Invited Article

Modified Tapered Slot-line Antennas for Special Applications

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Abstract– **Tapered slot-line antenna (TSA) is a well known printed end-fire antenna with traveling-wave feature. In order to further improve its performances and extend its functions, several techniques with patents were developed in SEU, and summarized in this article. Here include: grating-loaded TSA for gain enhancement, CPW back-fed TSA for broadening impedance bandwidth, asymmetric TSA structure for beam shaping and optimization, coupled TSA with hybrid network for monopulse beam forming. Both conceptual illumination and simulated/measured results are described.**

Keywords– **Tapered slot-line antenna, gain enhancement, metal-grating loading, bandwidth broadening, UWB feeding, beam shaping, dual-band antenna, monopulse-beam duplexer**

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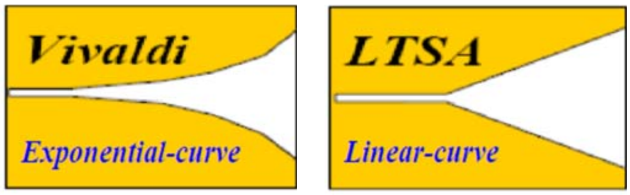
1 Introduction

Recently, miscellaneous printed antennas have been widely applied in various RF/microwave equipments or systems, from wireless communication to phased-array radar, from satellite telemetry to radio-frequency identification, from electronic counter-measures to embedded bio-electronic chip, etc. This enormous family can be classified into three branches according to their different radiation mechanisms: (1) resonant antennas as dipole, loop, slot, patch, etc. (2) traveling-wave antennas as tapered slot-line, meander-line, grating, etc. (3) optical antennas as reflect-array, transmit-array, compound air-fed array, etc. This paper is focusing to some new development of the tapered slot-line antenna (TSA).

The original structures of TSA were proposed by P.J. Gibson [1] and S.N. Prasad et al. [2] to the same forum of the 9th European Microwave Conference by using individual terminology and configuration as shown in Figure 1. Here both Vivaldi antenna and Linear-TSA are simply called as TSA.



(a) Vivaldi Antenna (b) Linear TSA

Figure 1. Original structures of tapered slot-line antenna.

In general, the slot-line is terminated by a backward short-circuit stub, and fed by a crossed microstrip-line which printed on other side of dielectric substrate with an open-circuit stub; as shown in Figure 2, those resonated stubs always restrict the impedance bandwidth of antenna. Hence, the feeding scheme will be a key technique of bandwidth enhancement.

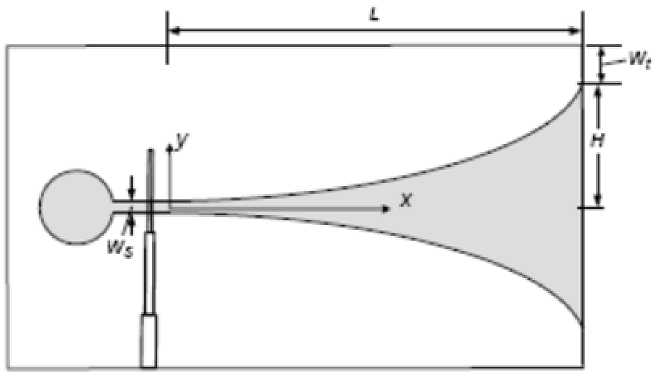


Figure 2. Traditional feeding structure with microstrip-line and slot-line stubs.

These traditional TSAs possess common features as: traveling-wave radiation with multi-octave bandwidth; end-fire pattern with moderate directive gain and obvious side- lobes; printed structure with small cross-section; and also integrating compatibility with devices or circuits. However, their performances are waiting to be improved for gain enhancement, side-lobe suppression, beam-width equality in E- & H- planes, and broadening impedance bandwidth. In addition, the possibility for extending the functions of TSA is expected.

In principle, some possible confused concepts on TSA should be clearly discriminated as follows:

1) TSA is neither a 'tapered slot antenna' chiseled on a conductive screen nor a 'tapered slot-line' as a pure transmission line; but the transmission and

radiation of TSA simultaneously betide on a slot-line with tapered slot-width.

2) TSA is different from a 'traveling-wave wire antenna' whose radiation is contributed by the currents along a pair of wires only; but all the currents distributed on a pair of metallic plates as shown in Figure 3 contribute to the radiation of TSA.
3) TSA possesses a longitudinal radiated aperture; it could not be named as a 'planar horn antenna' whose transversal aperture results in broadside radiation.

