Linear Tapered Slot Antenna with Substrate Integrated Waveguide Feed

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Introduction

Focal plane arrays (FPA's) are of increasing interest within the radio astronomy community. Several of the design concepts for the future square kilometer array (SKA) radio telescope require FPA's. The potential of radio image sampling, in which post processing can be applied to a large number of array elements - similar to CCD based techniques currently employed within the visible spectrum - has also generated a large level of enthusiasm [1].

Tapered slot antennas (TSA) are ideal for this application since they are lightweight, and low cost per element but retain directivity close to horn antennas. They are planar elements, so they can be integrated on the same substrate as an appropriate feed.

Traditional planar transmission lines have suffered from larger losses than waveguide at high frequencies. This makes them undesirable as feed systems in radio astronomy, where a low signal-to-noise level is often required. Substrate integrated waveguide (SIW) technology provides equivalent planar structures for several different types of waveguides. The loss characteristic of SIW is an order of magnitude better than microstrip but is still worse than normal air filled waveguide [2].

The TSA design presented in this paper utilizes antipodal flares and the backwards extension match technique presented in [3]. However the design investigates techniques to increase element gain using high permittivity substrates and demonstrates the TSA capability at high frequency (18-24 GHz).

Design

Tapered slot antennas (TSA's) are a class of endfire antennas known as surface wave antennas. Several TSA types exist, the most common being linear-tapered (LTSA), Vivaldi-tapered (VTSA) and constant-width (CWSA). TSA's - in spite of being planar - have performance close to horn antennas. Typically they have narrower beam widths than other planar antennas like patch antennas. Beamwidths of 15° as well as symmetric beam patterns have been reported in literature [4], [5]. In order for the TSA to behave as a surface wave antenna, the following effective substrate thickness (t_{eff}) requirements must be obeyed [4].

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$$0.005 < \frac{t_{eff}}{\lambda o} = \left(\sqrt{\varepsilon r} - 1\right)\frac{t}{\lambda o} < 0.03 \quad (1)$$

The beamwidths of CWSA's are typically the smallest, followed by LTSA's and VTSA's. As one would expect, the situation is opposite for the side lobe level. As such LTSA's are an ideal compromise between beamwidth and sidelobe level [4], [5]. The E-plane of the SIW feed is perpendicular to the E-plane of the LTSA element. Therefore, antipodal tapered metallic fins are utilized in the antenna element. Hence, the electric field is gradually rotated as the wave travels along the taper [3].

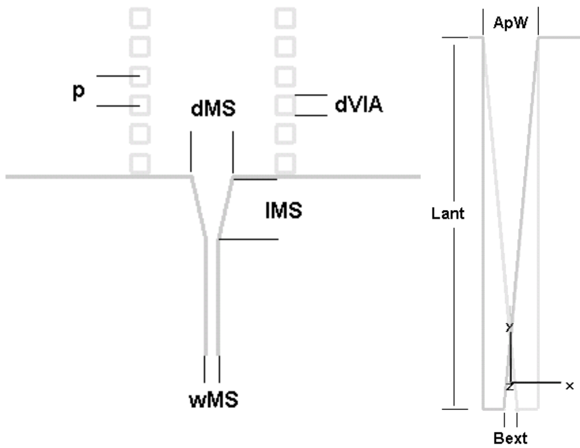
LTSA's, like all TSA's, provide very high bandwidth due to their constant impedance. Typical LTSA's have an input impedance of 80 Ω, which is doubled to 160 Ω by the antipodal taper technique. This causes a significant impedance mismatch with the SIW feed, which has low impedance, limited to around 33 Ω by the thin substrate height [3]. The mismatch is compensated for by backwards extending the antenna's taper, resulting in an overlap of the taper.

Results

An 18-24 GHz LTSA design was created and simulated in CST Microwave Studio. High-permittivity Duroid (ε_r=10.2, thickness b=0.635 mm) was used as a substrate in order to increase gain and because of its dielectric similarities to alumina based substrates that have well documented cryogenic behavior. Radio astronomy often requires that receivers be cooled to cryogenic temperatures for increased sensitivity and mixer use; however, alumina poses problems for the current fabrication facility. The design parameters are shown in Fig. 1.

For the prototype array consisting of 4x4 LTSA elements, each element will have a microstrip to SIW transition to allow for SMA measurement connections. Initial transition values were taken from [6] and then optimized within Ansoft HFSS; the final parameters are also given in Fig. 1. The impedance match between the LTSA and the SIW feed was accomplished with a backwards extension as discussed in the previous section. The extension width (Bext) was determined via a classic Powell-based optimizer within CST. The acceptable resultant impedance match is shown as $|S_{11}|$ in Fig. 2.

As previously discussed, the normalized effective thickness of the LTSA must fall between 0.005 and 0.03. The Duroid and alumina substrates examined have a fairly high relative permittivity of 10.2 and 9.8, respectively. For a 0.381 mm thick alumina design, the effective thickness is 0.271, which is significantly larger than the upper limit. To compensate, [7] suggested removing the substrate from the tapered region between the metal fins. This effectively makes the transition from the high permittivity substrate to free space more gradual, largely removing the split. This phenomenon has been verified in CST simulations.



