Cheap 0.36 dB NF broadband multipath LNA

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A two-path low-noise amplifier (LNA) designed for the planned MeerKAT radio telescope is presented. The LNA has a noise figure (NF) of less than 0.36 dB and input return loss of less than −12 dB from 0.7 to 1.8 GHz. It consumes 100 mW of power and costs about $10 to manufacture.

Introduction: Some modern radio telescopes arrays (such as phased-array feeds [1] and aperture arrays for the planned SKA [2]) have thousands of low-noise amplifiers (LNAs), making cooling the LNAs very expensive. These systems require extremely low-noise, broadband LNAs, which operate at 77K or even room temperature. Low-noise, room-temperature, pulse amplifiers are also required in various other fields, e.g. as preamplifiers for photon detectors.

South Africa's MeerKAT array serves as a technology demonstrator for the SKA and will be the largest and most sensitive radio telescope in the southern hemisphere. For the low-frequency band (0.9–1.75 GHz) the MeerKAT's goal specifications for the LNAs are a noise temperature (NT) of less than 12 K when cooled to 77K and less than 6K when cooled to 20K. Apart from requiring a low NT, a flat frequency gain profile (less than ±0.75 dB variation), low input and output return loss (less than −12 dB), good linearity ($P_{1dB} < -38$ dBm input) and low power consumption (less than 90 mW) are also required for MeerKAT. However, there is a trade-off between these requirements.

The challenge in designing broadband LNAs is to match the input (50 Ω) impedance to both the optimum source and the input impedance of a small (low power) transistor over the whole bandwidth. This will be called noise and input matching, respectively. Different LNA topologies to achieve this are being investigated for the SKA. Xu *et al.* [3], for example, employ dual-loop negative feedback and achieve a 0.5 dB noise figure (NF) from 0.6–1.6 GHz. The present author [4] recently described a multipath LNA technique, where the matching problem is solved by using a number of amplification paths in parallel. It was shown that the more paths, the better the matching that can be achieved over larger band widths. This Letter uses the multipath technique to design an LNA that meets MeerKAT's goal specifications.

However, multipath LNAs have the additional challenge of being prone to oscillate and stability must be ensured without increasing the NT. A circuit and design procedure is reported in this Letter that also meets this challenge.

Design procedure: The amplifier is simulated using ADS2009 and Modelithics v7.0 models are used for the surface mount components and the transistors (except for the transistors' noise for which the manufacturer's measured noise parameters are used). Microstrips on low-loss RT/Duroid 5870 substrate with a dielectric constant of 2.33 and thickness of 0.79 mm are used.

(i) Number of amplification paths: Two amplification paths using Avago's atf35143 transistors are enough to achieve good input and noise matching for 0.9–1.8 GHz. Each path consists of two cascaded transistors for sufficient gain, resulting in a total of four transistors. The transistors have the lowest M_{min} (minimum noise measure) at $V_{ds} = 2$ V and $I_{ds} = 10$ mA. The design procedure of [4] is used to design a multipath LNA. First the amplification path is designed for low M_{min}, then the input network is designed for noise matching and finally the output network is designed to combine the signals in the correct ratio for optimum noise cancellation.

(ii) Biasing: Any component before the gate of the first FET will have loss and increase the NT of the amplifier. The gates are therefore connected directly to the input through transmission lines. The gates are then at ground potential and passive biasing, using a source resistor R_s and NPO capacitors C_s, is used. These resistors increase the power consumption from 80 to 92 mW.

(iii) Stability:

- Stability above 6 GHz is ensured by adding a series resistor R_d to each transistor's drain so that each transistor stage is unconditionally stable. A loop around the resistor is optimised to give a minimum M_{min} for 0.9–1.8 GHz (see Fig. 1).
- Secondly, the amplification path (i.e. the two cascaded transistor stages) is designed to be unconditionally stable for 0.5–3 GHz. This is achieved by adding a resistor R_a at the output of the path. The power supply circuits (multilayer chip inductors L_1–L_4, resistors R_1 and R_2 and capacitors C_1 and C_2) and transmission lines are optimised for minimum M_{min} as well as a flat gain profile at M_{min}.
- Lastly, a resistor R_I is used at the end of the input network to ensure unconditional stability below 0.5 GHz. Two parallel capacitors C_I are added to suppress the noise of the resistor. The input network is optimised for input and noise matching and the output network is optimised for output impedance matching, a flat gain profile and low NT. To reduce the transmission line's size, parallel capacitors C_p are added. The series resistor R_c is added to achieve good noise cancellation between the stages.

