MMICs for the Australia Telescope Millimetre-Wave Receiver System

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***Abstract* — Cryogenically cooled receiver systems covering three millimetre-wave observing bands are being designed for the Australia Telescope National Facility Compact Array (ATCA), situated near Narrabri in northern New South Wales, Australia. The ATCA consists of six 22-metre dish antennas capable of operating up to 115 GHz. Millimetre-wave receiver systems covering the frequency ranges 16 to 26 GHz and 85 to 105 GHz have been installed. Future upgrades are planned to extend the upper frequency range to 115 GHz and to include coverage of the 30 to 50 GHz band.**

A range of monolithic microwave integrated circuits (MMICs) has been designed for the new millimetre-wave receiver systems. Indium phosphide MMIC low noise amplifiers in the front end are cryogenically cooled to 15 Kelvin to minimize their noise and maximise the sensitivity of the receiver system. Custom designed indium phosphide and gallium arsenide millimetre-wave MMIC mixers, power amplifiers and doublers are also used in the conversion and local oscillator systems.

I. INTRODUCTION

The Australia Telescope Compact Array (ATCA), situated near Narrabri in northern New South Wales, consists of six 22-metre, cassegrain, dish antennas capable of operating up to 115 GHz. Five of the antennas are moveable on an east-west rail track three kilometres in length, while the sixth dish is fixed at a position three kilometres further west.

Eight new, millimetre wavelength, dual linearly polarised receivers, which will ultimately extend the observing frequency coverage of the telescope to 115 GHz, are being constructed. The maximum frequency at which the telescope can operate is limited by site atmospheric conditions and the surface accuracy of the main reflector.

Receiver systems covering two new observing bands have been designed and are being installed in the ATCA antennas. The observing bands are 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. Provision has been made to extend the 3 mm band to 115 GHz and accommodate a third receiving band covering 30 to 50 GHz as future expansions.

The system block diagram, Fig. 1, illustrates the main sub-systems of the new receivers. Astronomical signals at millimetre wavelengths are first amplified in the cryogenically cooled, low noise amplifier (LNA) system. The broadband LNAs, for both receiver bands, use InP High Electron Mobility Transistor (HEMT) MMICs as the amplifying elements. The LNAs operate at 15 Kelvin

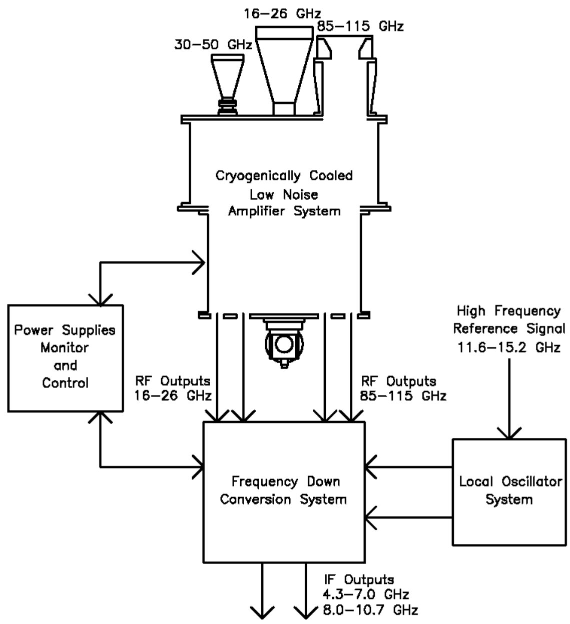

Fig. 1. Block diagram of the millimeter wave receiver system.

in a common vacuum dewar and are cooled by a closed cycle helium refrigerator system. After amplification, separate mixer and local oscillator (LO) systems down convert the signal from each polarization to intermediate frequency (IF) bands. The IF signals are further down-converted in the existing, antenna-based electronics [1].

