

## All-Metal Slot Antennas for PAF Feeds: Post-print

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### Abstract

Theoretical analysis, simulation, and optimization design were conducted on a linear slot antenna, and an experimental prototype unit was fabricated. Beginning with the analysis of the antenna feeding section, a coaxial probe feeding method was employed, wherein the inner conductor utilized multiple matching rings to improve the operating bandwidth. Compared with conventional linear slot antennas, a cavity-slot structure was incorporated into the antenna main body, enabling the antenna prototype to achieve a three-octave bandwidth in the 4–12 GHz frequency band. The simulated and measured E- and H-plane radiation patterns exhibit good consistency. The maximum gain across the entire band falls within the range of 4–8 dBi, satisfying the design requirements for wideband array antennas and offering a viable option for feed applications in the Square Kilometre Array radio telescope.

### Full Text

#### Application of All-Metal Slot Antennas in Phased Array Feed Systems

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## Abstract

This paper presents the theoretical analysis, simulation, and optimized design of a linearly tapered slot antenna (LTSA), with an experimental prototype unit fabricated for verification. Beginning with analysis of the feed structure, a coaxial probe feeding method is employed, with multiple matching rings implemented on the inner conductor to improve the operating bandwidth. Compared with conventional linear slot antennas, the proposed design incorporates a cavity-slot structure in the antenna body, achieving a three-octave bandwidth across the 4–12 GHz frequency band. Simulation and measurement results show good agreement for both E-plane and H-plane radiation patterns, with maximum gain ranging between 4–8 dBi across the full band. These results meet the design requirements for broadband array antennas and provide a viable candidate for feed applications in the Square Kilometre Array (SKA) radio telescope.

**Keywords:** linearly tapered slot antenna; feed; broadband; array

## 1 Introduction

Radio astronomical observations of galaxy evolution and complex interactions impose increasingly stringent requirements on telescope field of view and survey speed. Phased array feed (PAF) represents a revolutionary radio astronomy technology that can provide substantially larger fields of view while significantly improving survey speed. Functioning like a radio camera, PAF forms multiple instantaneous beams on the sky through weighted combination of element responses, creating numerous degrees of freedom for controlling beam patterns and sidelobes, optimizing aperture efficiency, and performing radio frequency interference (RFI) mitigation [1]. However, this complexity introduces considerable technical challenges compared to traditional horn feed systems, including array antenna bandwidth, scanning range, inter-element coupling, as well as difficulties in low-noise amplifier design, signal transmission, digital signal processing, and system calibration.

Due to its advanced scientific capabilities and high technical feasibility, PAF is a key technology under development in the SKA Advanced Instrumentation Programme. The Australian Square Kilometre Array Pathfinder (ASKAP) successfully developed an innovative “phased array feed” receiver with a wide field of view, marking the first application of this technology to radio astronomy observations. This paper introduces several PAF systems currently under development for existing and future telescopes, and proposes a novel array element design based on analysis of current PAF technologies.

The Netherlands’ APERTIF (APERTure Tile In Focus) [2] operates at 1–1.75 GHz, employing 121 Vivaldi elements with 56 actively fed units. In 2011, the Australian SKA precursor became the first radio telescope equipped with a phased array feed, featuring a dual-polarized focal plane array with 188 checkerboard patch elements printed on low-loss dielectric material, covering 700–1800 MHz [3]. Since 2015, Dunning et al. [4] have investigated an all-metal Rocket

5\$×\$4 array PAF operating at 0.55–1.8 GHz with 90 mm element spacing and differential feeding at 180  $\Omega$  input impedance. Canada’s National Research Council (NRC), through researcher Lisa, is developing cryogenic phased array feeds [5], designing 140 all-metal Vivaldi elements (96 active, 44 passive) for S/C-band operation at 2.8–5.18 GHz. The U.S. National Radio Astronomy Observatory (NRAO) and Brigham Young University (BYU) collaborated to install a single-polarized 19-element thick dipole PAF on the Green Bank 20 m telescope in 2010, operating at 1.36–1.84 GHz with 50  $\Omega$  input impedance [6]. In 2017, BYU and NRAO developed the dual-polarized 19-element Focal L-band Array for the GBT (FLAG) Phase II for the 100 m Green Bank Telescope, with a center frequency of 1350 MHz, element spacing of 0.68  $\lambda$ , and 150 MHz bandwidth [7]. The UK is conducting PAF research for SKA mid-frequency aperture array antennas, primarily covering 400–1450 MHz using capacitively coupled octagonal ring dipoles with dual polarization, bandwidth enhancement through three-layer dielectric metamaterials, and 117 elements [8].

