Current Status of Integrated Submillimeter-Wave Antennas

Gabriel M. Rebeiz

NASA/Center for Space Terahertz Technology
EECS Department - University of Michigan
Ann Arbor, MI 48109-2122

ABSTRACT

This paper summarizes the recent advances in efficient submillimeter-wave integrated antennas. The use of these antennas in planar receivers will result in very low- noise receivers for frequencies above 100 GHz. The antennas presented here are the quasi- monolithic integrated horn antennas, the substrate-backed spiral and log-periodic antennas, the endfire slot-line antennas on thin membranes, the double-dipole integrated reflector antenna and the dielectric-filled parabola. Another important antenna, the substrate backed dual-slot antenna, is presented in this session in a different paper.

I. INTRODUCTION

Millimeter-wave and terahertz systems are becoming increasingly important in many scientific and military applications. Integrated receivers are easier to manufacture, more reliable, smaller, lighter and much less expensive than waveguide receivers. However, planar antennas have traditionally suffered from poor patterns and low coupling efficiencies to reflector systems. Another limitation for submillimeter- waves systems was the unavailability of planar detectors which are compatible with integrated antennas. This hurdle has been overcome due to the tremendous advance in planar Schottky-diode [1] and SIS detectors technologies [2]. It is therefore important to develop high-efficiency integrated antennas which are compatible with planar detector technologies. This will result in planar receivers with comparable performance to the best waveguide-based systems at a fraction of the cost. This review paper presents a summary of recent high-efficiency integrated antennas suitable for low-noise submillimeter-wave receivers.

II. INTEGRATED HORN ANTENNAS

Elementary antennas on planar dielectric substrates suffer from power loss to substrate modes. Detailed analysis of the surface wave losses indicate that the found that the gain of an elementary slot and dipole antenna on a dielectric substrate drops very quickly as the thickness of the substrate increases [3]. One way to solve this problem and eliminate substrate modes is to use a substrate lens (see later). Another way is to remove the substrate altogether and integrate the antenna on a thin dielectric membrane. The membrane is so small compared to a free-space wavelength that the antenna effectively radiates in free-space and the substrate mode losses are eliminated. The membrane is fabricated on silicon (or GaAs), and therefore the detectors and electronics can be integrated on the surrounding semiconductor substrate.

We have concentrated our efforts into the development and optimization of a high- efficiency integrated horn antenna (Fig. 1) [4,5]. The antenna consists of a dipole suspended on a 1μm dielectric membrane in a pyramidal cavity etched in Silicon or GaAs. The horn collects the energy and focuses it to the probe antenna on the membrane. Alternatively, a monopole probe can be integrated on the membrane to guide the energy from the horn cavity to a coplanar waveguide transmission-line on the Silicon (or GaAs) wafer. Imaging arrays already fabricated include a 7x7 array with 1λ-square apertures at 92 GHz and a 9x9 array with 1.45λ-square apertures at 240 GHz [4]. Recently, a 16x16 element "CCD-like" imaging array with 1.4λ-apertures at 802 GHz [6] . Also, a 92 GHz 5x5 array of doubly-polarized horn antennas for polarimetric and balanced mixer receivers has been fabricated [7].

In a drive to further improve the radiation characteristics of horn antennas, a new multi- mode integrated horn antennas with performance comparable to that of waveguide-fed corrugated horn antennas has been developed. The quasi-integrated section consist of a flared machined section attached to a standard integrated horn antenna [8]. The minimum dimension of the machined section is about 1.5λ which permits the fabrication of the multimode horn up to 2 THz. Effectively, this antenna is very similar to a waveguide-fed Potter horn except that it is now fed by a dipole or monopole in a pyramidal cavity. A 20 dB horn was designed using a full-wave analysis technique already developed for dipole-fed horn antennas (Fig. 1). The measured characteristics at 91 GHz agree very well with theory, and provide a 97.3% coupling efficiency to a Gaussian-beam. Receivers using this antenna are being constructed at 91 GHz and 250 GHz.

