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# A 140 GHz to 170 GHz Active Tunable Noise Source Development in SiGe BiCMOS 55 nm Technology

Victor Fiorese<sup>1,2</sup>, Joao Carlos Azevedo Goncalves<sup>1</sup>, Simon Bouvot<sup>1</sup>, Emmanuel Dubois<sup>2</sup>,  
Christophe Gaquiere<sup>2</sup>, Guillaume Ducournau<sup>2</sup>, François Danneville<sup>2</sup>, Sylvie Lépilliet<sup>2</sup> & Daniel Gloria<sup>1</sup>

<sup>1</sup> STMicroelectronics, France

<sup>2</sup> IEMN – Institut d’Electronique de Microélectronique et de Nanotechnologie, France

victor.fiorese1@st.com

**Abstract** — A new approach of millimeter wave (mmW) integrated active noise source (NS) is introduced for noise characterization up to 170 GHz. This NS is based on a diode biased in avalanche regime in BiCMOS 55 nm (B55) technology from STMicroelectronics. In order to increase the noise sensitivity of setup using this NS, a two-stage cascode Low Noise Amplifier (LNA) composed of 4 high speed NPN transistors is cascaded at its output, targeting high available Excess Noise Ratios ( $ENR_{av}$ ).  $ENR_{av}$  levels have been extracted, showing tunable values ranged between 0 dB to 37 dB in the 140-170 GHz frequency range.

## I. INTRODUCTION

In the 5G development context, the increased need for accurate measurements at high frequencies (HF) has brought new concerns regarding testing setups. Indeed, the operating frequencies of recently developed transistors have exceeded 370 GHz for  $f_{max}$  [1], introducing the development of new mmW circuits. The design of such systems relies on accurate and reliable models of MOS or bipolar transistors that are obtained by small signal, large signal, and HF noise characterization. The usual frequency range of such noise models is limited to 110 GHz. Beyond this frequency limit, measurements are challenged by important interconnect losses and the difficulty to respect the minimum detectable signal (MDS) condition which is related to the noise receiver noise figure ( $NF_{RCV}$ ). Moreover, by operating above 110 GHz comes the difficulty to generate a sufficient Excess Noise Ratio (ENR) that is directly used during the Y-factor measurement method. This method is commonly used for noise measurement and consists in determining the ratio of measured noise power when the NS is in ON state ( $P_{HOT}$ ) and when it is in OFF state ( $P_{COLD}$ ). The NS is based on a B55 noise diode [2] biased in avalanche regime for the ON state. Such noise sources can generate around 17 dB of ENR at 130 GHz [3]. Output noise power can prove to be insufficient to comply with noise receiver’s sensitivity [4]. Indeed, the usual NF value for off-wafer noise receiver in these frequency ranges is 10 dB [5]. As suggested in [3], using a biased state instead of an unbiased state for noise source low state can help to validate the MDS condition. The drawback of such an approach is a decrease in the ENR maximum reachable levels, given that the delta between the two equivalent noise temperatures  $T_{hot}$  and  $T_{cold}$  corresponding respectively to the ON and OFF NS states is

smaller. Another solution can be the approach consisting in integrating a low noise amplifier (LNA) to have a constant output NS matching regardless of bias condition and higher ENR levels. Several works leveraging photodiodes [6], [7], NMOS transistors [8] or p-i-n diodes [9] showed conclusive results up to 40 GHz. In this work, the addressed frequency range is above 140 GHz. Limitations of HF noise measurement are detailed in section II while section III describes the solution proposed to ensure the MDS validation and a sufficient ENR level at the same time. Section IV describes the methodology used for  $ENR_{av}$  extractions. Finally, section V provides some results and prospects.

