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Radio Astronomy L-Band Phased Array Feed RFoF Implementation Overview

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***Abstract*—The Australian Square Kilometre Pathfinder ASKAP Design Enhancement (ADE) is the second generation architecture based on a distributed antenna system (DAS) with radio over fiber transmission (RFoF) from planar phased array feed (PAF) to the central site digital signal processing (DSP). With 36 x 12m reflector antennas and 188 elements per PAF, there are 6840 ports with signal and conversion (SAC) paths. Low cost implementation is key for phased array systems comprising thousands of elements. The implementation and component choices are critical to provide a viable project delivery; balancing component availability, RF performance, power consumption, maintenance and whole of life aspects. In this paper we mention discrete components used, basic subassembly performance and fiducial end to end compliance measurements.**

***Keywords*— ASKAP, ADE, PAF, RFoF, DAS, SAC**

I. Introduction

The ADE [2] is a contemporary software radio architecture [3] using long RFoF spans, standard singlemode fiber and semiconductor laser diodes (SLD) at 1310nm to form a geographically dispersed DAS. PAF elements receive a nominal -85.6dBm wideband signal on a balanced feedline and 56.7dB low noise amplification provides -32.3dBm/500MHz at the ADC input (TI ADC12D1600). Given losses of passive components, filters, RFoF and other parts in the signal cascade, a total 115dB of gain blocks are required, stable with time and temperature. High gain and high signal chain power levels (~1uW), in the context of weak radio-astrononomy signals, requires special attention to shielding and EMC conformance [7] to minimize self interference effects.

The PAF feedlines penetrate a rigid Aluminium/Nomex composite groundplane structure to interface directly into a dual channel RF module called the " the Domino". There are 94 Dominos on the groundplane for the 188 elements. The conditioned RF signal exits the Domino as directly modulated RFoF on singlemode fiber via an optical duplex LC/APC (LCA) connector. The PAF outer case is a conductive carbon fiber design with a shielding effectiveness (SE) of better than 20dB at L-band [7]. At the case exit bulkheads, 188 ports are distributed across 16 x MTP-12way connectors for connection to a 216 core underground ribbon fiber cable with direct connectivity back to the central site DSP building, optical receiver modules and then ADC inputs.

A low emissions radio quiet Serial Peripheral Interface (SPI) based 10Kbps communications interface unit (the PAF controller) is a DC coupled six fiber MISO, MOSI, SS, SCLK, Φswitch, Laser Safety Shutdown, interface to the central site. The SCLK is only active for transactions, in quiescent "observational" mode all clocks including internal FPGA clocks are disabled. The C&M data to/from all Domino's is via four PAF backplane distributor cards using 94 ribbon cables (copper). Domino power of 6VDC 450mA, -6VDC 100mA is also supplied on each ribbon.

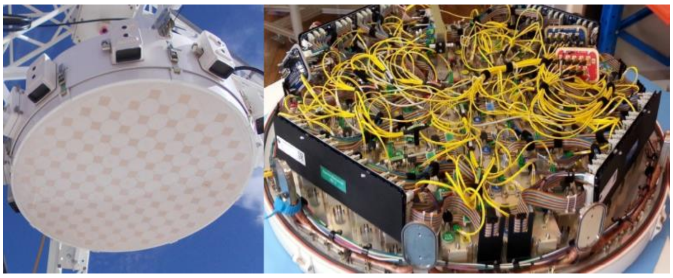

Fig. 1 The 188 Element PAF, mounted and case removed.

Total PAF RF power dissipation is approximately 400W, excluding ambient/solar heat load. Heat pipes form an integral part of the ground plane construction. Heat is removed at eight cold head locations using TEC units. Forced air ventilation of TEC fins external to the PAF case dissipates the heat. Remote control of the TEC DC supply voltage enables precise temperature regulation (+/-1C) over long time constants (1hr) maintaining RF amplitude +/- 0.026dB and phase +/-0.16deg stability (in a 1 minute period) specification [5].

RF power supplies (PS) are external to the PAF assembly on the antenna quadrapod prime focus structure. The PS require multiple star and delta extra low voltage AC (ELVAC) transformer secondary outputs. For EMC compliance schottky 12 diode fullwave rectifier arrays provide low ripple DC to high power MOSFET series pass linear regular designs with outputs 6.5VDC 60A and -6.5VDC 10A. The PAF controller module provides a single bit on/off command and PS voltage monitoring . The PAF controller module requires a separate +6VDC 1.5A supply. The telescope operating system (TOS) stages Domino turn-on commands over a one minute interval minimizing transient PS currents.