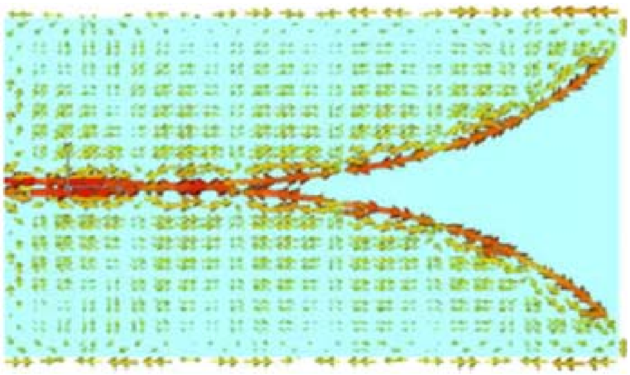


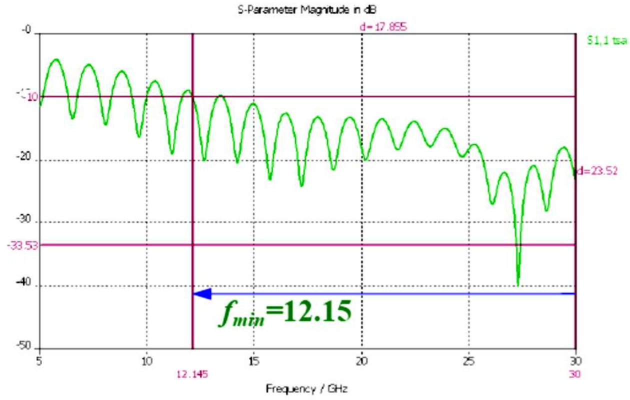
Figure 3. Currents distribution on whole plate of TSA.

2 Improvement of Traditional TSA

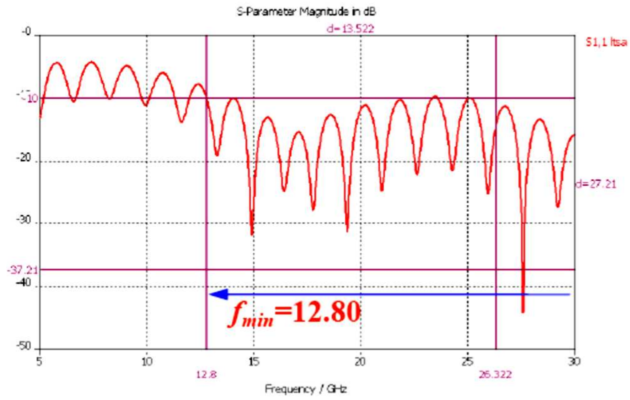
For comparing the main performances between Vivaldi antenna and Linear-TSA (LTSA) based on the same sizes 84×54 mm of substrate and traditional feeding, their typical frequency response curves of both $|S_{11}|$ and gain are simulated (excluding feed structure) as shown in Figure 4. Where (a) (b) show that Vivaldi antenna has slightly wider bandwidth from $f_{min} = 12.15$ GHz than LTSA from $f_{min} = 12.80$ GHz for $|S_{11}| \leq -10$dB; but (c) shows that gain rise *vs*. frequency started from 13.5 dBi (at 12.2 GHz) up to 15.9 dBi (at 18 GHz) for LTSA, it is faster than from 13.5 dBi to 14.1 dBi for Vivaldi antenna; also the cross-polar-level of Vivaldi antenna (X-$P \leq -33$ dB) is slightly lower than that of LTSA (X-$P \leq -31$ dB). In above TSA samples, to perform higher gain must increase electric length (L/λ) of antenna, so it usually suits in higher SHF band rather than lower SHF even UHF/ VHF bands.

2.1 Gain Enhancement

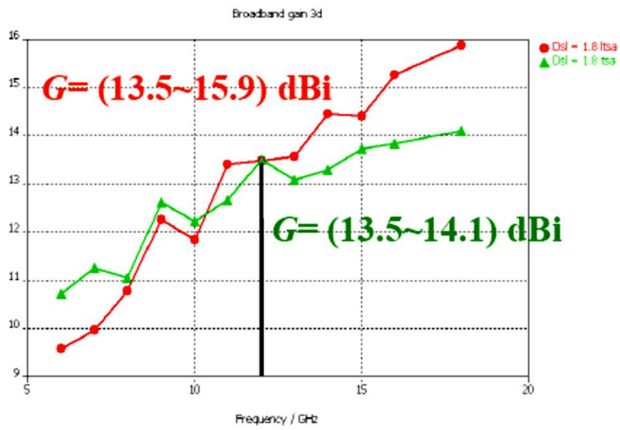
In order to enhance the gain for relatively shorter TSA, a scheme by loading metal-strip grating as additional director imbedded into the slot of LTSA (Figure 5) [3] is developed. Where the traditional LTSA of sizes 84×54 mm without directive grating provides about 8 dBi peak gain with stable frequency response and about $\sim 25\%$ practical bandwidth for joint gain-impedance as $|S_{11}| \leq -12.5$ dB.



