A MILLIMETER-WAVE INTEGRATED-CIRCUIT ANTENNA BASED ON THE FRESNEL ZONE PLATE

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ABSTRACT

A new type of millimeter-wave integrated-circuit antenna is investigated. The antenna is based on a quasi-optical design, with a Fresnel zone plate on one side of a dielectric substrate and a resonant strip dipole antenna at the focus of the zone plate on the opposite side of the substrate, Figure 1. The unique feature of this design is that all of the components are made using simple IC fabrication techniques: simple metal depositions on dielectric layers. Another unusual feature of this design is the short focal length of the zone plate; the f/d of the zone plate ranges from 0.1 to 0.5. The antennas described in the paper are for a frequency of 230 GHz (λ_o=1.3mm); however, the design is easily scaled to other millimeter-wave or submillimeter-wave frequencies. Moderate gains, above 20 dB, are obtained.

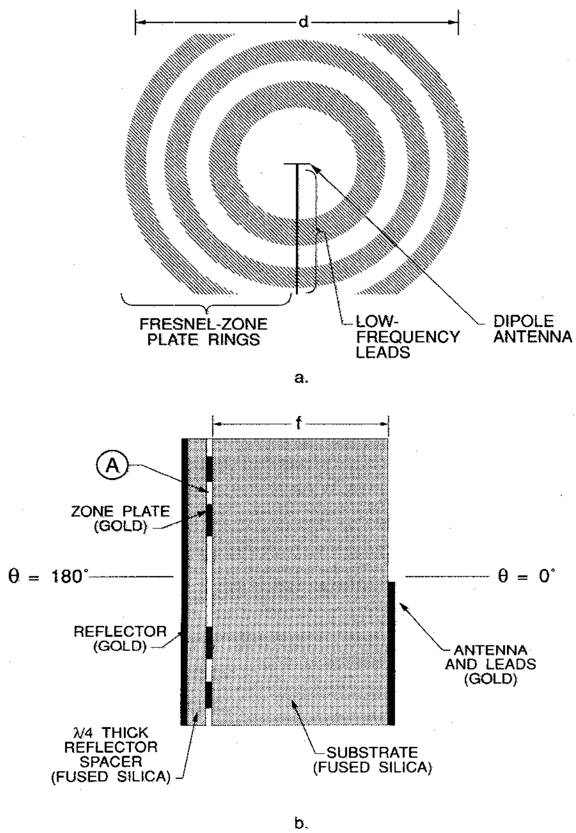

Figure 1. Schematic drawing of the IC zone-plate antenna, a. front view, b. side view.

DESIGN

The Fresnel zone plate concentrates energy at a focal point by blocking the portions of the incident wave that would add destructively at the focal point. The cylindrical symmetry about the normal to the zone-plate gives the zone plate its characteristic clear and opaque rings. Zone-plate antennas have been used in the microwave and millimeter-wave regions [1], but not in a form suitable for incorporation into an integrated circuit.

The antenna reported here can be easily incorporated into an integrated circuit. The dipole element is placed on the same side of the substrate as the integrated circuitry with the zone plate on the opposite, often unused, side, Figure 1. Following the approach of Van Buskirk [2] the gain is increased by approximately 6 dB over that of a simple zone plate by adding a planar reflector spaced $\lambda/4$ behind the zone plate, Figure 1. The reflector acts like a second zone plate, because it is illuminated only by the energy passing through the

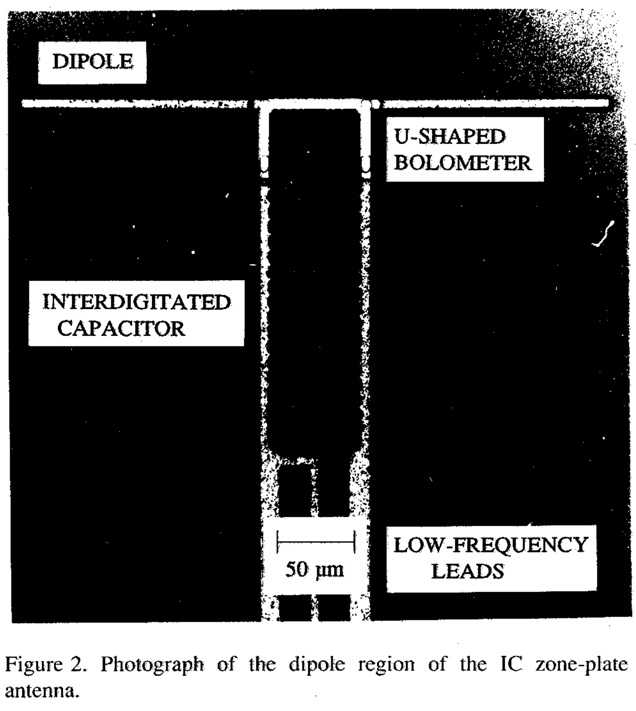

Figure 2. Photograph of the dipole region of the IC zone-plate antenna.

