AIP | Review of Scientific Instruments

Cooling a low noise amplifier with a micromachined cryogenic cooler

H. S. Cao, R. H. Witvers, S. Vanapalli, H. J. Holland, and H. J. M. ter Brake

Citation: Review of Scientific Instruments **84**, 105102 (2013); doi: 10.1063/1.4823528
View online: http://dx.doi.org/10.1063/1.4823528
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/84/10?ver=pdfcov
Published by the AIP Publishing

Cooling a low noise amplifier with a micromachined cryogenic cooler

H. S. Cao,[1,a)] R. H. Witvers,[2] S. Vanapalli,[1] H. J. Holland,[1] and H. J. M. ter Brake[1]
[1]*Energy, Materials and Systems, Faculty of Science and Technology, University of Twente, 7500 AE Enschede, The Netherlands*
[2]*ASTRON, P.O. Box 2, 7990 AA Dwingeloo, The Netherlands*

(Received 5 August 2013; accepted 13 September 2013; published online 2 October 2013)

The sensitivity of antenna systems increases with increasing active area, but decreases at higher noise figure of the low-noise amplifier (LNA). Cooling the LNA locally results in significant improvement in the gain and in lowering the noise figure of the LNA. Micromachined Joule-Thomson (JT) coolers can provide a cryogenic environment to the LNA. They are attractive because they have no cold moving parts and can be scaled down to match the size and the power consumption of LNAs. The performance of a LNA mounted on a JT microcooler with dimensions of 60.0 × 9.5 × 0.72 mm^3 is reported in this paper. The microcooler is operated with nitrogen gas and the cold-end temperature is controlled at 115 K. The measured net cooling power of the microcooler is about 43 mW when the LNA is not operating. The power dissipation of the LNA is 26 mW, with a supply voltage of 2 V. At room temperature the noise figure of the LNA is 0.83 dB and the gain lies between 17.9 and 13.1 dB, in the frequency range of 0.65 and 1.05 GHz. Upon cooling to 115 K, the noise figure drops to 0.50 dB and the increase in gain varies in the range of 0.6–1.5 dB.
[http://dx.doi.org/10.1063/1.4823528]

I. INTRODUCTION

The Square Kilometre Array (SKA)[1] is designed to detect very weak signals at frequencies from 70 MHz to 10 GHz in three bands (low: 70–450 MHz, middle: 0.45–1.4 GHz, high: 1.2–10 GHz). In the low and middle parts, two different types of aperture arrays will be adopted. Dish antennas will be used to observe signals in the high part of the frequency band. The purpose of this paper is to explore the improved performance of the telescope in the middle frequency band by cooling the low-noise amplifier (LNA) locally.

The telescope sensitivity is determined by the ratio of the active area to the noise temperature of the entire receiver. In the receiver system, the noise temperature is primarily determined by the first stage LNA,[2] which is a key component placed at the front-end of a radio receiver circuit. The reduction in noise temperature of a LNA by cryogenic cooling provides an effective way to improve the receiver sensitivity.[3] From the noise model developed by Pospieszalski,[4] the minimum noise temperature of a field effect transistor chip can be expressed by

$$T_{min} = 2\frac{f}{f_T}\sqrt{r_t T_g g_{ds} T_d}, \quad (1)$$

where T_{min} is minimum noise temperature, f is the frequency of radio waves, f_T is the intrinsic cut-off frequency, r_t is the total resistance including parasitic resistances of gate and source and the intrinsic gate resistance, g_{ds} is the drain-to-source conductance, and T_g and T_d are equivalent gate and drain temperature, respectively. T_g is approximately equal to the physical temperature of a device.