(a) Curve of $|S_{11}|$ for Vivaldi antenna



(b) Curve of $|S_{11}|$ for LTSA



(c) Curves of gain for Vivaldi antenna & LTSA

Figure 4. Comparison of frequency responses between Vivaldi antenna & LTSA.

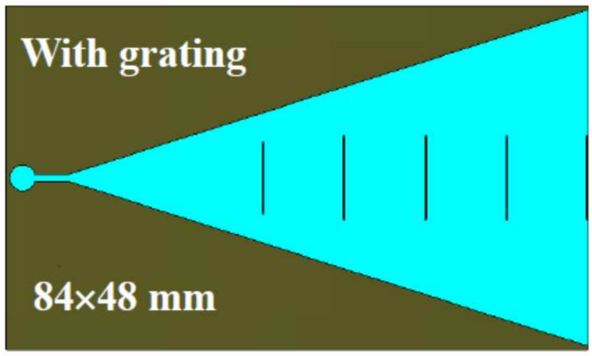
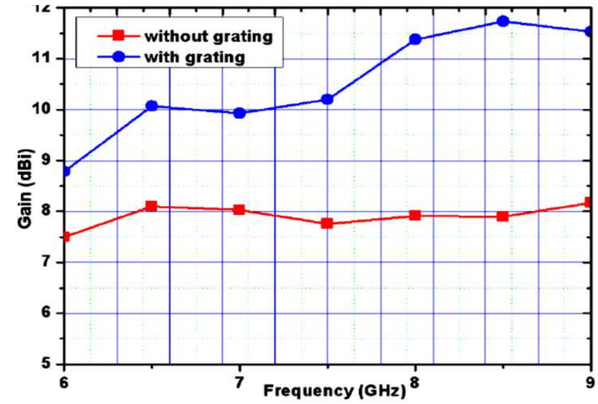
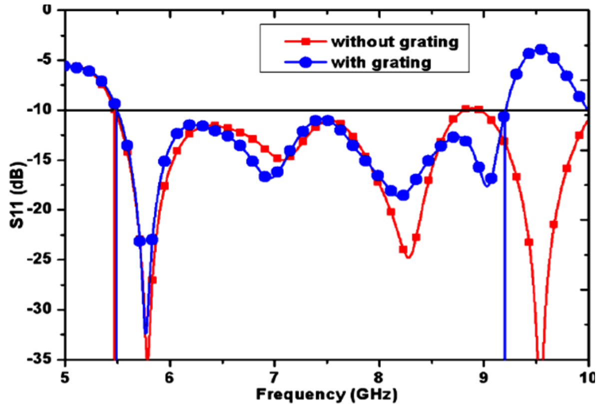


Figure 5. LTSA loaded by metal-strip grating.

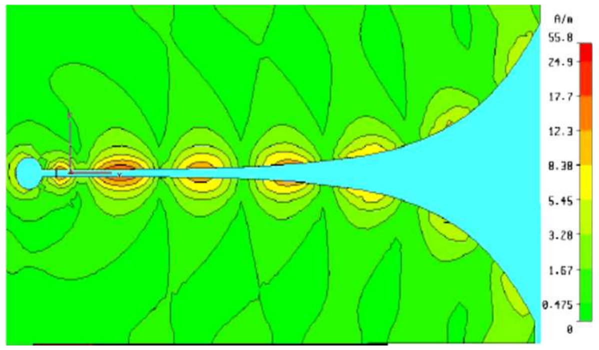


(a) Curves of gain

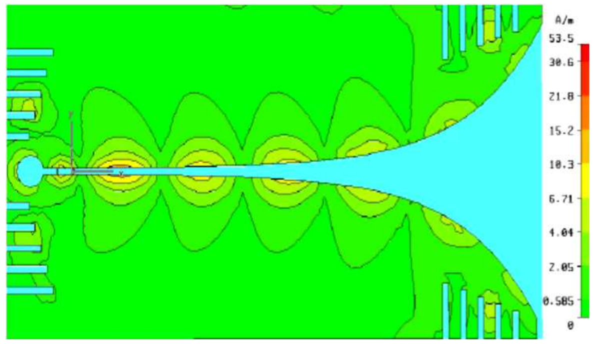


(b) Curves of $|S_{11}|$

Figure 6. Comparison of frequency responses without & with grating.



