32nd URSI GASS, Montreal, 19-26 August 2017

Realization of Phased Arrays for Reflector Observing Systems

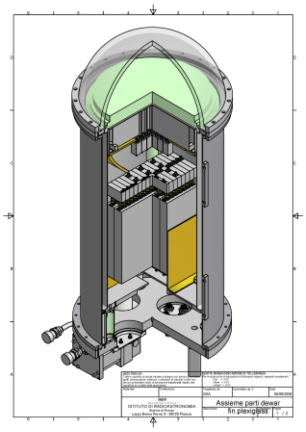
Lei Liu, Keith Grainge
Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy
University of Manchester, Oxford Road, Manchester M13 9PL, UK

Abstract

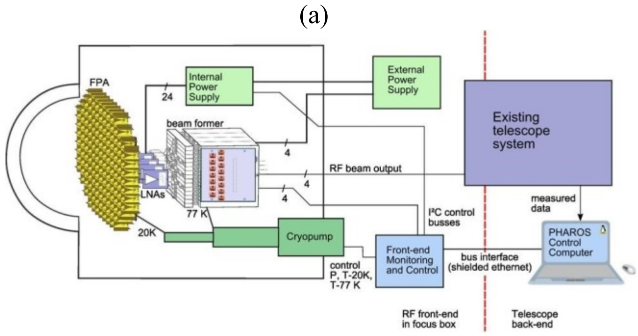
This paper presents a cryogenically cooled, dual polarization, low noise Phased Array Feeds receiver for radio astronomy application, which operated at 4 - 8 GHz. It is designed to be mounted at the focal plane of a dish antenna by producing 4 dense covered, simultaneously operated beams with benefits of increasing Field of View, survey speed, and improving the aperture efficiency of the dish. Development of Vivaldi antenna array, MMIC technology low noise amplifier and analogue beam formers are demonstrated. Receiver noise temperature test is carried out at room temperature and cryogenically cooled condition, which indicates a dramatically improvement from 250 K to 45 K.

1. Introduction

This paper introduces a fully cryogenically cooled Phased Array Feeds (PAFs) system - PHased Arrays for Reflector Observing Systems (PHAROS) developed for the Lovell telescope at Jodrell Bank Observatory. PAFs is a novel technology for astronomical use to operate with multi-simultaneously steered beams, increased field of view (FoV), survey speed, and improved aperture efficiency. The main researches of L band PAFs are carried out by a number of talent groups in the Netherlands, Australia, Canada, USA, and UK [1-5], which are developed for Westerbork Synthesis Radio Telescope, CSIRO Parkes 64-metre radio telescope, Lovell telescope, Green Bank Telescope, etc. and also a possibility for Square Kilometre Array (SKA) and precursor (ATA, ASKAP, and MeerKAT) [2, 4, 6-8]. PHAROS is part of a European technology demonstrate project which collaborates by the University of Manchester (UK), ASTRON (the Netherlands), INAF (Italy), and MECSA (Italy). It realizes the possibility of a cryogenically cooled C band radio telescope front end receiver with the main elements of a Vivaldi antenna array, 24 Low Noise Amplifiers (LNAs) and analogue beam formers developed by MMIC technology, a cryostat, an infrared filter plus a transparent Plexiglas window for shield and cooling purpose (Figure 1). The first stage plan of PHAROS is to form 4, single polarized, simultaneously steered, dense covered beams on sky. To achieve this goal, 24 elements out of 220 are selected from the Vivaldi antenna array by directly connecting with 24 low noise and high gain LNAs. Signal from each element is weighted by a Phase and Amplitude Control (PAC) unit in an analogue beam former [9]. A 16 way Wilkinson combiner is used to combine signal from



(a)



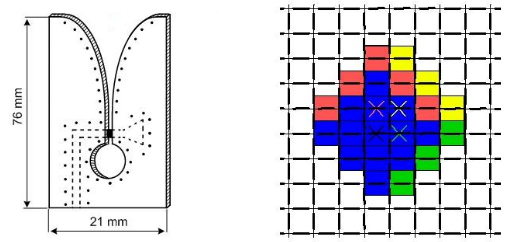
(b)

Figure 1. PHAROS (a) side view, (b) schematic.