## II. HIGH FREQUENCY NOISE MEASUREMENTS CHALLENGES OVERVIEW

### A. DUT Noise factor measurement with Y-factor method

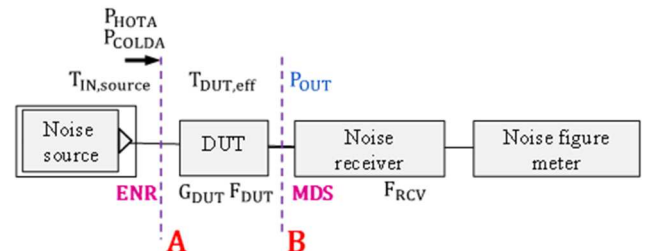


Fig. 1. Classical setup for NF measurement leveraging Y-factor method

The HF noise calibration is performed by connecting the noise source to the input of the noise receiver and making Y-factor measurement [4]. During the calibration, the noise figure ( $F_{RCV}$ ) and gain ( $G_{RCV}$ ) of the receiver are extracted allowing the calibration in plane B. Once the noise receiver is calibrated, the DUT can be characterized when inserted between noise source and noise receiver as shown in Figure 1. The noise figure of the DUT ( $F_{DUT}$ ) can be determined using the Y-factor method [10]. To perform noise characterization above 110 GHz with sufficient accuracy, the MDS condition must be validated. This step follows the noise receiver calibration and is necessary to perform a noise characterization with sufficient responsivity and accuracy. This condition described in (1) is based on the equivalent noise temperature  $T_{DUT}$  and the available power gain  $G_{DUT}$  of the DUT.

$$P_{OUT} = G_{DUT}k_B(T_{DUT} + T_{IN})\Delta_f \geq 2F_{RCV}k_B T_a \Delta_f. \quad (1)$$

With  $k_B$  being the Boltzmann constant,  $T_0 = 290\text{K}$ ,  $T_{IN}$  the equivalent temperature of the noise source,  $\Delta_f$  the frequency bandwidth,  $T_a$  the ambient temperature, close to  $T_0$ . The MDS condition ensures that the output noise power signal of the noisy system ( $P_{OUT}$ ) must exceed a certain value depending on the noise receiver NF in order to be detectable with a margin of 3 dB. Usually, at frequencies higher than 110 GHz, 10 dB is a relevant value for  $NF_{RCV}$ . In the case of a B55 high speed HBT noise characterization, the DUT contribution to  $G_{DUT}$  is not significant since this kind of component has roughly 1 dB of gain at 200 GHz. In the case of the Y-factor method, the two NS operating modes (ON and OFF) must validate the MDS criteria, the OFF state being the most challenging one.

### B. The ENR level requirement

A noise source is always associated to an ENR level, defined as the noise power that a noise source can generate compared to the noise floor power of  $-174 \text{ dBm/Hz}$ . This notion is introduced by the commonly used method of noise factor measurement involving the two operating states ON and OFF of a noise source, assigned to two noise temperatures  $T_{HOT}$  and  $T_{COLD}$ . From these two temperatures, a definition of the ENR can be introduced by (2), with  $T_0=290 \text{ K}$ .

$$ENR(\text{dB}) = 10 \log\left(\frac{T_{HOT} - T_{COLD}}{T_0}\right). \quad (2)$$

Commercial packaged noise sources have shown ENR levels of 12 dB up to 220 GHz [11] with a 2 dB flatness. Other works have developed on-wafer noise sources based on SiGe BiCMOS 55 nm noise diodes, showing monitorable ENR levels up to 260 GHz [12]. Such noise sources generate noise when biased in avalanche regime. By changing the biasing current value, several ENR levels can be reached, from 6 to 20 dB in the 130-170 GHz frequency range. Following the trend of these works, a new idea of an active noise source composed of a diode and a LNA is proposed. Such a solution can show a variable ENR level while respecting the MDS condition.

## III. TEST STRUCTURES AND CHARACTERIZATION SETUP DESCRIPTION

### A. Noise source and LNA description

The used NS is a SiGe BiCMOS 55 nm diode showing monitorable ENR levels up to 17 dB at 260 GHz when biased in avalanche regime [2]. The used LNA design and characterization well described in [4], has a 15 dB flat gain between 130 GHz and 160 GHz. It is structured as a classic cascode structure on two stages. Each stage is composed of two HBT NPN with an emitter width and length of respectively  $0.2 \mu\text{m}$  and  $5.56 \mu\text{m}$ . Since ENR measurements were performed between 130 GHz and 170 GHz, this LNA appears to be a relevant candidate for this study and is used as a buffer stage to enhance ENR levels. A layout view of this LNA is proposed in Figure 2.

