 1$ in (3) vanishes and the only significant remaining terms are those corresponding to $n = 3$ and $n = 5$. These terms can be minimized by properly choosing the angle ϕ_B (*i.e.* by properly choosing the total arc-slot length L). As a result, the surface-wave power is minimized and the corresponding radiation efficiency can be maximized.

III. NUMERICAL AND EXPERIMENTAL RESULTS

To validate the theory, a substrate having $\epsilon_r = 10.2$ and $h = \lambda_d/4$ is considered. The theoretical radiation efficiency is plotted vs. R at second resonance (*i.e.* $L = \lambda_e$) and is shown in Fig. 2. A maximum radiation efficiency of 90.7% is achieved near $R = 0.293\lambda_g$. Also plotted in Fig. 2 is the radiation efficiency vs. L with $R = 0.293\lambda_g$. The efficiency may be increased slightly to 91.9% by reducing L to approximately 92% of the second resonant length. The efficiency variation is small for L between approximately 80% and 100% of the resonant length, and in practice, resonance typically occurs for a slot length that is slightly shorter than that predicted by transmission line theory [5]. Note that 99.96% of the total power is radiated into the air, but 8.77% of this is lost to P_{back}.

The twin arc-slot antenna element shown in Fig. 1 was designed using HP-ADS assuming a *Rogers RT/duroid 6010LM* substrate having $\epsilon_r = 10.2$ and $h = 2.54mm = \lambda_d/4$. The actual size of the substrate was $12.5cmX12.5cm$. The antenna was fabricated using a wet chemical etching technique. A 180^o hybrid coupler was used to provide the required 180^o signal phase difference between the two CPW feed-lines so that the arc-slot aperture fields are excited in phase.

The best measured far-field E- and H-plane radiation patterns were obtained at a frequency of 8.6 GHz, and are shown in Fig. 3 with the corresponding theoretical patterns predicted using the method-of-moments. All patterns are normalized such that the co-polar components are 0 dB at broadside. The measured co-polar patterns are in very good agreement with theory and show no appreciable rippling effects indicative of surface-wave diffraction from the edges of the finite substrate. Some rippling effects observed may be attributable to the residual excitation of the TM_0 mode due to fabrication tolerances, lateral-waves which propagate with the free-space wavenumber k_0, and the fact that the substrate thickness is close to the onset of exciting the TE_0 mode. Theoretically, there is no cross-polarization in the two principal planes, and the measured cross-polarization levels are sufficiently low, being below -25 dB at most angles (see Fig. 3). Although not shown here, the measured patterns in the $\phi = 45^o$ plane also matched well with theory.

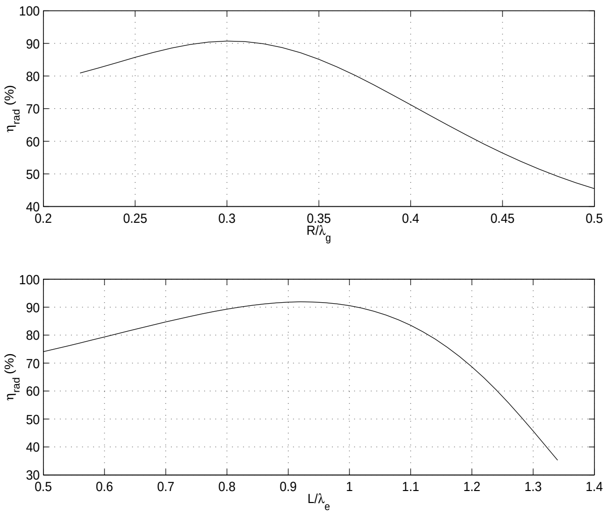

Fig. 2. Radiation efficiency vs. R, at second resonance (i.e. $L = \lambda_e$); and radiation efficiency vs. L, with $R = 0.293\lambda_g$.

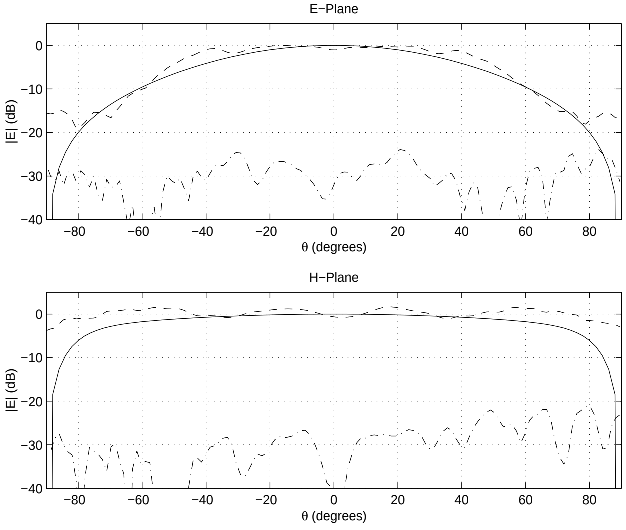

Fig. 3. Far-field E- and H- plane radiation patterns at 8.6 GHz. ——— : Theoretical co-polar; – – – : Experimental co-polar; and —·— : Experimental cross-polar

IV. CONCLUSIONS

A novel reduced surface-wave twin arc-slot antenna element has been proposed, designed, fabricated and tested.

The radius and length of the twin arc-slots may be chosen independently to achieve effective surface-wave cancellation and resonance simultaneously. The theoretical radiation efficiency of the twin arc-slot antenna element is significantly greater than that of any other planar slot antenna design in the literature. Indeed the proposed twin arc-slot allows more than 99% of the total power radiated into the air on electrically thick substrates. The measured far-field radiation patterns are in very good agreement with theory, and show no significant ill effects attributable to surface-wave propagation.

References

[1] R.L. Rogers and D.P. Neikirk, "Use of broadside twin element antennas to increase efficiency on electrically thick dielectric substrates," *Int. J. Infrared Millimeter Waves,* Vol. 9, No. 11, pp. 949-969, 1988.

[2] D. R. Jackson, J. T. Williams, A. K. Bhattacharyya, R. L. Smith, Stephen J. Buchheit, and S. A. Long, "Microstrip patch designs that do not excite surface waves," *IEEE Trans. on Ant. Propagat.* Vol 41, No. 8, pp. 1026-1037, 1993.

[3] G.V. Eleftheriades and M. Qiu, "Efficiency and gain of slot antennas and arrays on thick dielectric substrates for mm-wave applications: A unified approach." Accepted in *the IEEE Transactions on Antennas and Propagation.*

[4] M. Qiu, M. Simcoe and G. V. Eleftheriades, "High gain meanderless slot arrays on electrically thick substrates at mm-wave frequencies." Accepted in *the IEEE Transacions on Microwave Theory and Techniques.*

[5] J. B. Knorr and J. Saenz, "End effect in a shorted slot," *IEEE Trans. on Microwave Theory and Techniques* Vol. 21, No. 9, pp. 579-580, Sept., 1973.