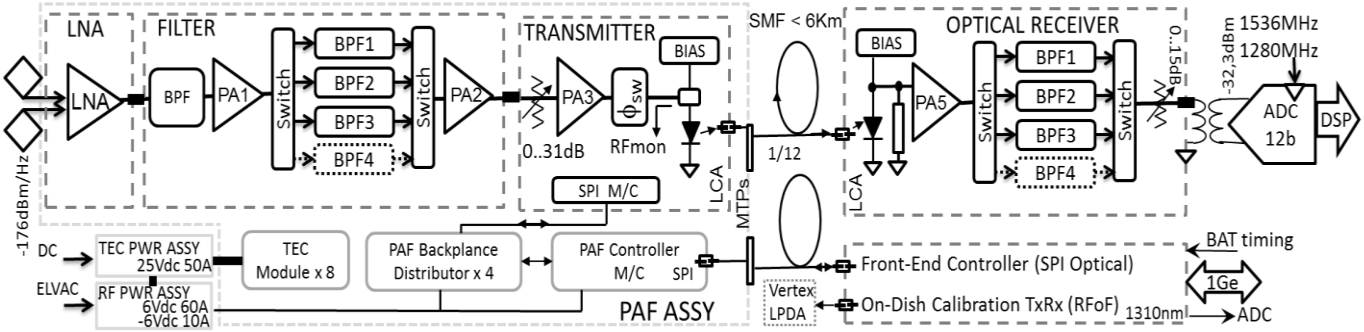

Fig. 2 Overview of a PAF assembly (1 of 36), single PAF RF channel highlighted (1 of 188) with auxiliary subsystems also shown.

II. THE DOMINO RF MODULE

The Domino module is a copper RF IN to Fibre OUT enclosure. The three section RF shielded design, SE > 40dB below 2GHz [7], consists of dual port LNA, Filtercard and Optical Transmitter subassemblies shown in Fig.3. The RF sections stack using MMBX coaxial "bullets". The Domino dual channel LCA output mates to a dual channel Optical receiver module over a maximum 6km span of standard G652B singlemode fiber. The optical loss at 1310nm is 0.35dB/km. Allowing 0.5dB for each series LCA (2off) and MTP (1off) interconnect, the worst case optical loss budget maximum is possibly 3.6dB. We use 3dB as a representative working value [1]. Port to port RF isolation is measured to be better than 40dB.

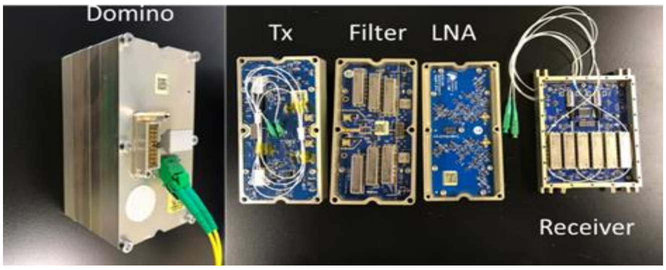

Fig.3 RF module subassemblies (including remote Optical Receiver)

A. LNA Section.

The LNA is a wideband, push-pull, two-stage common source amplifier (Fig. 4) using Avago ATF-35143 pHEMTs I_d=10mA and V_{ds}=2V. The outputs of two symmetric arms are subtracted in a balun transformer to form a differential amplifier of nominal 300Ω input impedance, optimally matched [6] to the checkerboard element feedlines for input noise figure (~ 30K). The LNA has a gain equalization stage and 50Ω single-ended output. The LNA differential gain is 27dB Fig.5. LNA IP1=10dBm. Second order suppression is approximately 20dB.

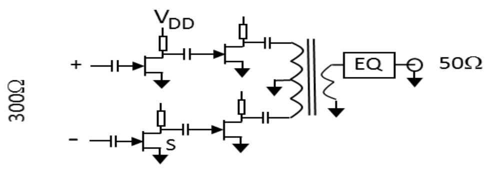

Fig.4 LNA differential amplifier arrangement G=16dB per pHEMT

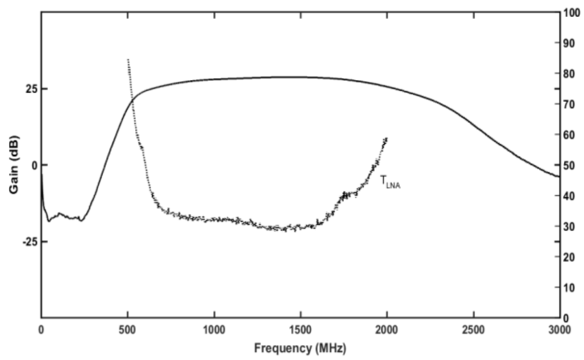

Fig.5 LNA Gain and Noise with Frequency. Input 300 Ω.