(a) Without side/back slots



(b) With side/back slots

Figure 7. Current distribution on TSA.

Usually, the cost to enhance the peak gain must be obviously extending electrically length and width of the antenna. Whereas the LTSA with the same sizes and loaded by directive grating improves the performances as: 11.7 dBi peak gain with 3.7 dB enhancement at 8.5 GHz; thus 42% (6 $\sim$ 9.2 GHz) practical bandwidth for both $VSWR \leq 2:1$ (for f_{max}) and $G_{drop} \leq$ 3dB (for f_{min}) as shown in Figure 6.

2.2 Side-lobe Suppression

In order to suppress the side/back-lobes produced mainly by edge currents, to etch slots acting as chokes on the side-/back-edges (Figure 7) is effective, while SLL can be reduced about 2 $\sim$ 4 dB.

In addition, a metal back-plate with appropriate sizes perpendicularly assemble to the TSA sheet can also effectively suppress the back-lobe-level.

3 TSA with UWB Feeding Sructure

Though the traveling-wave mechanism provides wide-band properties for both radiation pattern and impedance matching, and the frequency coverage of TSA with enough electrical-length can approach to 6 : 1 [4]; however, the microstrip-line stub (open-circuit) and the slot-line stub (short-circuit) in feeding structure always result in bandwidth limitation of entire TSA. In order to adequately dredge up the ultra-wide-band (UWB) feature of TSA, an improved design was developed [5] by employing bilateral TSA (B-TSA) and a coated dielectric back-plate cut with a Π-type slot as shown in Figure 8. Where a pair of upper-half B-TSA connect to the outside part of Π-type slot as a ground plane; another pair of lower-half B-TSA connect to the inside part of Π-type slot as a central strip. Then the combination of these ground plane and central strip on the back-plate just form an unbalanced coplanar waveguide (CPW), which directly feeds to the balanced B-TSA without frequency sensitivity.

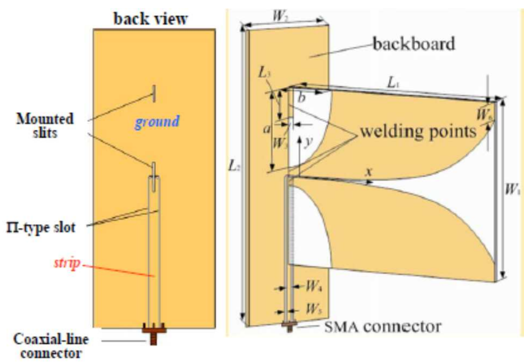
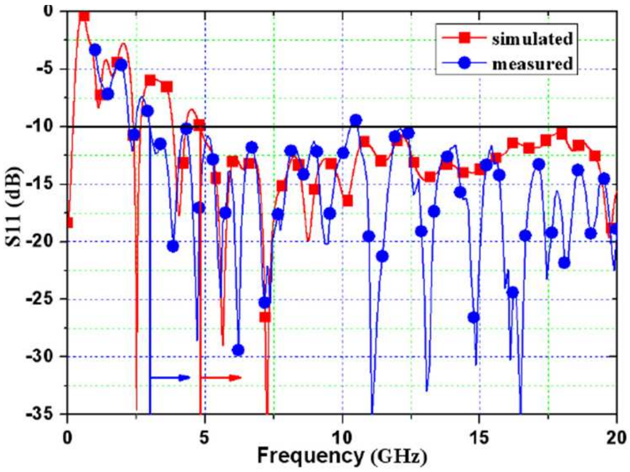
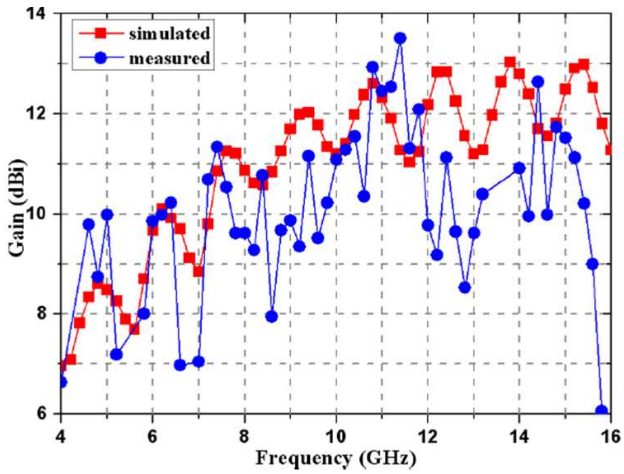


Figure 8. Structural sketch of UWB CPW-fed bilateral TSA.