BB

CH3141-9/92/0000-1145$01.00 © 1992 IEEE

III. SUBSTRATE-BACKED SPIRAL AND LOG-PERIODIC ANTENNAS

The substrate mode problem can be eliminated if the dielectric thickness is made infinite. In this case, the dipole and slot antennas radiate most of their power into the dielectric. The infinite dielectric can be synthesized using a lens of the same dielectric constant attached to the antenna substrate [see 3]. The substrate lens used is generally a hyperhemisphere which increases the gain of the radiating antenna by the index of refraction of the dielectric material. Planar log-periodic and spiral antennas [9] with a substrate lens offer an attractive replacement to double-slot and double-dipole antennas for wideband applications. The spiral antennas yield circularly polarized patterns with very low cross-polarization levels. The log-periodic antennas yield linearly polarized patterns with -20 dB cross-polarized component if suspended in free space or -5 to -12dB levels if placed on a substrate lens. The self-complementary designs have a constant impedance of 120Ω and 72Ω on Quartz and GaAs, respectively [10]. These antennas have been successfully used in submillimeter-wave receivers resulting in very low noise temperatures [11]. Recently, in an exciting development experimentally pioneered by Buttgenbach, the patterns of spiral and log-periodic antennas showed a marked improvement when placed behind the aplanatic focus of a hyperhemispherical lens. At the optimal position, the patterns are diffraction limited by the substrate lens, and therefore very high gains can be achieved by simply increasing the size of the lens (Fig. 2). Although a theoretical calculation has not been fully developed, it is believed that a uniform phase distribution results on the aperture plane of the lens from an antenna placed at the optimal position. More research is being done on the extended hemisphere and the results will be presented at the conference.

IV. DIELECTRICALLY-FILLED PARABOLA; DOUBLE-DIPOLES AND REFLECTOR ANTENNAS

A planar antenna, the dielectrically-filled parabola, that combines the substrate-lens approach and the high-gain reflector-based approach was developed by Siegel et al. [12]. In this case, a quartz substrate is machined as a parabola and a its curved edge is metalized thereby resulting in a parabolic reflector. The feed antenna is integrated on the flat portion of the dielectric lens and therefore radiates most of its power into the substrate. This radiation is subsequently reflected and collimated by the parabolic reflector (Fig. 3). The construction is rugged and suitable for space applications. Pattern measurements with dipoles, spiral, log-periodic, and bow-tie antennas placed at the focus of the dielectrically-filled parabola show good pattern with low cross-polarizations. A 230 GHz SIS-based receiver is currently under development at the NASA-Jet Propulsion Laboratory.

Double-dipole antennas have been previously investigated at millimeter-wave frequencies and have showed promise for high-efficiency applications. The design presented here consists of a double-dipole antenna integrated on a dielectric membrane and backed by a ground plane. The detector is integrated at the center of the coplanar stripline. The radiation pattern can be made rotationally symmetric [13] by the choice of the antenna lengths (l), the antenna spacing (d), and the ground-plane distance from the membrane (h). The double-dipole antenna of figure 4a has a calculated coupling-efficiency to Gaussian beams of 84%. We have constructed a 119μm antenna based on a similar double-dipole feeding a small machined paraboloidal reflector (Fig. 4b). The double-dipole antenna was built on a 1μm-thin membrane with dimensions of 4x4mm. The ground plane was built on another membrane and consisted of a circular patch of evaporated gold 1000Å thick with a diameter of 3.5λ. The ground-plane was aligned and attached to the antenna wafer using spacers made of silicon wafers polished to approximately 92μm thickness. The parabolic reflector is machined out of aluminum to a surface smoothness of 100Å and is 30λ (3.57mm) in diameter. The measured E, H, and 45°-plane patterns at 119μm. show a measured directivity of 37 dB. This makes the reflector ideally suited for coupling to high f-number Cassegrain imaging systems.

V. ENDFIRE SLOT-LINE ANTENNAS ON THIN MEMBRANES

Alot of research has been done on different types of endfire TSA (tapered slot antennas) [14]. TSA are integrated on low dielectric substrates by etching the metalization on both sides of the substrates and can feed directly into planar slotlines or fin-lines in waveguides. It was found experimentally that one can define an optimum range from 0.005 to 0.03 for the effective dielectric thickness $t_{eff}/\lambda_0 = (\sqrt{\epsilon_r} - 1)t/\lambda_0$ (t is the actual substrate thickness). For thicker substrates, the pattern will deteriorate rapidly so it is especially important to observe the upper limit. To solve this problem, a joint research effort was conducted between Chalmers University of Technology and the University of Michigan. The effort consisted of integrating a B(broken)L(linearly)TSA on a thin dielectric membrane [15]. The measured patterns on a 802 GHz design are symmetrical and show relatively low sidelobe levels (-10 dB) and a cross-polarization level of -9 dB (Fig. 5). A similar antenna was built for 350 GHz and resulted in nearly identical patterns from 320 GHz till 370 GHz. A submillimeter-wave SIS receiver is currently under construction using this antenna at Chalmers University of Technology.

This work is supported by the NASA-Center for Space Terahertz Technology, University of Michigan and by a National Science Foundation PYI Award.