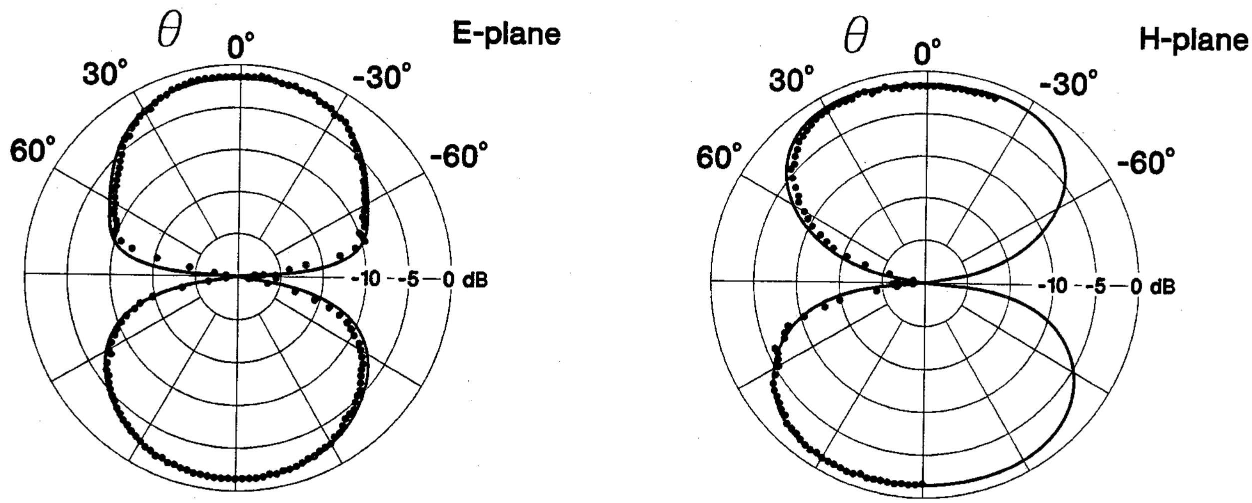

Figure 3. Power patterns for the dipole without the zone plate on a fused silica substrate, $f/\lambda=1.54$: —Theory, ● Experiment.

open rings of the zone plate. The added $\lambda/4$ spacer adjusts the phase so that the contribution from the reflector adds to that of the zone plate at the dipole.

A resonant dipole antenna collects the energy reflected from the zone plate at its focus on the opposite side of the substrate, Figure 2. The bismuth bolometer at the terminals of the dipole detects the power received by the antenna [3]. The interdigitated capacitor acts as a short circuit at the millimeter-wave frequency, thus preventing the signals induced in the leads from reaching the detector. The unique U-shaped bolometer prevents the capacitor from also short circuiting the terminals of the dipole. At the millimeter-wave frequency, the terminals of the antenna see two bolometers in parallel: the direct path between the terminals and the path through the capacitor.

MEASUREMENTS AND THEORY

Four different focal length zone-plate antennas on fused silica substrates were investigated. All had a nominal diameter of 21 mm but different focal lengths: f/d=0.10, 0.19, 0.29, and 0.47. In addition, a series of measurements was made to investigate the contributions of the various elements that make up the zone-plate antenna. First the dipole antenna on the substrate was measured alone. Then the zone plate was added to the opposite side of the substrate, and finally the full configuration (dipole, zone plate, spacer and reflector) was measured.

The power patterns for the dipole only on a substrate ($f/\lambda=1.54$) are shown in Figure 3. The theoretical curve in this figure is based on the electric field strength on the surface of the substrate calculated from the Fresnel reflection and transmission coefficients for a dielectric sheet. The magnitude of the theoretical gain has been normalized to the average of the measured on-axis gains. The good agreement between the measured and theoretical results confirms the validity of the measurement technique and the operation of the antenna range.

