A 1.4 GHz MMIC Active Cold Noise Source

Robert Scheeler and Zoya Popović

Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309, USA.
E-mail: robert.scheeler@colorado.edu, zoya.popovic@colorado.edu

***Abstract*—A GaAs MMIC active cold load for a wearable microwave radiometer is presented. A design procedure capable of achieving a minimum noise temperature at a specific bias point is described. A measured equivalent noise temperature of less than 90 K from 1.3 GHz to 1.5 GHz while maintaining an input return loss greater than 28 dB is demonstrated.**

***Index Terms*—Noise measurement, MMICs.**

I. Introduction

This paper presents an active noise source developed for a compact 1.4 GHz radiometer. The motivation for reduced size is a wearable microwave medical thermometer for monitoring internal body temperature, e.g. [1]. Radiometers are calibrated by switching the receiver from the antenna to a load of a known temperature [2]. The calibration is demonstrated in Fig. 1, showing hot and cold calibration standards. Cold standards are often cooled absorber loads, which tend to be large. An avalanche diode may be used as a more compact noise source. However, avalanche diodes result in a very high equivalent noise temperature, and are generally used as a hot calibration standards. A cold equivalent noise temperature can be a achieved by using an active cold load (ACL), which is represented by the cold standard T_c in Fig. 1. An ACL noise source using a MESFET device demonstrated a temperature of 48 K at 1.4 GHz [3]. Other hybrid designs have been done utilizing GaAs and InP FETs [4] and SiGe HBT [5]. MMIC designs of active cold loads from 2 to 26 GHz are presented in [6]. Although hybrid designs have been done below 2 GHz, to the authors' knowledge no MMIC designs have been presented at these frequencies.

II. Noise Source Model and Design Procedure

A. Noise Source Model

The theory presented in [7] gives an expression for the output noise power seen at the input of the transistor and is given here for completeness. The incident noise temperature at plane 1 of Fig. 2 can be expressed as

$$T_{s,1} = T_b + \left[\left(T_1\left(1-|\Gamma_S|^2\right)+T_a\right)G_{21}|\Gamma_L|^2 + T_2\left(1-|\Gamma_L|^2\right)\right]G_{12} \quad \text{[K]} \qquad (1)$$

where T_2 is the temperature of the termination and T_1 is the temperature of the system connected to the input of the transistor. G_{12} and G_{21} are power gains calculated from the S-parameters of the transistor. The alternate noise parameters T_a and T_b are given by [7]

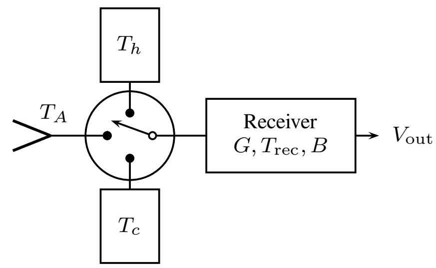

Fig. 1. Block diagram for a radiometer demonstrating calibration with hot (T_h) and cold (T_c) calibration standards.

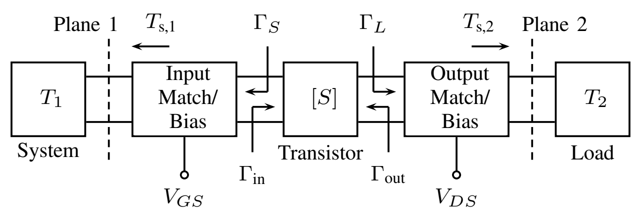

Fig. 2. Block diagram for the ACL design showing the input and output matching and bias networks necessary for the design in which the input of the device is presented with Γ_S and the output of the device is presented with Γ_L.