In the cryogenic LNA system, the various components of the system are integrated with the 15 Kelvin cryo-cooler to form a complete three-band front end. Critical components in this assembly include: the corrugated feed horns which fully illuminate the 22 metre telescope surface, the wide band OMTs and the broadband, MMIC LNAs. Careful design is required to minimise signal loss and added noise at the input to the LNA systems. To achieve this, critical input elements, including the MMIC amplifiers and OMTs for both wavelengths, and the 85 to 115 GHz feed horn, are cooled to 15 Kelvin. The cryogenic LNA system and some of the active and passive components that have been designed for this receiver system have been described in an earlier paper [2].

The LO reference distribution system distributes a high frequency reference signal, tunable over the range 11.6 to 15.2 GHz, to each antenna using optical fibre. This reference signal is used to produce the first LO for the millimetre-wave receivers.

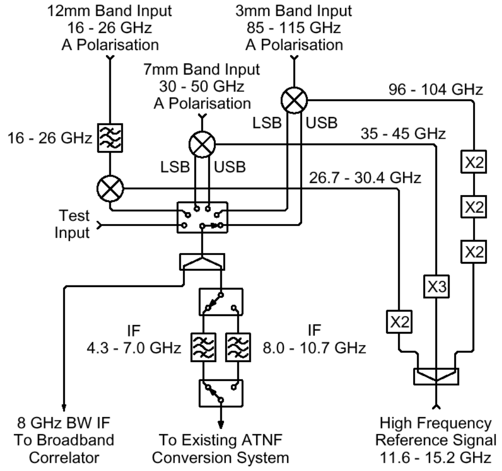

Fig. 2. Simplified bock diagram showing the local oscillator and down-conversion systems.

Fig. 2 shows how the required LO signals are generated from the reference signal and used in the down-conversion system. At the antenna, the frequency of the reference signal is doubled to provide a 26.7 to 30.4 GHz LO for the 12 mm band down-conversion. The doubler sub-assembly uses commercial chips to amplify and double the frequency of the reference tone. A lower-sideband conversion is used to down-convert a 6.4 GHz portion of the RF band to a 4.3 to 10.7 GHz IF band. The IF band is then further down-converted in the existing, antenna-based, electronics, sampled and sent to the central site for correlation.

For the 3 mm band, the frequency of the reference signal is doubled three times. The first doubler, which takes the reference tone in the range 12 to 13 GHz and doubles its frequency, is very similar to the doubler sub-assembly described above. The doubled signal, in the range 24 to 26 GHz, is doubled, amplified, doubled again and amplified again, using CSIRO designed MMIC circuits, to provide an LO in the range 96 to 104 GHz for the sideband separating, resistive-drain mixer. Either the upper or lower sideband output of the mixer, in the range 4.3 to 10.7 GHz, can be selected for further processing, as described above.

II. MMIC COMPONENTS

A number of custom MMIC components, including frequency doublers, mixers, low-noise amplifiers and medium power amplifiers, were designed for this receiver system. Some of the InP HEMT circuits, including the sideband separating, resistive-drain mixer, have been described previously [3]. The MMIC circuits were all designed at CSIRO, fabricated by Northrup Grumman Space Technologies[1] (NGST), and tested at CSIRO.

A. MMIC Doublers

The 50 GHz and 100 GHz MMIC doublers are used to double the frequency of reference tones in the range 24 to 26 GHz and 48 to 52 GHz respectively. The doubler circuits use an active multiplier topology [4] where the input signal is split in a wide bandwidth balun and used to drive two output transistors, with a common drain connection, in antiphase.

The 50 GHz doubler, fabricated using the NGST 0.15 micron GaAs pHEMT process [5], has two, 4-finger HEMTs, each with a total gate width of 200 microns, and is 2.8 mm x 2.7 mm. The 100 GHz doubler, fabricated using the NGST 0.1 micron InP HEMT process [6], uses two, 4-finger HEMTs, each with a total gate width of 40 microns, and is 2.1 mm x 2.25 mm.

