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

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***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.**

***Index Terms*—Coplanar radiation efficiency, integrated antennas, slot antennas, surface waves.**

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, nominally 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.

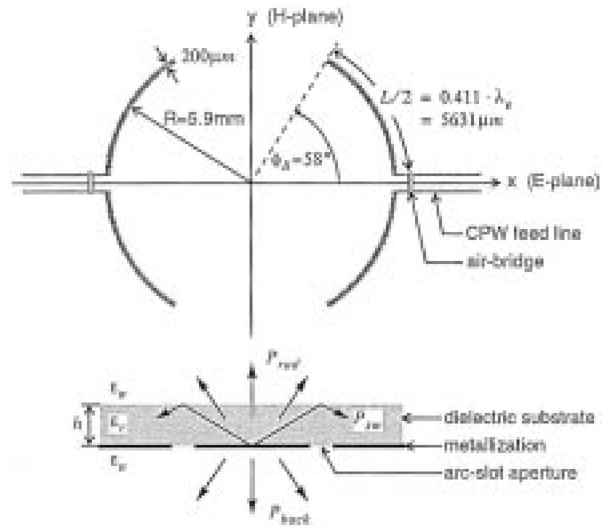

Fig. 1. Geometry of the twin arc-slot antenna.

The radiation efficiency of a slot antenna is defined by

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

where $P_{\rm rad}$ is the useful power radiated into the air through the substrate, $P_{\rm sw}$ is the power coupled into the TM_0 mode (trapped in the substrate), and $P_{\rm back}$ 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

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

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

The theoretical radiated space-wave power ($P_{\rm rad}$ and $P_{\rm back}$) of the twin arc-slot element can be calculated according to the

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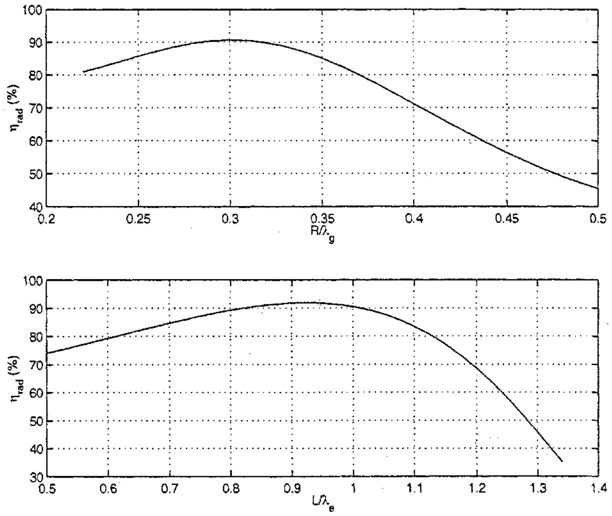

Fig. 2. Radiation efficiency versus R, at second resonance (i.e., $L = \lambda_e$), and radiation efficiency versus L, with $R = 0.293\lambda_g$.

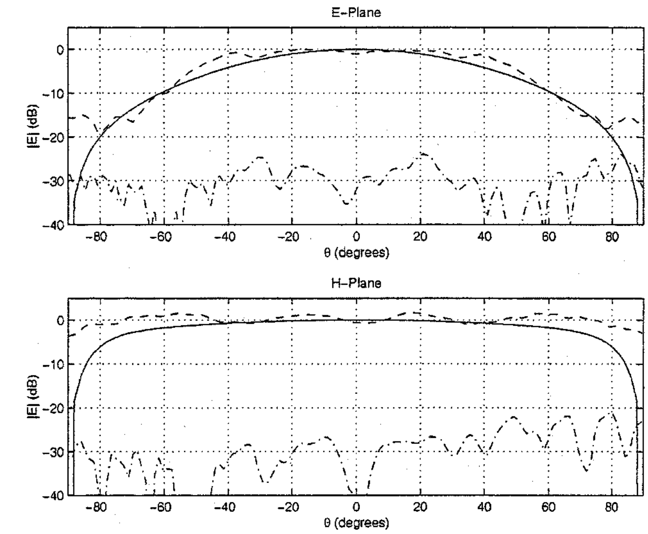

Fig. 3. Far-field E- and H-plane radiation patterns at 8.6 GHz.—: Theoretical co-polar; – – –: Experimental co-polar; and –·–: Experimental cross-polar.

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 according to [3] as

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

where $h_{\rm eff}$ 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

$$C_n = \frac{2[(-1)^n - 1]k_eR^2}{n^2 - (k_eR)^2} \times [\cos(k_eR\phi_B) - \cos(n\phi_B)][J_n'(\beta_{\rm TM_0}R)] \tag{4}$$

where $\beta_{\rm TM_0} = 2\pi/\lambda_g$ 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 $J_1'(\beta_{\rm TM_0}R) = 0$ (i.e., $R = x_1'/\beta_{\rm TM_0} = 0.293\lambda_g, x_1' = 1.8412$, 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 versus 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 versus 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 $P_{\rm back}$.

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 $h = 2.54$ mm $= \lambda_d/4$. The actual size of the substrate was 12.5 cm × 12.5 cm. The antenna was fabricated using a wet chemical etching technique. A 180° hybrid coupler was used to provide the required 180° 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. The TE_0 mode close to cutoff can contribute a 1/r-varying space-wave propagating along the substrate. 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 $\phi = 45°$ plane also matched well with theory.

IV. Conclusion

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.

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