[1] W.L. Bishop et al., "A micron-thickness planar Schottky diode chip for terahertz applications with theoretical minimum parasitic capacitance," *IEEE MTT-S Int. Microw. Symp. Digest,* pp. 1305-1308, 1990.

[2] H.G. LeDuc et al., "Submicron area Nb/MgO/Nb tunnel junctions for SIS mixer applications," *IEEE Trans. on Magnetics,* vol. MAG-27, pp. 3192-3195, 1991.

[3] D. B. Rutledge et al., "Integrated Circuit Antennas," *Infrared and Millimeter- Waves,* vol. 10, pp. 1-90, K.J. Button, Ed., New York, Academic Press, 1983.

[4] G.M. Rebeiz et al., "Monolithic millimeter-wave two-dimensional horn imaging arrays," *IEEE Trans. Antennas Propag.,* vol. AP-28, pp. 1473-1482, Sept 1990.

[5] G.V. Eleftheriades et al., "Millimeter-wave integrated-horn antennas, Part I: Theory, and Part II: Experiment" *IEEE Trans. Antennas Propag.,* vol. AP-28, pp. 1473- 1482, Sept 1990.

[6] W.Y. Ali-Ahmad et al., "802 GHz integrated horn antennas imaging array," *Int. J. Infrared Millimeter Waves,* vol. 12, pp. 481-486, May 1991.

[7] W.Y. Ali-Ahmad et al., "92 GHz dual-polarized integrated horn antennas," *IEEE Trans. Antennas Propag.,* vol. AP-39, pp. 820-825, July 1991.

[8] G.V. Eleftheriades et al., "A 20-dB quasi-integrated horn antenna," To appear in the February 1992 issue of the *IEEE Microwave and Guided Wave Lett.*

[9] R.H. Duhamel and D.E. Isbell, "Broadband logarithmically periodic antenna structure," *IRE National Convention Record,* Part I, pp. 119-128, 1957.

[10] T.H. Büttgenbach et al., "A Broad-band low-noise SIS receiver for submillimeter astronomy," *IEEE Trans.Microwave Theory Tech.* vol. 36, pp. 1720-1726, Dec. 1988.

[11] P.H. Siegel and R.J. Dengler, "The dielectric filled parabola: A new millimeter/submillimeter wavelength receiver/transmitter front end," *IEEE Trans. Antennas Propagat.,* vol. AP-39, pp. 40-47, Jan. 1991.

[12] D.F. Filipovic et al., "Double-dipole antennas for high-efficiency reflector illumination," To appear in the May 1992 issue of the *IEEE-Microwave Theory Tech.*

[13] K.S. Yngvesson et al.,"The tapered slot antenna—a new integrated element for millimeter-wave applications," *EEE Trans. Microwave Theory Techn.,* vol. MTT-37, pp. 365-374, Feb. 1989.

[14] S.S. Gearhart et al., "Submillimeter-wave endfire slotline antennas," to be presented at the *IEEE/AP-Symposium,* July 1992, Chicago, Illinois.

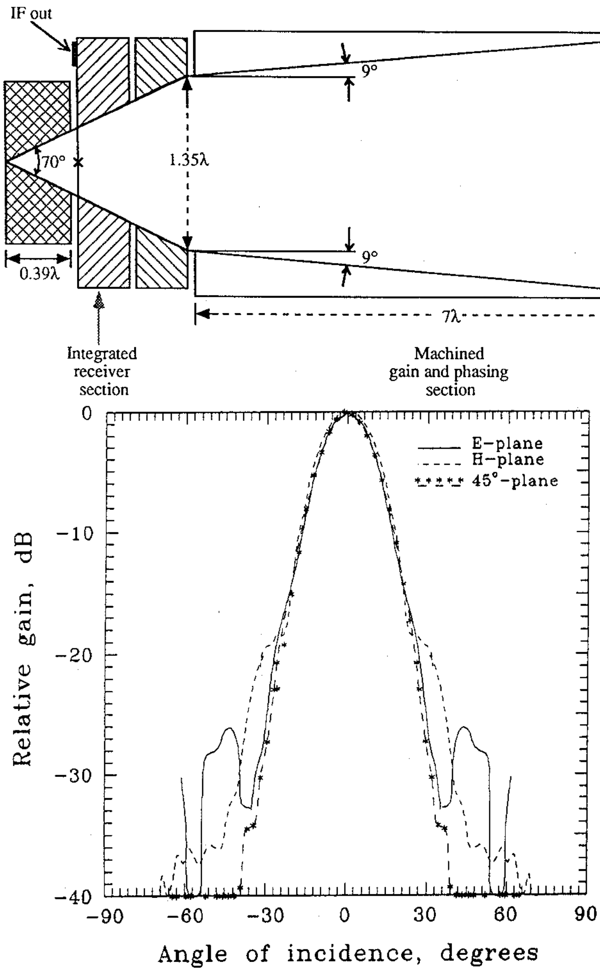

Figure 1: The 20dB quasi-planar horn design and the measured patterns at 91 GHz.