A prototype with sizes of 93×96 mm for B-TSA and 40×100 mm for back-plate was fabricated, then its simulated results verified by measured data provide both $VSWR \leq 2:1$ and $G \geq 6$ dBi on practical bandwidth of 4 $\sim$ 16 GHz (*i.e.* 4 : 1 frequency coverage) as shown in Figure 9.



(a) Curves of $|S_{11}|$



(b) Curves of gain

Figure 9. Frequency responses of UWB–fed bilateral TSA.

4 Beam-Shaped TSA Used in Base-Station

Normally, a TSA of symmetric structure with respect to its axis radiates symmetric beam; accordingly, an asymmetric TSA (A-TSA) will radiate asymmetric beam too. The latter may be utilized for a base-station of mobile communication service, to achieve a vertical pattern with uniform coverage without null in downward radiation and appropriately reduced upward radiation. While the parameter of directive gain becomes senseless, but a new parameter called as coverage efficiency η_c may be adopted as:

$$\eta_c = \frac{P_{r[downward]}}{P_{r[total]}} \times 100\% \tag{1}$$

where P_r is radiation power. Obviously, η_c must be $\geq$ 50%.

Firstly, a scaled prototype with 70×46 mm of A-TSA and 30×52 mm of back-plate was designed and fabricated [6] as shown in Figure 10. It performs: frequency coverage 3 : 1 (5.56 $\sim$ 16.8 GHz) for $VSWR \leq 2 : 1$; bandwidth 12% (9.5 $\sim$ 10.7 GHz) for $G \geq 11.2$ dBi with 4° tilt-down beam; $\eta_c \geq 60\%$; and $HPBW$ (half-power-beam-width) $\approx$ 65% in horizontal plane. It satisfies most specification of base-station antenna, except the

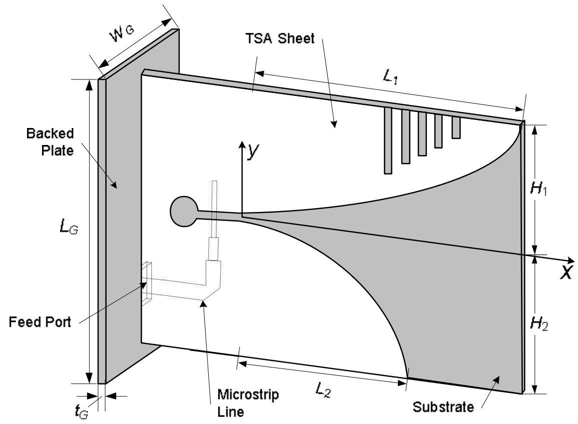


Figure 10. Asymmetric TSA for base-station .

gain is not high enough due to the uniform coverage service. The main advantages of this A-TSA is only one element with single feed point; avoids complicated feed network with many power dividers, transmission bends and connectors, which always result in power loss, bandwidth restriction and potential inter-modulation among signal channels. Figure 11 shows its typical patterns in both vertical and horizontal planes.

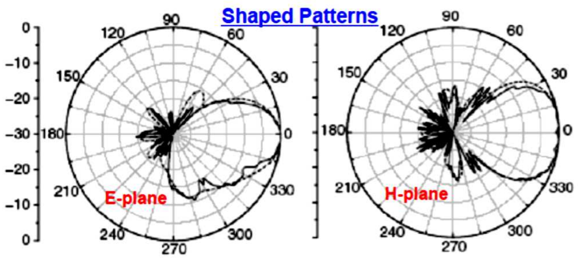
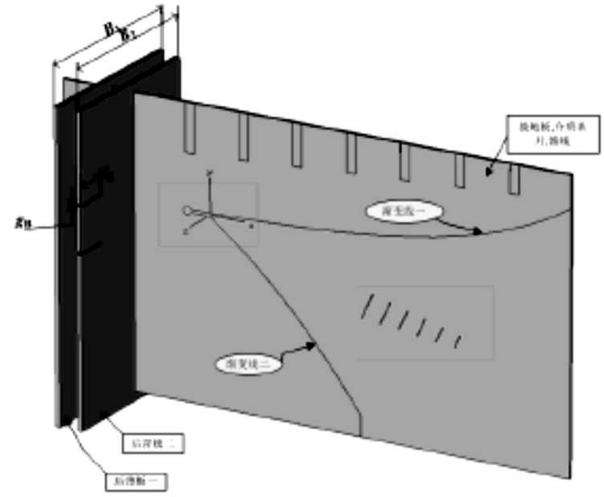


Figure 11. Typical patterns of asymmetric TSA.