B. Filter Section.

This uses MMIC gain blocks PA1 NF=2dB, G=30dB (Mini-circuits Lee-39) and PA2 NF=2.4dB G=15dB (Avago 30889). RFI from 477 MHz UHF and S-band is suppressed by the front-end BPF response in Fig.6. Analog Devices HMC241LP3 GaAS SP4DT switches select desired bands. Insertion loss is less than 0.5dB loss at 2GHz and isolation 43dB.

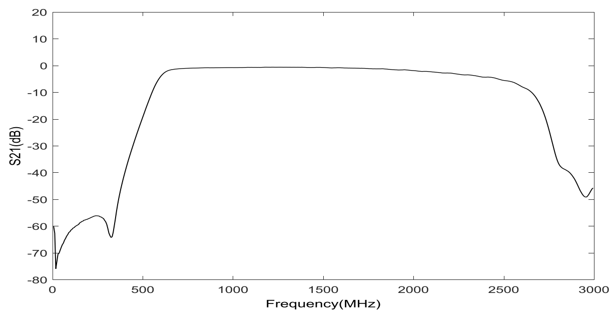

Fig.6 Wideband VNA BPF passband

The filter module provides RF preselection for sub-octave operation in three selectable bands, BPF1 (700-1200)MHz, BPF2 (840-1440)MHz and BPF3 (1400-1800)MHz using lumped element 9 pole Mini-circuits filters. The bands overlap in frequency to achieve the full ASKAP (700-1200)MHz specification. An experimental narrower band (BPF4) centred at 650MHz is included, passband shown in Fig.7. Leadertech

EA-LP012 EMI absorber strip affixed to the module roof suppresses cavity resonances.

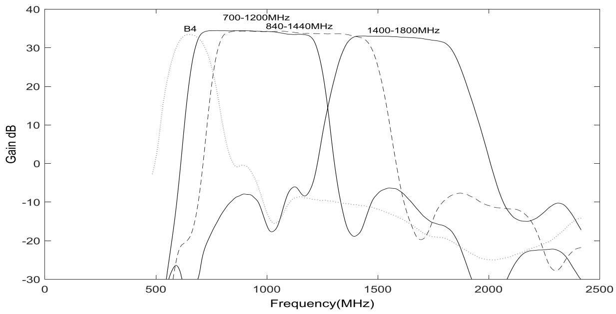

Fig.7 Filtercard VNA Frequency Response

C. *Transmitter Section (Tx).*

The Tx card is a densely populated 4 layer PCB. The module modulates the RF signal onto a linear 1310nm DFB optically isolated laser diode for transmission into a singlemode fiber LC/APC pigtail [4]. The DFB bias control IC-Haus WK-MSOPS uses the DFB back facet monitor diode to control the average optical output power to 4mW (6dBm). The DFB is a grounded anode package and uses -6VDC for the bias control rail. A digital pot MAX5483 sets the bias current set-point (generally 15mA-40mA) dependent on laser threshold and slope efficiency. The RF is amplified in gain block PA3 MGA-31389 G=20dB. RF gain adjustment is provided by step attenuator HMC4701 5bit 0..31dB to compensate for the variations in DFB slope efficiency and the spread of optical loss budgets for the full DAS. The Tx card includes the Domino SPI MCP23S17 controller. The SPI monitor and control clocks only when activated from the front end controller. This provides the Domino turn-on, reads the +/- 6VDC supply currents, sets gain, bias currents, reads modulation power levels, optical power levels, temperatures and serial number ident. An LT5534 log amplifier “taps” the dBm RF level to the DFB bias “Tee” via a 430ohm resistor. Tx card serial number and version is held in CAT25010 128x8b NV memory. The Tx card uses a low dropout regulator LP2989 for +5vdc, supplying PA3 and the filtercard PA1, PA2.