Typical performance of the 50 GHz doubler is shown in Fig. 3.

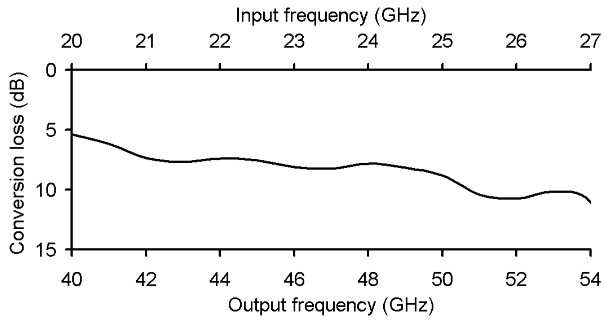

Fig. 3. Typical performance of the 50 GHz doubler with an input power level of +6 dBm.

B. GaAs MMIC Medium Power Amplifiers

The reference tone that drives the 100 GHz doubler is amplified by a 50 GHz MMIC power amplifier and the LO for the resistive-drain mixer amplified by a 100 GHz MMIC power amplifier. Both circuits were fabricated using the NGST 0.15 micron, GaAs pHEMT process [5] and have been described previously [7]-[8].

The 50 GHz power amplifier uses four, 4-finger HEMTs, each with a total gate width of 200 microns, and is 3.0 mm x 2.0 mm. At 50 GHz, the amplifier typically has 1 dB gain compression at an output power of +14 dBm.

The 100 GHz power amplifier uses four, 4-finger HEMTs, each with a total gate width of 50 microns, and is 2.8 mm x 1.6 mm. At 100 GHz, the amplifier has 1 dB gain compression at an output power of +6 dBm. The performance of the typical 50 GHz and 100 GHz MMIC power amplifier chips is shown in Figs. 4 and 5 respectively.

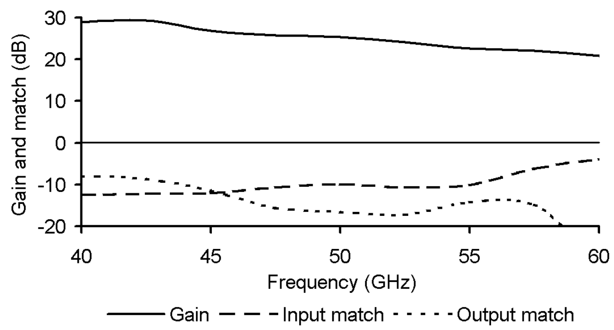

Fig. 4. Typical performance of the 50 GHz MMIC power amplifier chip.

[1] Northrop Grumman Space Technology was formerly known as TRW.

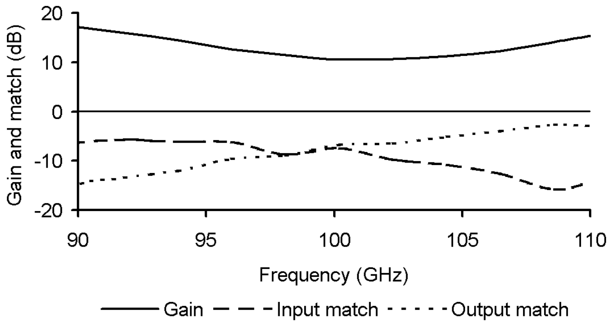

Fig. 5. Typical performance of the 100 GHz MMIC power amplifier chip.

C. InP HEMT MMIC Low-noise Amplifiers

InP HEMT MMIC low-noise amplifiers were designed for each of the receiver bands and fabricated using the advanced, 0.1 micron, InP HEMT process [6]. Each of the transistors in the MMIC amplifiers is individually biased, with the bias voltages supplied to the transistors through on-chip decoupling networks.