Most current research focuses on low-frequency narrowband phased array feeds. As part of the SKA pre-construction Advanced Instrumentation Programme (AIP), PAF development aims to effectively expand radio telescope field of view and improve survey efficiency. Investigating broadband PAF feasibility will expand frequency coverage of individual receivers while reducing receiver count and improving observation sensitivity, which is significant for both construction and operational maintenance. This paper focuses on research of broadband, structurally simple tapered slot antenna (TSA) array elements.

## 2 Design and Analysis of All-Metal LTSA Phased Array Feed Elements

Element configuration is crucial in PAF research. This work employs the linearly tapered slot antenna (LTSA), which is currently popular in ultra-wideband single- and dual-polarized antennas for communications, electronic warfare, and radar applications. TSA antennas exhibit excellent electrical performance, easy fabrication, low cost, high power handling, and durability.

First proposed by Lewis et al. in 1974 and later studied by Gibson in 1979 under the name “Vivaldi,” traditional TSA antennas consist of gradually flaring slotlines printed on microwave substrates, typically fed by microstrip or stripline. Three main taper profiles exist: exponential (Vivaldi), linear (LTSA), and constant width (CWSA). Each offers distinct advantages: exponential taper provides the widest bandwidth but lower gain; constant width yields maximum gain but narrower bandwidth; linear taper offers intermediate bandwidth and gain with stable input impedance [9]. As an end-fire traveling-wave antenna, LTSA can be printed on dielectric boards or fabricated as all-metal castings with gradually flaring slots to radiate electromagnetic energy. These antennas feature wide bandwidth, symmetric patterns, and improved matching through mutual coupling in arrays. The all-metal LTSA configuration, using direct SMA (Sub-Miniature-A) connector feeding, offers simpler structure, higher strength,

greater power capacity, and easier modular expansion compared to traditional printed Vivaldi arrays. Consequently, LTSA has found extensive application in phased arrays. This paper investigates an all-metal linearly tapered slot antenna.

Due to their wideband characteristics and simple structure, TSAs have been widely applied in dielectric antennas, such as LTSA antennas for UWB bands [10,11] and improved elliptical symmetric antipodal Vivaldi designs for UWB [12]. While dielectric antennas offer light weight, low cost, and simple fabrication, they suffer from high dielectric loss, complex installation and integration, and low structural strength. All-metal structures overcome these limitations, as demonstrated by Lekshmi and Raglend' s design of an all-metal Vivaldi single-polarized array at 9-9.8 GHz [13] and Kindt and Pickles' research on improved dual-polarized all-metal Vivaldi arrays at 725 MHz-8.7 GHz [14]. As a primary configuration for PAF feeds, this paper presents CST (Computer Simulation Technology) electromagnetic simulation models, design procedures, and prototype fabrication/testing of Vivaldi array elements for the 4-12 GHz band. Prototype testing included VSWR measurement using a vector network analyzer and pattern/gain testing in an anechoic chamber.

## 2.1 LTSA Antenna Design Principles

Yngvesson et al. [15,16] conducted extensive research on LTSA feed arrays, establishing empirical formulas that specify the following requirements for high radiation efficiency (illustrated in [Figure 1: see original paper]):

1. For effective radiation, the tapered slot aperture width  $W_1 > \lambda_c/2$ , where  $\lambda_c$  is the wavelength at the center frequency of 8 GHz in air;
2. The taper opening angle  $2\alpha$  should range between  $5^\circ$  and  $20^\circ$ ;
3. The antenna taper length should be  $2\lambda_c$  to  $10\lambda_c$ ; lengths below  $2\lambda_c$  prevent traveling-wave current formation, while lengths exceeding  $10\lambda_c$  provide minimal gain improvement.