A phase switch for use with decorrelation techniques is included. This balanced design using a PE4140 FET ring as a switching mechanism provides precise RF signal inversion with low transients. Mini-circuits TC1-1-13M transformers are used on the input and output. The switching control from the central site is “DC coupled over fiber” with a 10MHz switching bandwidth (TC~ 33nS), stable to 1nS. The FET ring is driven hard with the switching waveform to ensure a high IP1 is maintained at the input to the DFB matching network (the IIP1 of the DFB can be as high as +10dBm). The phase switch waveforms are typically Walsh functions where crosstalk between antennas becomes problematic at micro Jy sensitivity deep continuum integrations.

The Tx card frequency response Fig.8 is measured with a wideband R=0.85A/W PIN photodiode terminated in 50Ω used as the RF demodulator. The fiber length is 1m and the loss approximately 0dB. Results with 6km fiber length reduces the PIN receive optical power a further 6km x 0.35dB/km = 2.1dB (therefore reducing S_{21} a further 4.2dB).

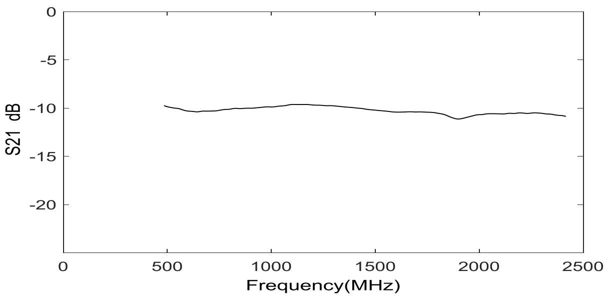

Fig.8 Tx card VNA Frequency Response (Tx atten=5dB)

D. *Domino Performance.*

The complete Domino assembly is measured for gain and IP1 during production acceptance. The balanced LNA feedlines are driven with a single-ended to balanced resistor network for wideband performance, the PIN photodiode in section C is used as the optical Rx. The IIP1 is measured to be -60dBm. The gain of the ADE preselected bands are shown in Fig. 9.

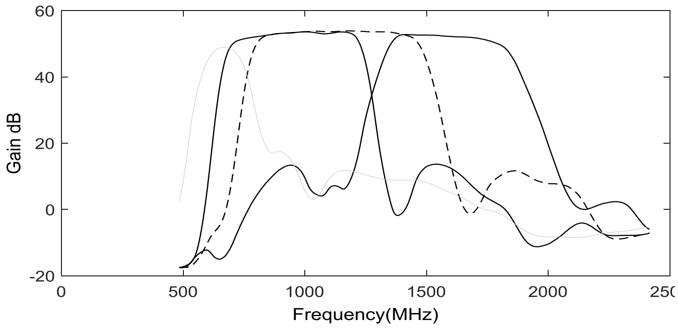

Fig.9 Domino VNA Response (Tx atten=10dB)

III. The Optical Receiver Module (Rx)

The optical Rx demodulates the RF signal Fig.10 from the optical carrier using a high responsivity PIN diode. The Rx is designed for optical power levels in the range -10dBm to +6dBm, (0dBm to +4dBm being a nominal operational range for ADE). The gain block PA5 is a series MGA30889 + 6dB pad + MGA30889 with a flat 24dB gain response. The filters BPF1..4 are identical to those used in the Domino module. Module RF gain control is a HMC540LP3 4bit 0..15dB step attenuator and serves as a ADC input power level “trim” adjustment. The Rx is programmed with a unique serial number ident on factory test into a Microchip 24AA014H 1Kb serial EEPROM. The Rx module requires 3.3Vdc, 12Vdc and 5.5Vdc supply rails. The 12Vdc is regulated to 10Vdc for supplying reverse bias to the photodiode necessary for a wideband frequency response. The 5.5Vdc is regulated to 5Vdc for components in the RF chain. An unregulated, filtered, 3.3Vdc is used for control logic. A LTC2305 I^2C 12bit ADC monitors photodiode current (ie the Rx optical power level) using MAX4638 8:1 switches configured to provide analog tri-state addressing levels. An I^2C 16 bit I/O expander MCP23017, sister chip to the Tx card SPI MCP23S17, controls the RF band selection, attenuator setting and monitor points. The I^2C interface clocks at 25KHz.