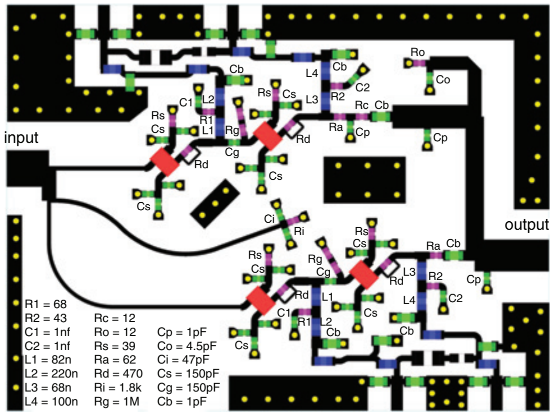

Fig. 1 *PCB layout of amplifier*

Transistors are coloured red, capacitors green, resistors purple, inductors blue and vias yellow. Size is 46 × 35 mm

Manufacturing cost: The PCB substrate and components cost about $3 and $6, respectively (while equivalent Taconics substrate is even cheaper). Manufacturing the PCB costs less than $1 when mass produced, giving a total cost of about $10 (excluding the SMA connectors and housing).

Measurements: Fig. 2 shows that the measured and simulated *S*-parameters correspond quite well and are within the MeerKAT's specifications (except S_{22} below 1 GHz, which is not that important). The difference between the simulated and measured S_{11} is due to the large signal of the vector analyser driving the amplifier into nonlinearity.

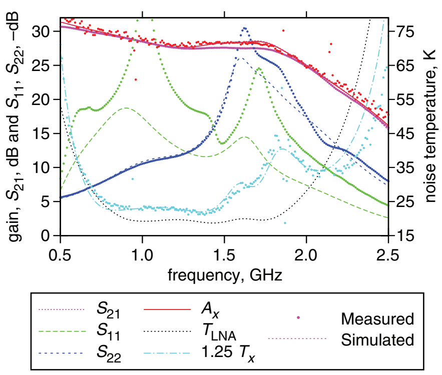

Fig. 2 *Simulated and measured gain, input and output reflection coefficient and noise temperature*

The amplifier's NT (T_{lna}) was measured at room temperature using the self-termination noise measurement procedure described in [5]. The output noise power was measured with a spectrum analyser at an ambient temperature $T_{amb} = 300$K when the input of the amplifier is terminated by 50 Ω (P_t), open input (P_o) and short-circuit input (P_c). $P_{os} = (P_o + P_s)/2$ is the output power of a 'cold' load ($T_{cold} \simeq T_{lna}$), giving a Y-factor of $Y = P_t/P_{os}$, noise temperature of $T_x = T_{amb}/(2Y - 1)$ and gain of $A_x = P_t/kB(T_{amb} + T_x)$. The measured A_x corresponds well with the simulation and the measured T_x is about 25% larger than simulated with the same frequency profile. The amplifier therefore has a noise temperature of about 25K (noise figure of 0.36 dB). The extra 5K (corresponding to a 0.1 dB loss at the input) is most probably due to the SMA input connector, which was not modelled or may be due to uncertainties in the transistor's noise parameters. In a radio telescope receiver, the connector loss can be eliminated by integrating the LNA with the antenna (for example in [1]). When taking this loss into consideration, the simulated noise is less than 12K and 6K at $T_{amb} = 77K$ and 20K, respectively (assuming the transistor's noise decreases like the square root of the ambient temperature and other noise proportional to the temperature).

There is an additional 0.2 V across the power supply filters, resulting in a 100 mW power consumption. The power consumption may be reduced to 90 mW with only a small penalty in NT by reducing the drain-source voltage (V_{ds}) from 2 to 1.75 V.

Comparison: The APERTIF prototype [1] uses a similar Avago GaAs transistor and achieves $T_{lna} < 40K$ and $S_{11} < -7.5$ dB for 1–2 GHz. On the other hand, Miteq has a commercial LNA [6] with $T_{lna} < 28K$ and $S_{11} < -10$ dB but its power consumption is 2.7 W.

Other technologies exist that give a lower noise figure than GaAs technology. The multipath LNA technique, however, can be applied to these technologies as well. For example, Belostotski and Haslett [7] used 90 nm CMOS technology and report a noise figure of less than 0.2 dB for 0.8–1.4 GHz, but they had to use an 85 Ω input impedance. The multipath technique will make it possible to achieve the same (or maybe an even lower) NF with a 50 Ω

Conclusions: The LNA presented in this Letter has the lowest noise figure GaAs LNA and the cheapest sub-0.4 dB noise figure LNA known to the author for an octave bandwidth. By using multiple amplification paths, an LNA can be designed that meets MeerKATs specifications, be comparable to the best available LNAs and cost only a few dollars to manufacture. However, such amplifiers must be designed carefully to ensure stability without compromising the noise figure.

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One or more of the Figures in this Letter are available in colour online.

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