The performance improvement of cryogenically cooled LNAs has been demonstrated in many studies.[5–7] For the SKA telescope, cryogenic cooling reduces the active area required for a given telescope sensitivity or allows higher sensitivity with the same active area. It is not necessary to cool the whole radio receiver for this application, but only the localized LNA chip. A miniature cryogenic cooler is attractive for the local cooling of the LNA chip. Localized LNA thermoelectric cooling has been investigated by Schreuder and Bij De Vaate. The noise figure of the LNA at 2.6 GHz reduced from 1.40 dB at 293 K to 1.15 dB when the LNA was cooled down to a temperature of 250 K.[8] Compared to thermoelectric coolers, Joule-Thomson (JT) coolers can offer lower cold-end temperature. Besides, JT coolers are also suitable for miniaturization because they have no cold moving parts and therefore can be scaled down to match the size and the power dissipation of LNA chips.[9,10] In this paper, the utilization of JT microcoolers for cooling LNAs is investigated. As a demonstration, we have integrated a commercial gallium arsenide monolithic microwave integrated circuit LNA with a single-stage 110 K microcooler. It shows a 0.33 dB noise figure improvement in the frequency range between 0.65 and 1.05 GHz.

II. MICRO JOULE-THOMSON COLD STAGE AND LNA

The micromachined JT cooler is made from a stack of three glass wafers with dimensions of 60.0 × 9.5 × 0.72 mm^3. The operating principle and the fabrication process are described in detail by Lerou *et al.*[11] The microcooler is mounted into a vacuum flange and surrounded by a printed circuit board (PCB) as shown in Fig. 1. The cold-end temperature of the microcooler is measured with a platinum resistor (Pt1000). A surface mounted device resistor is used as a heater to apply heat and thus to control the cold-end temperature of the microcooler. The LNA together with the temperature sensor and the heater is glued to a silicon piece that is thermally connected to the cold end of the microcooler with

a) Author to whom correspondence should be addressed. Electronic mail: H.Cao@utwente.nl

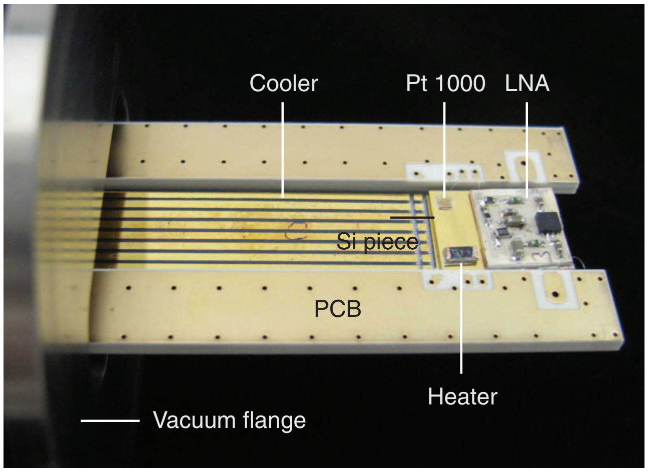

FIG. 1. Photograph of the microcooler with a temperature sensor, a heater, a LNA, and a silicon piece mounted into a vacuum flange and surrounded by a PCB.

conducting silver paint similar to the procedure described by Derking *et al.*[12] The function of the silicon piece is to uniformly distribute the heat and to reduce temperature gradients along the LNA. The temperature sensor, the heater, and the LNA are electrically connected to the PCB with bond wires made of 99% aluminum and 1% silicon having a diameter of 25 μm. Both the temperature sensor and the heater are connected to the PCB with 2 bond wires. The LNA requires 7 bond wires consisting of 2 radio frequency (RF) signal wires, 4 ground wires, and 1 direct current (DC) wire.

The PCB transports the RF signals to the LNA attached on the cold end of the microcooler. The RF power losses associated with PCB transmission lines have a significant effect on a propagating signal in the radio frequency range or higher. Some of the power losses are caused by its resistance, that is, ohmic or resistive loss. At high frequencies, the insulating material around the transmission line can also absorb energy from the alternating electric field and converts it to heat, which is called dielectric loss. The resistive and dielectric losses vary in proportion to the length of the transmission line. Therefore, a shorter transmission line means lower RF loss. When a signal is transmitted along a transmission line, some of the signal power may be reflected back to the transmitting device rather than being carried all the way along the transmission line to the receiver. The power losses will increase due to the signal reflection. To decrease the power losses caused by reflection, the characteristic impedance of the transmission line should be equal to the load impedance. For a uniform transmission line, the characteristic impedance is determined by the geometry and materials of the transmission line, where it does not depend on its length. The PCB shown in Fig. 1 is a multilayer board with the RF and DC lines inside. The RF lines are laid out in the form of strip-line configuration to shield the RF signals from the environment and the flange. The loss of the RF lines will increase the overall noise figure of the LNA and thus needs to be as low as possible. The measured RF loss of the PCB is given in Fig. 2.

