MM-Wave Tapered Slot Antennas on Micromachined Photonic Bandgap Dielectrics

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Abstract - **Dramatic improvements in the radiation properties of tapered slot antennas (TSA) integrated on high dielectric constant substrates have been achieved through micromachining techniques. A periodic hole structure was micromachined into the substrate converting it into a photonic bandgap material. The measured directivity of a $4\lambda_0$ TSA on a 50 mil (1.27mm) thick Duroid substrate (ε_r = 10.5) was increased by 240% using micromachined holes with a hexagonal geometry. A similar improvement was observed when the process was performed at 30 GHz on a 14 mil (350 μm) silicon wafer. We believe the technology can be scaled to 60 GHz and 94 GHz for communication systems, low-cost millimeter wave imaging arrays, and power combining systems.**

I. INTRODUCTION

The tapered slot antenna, sometimes referred to as the "Vivaldi" antenna, was first introduced by Gibson in 1979 [1]. Yngvesson et al. have published many papers on this antenna and have introduced several variations, including the "Constant Width Slot Antenna" and the "Broken Linear Tapered Slot Antenna" [2,3]. The TSA has also been theoretically analyzed by Janaswamy and Schaubert with excellent results for electrically thin dielectric substrates [4]. One of the main problems with the TSA is its sensitivity to the thickness of the supporting substrate. The "effective" thickness of the substrate has been defined as:

$$t_{eff} = t(\sqrt{\varepsilon_r} - 1) \qquad (1)$$

and represents the electrical thickness of the dielectric material supporting the antenna. It has been previously reported that the range of "effective" thickness for good operation of a TSA is approximately:

$$0.005 \leq t_{eff}/\lambda_0 \leq 0.03$$

This results in a very thin supporting structure for antennas at 30 GHz and above on high dielectric constant substrates such as Silicon or Gallium Arsenide. For a silicon carrier the maximum thickness allowed at 30 GHz is approximately 5 mils (120 μm). This makes the integration of a TSA somewhat impractical for commercial applications at millimeter-wave frequencies. One solution to this problem is to construct the antenna on a thin silicon nitride dielectric membrane. The membrane is only 1.5 μm thick and is compatible with silicon IC fabrication techniques. This technique has been successfully demonstrated at very high frequencies (348 GHz and 802 GHz) [5,6]. At lower frequencies, however, the membranes cannot be reliably fabricated to support the large surface areas required for the antennas.

In 1993, Brown et al. introduced the concept of photonic bandgap materials for slot and dipole antennas on dielectric substrates [7,8]. The idea is to etch a series of holes in a *stack* of Stycast wafers to synthesize a face-centered-cubic lattice structure within the dielectric. The photonic structure underneath the antenna resulted in large stop-bands for normally propagating waves, resulting in a large percentage of the power fed to the dipole to be radiated out into the space above the dielectric, greatly increasing the directivity of the antenna. We have expanded on this idea and developed Tapered Slot Antennas at 10 and 30 GHz on dielectrics

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micromachined to disrupt substrate mode formation (Fig. 1). The results, presented in this paper, are the first known to the authors and show that the TSA can be successfully designed and operated on the thick dielectric substrates needed for commercially viable applications.

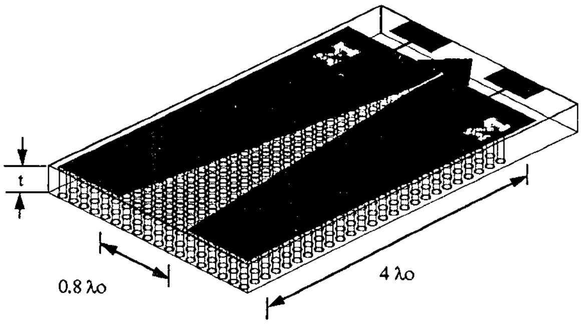

Fig. 1. Micromachined Tapered Slot Antenna

II. DESIGN

In this work we developed and tested four linearly tapered slot antennas with a center frequency of 10 GHz on Duroid, and one scaled version at 30 GHz on a high resistivity silicon substrate. All antennas are 4 λ_o long with a flare angle of 12°, resulting in an aperture width of 0.8 λ_o (Fig. 1). One antenna is made on a thin, low dielectric constant Duroid substrate (ε_r = 2.2) and is used as a reference antenna for performance comparison. Another antenna was fabricated on thick (50 mil), high dielectric constant Duroid (ε_r = 10.5). The last two were made on the same thick Duroid substrate but were machined with holes to suppress the substrate modes that are normally excited. Two different patterns of holes were machined, one with a rectangular geometry and the other with a hexagonal geometry (Fig. 2).

