Measurements of Strip Dipole Antennas on Finite-Thickness Substrates at 230 GHz

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Abstract—**Gain and field pattern measurements at 230 GHz are reported for strip dipole antennas on finite-thickness substrates without ground planes. Four substrate thicknesses are investigated ranging from 0.25 λ to 1.53 λ (λ = wavelength in substrate material). Measured results are in good agreement with theoretical predictions. A unique detector/low-pass filter design, composed of a bolometer and an interdigitated capacitor, is used to eliminate the distortion of the measured field patterns caused by the reception of the leads connecting the antenna with the monitoring instrumentation.**

I. Introduction

In microwave and millimeter-wave integrated circuits, integrating the antenna on the substrate with the circuitry offers smaller-size and reduced-cost for some applications. As the frequency is increased, however, guided waves in the substrate lower the efficiency of integrated circuit antennas [1], [2]. For antennas on ungrounded substrates, considerable attention has been given to techniques to reduce the loss to the guided waves. These include placing a quasi-optical element, such as a dielectric lens, on the opposite side of the substrate from the antenna [3] or constructing the antenna on a thin dielectric membrane suspended from the thicker, supporting substrate [4]. The simplest antenna element used with these techniques is the substrate mounted strip dipole. Despite considerable discussion of the properties of this antenna, such as the field pattern and gain variations with substrate thickness, there are few experimental results presented in the literature. In this letter, measured field pattern and gains are reported for strip dipole antennas on four substrates with thicknesses ranging from 0.25 λ to 1.53 λ. All substrates are fused silica, ϵ_r = 3.8, and the measurements are for the frequency 230 GHz (λ_0 =free space wavelength= 1.3 mm). Where possible, the measured results are compared with theory.

II. Design

The dipole structure, shown in Fig. 1, is composed of four elements: a dipole, a unique U-shaped bolometer, an interdigitated capacitor, and low-frequency leads. The current induced in the low-frequency leads is prevented from reaching the bolometer by the capacitor, which acts as a short circuit at the millimeter-wave frequency. The two resistors (vertical arms of the U-shaped bolometer) in series with the capacitor prevent it from also short-circuiting the dipole. The dipole essentially has two bolometers connected in parallel at its terminals: the first is directly across its terminals, while the second contains the capacitor in its electrical path. The strip dipoles were of the same design for all substrate thicknesses. The length of the dipole was set to the theoretical value for a resonant dipole on a semi-infinite substrate, $l_{\text{RES}} \approx 0.3\,\lambda_0$, and the total bolometer resistance was made roughly equal to the resistance at resonance, $R_{\text{RES}} \approx 55\ \Omega$ [5]. The square substrates were electrically large, 39 λ_0 by 39 λ_0, with the edges covered by absorbing material to reduce reflections.

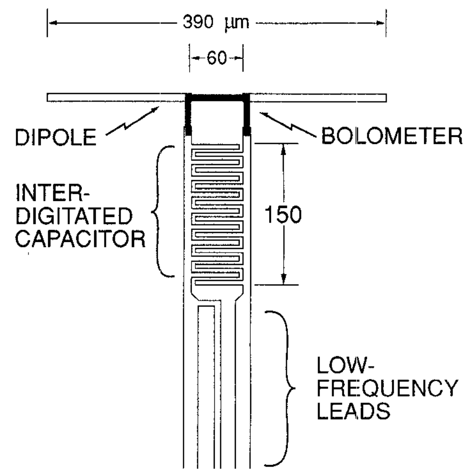

Fig. 1. Schematic diagram of the dipole structure. All dimensions are in μm.

III. Measured Results, Comparison With Theory, and Discussion

The measured E-plane patterns for the dipole on the thinnest and thickest substrates, 0.25 λ and 1.53 λ respectively, are shown in Figs. 2(a) and 2(b) (solid dots). Also shown in these figures are patterns computed from a simple theory (solid line). In this model, the dipole is viewed as a probe on the surface of the substrate that senses the local electric field. The time-average power received by the dipole is then

$$P = C|\hat{z} \cdot \vec{E}_{\text{LOC}}|^2, \tag{1}$$

where $\hat{z}$ is the unit vector in the direction of the dipole's axis. When the dipole is on the incident-wave side of the substrate

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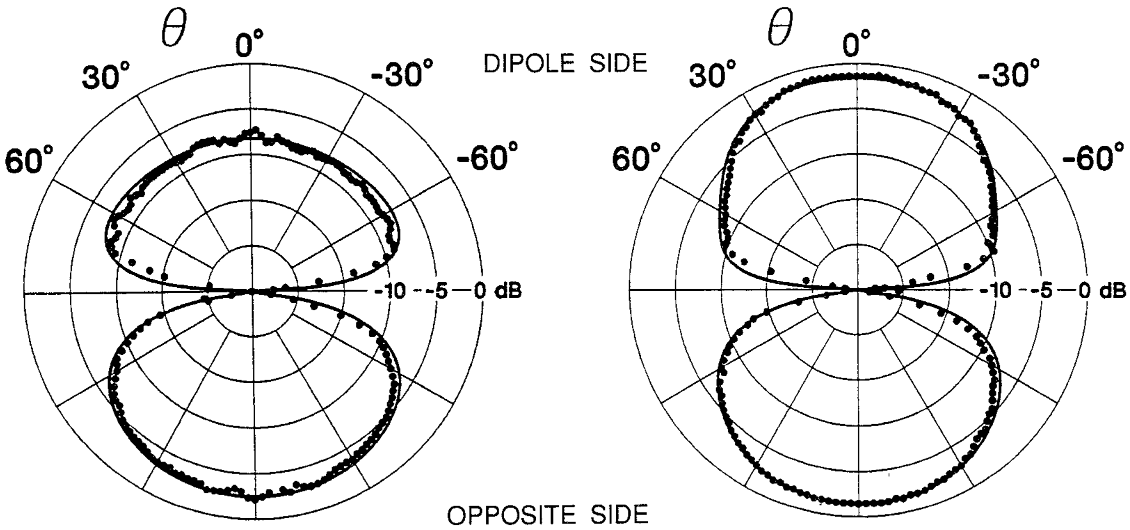