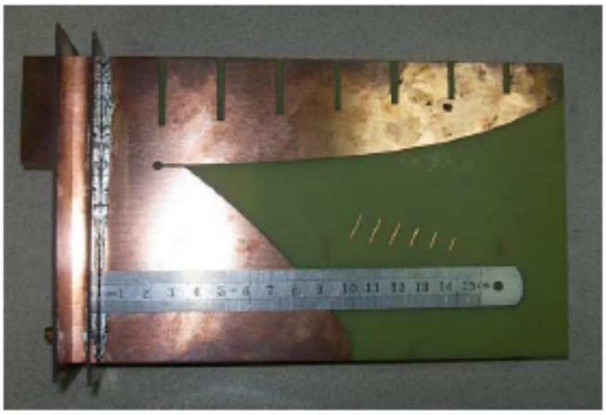
Secondary, a further prototype for dual-band WIMAX application with 210×120 mm of A-TSA and 40×120 mm of double-layer back-plates was designed and fabricated [7] as shown in Figure 12.

In which, a set of tilted metal-strips grating is employed for coordinating the impedance matching and coverage efficiency. For the former, the bandwidth for $VSWR \leq 2 : 1$ is quite wide as (2.0 $\sim$ 6.0GHz) in measurement; but for $VSWR \leq 1.5 : 1$ in simulation covers two separated WIMAX bands as lower (3.3 $\sim$ 3.8) GHz and higher (5.1 $\sim$ 5.8) GHz bands. For the latter, the coverage efficiency $\eta_c \geq 69.5\%$ & 73.2%, and $G = (9.2 \sim 9,7)$ dBi & (8.5 $\sim$ 10.5) dBi, respectively, for lower & higher bands. Besides, the beam have $(8 \sim 12)^\circ$ tilt-down in vertical plane.

In addition, the slots etched along the upper side-edge suppress the upward radiation; and the double-layer back-plates forms a choke at the side of back-plates for suppressing the back-lobe level under -20 dB.

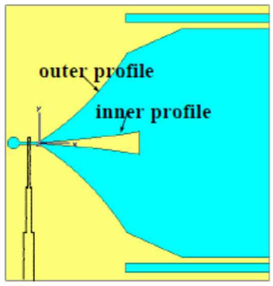


(a) Sketch

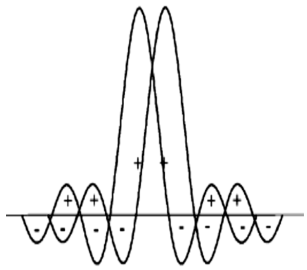


(b) Photo

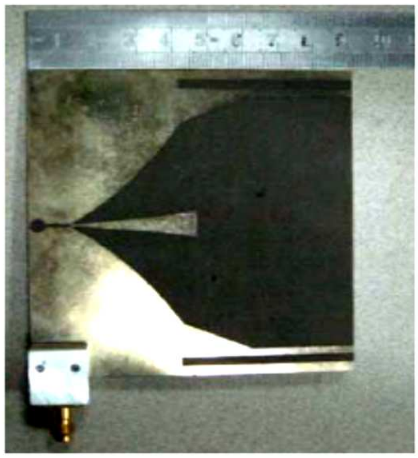
Figure 12. Dual-band Asymmetric TSA for WIMAX.



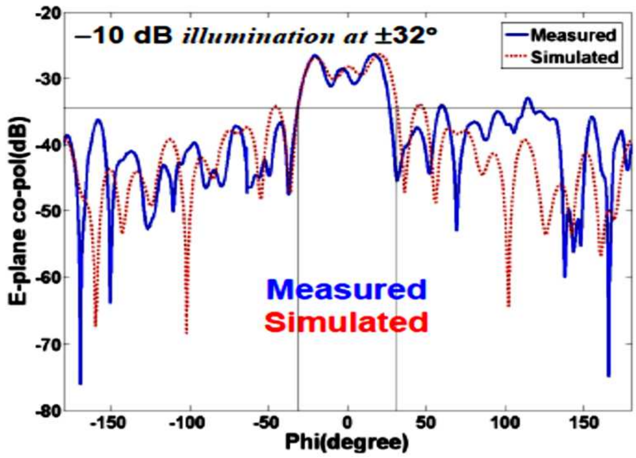
(a) Sketch



(b) Combination scheme of beams



(c) Prototype



(d) 1-D saddle-shaped in E-plane

Figure 13. Beam-shaped TSA as a feed of reflect-array.