13 elements to form one beam. Totally there are 4 beams to be formed with some elements are contributed more than once. The Vivaldi antenna array and LNAs are connected with the first stage of cryostat which is cooled down to around 20 K, while the analogue beam former is connected with the second cooling stage with 77 K. Tests have been carried out at both room and cryogenically cooled temperature to demonstrate the improvement of the system performance and also verified the MMIC technology usage at extreme environment.

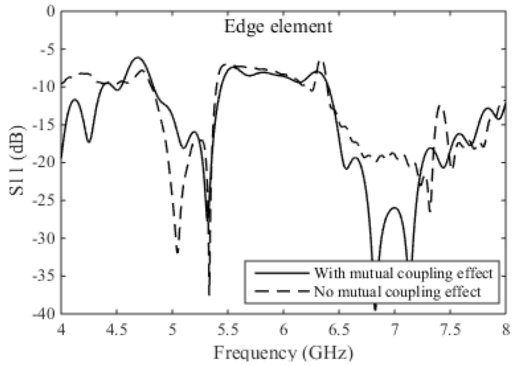
2. Vivaldi Antenna Array

For PAFs application, active researches are carried out on array technology such as dipole array, and Vivaldi array [1-3, 5, 10, 11]. Vivaldi array antenna is a strong candidate for PAFs due to its strong mutual coupling effects, easy to integrate, and consists of sufficiently large number of elements. Continued FoV is required by astronomy community which results in dense beam overlapping on the sky.



(a) (b)

Figure 2. Vivaldi antenna array (a) shape and dimension of a single element, (b) subarray elements selection [9].



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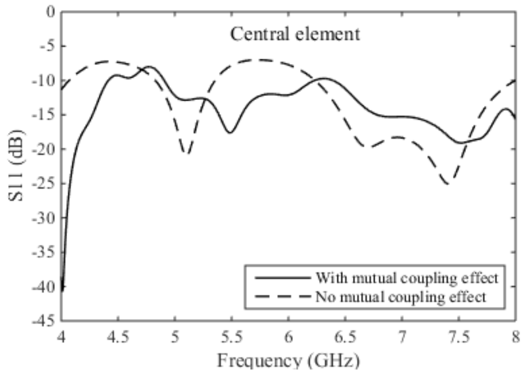


(b)

Figure 3. Comparison of S_{11} with coupling effects (a) edge element, (b) central element.

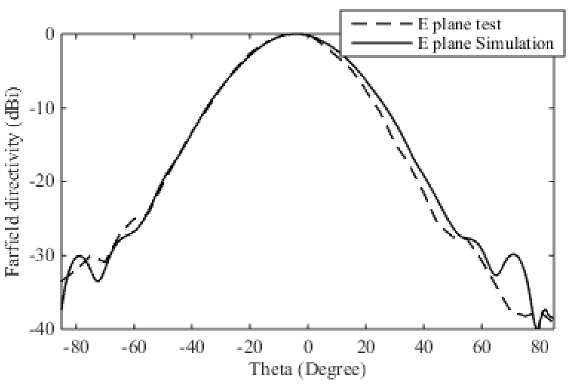


Figure 4. E plane beam pattern.

The one designed for PHAROS (Figure 2) with a pitch dimension of 21*76*2.28 mm, using TLY-5-0450 as substrate and copper printed on two sides. L shape stripline feed is sandwiched at the middle. The whole array includes 220 elements for dual polarization, but for current stage, only single polarization has been used with unused elements terminated with 50 Ohms impedance loads. A finite elements model of this Vivaldi array has been built up and analysed by a commercial electromagnetic simulation tool - CST. Comparison of reflection coefficient S_{11} has been carried out by effects of mutual coupling with same weights applied on all active elements in Figure 3. A centre element and an edge element of have been selected for comparison and simulations indicate the central element is more affected than the edge as the S_{11} of the centre element has more improvement. The less good matching before 5 GHz degrades noise performance of the system. Far field pattern has been simulated and measured (shown in Figure. 4), which indicate good agreement of 3 dB beam width which around 30 degrees.

3. Low Noise Amplifiers Package

First stage LNAs are the main elements which affect the noise performance of front end receiver. Extreme low noise cryogenic LNAs are mainly developed at groups in Sweden, Spain, Canada, USA, and UK. The C band GaAs MMIC LNA (Figure 5.) is developed with three stages amplification and decoupling capacitors on the left mounted on gold plated pads. On the right side of the MMIC is the microstrip band pass filter which is used to get rid of signal not required. On the other side of the board is the bias wires and decoupling capacitors which allow bias voltage of 2 V for drain and around 0.6 V for gate. Results (Figure 6.) indicate a large improvement from 80 - 90 K to 20 - 25 K after cooling a LNA down to 20 K physical temperature.