$$T_a = T_{e(\text{min})} + \frac{T_k|\Gamma'_{\text{opt}}|^2}{1-|\Gamma'_{\text{opt}}|^2} \quad \text{[K]} \qquad (2)$$

$$T_b = \frac{T_k}{1-|\Gamma'_{\text{opt}}|^2} - T_{e(\text{min})} \quad \text{[K]} \qquad (3)$$

where $T_{e(\text{min})} = T_0(\text{NF}_{\text{min}} - 1)$ and $T_k = 4T_0R_nG_{\text{opt}}$ where R_n is the equivalent noise resistance and G_{opt} is the optimum noise conductance for the transistor. Γ'_{opt} for an unmatched load is related to Γ_{opt} by

$$\Gamma'_{\text{opt}} = \frac{\Gamma^*_{\text{in}} - \Gamma_{\text{opt}}}{\Gamma_{\text{opt}}\Gamma_{\text{in}} - 1} \qquad (4)$$

The input and output matching/bias networks as seen in Fig. 2 must be designed to transform source and load impedances to present the necessary Γ_S and Γ_L to the device. The noise power $T_{s,1}$ incident on plane 1 given in (1) will be minimized by appropriate circuit design. To minimize $T_{s,1}$, first the optimum noise match condition is utilized by designing an input matching network such that $\Gamma_S = \Gamma_{\text{opt}}$. The input power match condition is satisfied then by $\Gamma_{\text{in}} = \Gamma^*_{\text{opt}}$. To achieve the input power match condition the reflection coefficient at the

978-1-4799-0583-6/13/$31.00 ©2013 IEEE

output of the transistor must be

$$\Gamma_L = \frac{\Gamma_{\text{opt}}^* - S_{11}}{S_{12}S_{21} + S_{22}\left(\Gamma_{\text{opt}}^* - S_{11}\right)} \tag{5}$$

The input power match condition will result in $\Gamma'_{\text{opt}} = 0$ which can be used to simplify (1). The simplified expression is minimized with respect to $|\Gamma_L|$ by solving $\partial T_{s,1}/\partial|\Gamma_L| = 0$ where

$$\frac{\partial T_{s,1}}{\partial|\Gamma_L|} = 2\left[\left(T_1\left(1-|\Gamma_S|^2\right) + T_{e(\text{min})}\right)G_{21} + T_2\right]G_{12}|\Gamma_L| \tag{6}$$

Therefore, minimizing $T_{s,1}$ under the conditions of optimum noise match and input power match is done by minimizing $|\Gamma_L|$. The minimum will occur as $|\Gamma_L| \to 0$. Under this condition, the reflection coefficient looking into the transistor is $\Gamma_{\text{in}} = S_{11}$. When $\Gamma_L = 0$ the input power match condition dictates that $\Gamma_{\text{opt}} = S_{11}^*$. This can be satisfied by altering the S-parameters of the device which can be done by changing the bias point or varying the source inductance.

B. Minimized $T_{s,1}$ Example

To demonstrate $T_{s,1}$ is minimized when the input power match condition requirement on $|\Gamma_L| \to 0$, two separate bias points were considered for a TriQuint 0.5 μm GaAs pHEMT device. Simulations were carried out using AWR Microwave Office and the device was modeled with TriQuint's nonlinear TOM3 model. A 300 μm gate periphery TriQuint device was biased at two different gate bias points ($V_{GS} = 0.5$ V, $V_{GS} = 0.788$ V) while the drain was biased at $V_{DS} = 1.7$ V. An ideal inductor was placed on the source of the transistor and its inductance was varied. The device, source, and load temperatures are assumed to be at 298 K. The input is assumed to be matched to Γ_{opt} and the output reflection coefficient is given in (5) to achieve an input power match. Fig. 3 demonstrates a minimum in $T_{s,1}$ is achieved when the magnitude of the load reflection coefficient Γ_L from (5) is minimized. For a gate bias of $V_{GS} = 0.788$ V a minimum occurs with a source inductance of 1.03 nH corresponding to $T_{s,1} = 19$ K and $|\Gamma_L| = -58.4$ dB which is approximately zero. If $|\Gamma_L| = 0$ then the following relation is true $\Gamma_{\text{opt}} \approx S_{11}^*$. If Γ_L is not zero, a minimum in $T_{s,1}$ will still occur when $|\Gamma_L|$ is minimized. This is demonstrated in Fig. 3 for a gate bias of $V_{GS} = 0.5$ V and a source inductance of 1.95 nH corresponding to $T_{s,1} = 304.4$ K and $|\Gamma_L| = -13.3$ dB.