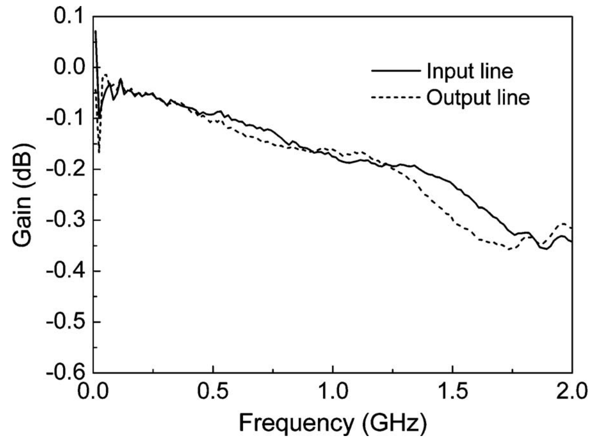

FIG. 2. RF loss of the PCB in the setup of Fig. 1.

III. MEASUREMENT

A. Measurement set-up

The working fluid, nitrogen gas, is supplied to the microcooler from a pressurized gas bottle. The inlet high pressure to the microcooler is controlled with a pressure control. The nitrogen gas is purified with a getter filter to remove most impurities (especially water) to less than parts-per-billion level to prevent clogging due to water deposition.[13] The outlet low pressure and mass-flow rate of the nitrogen gas are measured at the outlet of the microcooler. A pressure relief valve maintains a constant outlet pressure of 0.11 MPa and also prevents air from flowing into the system. A vacuum pressure of less than 10^{-4} mbar is maintained around the microcooler during the experiment.

B. Cool-down measurement

The operating low and high pressures of the microcooler are 0.11 and 8.50 MPa, respectively. Fig. 3 shows the measured cold-end temperature and mass-flow rate. From a room temperature of 295 K, the cold end cools to about 110 K in 18 min. As the cold-end temperature decreases to 125 K, the mass-flow rate increases from 4.2 to 15.3 mg s^{-1} due to the temperature dependence of density and viscosity of the nitrogen gas. When the cold-end temperature is lower than 125 K, the mass-flow rate decreases

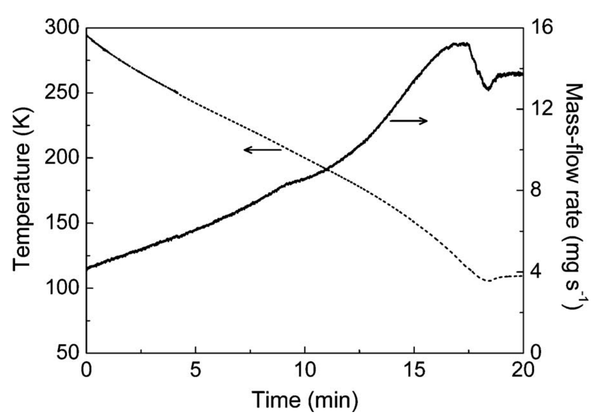

FIG. 3. Measurement of the cool down of the microcooler.

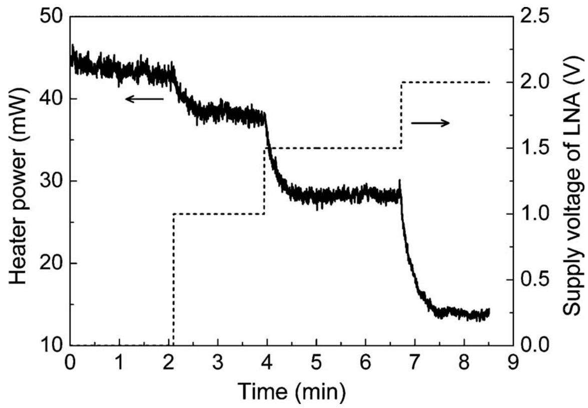

FIG. 4. Measurement of the net cooling power of the microcooler with attached LNA operating at different supply voltages. The microcooler is controlled at 115 K with a mass-flow rate of 15 mg s^{-1}.

to 13.0 mg s^{-1} because liquid forms in the restriction. In the steady state, the mass-flow rate is constant at 13.8 mg s^{-1}.