The calculated "effective" dielectric constant of the micromachined structures is

$$\varepsilon_{eff} = \varepsilon_r \left(1 - \frac{\pi D^2}{4 W^2}\right) \qquad (2)$$

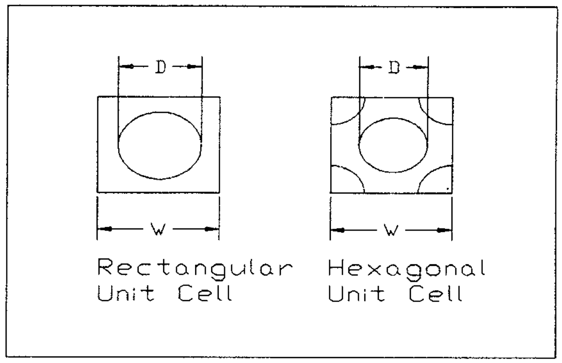

Fig. 2: Cell structure of the machined hole patterns.

for the rectangular geometry and

$$\varepsilon_{eff} = \varepsilon_r \left(1 - \frac{\pi D^2}{2 W^2}\right) \qquad (3)$$

for the hexagonal one. These values are based on quasi-static, volumetric principles. The above analysis was verified by the design and construction of transmission-line resonator elements on the machined substrates. The measured results agree quite well with the predicted values and confirm that the above "effective" dielectric constant is accurate. However, as will be shown in section III, the TSAs on micromachined dielectrics result in very good patterns even for large ε_{eff} and large t_{eff}/λ_0 .

The antennas at 10 GHz are fabricated on 5" x 5" Duroid circuit boards (12.7cm x 12.7 cm). It is expected that energy coupled into substrate modes would eventually be radiated from the edges and the backside of the Duroid carrier. This stray energy will effect the directivity and patterns of the antenna. The Duroid material was machined using a CNC milling machine. The antennas were all fed with an 0.085" (2.16mm) coax line with the center conductor soldered across the slotline gap. The slotline feed is shorted λ/4 away (at 10 GHz) from the probe for best transition performance. The 30 GHz silicon TSA was tested by mounting a zero-bias schottky detector diode across the slot feed λ/4 away from an RF shorting capacitance All design parameters are listed in Table 1.

	Reference	Thick	Hexagonal	Rectangular
ε_r	2.2	10.5	10.5	10.5
t (mils)	30	50	50	50
ε_{eff}	2.2	10.5	9.6	8.4
t_{eff} / λ_o	0.012	0.095	0.081	0.089
W(mils)	---	---	125	200
D(mils)	---	---	125	200

Table 1: Design Parameters for 10 GHz TSA

III. 10 GHz MEASUREMENTS

The radiation patterns at 10 GHz for the antennas are shown in Fig.3-5 and the measured antenna properties are shown in Table 2. The patterns and directivity measured for the reference antenna (ε_r = 2.2 , t = 30 mils) agreed well with previously published results [1,2]. The antenna on the standard high dielectric constant material performed as poorly as expected with a directivity of 4.4 (compared to 13.7 for the reference antenna).

The directivity is calculated using:

$$D = \frac{4\pi U \max}{\iint (P_{co-pol} + P_{x-pol}) d\Omega} \quad (4)$$

and the main beam efficiency is calculated using:

$$\eta_{main} = \frac{\iint P_{main-beam(-10dB)}}{\iint P_{total}} \quad (5)$$

As seen in Figs 3-5, the antenna patterns on the micromachined substrates clearly show a dramatic improvements over the same antenna when supported by a standard high dielectric substrate.

There is a 240% increase in the directivity of the antenna when the supporting dielectric has been properly machined to suppress substrate modes (also note that the rectangular hole pattern showed an 81% increase in directivity, indicating that the geometry of the machining is important for optimum performance). This would make the TSA on high dielectric substrates suitable for medium size imaging arrays.

IV. 30 GHz MEASUREMENTS

A 30 GHz TSA was fabricated on 14 mil (350 μm) silicon substrate. The antenna was patterned and plated with gold to a thickness of 2 μm. The holes were etched using an HF Nitric solution and a silicon nitride masking layer. The process resulted in an anisotropic etch with nearly vertical sidewalls. This TSA has a rectangular geometry, with a hole diameter of 45 mils (1.14 mm) and spacing of 70mils (1.78 mm). The resulting effective dielectric constant is approximately 8. The measured pattern (Fig.6) shows again that substantial improvement can be achieved through the use of micromachined dielectric substrates (note that the improvement would have been greater had a hexagonal pattern been used for the holes). These improvements appears to be due not to the lower "effective" dielectric constant of the micromachined material but to the disruption of the dominate substrate modes imposed by the structure. Also, although the silicon wafer had been machined with holes it remained mechanically stable, was lighter, and should endure the types of environments required for commercial applications.