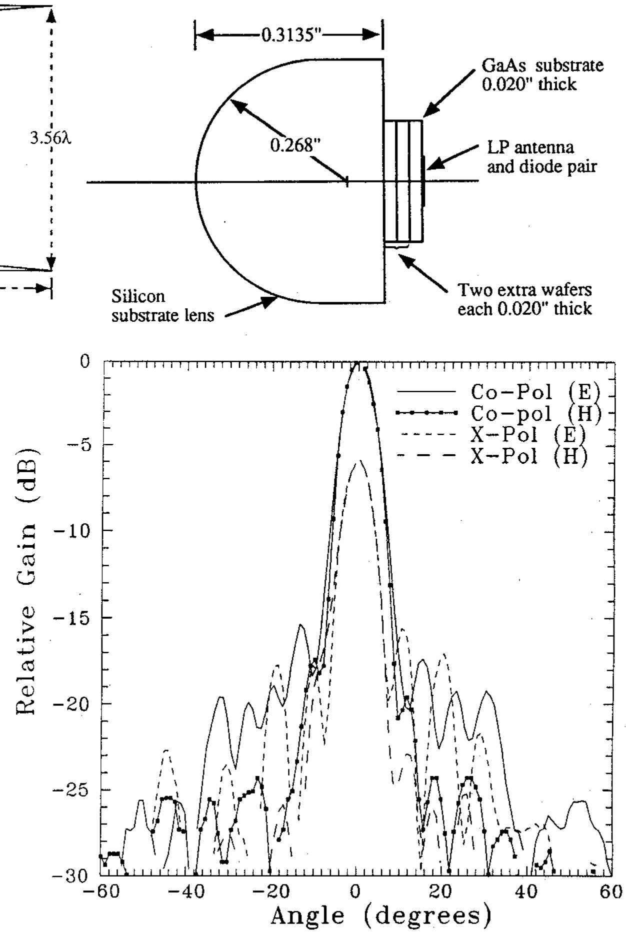

Figure 2: The measured patterns (180 GHz) on a log-periodic antenna placed at the optimal position of an extended hemisphere.

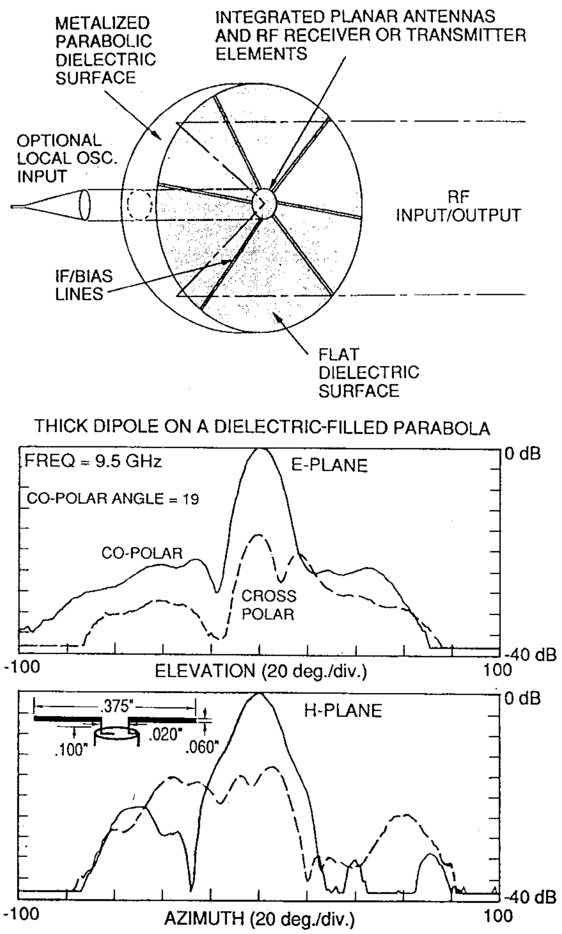

Figure 3: The dielectric filled parabola and the measured patterns with a thick dipole feed at 9.5 GHz.