Par.	Value (mm)
b	0.635
Lant	120
Bext	4.378
ApW	17.845
dVIA	0.510
p	0.836
dMS	1.185
IMS	1.797
wMS	0.366

Fig. 1: Design parameters.

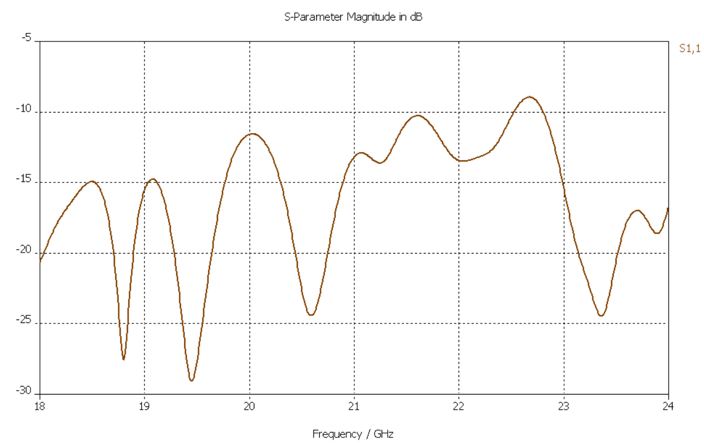


Fig. 2: $|S_{11}|$ (in dB) of Duroid LTSA.

Fig. 3 shows two E-plane radiation patterns for an 18-24 GHz alumina LTSA design. The left plot is obtained with the substrate present in the tapered region and shows high grating lobes as predicted in [7]. The right plot shows the pattern when the substrate isremoved; the grating lobes have been significantly reduced.

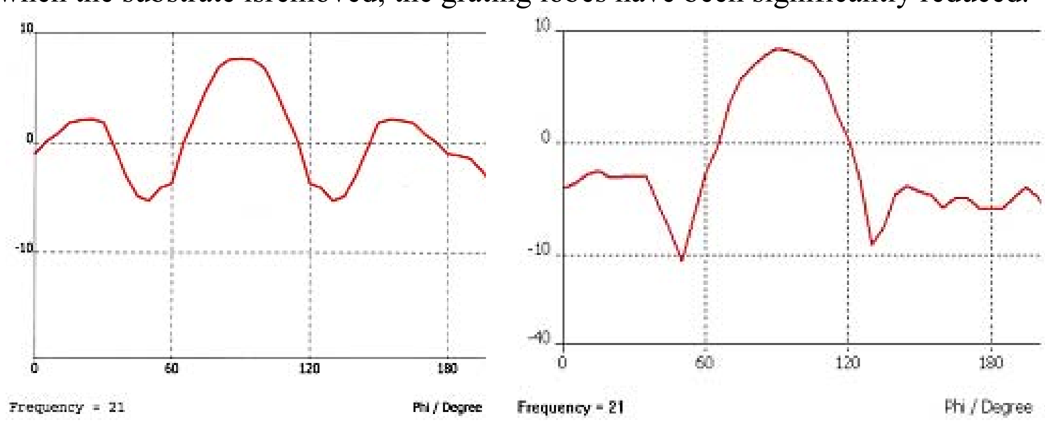


Fig. 3: E-plane pattern 18-24 GHz alumina LTSA; substrate in taper included (left) and removed (right).

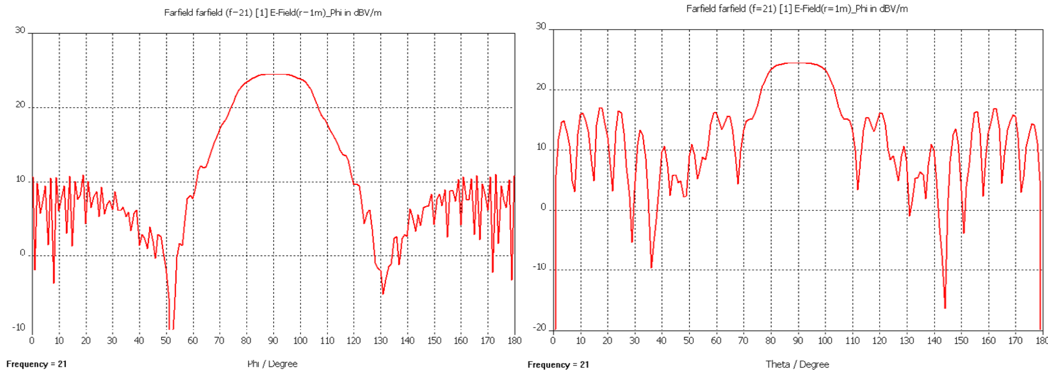


Fig. 4: E- (left) and H- (right) plane radiation patterns of Duroid LTSA.

Simulated electric field radiation patterns for the final Duroid LTSA design are shown in Fig. 4. Symmetrical 3dB beam widths of 27° in both the E- and H-planes were achieved. 10dB beamwidths were slightly better in the H-plane, 32°, than in the E plane, 43°, although this is clearly at the expense of the sidelobe level.

Simulation of the array behavior of the Duroid element design was not feasible due to the lengthy simulation times required for even a single element. Fabrication is currently in process, and measurements will be included in the presentation.

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