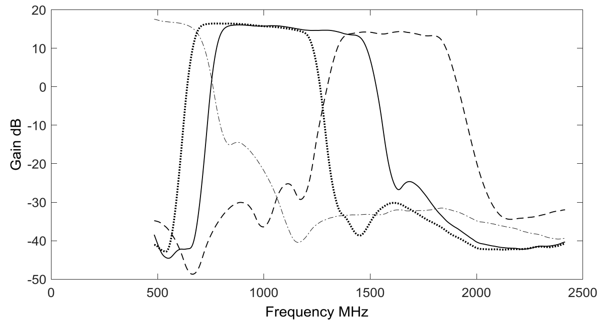

Fig.10 Optical Receiver VNA Response (Rx atten=5dB)

IV. SAC END TO END RESULTS

We measure performance for the full cascade Fig.3 of modules. Using typical gain settings at the Tx and Rx modules, the end to end gain Fig.11 measured by VNA is approximately 56dB. The anti-aliasing specification (better than -40dB at Nyquist frequency points) is satisfied with the cascade of Domino filtercard and optical Rx module passbands, identical bands selected.

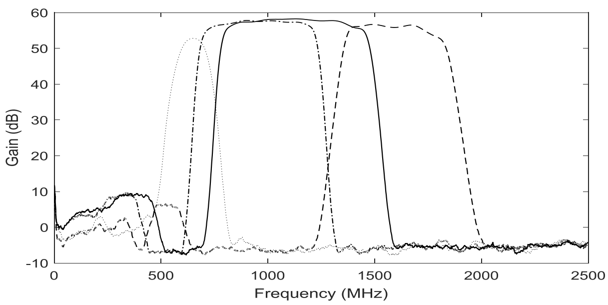

Fig.11 Response 0km span (TX atten =15dB RX atten=5dB)

We imitate the ADC noise floor (NF=27dB) using a spectrum analyser with the input attenuators set for -147dBm/Hz displayed noise level. The LNA is excited by a 300Ω room temperature termination. The passband response at the output of the Rx is shown in Fig.12.

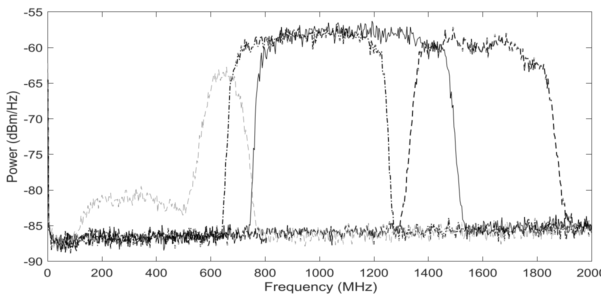

Fig.12 Assessing SNR with practical noise levels.

Rapid changes in delay with time and temperature are mitigated by defining the bandpass by -2dB points. The delay extrema typically confined to +/- 1ns over the bandpass.

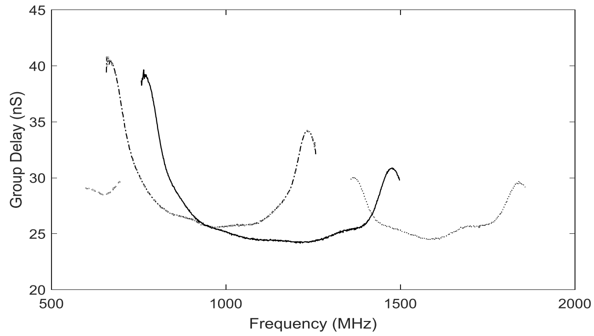

Fig.13 RF chain VNA group delay

V. SUMMARY

The mixed signal design and implementation of a phased array SAC system using RFoF and COTS components has been successfully demonstrated. Finally, we present the ADC output using a Band3 exemplar Fig.14, sample rate 1280MS/s, with 640 x 1MHz coarse digital filterbank (CFB) channels (oversampled 32/27 = 1.18MHz channels) and 2sec integrations. Typical RF gain settings are used. The CFB noise floor is represented by adjacent unused ADC ports. The anticipated SNR and bandpass characteristics compliment analog measurements in the RF domain. All presented results also confidently agree with analysis in Matlab models.

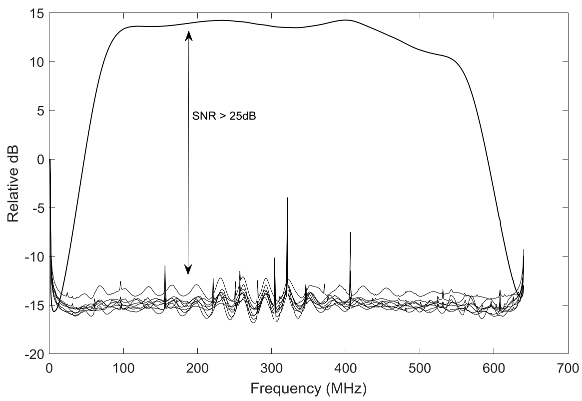

Fig.14 Coarse Digital Filterbank passband

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