A 77 – 117 GHZ CRYOGENICALLY COOLED RECEIVER FOR RADIOASTRONOMY

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ABSTRACT

A new receiver system was recently installed in a radioastronomy antenna, situated near Coonabarabran, NSW, as part of the Major National Research Facility (MNRF) funded project to extend the frequency coverage of the Australia Telescope National Facility antennas. The cryogenically cooled receiver and the active and waveguide components required to achieve the very wide, 77 to 117 GHz, frequency coverage will be described. An early observation from this receiver system will be presented.

INTRODUCTION

The Australia Telescope National Facility comprises the 64m-diameter dish at Parkes, NSW, the six 22m-diameter dish antennas of the Australia Telescope Compact Array (ATCA), situated near Narrabri, NSW, and a single 22m-diameter dish antenna situated near Coonabarabran, NSW. Two important factors that limit the maximum frequency at which an antenna can operate are the atmospheric conditions at the site and the surface accuracy of the reflector surfaces. The Australia Telescope 22m-diameter, cassegrain, dish antenna at Mopra, near Coonabarabran, is capable of operating at frequencies in excess of 115 GHz.

Five of the ATCA antennas have been equipped with receiver systems covering two “millimetre-wave” observing bands: 16 to 26 GHz, which is referred to as the 12 mm band, and 85 to 105 GHz, which is referred to as the 3 mm band. The receiver system described in this paper replaces an 86 to 115 GHz Superconductor-Insulator-Supercoductor mixer based receiver system that has operated on the Mopra antenna since 1994. The new cryogenically cooled receiver system covers both the 12 mm band and an extended 3 mm band: 77 to 117 GHz. Provision has been made to accommodate a third receiving band covering 30 to 50 GHz as a future expansion. The three bands will not be available simultaneously, as the relevant feed horn needs to be at the focus of the antenna.

The receiver system architecture is broadly similar to that of the receiver systems installed in the ATCA antennas which have already been extensively described [1-3]. The system block diagram, Fig. 1, illustrates the main sub-systems of the new receiver. The 3 mm signal path is depicted in Fig. 2.

The receiver dewar contains all the cryogenically cooled RF components to obtain dual linear orthogonal polarisation
channels for the 3 mm and 12 mm bands and mechanical mountings for the proposed 7 mm (30 to 50 GHz) band. Careful design is required to minimise signal loss and added noise at the input to the low noise amplifier (LNA) systems.

Critical components in this assembly include the smooth-wall feed horn [4] which fully illuminates the 22 metre telescope surface, the wide band orthomode transducer (OMT), calibration injection couplers and the broadband, monolithic microwave integrated circuit (MMIC) LNAs, isolators and gain equalisers. To achieve the lowest possible receiver noise temperature, the RF input components are cooled to 15 Kelvin by a closed cycle helium refrigerator system.

After amplification, separate mixer and local oscillator (LO) systems down convert the signal from each polarization to an 8 GHz wide intermediate frequency (IF) band, 4 to 12 GHz. The IF signals are further down-converted in the existing, antenna-based, electronics [5].

The broad frequency coverage of the extended 3 mm band necessitated the design of new directional couplers for the injection of a noise step for calibration, wider band low-noise amplifiers and waveguide gain equalisers. These will be described in this paper. Extensive changes were also required to the local oscillator and frequency down-conversion systems which are described in a companion paper [6].

**3 MM BAND ORTHO-MODE TRANSDUCER**

Due to the insufficient bandwidth of commercially available cryogenic temperature orthomode transducers (OMTs) in the 3 mm band (77 to 117 GHz) a new design was developed. This OMT was based on the OMT designed for the 16 to 26 GHz band [7] and is similar to that of Bofiot [8]. The OMT consists of a square to double ridged guide transition followed by a junction of two side arms with the central guide. Figure 3 shows the OMT waveguide design. The A polarisation goes through a further stepped transition and a bend allowing it to exit through the top of the OMT. The B polarisation, which is split equally in the two side ports, is transformed through another stepped transition and recombined at the rear of the OMT.

By maintaining symmetry in both polarisations the excitation of many higher order modes, including TE_{11} and TM_{01}, is eliminated. This greatly improves the polarisation isolation and bandwidth of the OMT. To achieve symmetry in both polarisations at least one polarisation must be split into two side branches and recombined.