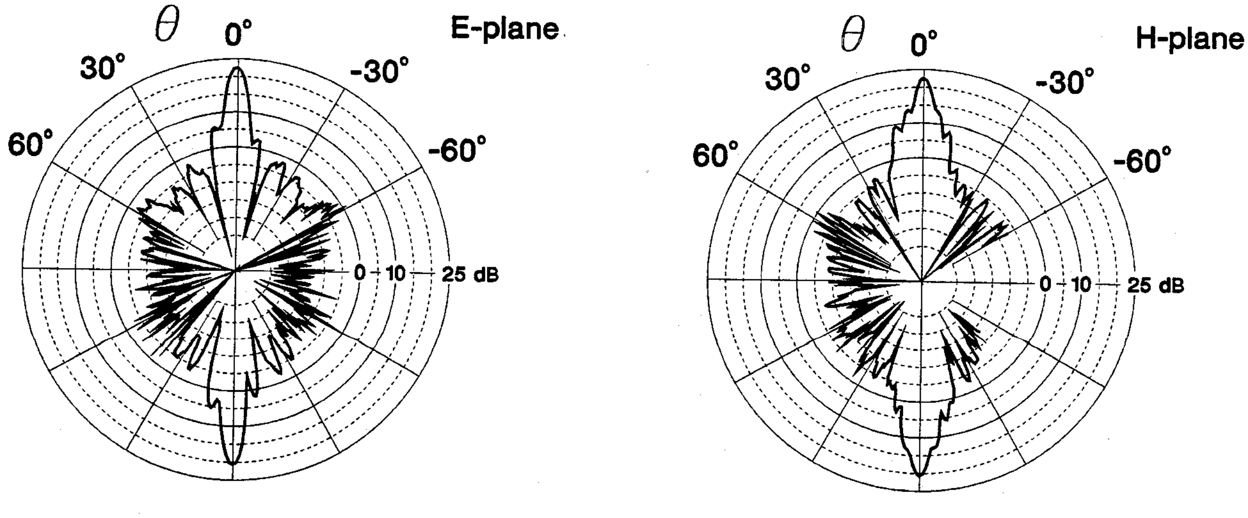

Figure 4. Power patterns for the dipole and zone plate without reflector, $f/d=0.29$, $f/\lambda=9.0$.

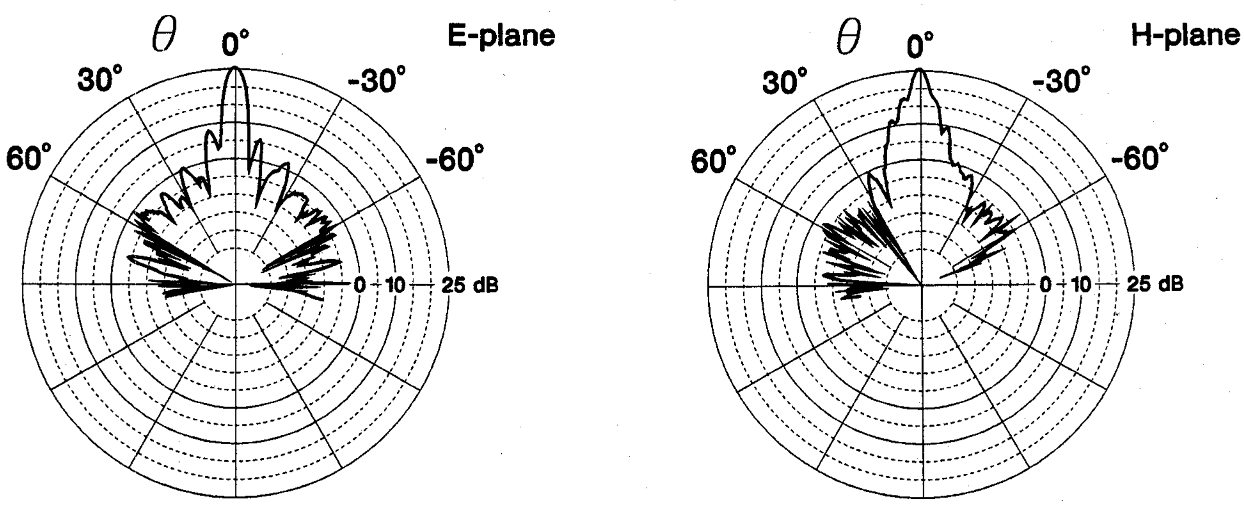

Figure 5. Power patterns for the dipole with zone plate, spacer and reflector: the fully assembled integrated-circuit zone-plate antenna, f/d=0.29, f/λ=9.0.