The low-noise amplifier circuit for the 12 mm band was designed for minimum noise in the 16 to 25 GHz band with flat, 30 dB gain and input and output return losses better than 15 dB. The circuit uses three HEMTs, each with a total gate width of 120 microns, and is 3.1 mm x 2.25 mm. When measured on-wafer, the circuit has a noise figure of less than 2.7 dB, and gain and input and output return losses close to the design.

The low-noise amplifier circuit for the 3 mm band was designed for minimum noise in the 85 to 115 GHz band with 12 to 14 dB gain up to 110 GHz. Input and output return losses were designed to be better than 10 dB in the frequency range 92 to 115 GHz. The circuit uses four, 4-finger, HEMTs, each with a total gate width of 40 microns, and is 2.1 mm x 2.25 mm. The measured input and output return losses are both poorer than simulated; the gain is higher than simulated, but falls off at the high frequency end of the band. A noise figure of less than 4.5 dB in the frequency range 90 to 98 GHz was measured on-wafer.

The design and performance of the low-noise amplifiers has been described in greater detail previously [9].

III Packaged MMIC Components and Subassemblies

A. Ambient Temperature Components

Fig. 6 is a block diagram of the reference frequency multiplication chain and first conversion for the 3 mm receiver band. It shows the integrated sub-assemblies of doublers, amplifiers and mixers used to multiply the frequency of the reference signal and mix down the signals from the front end.

The first doubler sub-assembly, which uses commercially available MMIC amplifier and doubler chips, is similar to the doubler sub-assembly for the 12 mm band LO, described above. Following the first doubler sub-assembly is a 50 GHz doubler/amplifier sub-assembly comprised of the 50 GHz doubler chip followed by the 50 GHz amplifier chip. The coaxial input to the sub-assembly is

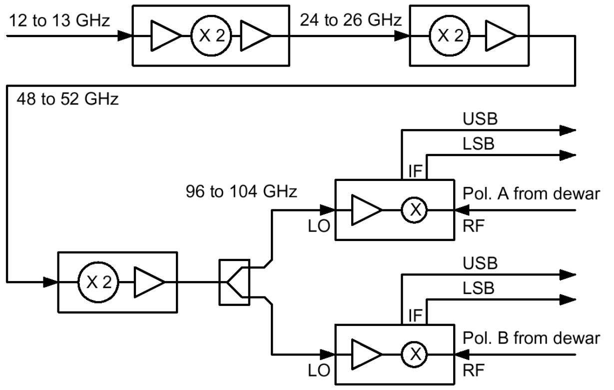

Fig. 6. Block diagram of the reference frequency multiplication chain and first conversion for the 3 mm receiver band.

connected to the doubler chip by a microstrip line on alumina substrate. The doubler chip output is wire-bonded directly to the input of the 50 GHz amplifier chip, and the output of the amplifier chip is wire-bonded to a probe in the WR-19 output waveguide. Bias voltages are supplied to the packaged chips through additional, off-chip, decoupling circuits in the package. Typical performance of a 50 GHz doubler/amplifier sub-assembly is shown in Fig. 7.

The reference frequency is doubled a third time in a subassembly, comprised of the 100 GHz doubler chip followed by the 100 GHz amplifier chip, which has waveguide (WR-19) input and waveguide (WR-10) output.

A ring hybrid waveguide power divider splits the LO signal to drive mixers for each polarization. Due to the relatively low power available from the 100 GHz amplifier chips, another 100 GHz amplifier chip is integrated into the mixer sub-assembly to boost the LO power to the mixer. The input and output of the mixer sub-assembly is in waveguide (WR-10).

The level of integration used in this assembly has kept the overall size of the 3mm band LO/conversion package small, while still allowing ease of maintenance and testing.