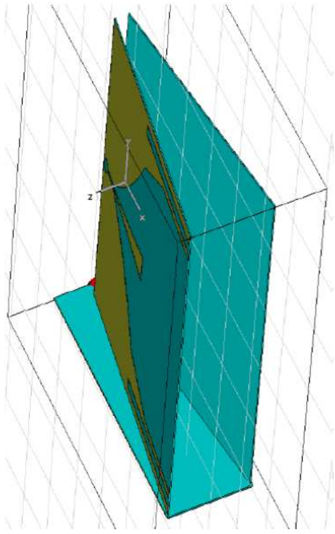
5 Beam-Shaped TSA As A Feed of Air-Fed Array

By means of wideband property, the TSA had been popularly applied alone as a reference in antenna test, or a receptor in electronic counter-measuring; or the element of phased-array. However, it can also be used as a feed of air-fed array antenna, while a saddle-shaped beam is required for achieving uniform amplitude distribution on aperture within the illuminated angle of the feed, and sharply slope-down outside the angle.

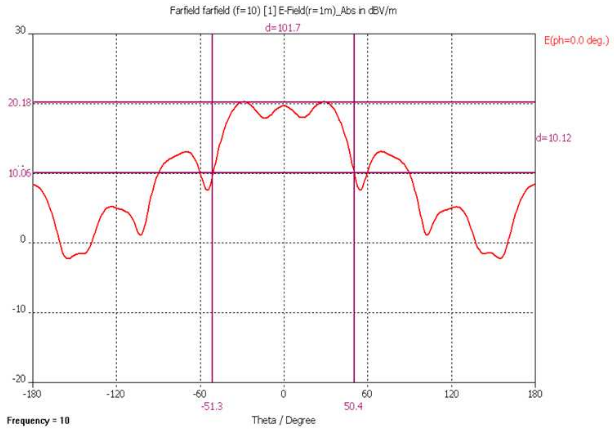
A radiation pattern with symmetric saddle-shaped beam possesses a pair of peaks out-of-the-axis, so to combine a pair of asymmetric TSAs into a symmetric structure is a natural idea as shown in Figure 13a [8]. Their resultant pattern in E-plane is just a 1-D saddle-shaped beam in E-plane. In order to perform sharply slope-down, let the first (negative) side-lobe of one-half just coincide with the (positive) slope-down part of the main-lobe of another-half, as shown in Figure 13b.

A prototype of TSA (Figure 13c) with 1-D saddle-shaped beam (Figure 13d) was designed as a feed of 1-D reflect-array. Comparing with a traditional TSA feed with single peak in pattern, the 1-D aperture efficiency is increased from 70.6% up to 83.7% (corresponding to the antenna efficiency increased from 56.5% up to 66.4%). However, the phase-pattern of beam-shaped feed has about $\pm 28^\circ$ difference, it should be compensated by each element in reflect-array or transmit-array, but becomes unacceptable in a mirror reflector.

In the case of 2-D saddle-shaped beam-forming, two pieces of 1-D feed placed with appropriate out-of-the axis in H-plane had been adopted (Figure 14a). However, the small intersected angle results in strong coupling between them, but larger intersected angle forms a wider saddle in beam (Figure 14b), which can be only used for a elliptical aperture of array.



(a) Sketch

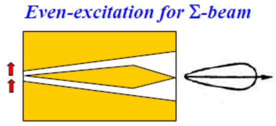


(b) Second 1-D saddle-shaped beam in H-plane

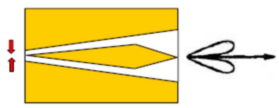
Figure 14. 2-D beam-shaped TSA as a feed of reflect-array.

6 Coupled TSA for Monopulse Beam Forming

Actually, early than developing a TSA with saddle-shaped beam, a similar structural scheme was proposed to compose a slightly broader beam with single-peak in E-plane for making equalization to the beam-width in H-plane [9]. This structure can be considered as coupled TSA (C-TSA) fed by a pair of coupled slot-lines in even-mode excitation as shown in Figure 15a, and then radiates a sum-beam (Σ-beam). Hence, a reasonable deduction was led to odd-mode excitation if the slot-line pair is considered as a CPW as shown in Figure 15b, then to form a difference-beam (Δ-beam).



(a) Co-phased feeding



(b) Counter-phased feeding

Figure 15. Different feeding and patterns of C-TSA.