C. Performance of LNA mounted on the microcooler

The net cooling power that can be used to balance the heat generated in the LNA is measured using a proportional-integral-derivative (PID) control loop that consists of a temperature sensor and a heater (indicated in Fig. 1). At a controlled temperature of 115 K and a mass-flow rate of 15 mg s^{-1}, the measured net cooling power of the microcooler is about 43 mW as shown in Fig. 4. At the cold-end temperature of 115 K, the estimated conductive heat flow through a total of 11 bond wires each with a length of 5 mm is about 38 mW, and the radiative heat flow to the LNA with dimensions of 10 × 10 × 0.5 mm^3 is about 47 mW. Therefore, the cooling capacity of the microcooler at 115 K is about 128 mW.

As shown in Fig. 4, the LNA is switched on after about 2 min, and the supply voltage of the LNA at that point is set to 1.0 V with a power dissipation of 4 mW. The net cooling power of the microcooler reduces 4–39 mW accordingly. With the supply voltage increasing to 1.5–2.0 V, the net cooling power decreases to 28 mW and 14 mW. This means that the power dissipations of LNA are 15 mW and 29 mW with supply voltages of 1.5 and 2.0 V, respectively, which also match with the product of applied voltage and the electric current read from the power supply. During the measurement, the temperature fluctuations are less than 0.5 K.

Fig. 5 shows the measurement of the noise figure and gain of the LNA with a supply voltage of 2 V at 295 and 115 K in the frequency range between 0.65 and 1.05 GHz. The average noise figure of the LNA decreases from 0.83 to 0.50 dB when the cold-end temperature reduces from room temperature of 295 to 115 K. At room temperature, the gain decreases from 17.9 to 13.1 dB with the increasing frequency from 0.65 to 1.05 GHz. Upon cooling to 115 K, the corresponding increase in gain varies in the range of 0.6–1.5 dB.

IV. DISCUSSION

By cooling the LNA from 295 to 115 K, the average noise figure decreases from 0.83 to 0.50 dB, corresponding to a re-

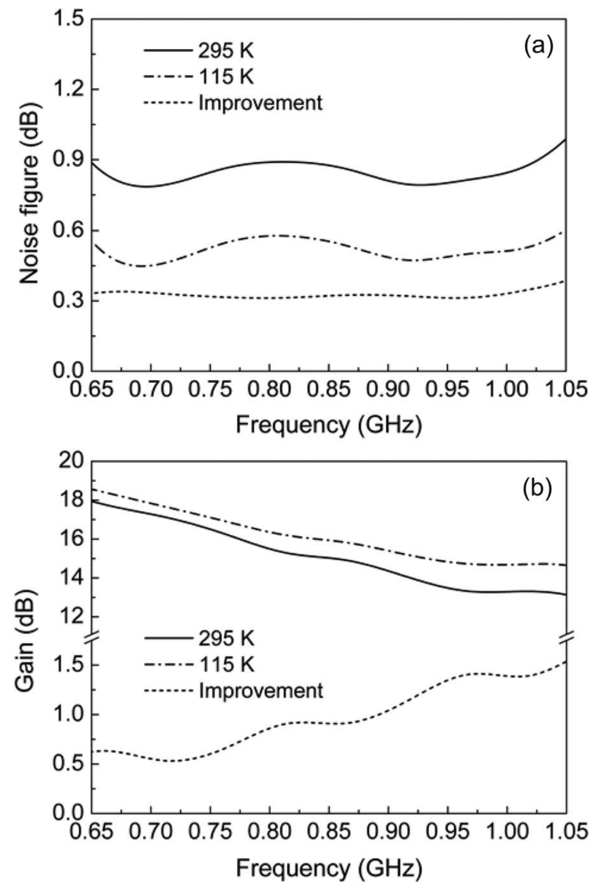

FIG. 5. Noise figure (a) and gain (b) versus frequency at different temperatures.

