Instrument Development for PAPER: A Precision Array to Probe the Epoch of Reionization

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***Abstract*— This report describes the instrument development of PAPER for the detection of the faint HI signature of the Epoch of Reionization. The design of the RF components including dipole antenna, active balun, cable transmission system and radio frequency processor is described along with the measurement results. The future experiments are also mentioned in the report.**

***Index Terms*— Antenna array, balun, receiver**

I. Introduction

We are developing a portable, dual polarization dipole array, working in the frequency range of 100-200 MHz, for the detection of the faint Neutral Hydrogen (HI) signature of the Epoch of Reionization (EoR). EoR refers to the period in the history of the universe when the first stars started to form. The ultraviolet radiations from the first stars excited the 21 cm (1420 MHz) hydrogen line above the ambient radiation temperature and caused the ionization of the surrounding HI. Estimates of this process indicate that the redshifted HI signals will likely be in the range of 100-180 MHz with the signal level at approximately 10-20 mK above the foreground.

Our experiment is in collaboration with University of California, Berkeley. We plan to deploy a 32-element array in Green Bank, WV. The next generation instrument will consist of a 128-element array to be located in Western Australia. One of the challenges of this experiment is to distinguish the HI signal from foreground contaminants such as discrete sources and galactic synchrotron radiation which will require excellent instrumentation stability with the sensitivity at mK level. Achieving mK level sensitivity will demand that all instrument components and sub-systems are designed and constructed with the utmost care so that systematic errors can be controlled through either mitigation or modeling techniques. All the devices have been carefully chosen for high dynamic range, low noise, low sensitivity to temperature, low power dissipation and excellent stability. In the laboratory, the network analysis is used to carefully measure gain and delay variations through each component as a function of temperature and humidity. We plan to use linear power supplies, apply proper RFI shielding, employ well matching techniques and adhere good grounding standards. The portable antenna elements provide us with the ready means to explore imaging with major array configuration as well as with simple dithering of locations [1]. Figure 1 shows the block diagram of a single element of the array. The digital correlator is developed by CASPER group of University of California, Berkeley.

The following section describes the technical details of the RF system including dipole antenna and the front end electronics.

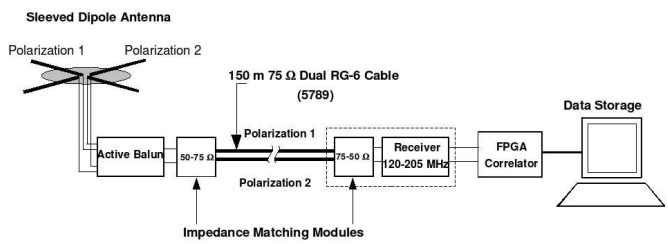

Fig. 1. Block diagram of a single element of the array

II. Technical Details

A. Dipole Antenna System

The dual-polarization antenna design is based on the sleeved dipole concept which provides good performance over approximately 2:1 frequency range. The antenna design was simulated using a 3D EM simulator, CST Microwave Studio. A pair of orthogonal dipoles are positioned midway between a pair of circular metal disks. The ground screen consists of a 6' $\times$ 6' wooden frame with a 0.5 in $\times$ 0.5 in galvanized steel mesh which serves as the reflecting surface. The antenna is supported above the ground screen by a PVC pipe. The active balun is mounted directly to the lower disk of the antenna inside the PVC pipe and is connected to the dipole through a pair of low loss transmission lines.

B. Active Balun

The signals from the two active dipole arms are amplified in a high dynamic range active balun. This balun utilizes a bipolar junction transistor in a common base circuit configuration with a transformer coupled lossless feedback. The lossless feedback common base amplifier was introduced by David E. Norton and Allen Podell in 1975 [2]. Lossless feedback has been proved to be a highly effective method for achieving high dynamic range. Large amount of feedback can be applied without increasing noise figure above that of the transistor used, or without subtracting from the output power delivered by the transistor [4]. This topology was first used in an active balun for use on the Green Bank Solar Radio Burst Spectrometer (GBSRBS-L 10-70 MHz). This balun utilizes a 2N5109 transistor and has been operating since January, 2004 without any failures or degradation. A revision of this balun for higher frequency band (70-300 MHz) utilizes the NEC NE461

transistor [3]. This balun has been proved to have outstanding performance in terms of linearity, high dynamic range and low noise temperature and hence was also chosen for PAPER.

The schematic of the amplifier is shown in Figure 2. The feedback is realized with a three-winding transformer connected to a common base transistor so that it can simultaneously provide gain and impedance matching [5]. This basic circuit configuration provides around 8 dB of gain over the frequency range of 20-350 MHz.

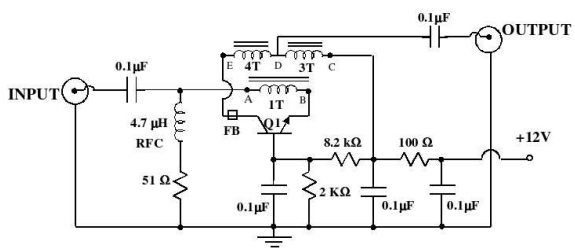

Fig. 2. Schematic diagram of the basic circuit configuration used in the active balun.