These principles guided the LTSA antenna design in this work.

### 2.1.2 LTSA Antenna Model Design

The LTSA antenna main structure was optimized for the following parameters, with the simulation model and parameters shown in [Figure 2: see original paper]. The final optimized parameter values are listed in .

The feed point configuration and coaxial probe inner conductor design are illustrated in [Figure 3: see original paper], featuring two matching rings added to the inner conductor to improve VSWR characteristics across the full band and achieve stable input impedance.

### 2.1.3 LTSA Antenna Simulation Analysis

CST software optimization yielded a taper length  $L_1$  of 79 mm, satisfying VSWR  $< 2$  across the full band. With a simulation step of 5 mm, longer  $L_1$  (84 mm) increased VSWR at 5 GHz, while shorter  $L_1$  (74 mm) raised VSWR at 4 GHz. The slot length  $L_3$  was optimized to 6 mm, maintaining VSWR  $< 2$  across the band. With a 3 mm simulation step, longer  $L_3$  (9 mm) elevated VSWR across all frequencies above 5 GHz, while shorter  $L_3$  (3 mm) increased VSWR at 4.5 GHz. The slot width  $W_2$  was optimized to 2.5 mm, achieving VSWR  $< 2$  across the band. With a 0.5 mm step, wider  $W_2$  (3 mm) raised VSWR at 4.5 GHz, while narrower  $W_2$  (2 mm) increased VSWR for all frequencies above 5 GHz. Analysis of matching ring effects showed that adding only matching ring 1 reduced VSWR at 4.5 GHz and 7–8 GHz; adding only matching ring 2 improved low-frequency VSWR at 4.5–5.2 GHz; while adding both matching rings 1 and 2 effectively reduced VSWR across the entire band.

In summary, introducing a cavity-slot structure to the linear slot antenna achieved excellent matching and favorable VSWR characteristics. The coaxial probe feed with multiple cascaded matching sections and inner conductor matching rings eliminated VSWR discontinuities, enabled 50  $\Omega$  impedance matching, and thereby realized broadband performance.

## 2.2 LTSA Antenna Unit Prototype and Testing

To verify the theoretical analysis and design methodology, a single-port all-metal aluminum LTSA antenna unit prototype was fabricated ([Figure 5: see original paper]) and tested for VSWR and far-field radiation patterns.

**2.2.1 VSWR Testing** The LTSA feed unit prototype was tested using a vector network analyzer, with results compared to CST simulation data. As shown in [Figure 6: see original paper], measured and simulated VSWR data show good agreement, with values below 2 across the band except at 5 GHz, achieving a three-octave operating bandwidth of 4–12 GHz.

**2.2.2 Pattern and Gain Testing** Far-field pattern testing was conducted in an anechoic chamber. [Figure 7: see original paper] and [Figure 8: see original paper] demonstrate that measured and simulated E-plane and H-plane co-polarized patterns agree well at most frequencies, with 10 dB beamwidth maintained at approximately 36° across most of the band and maximum gain ranging between 4–8 dBi across the full frequency range.

## 3 Conclusion

This paper has presented the design and analysis of an all-metal linearly tapered slot antenna phased array feed element, with prototype fabrication and testing. Simulation and measurement results show good agreement for E-plane and H-plane co-polarized patterns, with 10 dB beamwidth of approximately 36°

across most frequencies and maximum gain of 4–8 dBi across the band, achieving a three-octave bandwidth of 4–12 GHz. Compared to conventional LTSA antennas, the proposed design incorporates a cavity-slot structure for improved matching and VSWR characteristics. Additionally, the coaxial probe feed with inner conductor matching rings eliminates VSWR discontinuities and achieves 50  $\Omega$  impedance matching, thereby realizing broadband performance. As shown in , comparing recent radio astronomy phased array feed element performance, this novel all-metal LTSA design with cavity-slot structure and inner conductor matching rings meets broadband design requirements and is ready for array development, offering a promising candidate for high-performance SKA radio telescope feeds.

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