The use of double ridged waveguide provides many advantages over square waveguide. The electric field of the A polarisation becomes concentrated in the centre of the waveguide so the disruption caused by the side ports is reduced. This eliminates the necessity of posts or irises in the side ports. The waveguide impedance is also reduced in ridged guide making the transition from ridged to rectangular waveguide much less abrupt than the transition from square to rectangular waveguide. This allows a direct transition from the ridged to rectangular waveguide. The reduced cut off frequency of the ridged waveguide also allows the width of the waveguide to be reduced. Consequently the side ports may have a lower impedance. This has a two fold advantage in that the impedance of the side ports does not have to be transformed at a later stage and the narrowing of the side ports further reduces the disruption to the A polarisation.

Each stage of the design was done by first creating a simplified model in Matlab [9]. Guide impedances and cut off frequencies in this model were calculated using a finite element approximation and discontinuities were ignored. Once an approximate model had been created, Ansoft Optometrics [10] was used in conjunction with Ansoft HFSS[10] to optimise the model.

The design was implemented in a split block using a central insert. Figure 4 shows a photograph of the fabricated device. The overall dimension of the OMT is 20 × 20 × 24 mm. The mating faces of the split block sections were relieved to ensure good contact at the waveguide wall. The loss was minimised by making the split in the centre of the...
waveguide broad wall wherever possible. This minimises the current that flows through the split, which is a major cause of loss in many split block designs.

Figure 5 shows the measured and simulated return loss of the OMT. The return loss was measured with a sliding load on the square port. At each frequency the return loss was derived from measurements made at five positions of the sliding load. The OMT exhibits a return loss better than 20 dB from 71 to 118 GHz. Figure 6 shows the insertion loss of the OMT which was measured by mating the square ports of two OMTs and measuring the insertion loss of the pair. The OMT has an insertion loss at room temperature of less than 0.16 dB for both polarisations. Measurements of the port to port isolation with the square port terminated showed the isolation to be better than 45 dB. All measurements were made using an HP8510C network analyser.

3 MM-BAND NOISE INJECTION COUPLER

The noise injection system required the fabrication of a low loss, high directivity, waveguide coupler to inject noise into the signal path for receiver calibration purposes. A multihole broad wall coupler was found to best fulfil these requirements. The coupler consists of two waveguide sections machined into a central plate. The waveguide sections are separated by 0.1mm forming a thin shim between them. This plate is then clamped between two blocks to close the waveguides. Coupling occurs between two rows of four holes between the waveguides. The coupled port is internally terminated with a ferrite spear.

Fig. 5 Measured and simulated return loss and insertion loss of 3 mm band orthomode transducer.
An image of the coupler is shown in Fig. 7. To reduce the loss in the waveguide a groove was machined in the mating face of the block a quarter wavelength from the waveguide wall. This reduces the unwanted coupling of energy into the mating interface which is a cause of additional loss. When gold plated, the loss of the through path of the coupler was less than 0.2 dB. Coupling in the forward and reverse directions is shown in Fig. 8.

**CRYOGENICALLY COOLED MMIC AMPLIFIERS FOR THE EXTENDED 3 MM BAND: 77 TO 117 GHZ**

Receiver systems are designed to have about 30 dB of cooled gain before the room temperature frequency down-conversion system. At frequencies up to 50 GHz, this gain can be obtained with a 3- or 4-stage Indium Phosphide (InP) MMIC amplifier [11]. The MMIC amplifiers used in this receiver system were designed for an 85 to 115 GHz band. In this band it is difficult to design a 4-stage MMIC amplifier with 30 dB of cooled gain, so the MMIC amplifier chips were designed to have a minimum gain of 15 dB. The receiver was initially designed to have two cryogenically cooled MMIC amplifier chips, with another 15 dB of room temperature gain before the mixer.

The cryogenically cooled MMIC amplifier circuit was designed, packaged and tested at CSIRO. The amplifier circuits were fabricated by the Space Technology division of Northrop Grumman Corporation¹ using their 0.1 micron InP HEMT process [12]. This process includes thin film capacitors (0.3 fF per square micron), thin film resistors (100 ohms/square) and via holes on 75 mm diameter, 75 micron thick, indium phosphide substrates.

The cooled, 3 mm band, MMIC low-noise amplifiers use grounded coplanar waveguide (GCPW) technology as this allows a greater flexibility in layout and a greater range of transmission line impedances than microstrip. The GCPW amplifier was designed for minimum noise and 15 to 17 dB gain in the 85 to 115 GHz band. The circuit uses four, 4-finger High Electron Mobility Transistors (HEMTs), each with a total gate width of 40 microns and is 2.5 × 2.0 mm. Each of the transistors in the MMIC amplifier is individually biased, with the bias voltages supplied to the transistors through on-chip decoupling networks.