(a) (b)

Fig. 2. E-plane patterns for dipoles on fused silica substrates • measured, — theory. (a) $t/\lambda = 0.25$. (b) $t/\lambda = 1.53$.

$$\vec{E}_{\mathrm{LOC}} = [1 + R(\Theta)]\vec{E}_{\mathrm{INC}}, |\Theta| \leq \frac{\pi}{2}, \quad (2)$$

and when the dipole is on the transmitted-wave side of the substrate

$$\vec{E}_{\mathrm{LOC}} = [T(\Theta)]\vec{E}_{\mathrm{INC}}, \frac{\pi}{2} \leq |\Theta| \leq \pi, \quad (3)$$

where $R(\Theta)$ and $T(\Theta)$ are the plane-wave reflection and transmission coefficients for a dielectric slab. For each substrate thickness, the constant C is chosen to give the best agreement between the theoretical and measured patterns. The good agreement demonstrated in Fig. 2 shows that this simple theory accurately predicts the shapes of the patterns. The agreement for the H-plane patterns and the other substrate thicknesses that were measured is equally good [6]. Notice that the pattern in Fig. 2(a), which is for a substrate that is roughly a quarter of a wavelength thick ($t/\lambda = 0.25$), is fairly asymmetrical. While the pattern in Fig. 2(b), which is for a substrate that is roughly three-halves of a wavelength thick ($t/\lambda = 1.53$), is symmetrical. The on-axis gains for the former case are lower than those for the latter case. The results in Table I show that the asymmetrical behavior occurs whenever the substrate is roughly an odd multiple of a quarter wavelength thick ($t/\lambda = 0.25, 0.69$), and that the symmetrical behavior occurs whenever the substrate is roughly an even multiple of a quarter wavelength thick ($t/\lambda = 0.45, 1.53$).

In Fig. 3, the measured gains are compared with the theoretical gains calculated by Rutledge *et al.* for an infinitesimal dipole on a finite-thickness substrate ($\epsilon_r = 4.0$) [3]. Their curves are only for the range $0 \leq t/\lambda \leq 0.4$ and have been extrapolated slightly beyond this range (dashed line) for the comparison. The extrapolation was based on the trend exhibited in their curves for a higher permittivity substrate ($\epsilon_r = 12$). In general the two sets of results are in good agreement: both show minimum gain occurring when $t/\lambda \approx$ 0.25 and maximum gain occurring when $t/\lambda \approx 0.50$. These results give some confidence that the loss due to guided waves in the substrate is correctly understood.

TABLE I
PHYSICAL PARAMETERS AND MEASURED GAINS FOR THE DIPOLE ANTENNAS OF FINITE THICKNESS SUBSTRATES

Substrate Thickness			Gain (dB)	
mm	t/λ	t/λ_o	$\Theta = 0°$ (into air)	$\Theta = 180°$ (into sub.)
0.17	0.25	0.13	-8.1	-2.7
0.30	0.45	0.23	-1.3	-1.1
0.46	0.69	0.35	-7.2	-3.0
1.02	1.53	0.78	-1.4	-1.3

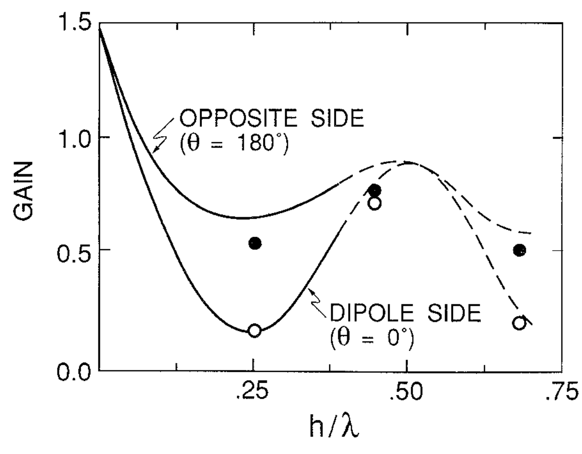

Fig. 3. Gain versus substrate thickness (wavelengths in the dielectric material). Measured gain on: o dipole side of substrate. • opposite side of substrate ($\epsilon_r = 3.8$). Theoretical gain — and extrapolation ---($\epsilon_r = 4.0$) from [3]

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