The block diagram of the active balun is shown in Figure 3. The first stage of amplification consists of a cascade of two amplifier blocks such that Z-block employs a different turns ratio to provide impedance transformation from antenna impedance to 50 Ω and G-block provides about 8 dB of gain. The push-pull configuration of these circuits helps to reduce the intermodulation distortions and improves the 1 dB compression point by 3 dB. The two 180^0 out of phase signals are combined in a M/A-COM HH-128 180^0 hybrid which is followed by another gain stage. Two complete active baluns, one for each polarization, reside in a cylindrical housing that is 5 cm in diameter and 8 cm in length [3] .

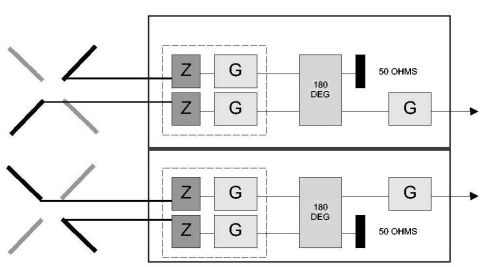

Fig. 3. Block diagram of the active balun showing push-pull first stage, 180^0 hybrid, and second gain stage.

This balun was tested to evaluate its performance. Figure 4 shows the S-parameter measurement results. The gain of the balun is around 16 dB. The results show a good level of input and output match. In addition to this, the isolation between the polarizations is better than 75 dB. The typical noise temperature of the balun is around 120 K.

A single stage prototype of this balun was tested to evaluate the 1 dB compression point and the intermodulation distortions (IMD) using a two-tone measurement. The amplifier reaches its 1 dB compression point at an input power level of +8 dBm. The second order and third order intercepts occur at an input level of +16.8 dBm and +29.3 dBm respectively. The balun

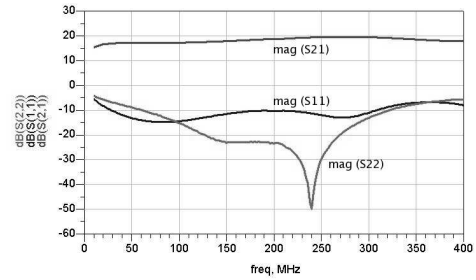

Fig. 4. S-parameter measurement plots of the active balun

was also tested in the environmentally controlled chamber for the temperature range 0-50^0C to determine its gain sensitivity to temperature. The temperature coefficient of gain was found to be around -0.028 dB/^0C. This measurement will be very useful in order to remove the temperature dependent bias in the study of the overall system stability.

Thus, the amplifier configuration as described yields an unconditionally stable active balun with moderate gain, high dynamic range, low noise temperature, low power dissipation, good temperature stability, and low cost.

C. Cable Transmission System

Due to a relatively large number of antenna elements and a considerable path length, the cable transmission system could be a significant cost driver. Therefore, to minimize the cost of the overall system, we are using an inexpensive alternative to conventional (expensive and low loss) 50 Ω coaxial cable: 75 Ω RG-6/U cable. This cable has more loss (6.72 dB/100m) which can be compensated using additional amplification stages. The RG-6/U coaxial cables and corresponding F-type connectors are manufactured by CommScope for CATV and Satellite receiver applications. The dielectric material is polyethylene (PE) foam yielding a nominal capacitance of 53.1 pF/m with $\epsilon_r = 1.48$. The corresponding velocity factor is 82 %. The F-type connectors are environmentally sealed to protect drops from harsh environments and offer superior corrosion resistance and RF integrity [6]. The assembly of the connector to the cable is simple and quick.

Several laboratory measurements were conducted to study the manufacturing quality and ruggedness of such inexpensive cable and F-type connectors. Vector network analyzer measurements are critical for such a study, and proper calibration is essential to such measurements. Therefore, a set of calibration standards for use with 75 Ω system was developed. An EM simulation using CST Microwave Studio followed by a circuit simulation using Agilent's Advanced Design System (ADS) was performed for the same. The standards include an RF OPEN circuit termination, an RF SHORT circuit termination, a 75 Ω resistive load, and a THRU standard. The measurements of the cable and connectors include mechanical stability, connector repeatability, sensitivity to temperature and relative humidity etc. Based on these measurements, the cable and connectors are found to have a good manufacturing quality. The performance of a 10 m cable Vs temperature was also

measured. The change in delay and insertion loss per ^0C for a 10 m cable are -1.32 pS/^0C and 0.0019 dB/^0C respectively.

To maximize the power transfer and minimize the reflection in the line the 75 Ω system must be matched with the 50 Ω system. Hence, 50-75 Ω and 75-50 Ω impedance matching networks, working in the frequency range of 100-200 MHz, were developed. The impedance transformation was achieved with a three section L-C network. In addition to this, a 8 dB gain block (same as used in the active balun) was included in each module for line loss compensation. A dual polarization impedance matching module resides in a 2 inch × 2 inch box.