The lowest value for $T_{s,1}$ was achieved for the gate bias point of $V_{GS} = 0.788$ V by varying the source inductance such that $\Gamma_{\text{opt}} \approx S_{11}^*$. The conjugate of the device input reflection coefficient S_{11}^* along with the optimum noise reflection coefficient for the two bias points vs. source inductance from 0.5 to 3 nH are plotted on a Smith chart shown in Fig. 4. It is seen that S_{11}^* and Γ_{opt} are approximately equal ($S_{11}^* \approx \Gamma_{\text{opt}} \approx 0.586 + j0.224$) at a point corresponding to 1.03 nH which is the source inductance corresponding to a minimum in $T_{s,1}$. If the two are equal the input to the noise source is matched and the load should be terminated in a matched load. This is not the case for a gate bias of $V_{GS} = 0.5$ V and therefore Γ_L is not zero for an input power match.

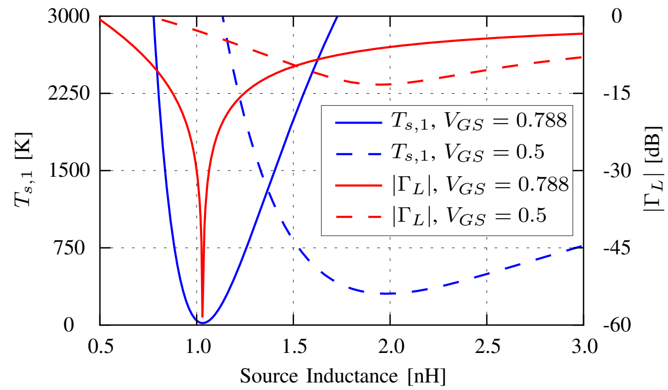

Fig. 3. Simulated $T_{s,1}$ and $|\Gamma_L|$ calculated from (5) for a TriQuint 0.5 μm pHEMT device. The transistor was biased at 1.7 V on the drain and the ideal source inductance was varied from 0.5 nH to 3 nH for two different gate biases corresponding to 0.5 V and 0.788 V. A minimum in $T_{s,1}$ is achieved when $|\Gamma_L|$ is minimized.

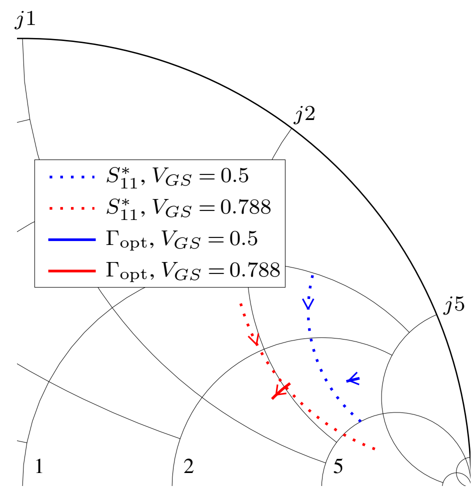

Fig. 4. The optimum noise match (Γ_{opt}) and conjugate of device input reflection coefficient vs. ideal source inductance ranging from 0.5 to 3 nH for two different gate bias points ($V_{GS} = 0.5$ V and $V_{GS} = 0.788$ V) with the drain biased at $V_{DS} = 1.7$. For the gate bias $V_{GS} = 0.788$ V S_{11}^* and Γ_{opt} are approximately equal ($S_{11}^* \approx \Gamma_{\text{opt}} \approx 0.586 + j0.224$) for a source inductance of 1.03 nH. The Smith chart is normalized to 50 Ω.