However, in a monopulse radar system, which transmit Σ-beam and receive both Σ- & Δ-beam should be simultaneously, a printed duplexer as hybrid network is necessary. Successively, a 1-D and a 2-D printed Σ/Δ duplexer [10] for Ka-band was developed.

The performances of 1-D duplexer (Figure 16): both $VSWR \leq 2:1$ and isolation between Σ- & Δ- ports ≥ 35 dB within $(34.5 \sim 40.0)$ GHz have been simulated and then verified by test.

The performances of 2-D duplexer (Figure 17): the $VSWR \leq 1.5:1$ in simulation but $\leq 2.5:1$ (at Δ_E-port) & $3.5:1$ (Δ_H-ports) within $(33 \sim 40)$ GHz in test; the isolation for $[\Sigma - \Delta_E] \geq 40$ dB and $[\Sigma - \Delta_H] \geq 27$ dB within $(28 \sim 40)$ GHz for both simulation and test.

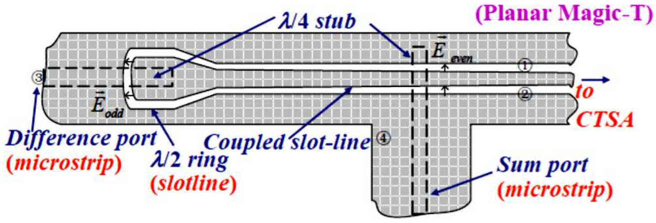


Figure 16. 1-D printed Σ/Δ duplexer for feeding C-TSA.

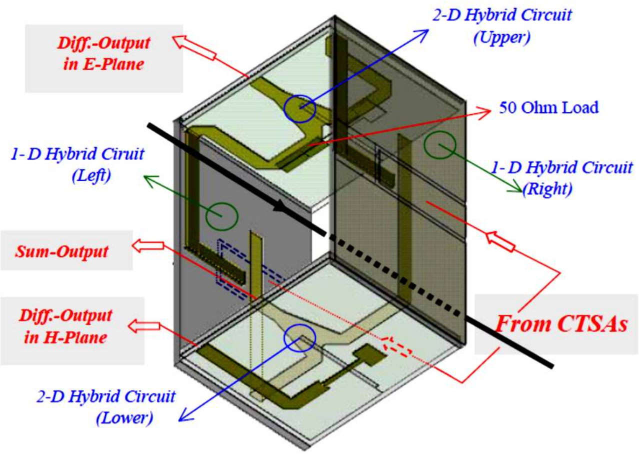


Figure 17. 2-D printed Σ/Δ_E & Δ_H duplexer for feeding C-TSA pair.

In view of the contradiction between gain of Σ-beam and null-depth of Δ-beam needs to be coordinated, that means the configuration of C-TSA should be designed by optimization with multiple-objectives (gain and $VSWR$ for Σ-state, null-depth and $VSWR$ for Δ-state). Thus, the method of moments was adopted in analysis program [11, 12] and the genetic algorithm was employed for optimization [13, 14]. An optimized C-TSA combined with a 1-D duplexer for $(35 \sim 40)$ GHz is described in Figure 18, its typical patterns at central frequency 37.5 GHz are shown in Figure 19 too.

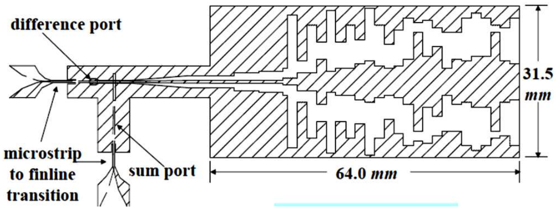


Figure 18. Optimized C-TSA for Σ-/Δ- beams coordination.

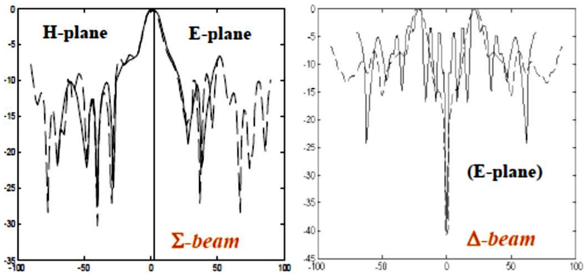


Figure 19. Σ-/Δ- beams of optimized C-TSA
[solid: tested / dot: simulated].

7 Conclusion

This article briefly reports several varietal tapered slot-line antennas with individual features and applications, where the initial idea, structural scheme, simulated and measured results are explained for each one. More detailed information may be found from relative references.

Acknowledgement

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