The power patterns for the dipole and the Fresnel zone plate, without reflector or spacer, are shown for the case f/d=0.29, f/λ=9.0 in Figure 4. This figure shows that the zone plate can be used in both reflection (θ=0°) and transmission (θ=180°) configurations. The on-axis gains for the reflection and transmission configurations are 22.6 dB and 20.7 dB, respectively. The difference in the gains for these two cases is discussed in more detail below. The power patterns for the fully assembled integrated- circuit zone-plate antenna, which includes the spacer and reflector, are shown in Figure 5. The on-axis gain for this configuration is 25.6 dB, about 3 dB above that for the reflection zone plate and 5 dB above that for the transmission zone plate.

The on-axis gains and beamwidths for four different focal length zone-plate antennas are given in Table 1. The gain is maximum (25.6 dB) for f/d=0.29. For shorter focal lengths, the gain decreases with a corresponding increase in beamwidth.

The aforementioned difference between the gains of the reflection and transmission zone plates prompted another series of measurements to investigate the contribution of the reflections from the dielectric-air interface, indicated by A in Figure 1. The three curves in Figure 6 are for the wave incident from the dipole side of the substrate (θ=0°), i.e. the reflection configuration. The curve with the lowest on-axis gain (20.6 dB) was made with a dielectric matching layer (λ/4 - Teflon FEP) behind the zone plate. With the matching layer, only one set of zone plate rings, the metal rings, reflects energy back to the dipole. The curve with the intermediate on-axis gain (22.6 dB) was made with nothing behind the zone plate. In this case there is a contribution from both sets of rings. The metal rings contribute to the gain as in the first case, but now the reflection from the dielectric-air interface, the open rings, also contributes to the gain. Note that there is a 180o phase difference between the reflection from the metal rings and the reflection from the open rings (dielectric-air interface) so that both reflected waves add in phase at the antenna. The curve with the highest on-axis gain (26.6 dB) is for the zone plate with the λ/4 spacer and reflector.

A simple theory was developed for this antenna. To begin, the dipole is assumed to be infinitesimal, and its far-zone magnetic field is determined within the substrate. This field is then used to obtain the physical optics current on the zone-plate rings and reflector. Finally the field of the physical optics current is expressed as a plane wave spectrum and transformed through the substrate to the region above where it is combined with the field radiated directly by the dipole [4]. In Figure 7, power patterns from this theory are compared with the measured results for the antenna with f/λ=9.04. There is good agreement over the main beam of the patterns and for the theoretical and measured on-axis gains, 24.0 dB and 25.3 dB, respectively.

Focal Length f		Diameter d			f/d	Gain	Beamwidth (FWHM)	
mm	f/λ	mm	d/λ	No. of zones		dB	E plane	H plane
2.0	3.01	20.87	31.46	26	0.096	17.0	14°	22°
4.0	6.03	21.13	31.85	22	0.19	21.9	6.5°	8.0°
6.0	9.04	20.72	31.28	18	0.29	25.3	4.3°	4.0°
10.0	15.07	21.40	32.26	14	0.47	23.8	3.8°	3.0°

Table 1. Measured on-axis gains and beamwidths of the zone-plate antennas.

CONCLUSION

A moderate gain, easily constructed millimeter-wave integrated-circuit antenna based on the Fresnel zone plate was developed. The gain and beamwidth of the antenna can be varied by adjusting the f/d ratio of the zone plate; this gives the designer some latitude in fitting particular system requirements. The effect of adding the reflector behind the zone plate to increase the gain of the antenna was investigated. It was found that even without the reflector, the gain of the zone plate was increased because of the 180° degree phase difference between the reflection off the metal rings and the open rings (dielectric-air interface). As the dielectric constant of the substrate is increased, the performance of the zone plate without the reflector approaches that of the zone plate with the reflector. Thus on substrates with high permittivity, such as alumina and gallium arsenide, the reflector and $\lambda/4$ spacer may not be necessary.

ACKNOWLEDGEMENT

This work was supported by the Georgia Tech Research Institute under Projects E904-017 and E904-034 and by the Joint Service Electronics Program under Contracts DAAL03-87-K-0059 and DAAL-03-90-C-0004. The authors would like to thank James Gallagher and James Wiltse of the Georgia Tech Research Institute for continued interest in and support of this work.