The decoupling circuits are critical to the stability of the amplifiers, especially at cryogenic operating temperatures, as the gain of the active devices increases as the operating temperature is decreased. Figure 9 is a photograph of the MMIC amplifier chip and Fig. 10 shows typical S-parameters of the amplifier measured on-wafer. The amplifier has usable gain from 75 GHz to over 115 GHz.

Two different MMIC amplifier assemblies were designed and manufactured: one containing a single MMIC circuit and a dual containing two MMIC circuits. In both the single and dual MMIC amplifier assemblies the MMIC chip is mounted in a cryogenically coolable Silvar package that has waveguide input and output. Silvar [13] is a sintered composite of silver and Invar, the coefficient of thermal expansion of which closely matches that of the InP, the MMIC substrate material. The waveguide probes, used to couple the input and output signals from the waveguide to the

¹ Space Technology division of Northrop Grumman Corporation was formerly known as TRW.
MMIC chip, are fabricated on 0.1 mm thick alumina substrate. The waveguide probes, that have an E-field probe and a microstrip to coplanar waveguide transition, were designed using HFSS [10]. Bias voltages are supplied to the packaged chips through additional, off-chip, decoupling circuits in the package. The gate bias voltage of each transistor is servo controlled by external bias circuitry to maintain a fixed transistor drain current. Thin-sheet flexible microwave absorber [14] was located above the MMIC amplifier chips to reduce feedback within the package.

If the single MMIC amplifier were to be used at the input to the (room temperature) down conversion system, the noise temperature at the input of the down conversion system would be about 15000 K. At 115 GHz the cooled dual MMIC amplifier has less than 30 dB of gain, so the room temperature down conversion system would contribute more than 15K to the receiver system input noise. To minimise this noise contribution, the single MMIC amplifiers were integrated into the dewar as indicated in Fig. 2.

Figure 11 is a photograph of dual MMIC amplifier with two coplanar chips in the one package. The gain of the single chip package at cryogenic temperatures, which is reasonably flat, and the gain of the dual chip package, which shows greater gain variation, are shown in Fig. 12. The third plot in Fig. 12 is an estimate of the total cooled gain of the amplifier chain depicted in Fig. 2, but without the equaliser. The total gain could not be measured directly as the 1 dB compression point of these amplifiers is less than 0 dBm and any reasonable input signal could over-drive the output.

The frequency down conversion system [6] relies on the image rejection inherent in the sideband-separating mixer. Rejection of the image band will be compromised if the gain in the image band is much greater than the gain in the observing band, so flat gain across the whole amplifier band is important. A waveguide equaliser, shown in Fig. 13, was designed using HFSS to correct the gain variation expected when the amplifiers were cascaded. The equaliser was
designed by optimising the attenuation in the stop-band of a band pass-filter. This type of equaliser is highly reflective, so isolators were used at the input and output of the equaliser to provide a well matched load for the amplifiers before and after the equaliser. Figure 14 shows the equalised gain which is about 40 dB. The gain at the low-frequency end of the band is greater than had been expected because the isolator that was cooled and measured to estimate the loss contribution from the three isolators in the cooled amplifier chain was greater than typical.

The components that comprise the two amplifier chains were assembled and tested prior to installation in the receiver system. A commercial smooth-walled feed horn was connected to the input of the dual MMIC amplifier and the amplifier chain and feed horn were cooled to 15 Kelvin. The noise performance of both amplifier chains, including the noise contribution from the feed horn and the down conversion system, is shown in Fig. 15.

INITIAL OBSERVATIONS

The new receiver system was installed and commissioned in September, 2005. The control and monitoring of the receiver, the ease of tuning and the overall performance of the receiver exceeded the expectations of the astronomers.

The spectra shown in Figs. 16 and 17 were obtained at Mopra with the new 77 to 117 GHz receiver system [15]. The correlator was configured to output 4097 channels each with a bandwidth of 33 KHz, which corresponds to a velocity resolution of about 100 m/s in this band. Figure 16 is a spectrum of deuterated water in the Orion nebula at 80.6 GHz and Fig. 17 is a spectrum of carbon monoxide in the Horsehead nebula at 115.3 GHz, obtained after about 2 minutes integration.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the valuable assistance of P. Sykes, E. Hakvoort and D. Gain for their work on the cryogenics system, and assembly of the receiver systems. The authors also wish to...
acknowledge the contribution of G. Cook, M. Huynh and O. Iannello who machined, with precision, the MMIC sub-assembly packages, orthomode transducers, equalisers and many other high precision parts for the receiver system.

REFERENCES


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