C. Design Procedure

To design an ACL with a minimum noise temperature the following procedure is applied:

1. Select a bias point for the transistor and determine the scattering and noise parameters for the biased transistor.
2. Calculate Γ_L from (5) and vary the source inductance to find a minimum for the calculated value of $T_{s,1}$ and $|\Gamma_L|$.
3. Design output matching network to meet the condition for Γ_L given by (5).
4. Design the input matching network such that $\Gamma_S = \Gamma_{\text{opt}}$.

The design procedure can be iterated for different bias points such that a minimum in $T_{s,1}$ and $|\Gamma_L|$ can be attained.

III. GaAs MMIC Noise Source Design and Measurements

A. Design and Simulation

To develop a compact cold calibration load for a 1.4 GHz wearable microwave radiometer system, the design procedure above was applied to a TriQuint 0.5 μm GaAs pHEMT with 300 μm gate periphery using TriQuint's nonlinear TOM3 model biased at $V_{GS} = 0.72$ V and $V_{DS} = 1.7$ V. The source inductance was varied to achieve a minimum in $|\Gamma_L|$. An inductor was designed and simulated using the 3D planar Method of Moments solver AXIEM available in AWR Microwave Office. Once a minimum in $|\Gamma_L|$ was achieved the cold noise source could be designed by matching the input and placing bias tees at the input and output as seen in Fig. 5. The input network and bias tee were simulated in AXIEM. The match was achieved using a shunt capacitor and series inductor. The bias line consisted of a shunt capacitor and series inductor to achieve a 90° phase shift and an RF shorting capacitor, and finally a series capacitor was placed to block DC.

Fig. 6 shows the source reflection coefficient, optimum noise match, and transistor S_{11}^*. The input network is designed as a compromise between input power match and noise match which can be seen by the markers placed at 1.4 GHz. Additionally, the reflection coefficient looking into the noise source (Γ'_{in}) is plotted to demonstrate the input match is better than 25 dB at 1.4 GHz denoted by the marker. The output was terminated in a 50 Ω bias tee.

To determine the value of $T_{s,1}$ at the output of the MMIC, (1) was used. After placing the simulated input and output networks on the transistor biased at $V_{GS} = 0.72$ V and $V_{DS} = 1.7$ V, the whole ACL is considered as a 2 port network characterized by its S-parameters and noise parameters. These are determined in simulation by combining the AXIEM simulations with the nonlinear TOM3 model. $T_{s,1}$ is determined assuming the source and load are terminated in the system impedance ($\Gamma_S = \Gamma_L = 0$). The resulting equivalent noise temperature and input match of the MMIC ACL are shown in Fig. 7 demonstrating a $T_{s,1} = 70.9$ K with an input match of -27 dB at 1.4 GHz. The final layout of the chip is shown in Fig. 8 where the dimensions of the chip are 2.5 mm× 2.5 mm.

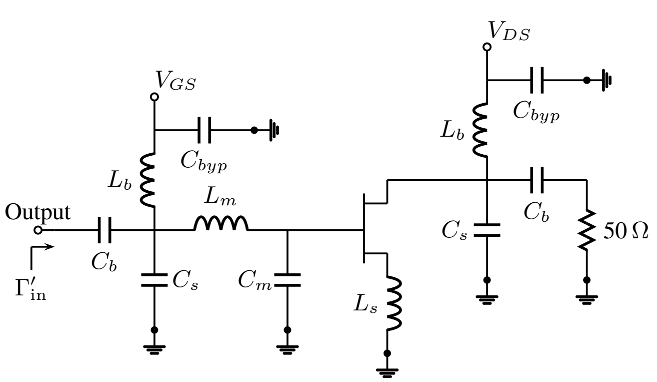

Fig. 5. Schematic of the active cold noise source. Additional source inductance was added such that the optimum load impedance is 50 Ω such that no output matching network is needed.