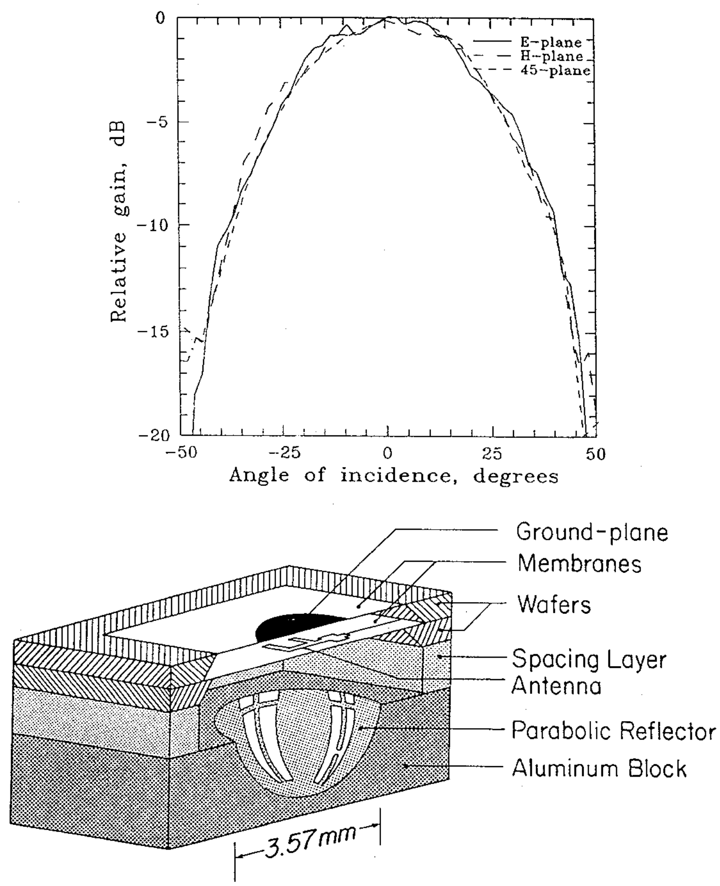

Figure 4: The measured patterns for a double-dipole antenna with parameters (l, d, h) of $(0.7\lambda, 0.55\lambda, 0.77\lambda)$, and a cross-sectional view of a submillimeter-wave double-dipole fed paraboloidal antenna.

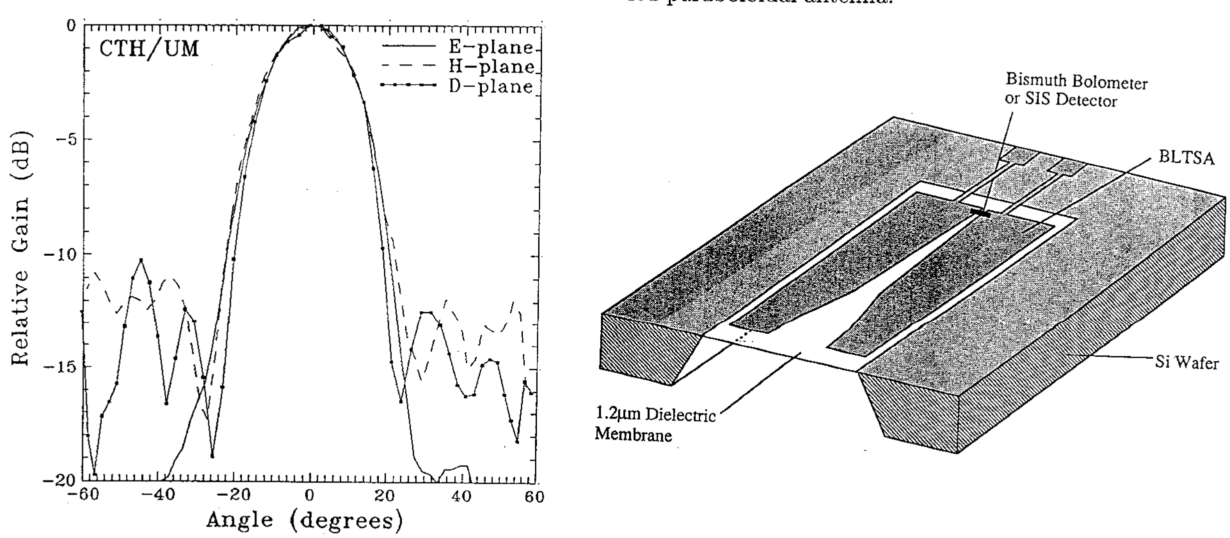

Figure 5: An endfire slot antenna on a thin membrane and the measured patterns at 802 GHz.