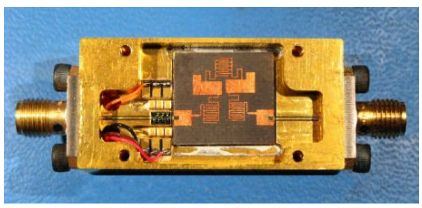


Figure 5. LNA package with MMIC, decoupling and filter.

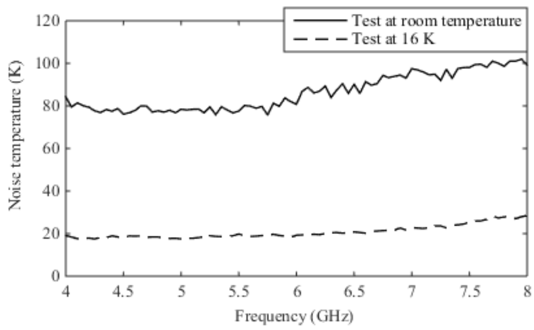
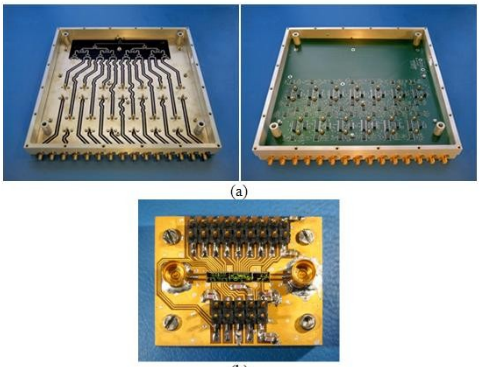


Figure 6. Measurement noise temperature results of PHAROS LNA at 290 K and 16 K.

4. Beam Former and PAC Module

The beam former (Figure 7) is used to combine signal coming from active elements and adjust phase and amplitude of each signal electronically by PAC module. There are totally 24 signals from antenna and LNAs which are split and combined by 4 beam former boxes. For each box, a 16 way Wilkinson combiner is used to combine 13 amplified signal which transferred by stainless steel semi-rigid cables. A PAC board is plug into each signal channel to control phase and amplitude by a sandwiched I2C digital control board, which is responsible for the logic control and bias of the PAC modules. The PAC module requires 9 logic connections (0V to -3.3V), for phase control, and 9 connections for amplitude control. So for total 4 beams there are 936 logic lines which are noisy. I2C serial bus is used to facilitate this which is not continuously clocked and noise only occurred when digital setting changes. Tests have been carried out and approved the beam former works well at around 55 K, also have very low power consumption which allows 8 control wires to reduce complexity of connections. In each PAC module there are 3 key elements embedded which is a buffer amplifier, a phase shifter, and an attenuator in sequence. The buffer amplifier is used to compensate loss from cable, splitter, and the beam former board. The phase shifter is able to produce 360 degree phase shift with 5, 11, 22, 45, 90 and 180 degrees steps. The attenuator is connected with RF output which offers attenuation with step of 0.5, 1, 2, 4, 8 and 16 dB. Measurement of phase shifters and attenuators have been carried out to verify the symmetry of each channel which acquired by the system (Figure 8).



(a)

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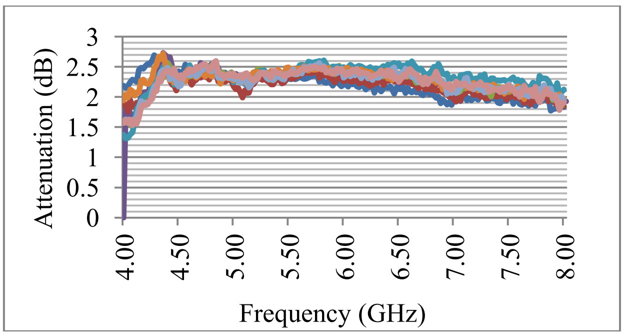
Figure 7. Analogue beam former (a) 16 ways Wilkinson combiner RF tracks and digital control board, (b) PAC module.