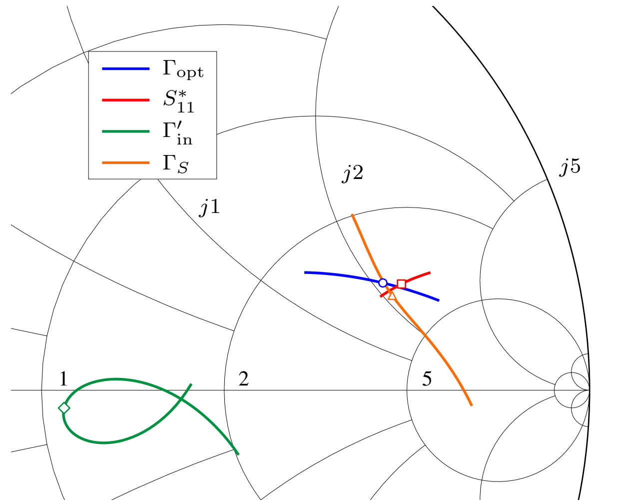

Fig. 6. Simulated optimum noise match and the conjugate of the reflection coefficient looking into the device are shown along with the reflection coefficient looking towards the source (Γ_S) through the input match and bias network vs. frequency from 1 to 2 GHz. The input match is shown looking into the noise source (Γ'_{in}). The Smith chart is normalized to 50 Ω, and the markers on the plot correspond to 1.4 GHz.

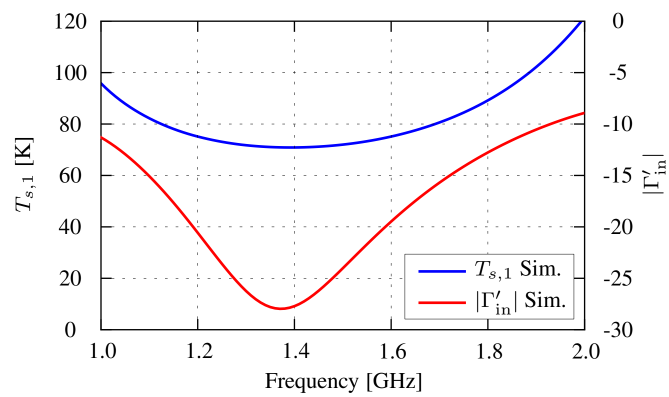

Fig. 7. Simulated $T_{s,1}$ and input match of the MMIC ACL demonstrating a $T_{s,1} = 70.9$ K with an input match of -27 dB at 1.4 GHz.

B. Experimental Results

The MMIC shown in Fig. 8 was placed on a microwave substrate carrier and connected with bond wires. The board was then placed in a shielded box and the input of the cold noise source was connect to an SMA connector. The MMIC was measured at the National Institute for Standards and Technology (NIST) using an automated coaxial radiometer system (NFRad). First, the input match of the noise source was measured to correct the raw noise measurements due to mismatch. The noise source demonstrated a measured equivalent noise temperature of less than 90 K from 1.3 GHz to 1.5 GHz. Some of the temperature increase is due to parasitics from placing the MMIC on a carrier. If the packaging parasitics are accounted for along with an additional 220 pH of source

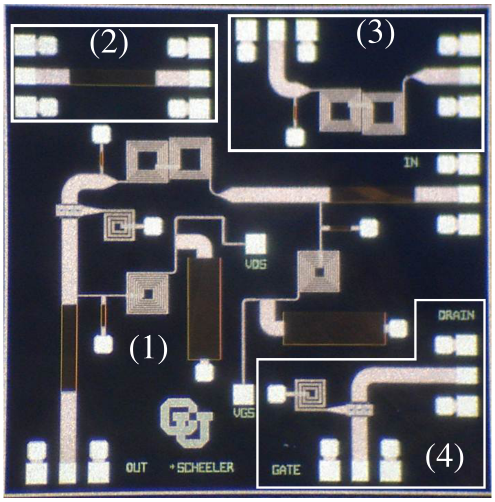

Fig. 8. Photo of the 1.4 GHz GaAs MMIC. The noise source with the input and output bias tees and input matching network is labeled by (1). The test circuits are a blocking capacitor (2), input matching network (3), and transistor test circuit (4).

inductance the simulated temperature is approximately 75 K as opposed to the original simulation without parasitics which was 71 K. The comparison between simulated and measured equivalent noise temperature and input reflection coefficient is shown in Fig. 9. The measured input match is better than simulation, and the temperature $T_{s,1}$ is within 6 to 15 K (8 to 17%) of simulation.