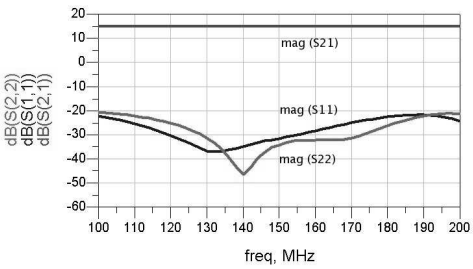

Fig. 5. S-parameter measurement plots of the impedance matching modules together with a 25 cm RG-6 (5789)

The S-parameter measurement results of the impedance matching modules together with a 25 cm RG-6 (5789) are shown in Figure 5. The amplifier stages provide a total gain of 15 dB. The input and output return loss (S_{11} and S_{22}) are $\leq$ 25 dB over the entire frequency band which shows a very good level of impedance matching.

The transmission line for each element is a 150 m dual RG-6 (5789) 75 Ω cable which has a third wire that we are using to bring 12 V power supply to the balun located at the antenna element and returning via common coaxial ground.

D. 120-205 MHz Receiver Design

The coaxial cables terminate on receiver boards located inside the central electronics hut. These boards contain a pair of receivers for dual polarization each consisting of 75-50 Ω impedance transformation module, four amplification stages using Hittite HMC476MP86 MMIC amplifiers, an effective 120-205 MHz bandpass filter, and 3 dB attenuators for inter-stage isolation. The cutoff frequency of the high pass filter was chosen to be 120 MHz so that the RFI in Green Bank, WV below 120 MHz can be avoided. Figure 6 shows the block diagram of the single-polarization receiver. A picture of the dual-polarization receiver is shown in Figure 7.

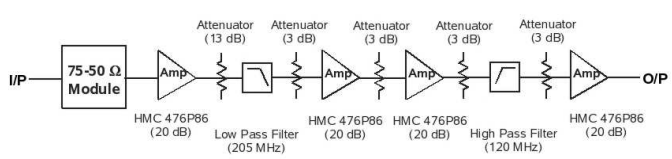

Fig. 6. Block diagram of the single-polarization receiver.

The total gain of the receiver excluding the amplifier gain in the 75-50 Ω circuit is around 53 dB. Figure 8 shows the

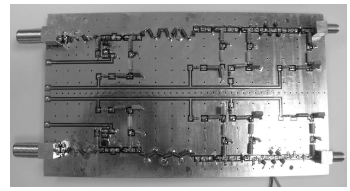

Fig. 7. Photograph of the dual-polarization receiver.

response of the 120-205 MHz receiver together with a 150 m RG-6 (5789) cable and the impedance matching modules. The gain of the amplifier stages in the impedance matching modules (total 15 dB) and the cable loss (∼11 dB) add a gain of ∼4 dB with a slope of -0.034 dB/MHz.

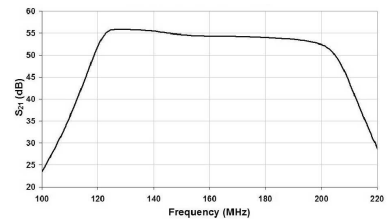

Fig. 8. Response of 120-205 MHz Receiver with a 150 m RG-6 (5789) cable and impedance matching modules.

Also, the temperature stability measurement of the receiver together with the impedance transformation circuits and a 25 cm RG-6 cable shows the gain sensitivity of approximately -0.06 dB/^0C.

III. Current Status

Currently, a 8-element array located at Galford Medow of Green Bank, WV is operational. The array is configured in a circle of 300 m diameter for minimum redundancy. All the electronics such as receivers and the correlator is mounted inside RFI shielding enclosures to reduce the RFI that is generated by the electronics itself. The electronics is located inside the central electronics hut. Secondly, all the components are being modified for better system performance and easier assembly.

IV. Conclusions and Future Work

The first generation of the instrument for PAPER is developed. Currently, we are accumulating the data with a 8-element array in Green Bank, WV.

One of the major future experiments consists of the measurement and evaluation of the system stability and sensitivity. Secondly, the same system is being used for the experiment to determine the power pattern of an antenna in situ through use of signals obtained from low earth orbiting (LEO) satellites. We will also develop a new, network based model of mutual coupling between the antenna elements and have embarked on a series of lab experiments to verify this methodology.

References

[1] *PAPER - Precision Array to Probe the Epoch of Reionization*, NSF Proposal, November 2005.

[2] D. Norton and A. Podell, *Transistor Amplifier with Impedance Matching Transformer*, U.S.Patent 3,891,934, June 1975.
[3] Bradley, R., Parashare, C., White, S. M., and Bastian, T. S., *Instrument Development for the Green Bank Solar Radio Burst Spectrometer (GB/SRBS)*, ASP Conference Series, Vol. 345, 2005.
[4] *High Dynamic Range Amplifiers Using Lossless Feedback*, Anzac Division, Adams-Russell Co.,Inc.
[5] Jack R. Smith, *Modern Communication Circuits*, 2nd ed., McGraw-Hill Book Company, 1998
[6] www.mjsales.net