	Reference - ε_r=2.2	Thick - no holes - ε_r=10.5	Hexagonal holes - ε_r=10.5	Rectangular holes - ε_r=10.5
Directivity	13.7	4.4	14.9	8.0
Beamwidth (-10 dB)	E = 30° H = 45° D = 45°	E = 45° H = 90° D = 70°	E = 40° H = 45° D = 45°	E = 50° H = 65° D = 65°
X-Pol (45° Plane)	-7 dB	-7 dB	-13 dB	-10 dB
Main Beam η	50 %	57 %	57 %	60 %
F# lens	0.6	0.2	0.5	0.3

Table 2: Measurement Results of the 10 GHz TSA.

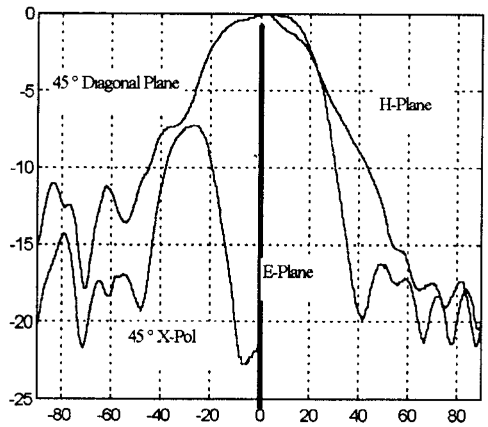

Fig. 3: Reference antenna patterns (ε_r=2.2) at 10 GHz.

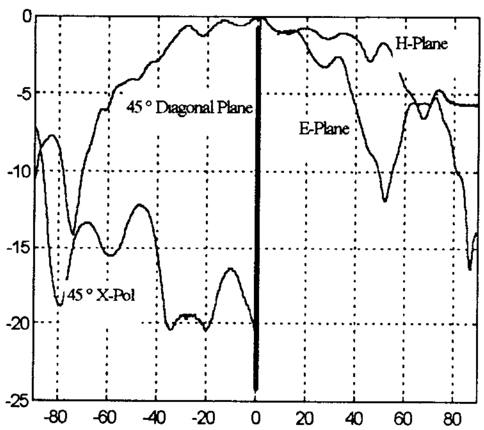

Fig. 4: Thick Duroid antenna patterns (ε_r=10.5) at 10 GHz.

V. Acknowledgments

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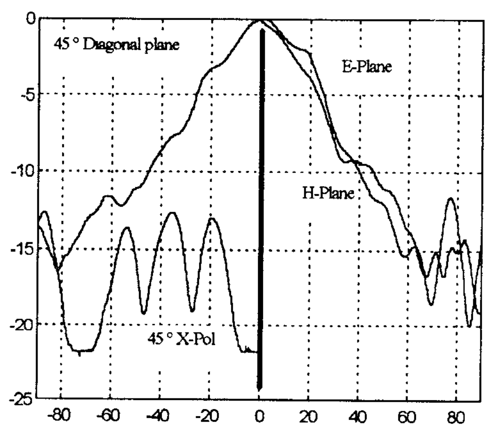

Fig. 5: Micromachined antenna patterns (ε_r=10.5) (Hexagonal hole geometry) at 10 GHz.

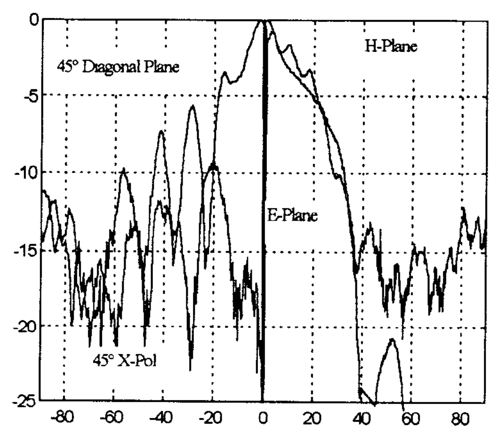

Fig. 6: TSA patterns on a thick (14 mil) micromachined silicon substrate with rectangular hole pattern at 30 GHz.