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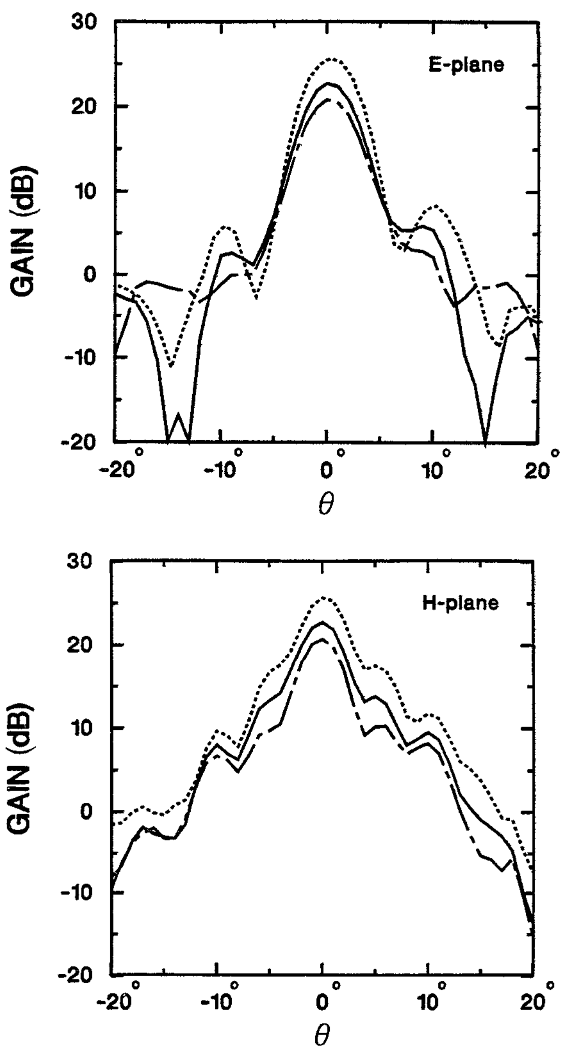

Figure 6. Power patterns showing the contribution of the dielectric-air interface: — — — dielectric matching layer behind ZP, ——— ZP with nothing behind, - - - - ZP with $\lambda/4$ spacer and reflector.

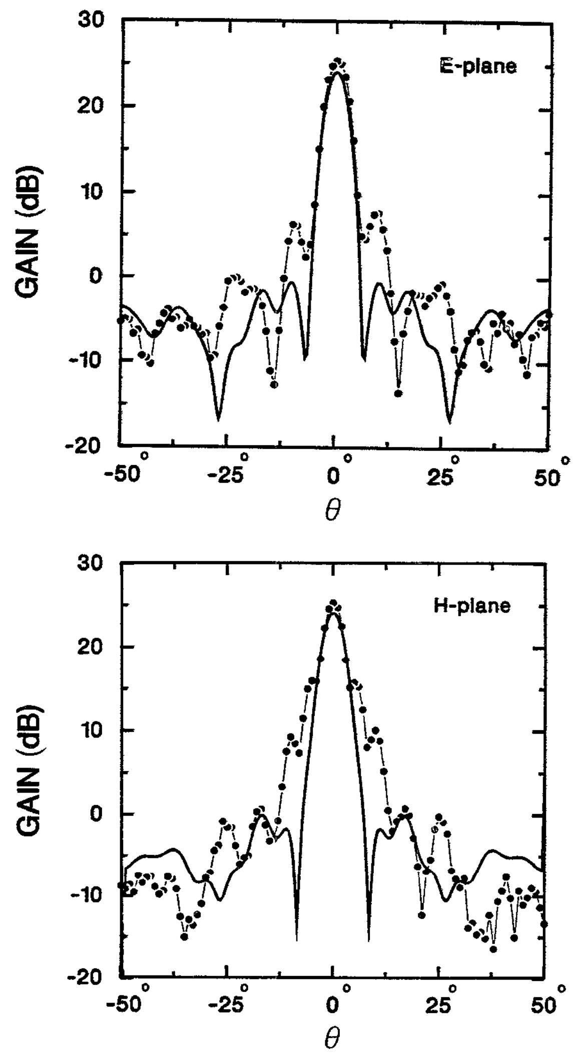

Figure 7. Comparison of theoretical and measured power patterns for the integrated-circuit zone-plate antenna, f/d=0.29, f/λ=9.0: ——— Theory, ●—●—● measured.