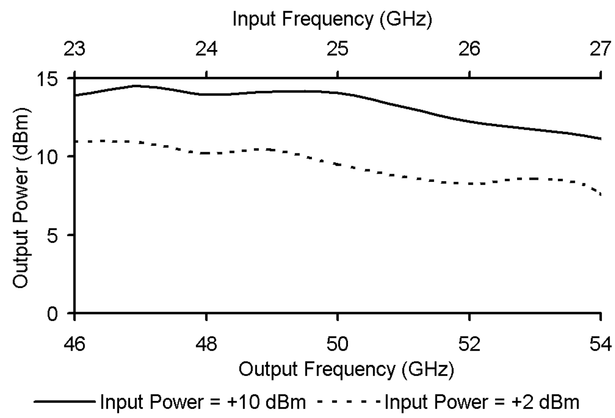

Fig. 7. Typical performance of a 50 GHz doubler/amplifier sub-assembly with an input power level of +2 and +10 dBm.

B. Cryogenically Cooled Components

A gain of about 30 dB is required in the low-noise amplifier system so that the noise contribution from the room-temperature microwave components in the down-conversion system is negligible. For the 12 mm band, a single MMIC amplifier has sufficient gain but, for the 3 mm band, where the four stage MMIC amplifiers have a gain of only 15-17 dB, two packaged MMIC amplifiers, each having an isolator at its input, are used in each polarization.

Bias voltages are supplied to the packaged chips through additional, off-chip, decoupling circuits in the packages. These decoupling circuits, which are in addition to the on-chip 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. The design of the decoupling circuits, which has been described in an earlier paper [10], is important in eliminating the possibility of low-frequency bias circuit oscillations.

The 12mm MMIC chip is mounted in a cryogenically coolable package that has coaxial input and output connectors. The 3mm MMIC chip is mounted in a cryogenically coolable package that has waveguide input and output. Waveguide probes, connected to short lengths of microstrip transmission line on a GaAs substrate, are used to couple the input and output signals from the WR-10 waveguide to the MMIC chip.

The noise temperatures of the cryogenically cooled 12 mm band and 3 mm band low noise amplifier systems, measured by placing hot (300 Kelvin) and cold (77 Kelvin) loads in front of the feeds, are shown in Figs. 8 and 9 respectively.

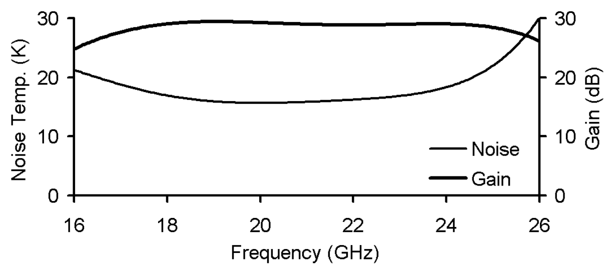

Fig. 8. Performance of the cryogenically cooled, 12 mm band, low noise amplifier system.

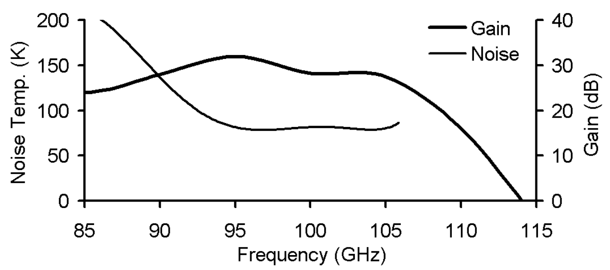

Fig. 9. Performance of the cryogenically cooled, 3 mm band, low noise amplifier system.

VI. Conclusion

In April 2003, six receivers, equipped to observe in the 12 mm band, were installed in the ATCA antennas. In July 2004, five of these receivers were equipped to observe in the 3 mm band, up to 105 GHz.

System temperatures of 35 Kelvin and 150 Kelvin were measured on the antenna at 20 GHz and 90 GHz respectively. These system temperatures include noise contributions from the atmosphere, antenna spillover and scattering.

With further development the LNA systems will be upgraded to extend the upper frequency to 115 GHz.

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