duction in the average noise temperature of the LNA from 61 to 35 K. The telescope sensitivity is proportional to the ratio of the active area to the noise temperature of the entire receiver. This implies that the active area of a telescope with a certain sensitivity can be reduced about 43% by using JT microcooling. The RF loss of the PCB is between 0.11 and 0.18 dB in the frequency range of 0.65 and 1.05 GHz as shown in Fig. 2. Therefore, the effective improvement in noise figure due to the cooling system varies in the range of 0.15–0.22 dB. The RF loss of the PCB can be reduced by a better PCB material and/or a shorter RF line length. In the cooling system mentioned above, the RF line length is the distance between the cold end of the microcooler and the flange. To reduce the RF line length, the first measure is to separate the fluid and electrical feedthroughs by placing another flange with electrical feedthroughs on the side of the cold end of the microcooler. The second measure is to modify the microcooler geometry to a "U" shape with the cold end placed close to the warm-end flange. More improvements can be achieved by improving the impedance match between the PCB, bondwires, and the LNA since the LNA is not performing optimally. Compared to the heat generated in the LNA, the conductive heat of the bond wires and the radiative heat of the LNA are relatively large. Therefore, the wires need further optimization based on the acceptable impedance and the LNA chip should be made as small as possible to reduce the radiative loss.

V. CONCLUSIONS

In general, the performance of an antenna system can be improved by cooling the LNA stage in order to reduce the noise figure. Cooling the LNA locally can decrease the noise figure with low cooling power since not the whole system has to be cooled. In this paper, localized LNA cooling using a JT microcooler has been demonstrated. The noise figure of the LNA under study drops by about 0.33 dB from 0.83 to 0.50 dB in the frequency range between 0.65 and 1.05 GHz with its operating temperature decreasing from 295 to 115 K. Due to the decreasing operating temperature, the gain improvement varies in the range of 0.6–1.5 dB, dependent on the frequency. The length of RF lines along the PCB should be further reduced in order to decrease the loss before the LNA and therefore the noise figure.

ACKNOWLEDGMENTS

We thank Hendrie Derking from CERN for helpful discussions. We acknowledge financial support from the Dutch Technology Foundation (STW) under Contract No. 08014.

[1] C. L. Carilli and S. Rawlings, New Astron. Rev. **48**, 979–984 (2004).
[2] A. Cappy, IEEE Trans. Microwave Theory Tech. **36**, 1–10 (1988).
[3] M. W. Pospieszalski, IEEE Microw. Mag. **6**, 62–75 (2005).
[4] M. W. Pospieszalski, IEEE Trans. Microwave Theory Tech. **37**, 1340–1350 (1989).
[5] C. Risacher and V. Belitsky, IEEE Microw. Wirel. Compon. Lett. **13**, 96–98 (2003).
[6] S. Weinreb, J. C. Bardin, and H. Mani, IEEE Trans. Microwave Theory Tech. **55**, 2306–2312 (2007).
[7] J. Schleeh, N. Wadefalk, P. A. Nilsson, J. P. Starski, and J. Grahn, IEEE Trans. Microwave Theory Tech. **61**, 871–877 (2013).
[8] F. Schreuder and J. G. Bij De Vaate, in *Proceedings of the 12th International Workshop on Thermal investigation of ICs and Systems, Nice, France, 2006* (EDA Publishing Association, 2006), pp. 175–179.
[9] W. A. Little, Rev. Sci. Instrum. **55**, 661–680 (1984).
[10] R. Radebaugh, J. Phys.: Condens. Matter. **21**, 164219 (2009).
[11] P. P. P. M. Lerou, G. C. F. Venhorst, C. F. Berends, T. T. Veenstra, M. Blom, J. F. Burger, H. J. M. ter Brake, and H. Rogalla, J. Micromech. Microeng. **16**, 1919–1925 (2006).
[12] J. H. Derking, H. J. Holland, T. Tirolien, and H. J. M. ter Brake, Rev. Sci. Instrum. **83**, 045117 (2012).
[13] H. S. Cao, S. Vanapalli, H. J. Holland, C. H. Vermeer, and H. J. M. ter Brake, Appl. Phys. Lett. **103**, 034107 (2013).