IV. Conclusion

A design procedure for obtaining a minimum equivalent noise temperature of an active cold load is presented utilizing the equations given in [7]. An example is shown demonstrating a minimum in $T_{s,1}$ for two different bias points of a TriQuint 0.5 μm GaAs pHEMT device using TriQuint's nonlinear TOM3 model. The procedure is applied to a 1.4 GHz GaAs MMIC design for a wearable microwave radiometer for core body temperature measurement. The packaged MMIC demonstrated an equivalent noise temperature of less than 90 K from 1.3 GHz to 1.5 GHz while maintaining a return loss greater than 28 dB.

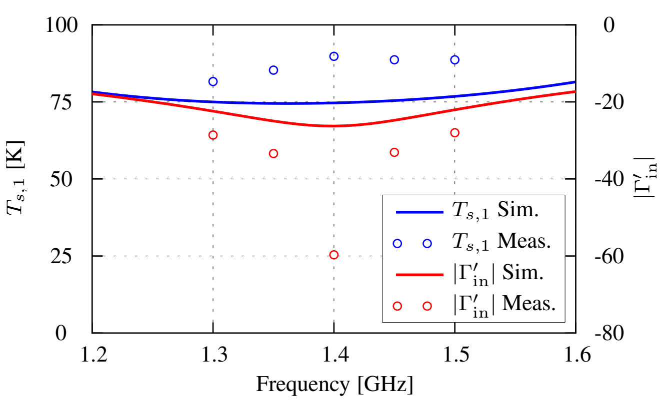

Fig. 9. Measured $T_{s,1}$ and reflection coefficient of the packaged MMIC noise source demonstrating an equivalent noise temperature of approximately 90 K while maintaining an input reflection coefficient of less than -50 dB at 1.4 GHz.

Acknowledgment

The authors wish to thank Dr. David Walker and Rob Billinger of the National Institute of Standards and Technology (NIST), Boulder, CO for their help with the measurements and TriQuint Semiconductor for access to their 0.5 μm GaAs pHEMT process.

References

[1] S. Jacobsen and O. Klemetsen, "Improved detectability in medical microwave radio-thermometers as obtained by active antennas," *Biomedical Engineering, IEEE Transactions on*, vol. 55, no. 12, pp. 2778–2785, Dec. 2008.

[2] J. D. Kraus, *Radio Astronomy*, 2nd ed. Cygnus-Quasar Books, 1976, ch. 7.

[3] R. Frater and D. Williams, "An active "cold" noise source," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 29, no. 4, pp. 344–347, Apr. 1981.

[4] L. Dunleavy, M. Smith, S. Lardizabal, A. Fejzuli, and R. Roeder, "Design and characterization of FET based cold/hot noise sources," in *Microwave Symposium Digest, 1997., IEEE MTT-S International*, vol. 3, Jun. 1997, pp. 1293–1296.

[5] E. Leynia de la Jarrige, L. Escotte, J. Goutoule, E. Gonneau, and J. Rayssac, "SiGe HBT-based active cold load for radiometer calibration," *Microwave and Wireless Components Letters, IEEE*, vol. 20, no. 4, pp. 238–240, 2010.

[6] P. Buhles and S. Lardizabal, "Design and characterization of MMIC active cold loads," in *Microwave Symposium Digest., 2000 IEEE MTT-S International*, 2000.

[7] M. Weatherspoon and L. Dunleavy, "Experimental validation of generalized equations for FET cold noise source design," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 54, no. 2, pp. 608–614, 2006.