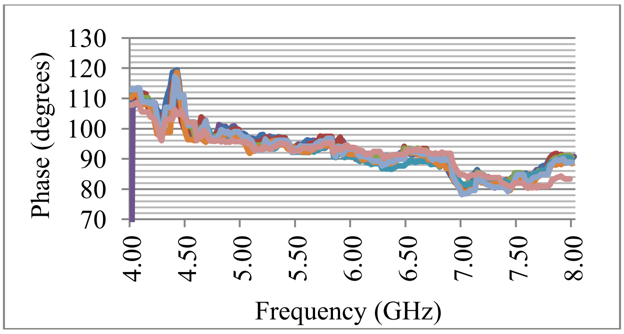


Figure 8. Phase shifters and attenuators test.

(a) (b) (c)

Figure 9. PHAROS cryostat (a) no heat shield and IR filter, (b) with heat shield and IR filter, (c) fully assembly with Plexiglas and outer shield.

5. Cryostat and Assembly

Two cooling stages cryostat (Figure 9) has been developed to cool Vivaldi antenna array, and LNAs to around 20 K and beam former to around 77 K. Multilayer of aluminium and mesh shields are used to isolate with room temperature environment. IR filter is placed on top of Vivaldi array to block heat transfer through transparent Plexiglas window on the top. The outer shield is used for vacuum and cooling purpose, and also blocked interference from outside of cryostat. The bottom plane is designed for connections of signals and bias of electronic devices inside the cryostat.

6. Measurement

Noise temperature measurements (Figure 10) have been carried out for one beam by using hot/cold load method by placing room temperature absorber as hot load and sky as cold load. A ground shield has been made to shield direct and reflected interference from ground and room temperature environment. HP 8970B noise figure meter with 8350B sweep oscillator have been used for calculation. Test results indicate receiver noise temperature has reduced from around 250 K to 45 K. The bad performance before 5 GHz and after 7 GHz is because the matching from Vivaldi array and also the Plexiglas dome window, which has about 20% blockage at low and high end of C band (from dome data sheet).

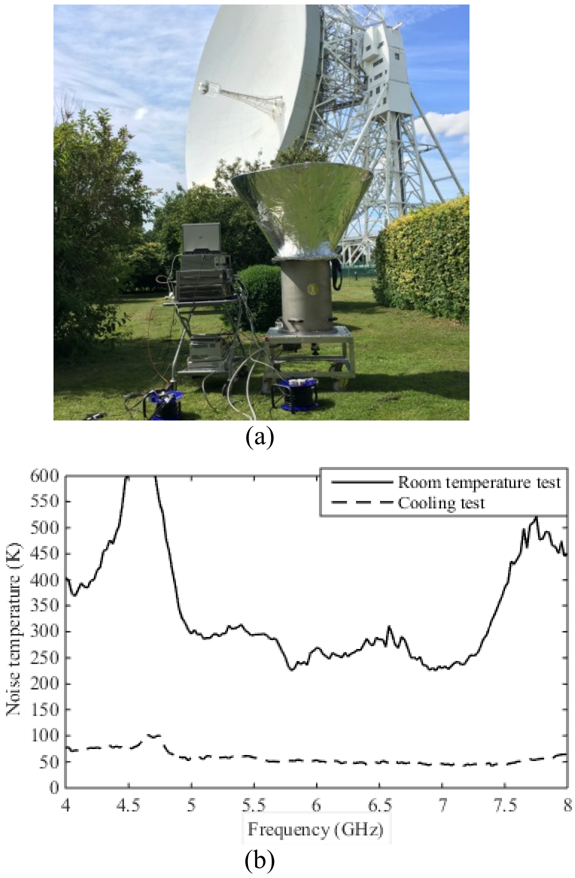


Figure 10. (a) Measurement setup, (b) receiver noise temperature test results.

7. Conclusion and Future Work

A C band cryogenically cooled PAF - PHAROS was introduced and realized. Vivaldi antenna array with mutual coupling was analyzed and simulated by CST shown more affection on centre element. LNAs and analogue beam formers were successfully built and tested. The prototype of PHAROS was finalized and receiver noise temperature was measured, which indicated improvement from 250 K to 45 K. Due to loss from Plexiglas dome and recently development of LNA technology, a future upgrade of PHAROS will focus on replacement of dome windows and lower noise performance amplifiers.

8. Acknowledgements

Thanks for all the help by colleagues from Jodrell Bank Observatory and other colleagues who have helped with PHAROS project.

9. References

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