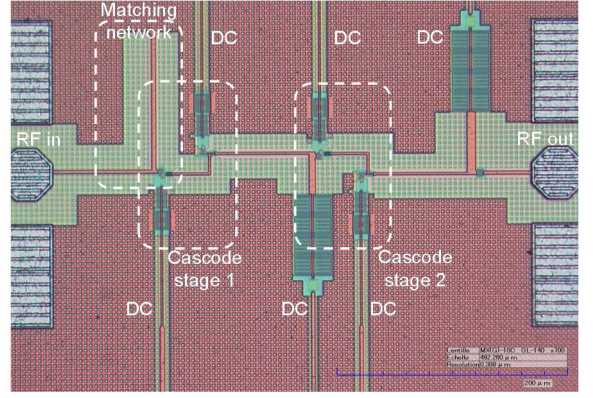


Fig. 2. Layout view of the LNA used in the present active noise source [4].

This LNA has been characterized in Sparams and noise in D band (140-170 GHz), showing a NF lower than 8 dB between 135 GHz and 170 GHz as described in Figure 3. The lower NF level corresponds to the NF of the LNA de-embedded of the RF pads.

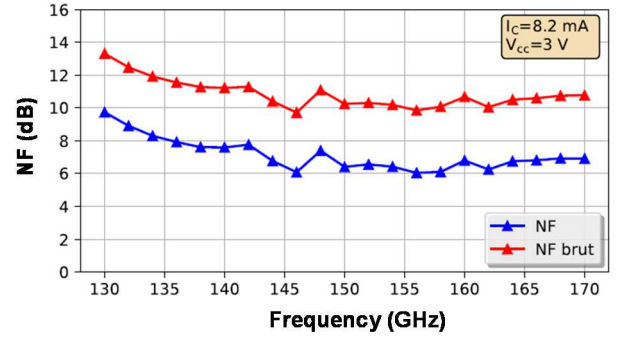


Fig. 3. NF measured in D-band of the 2 stage LNA [4].

### B. ENR extraction when using a noise source and LNA setup

In order to assess the interest of adding a LNA to increase the ENR value, complementary extractions were performed in the setup illustrated on Figure 4:

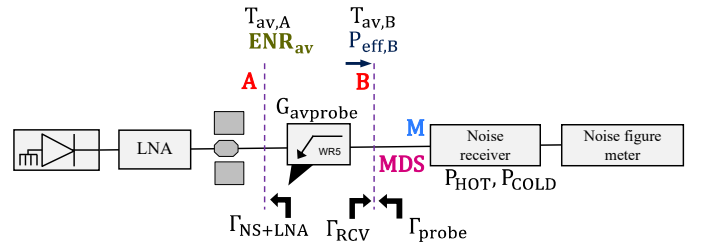


Fig. 4. Block diagram of the noise source and LNA ENR extraction setup

This setup has been used to extract ENR levels in several planes A and B to analyse the ENR level contribution of each element. To be able to extract ENR levels in plane A, measurements of the NS and LNA were performed in ON and OFF states. Besides this noise power level aspect, another advantage of using the chosen LNA is to greatly improve the output matching, regardless of NS bias current, due to its

isolation of 35 dB in the 140-170 frequency range, as shown in Figure 5.

$$ENR(dB) = 10 \log \left( \frac{T_{av,A,HOT} - T_{av,A,COLD}}{T_0} \right). \quad (3)$$

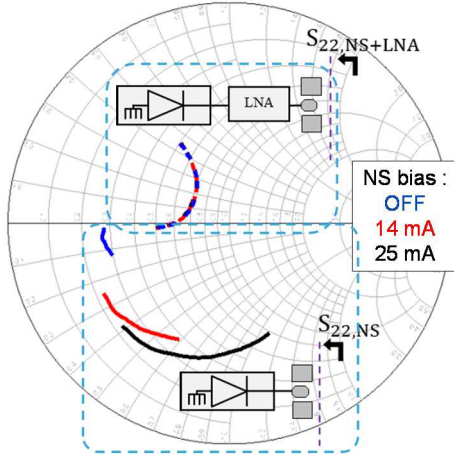


Fig. 5. Output matching comparison of NS (solid lines) and NS+LNA (dot lines) between 140 GHz and 170 GHz for 3 NS biasing.

#### IV. METHODOLOGY

In order to calculate the ENR, calibrated noise powers were measured in ON and OFF states at the input noise receiver plane [C]. To take into account the mismatch between the components, reflection coefficients and available gains calculation of the several blocks was made. Figure 2 shows the several parameters calculated to extract the ENR<sub>av</sub> in planes A and B. At first, calculation of each reflection coefficient and available gain is done. This is possible due to the knowledge of the noise receiver and noise source reflection coefficients  $\Gamma_{RCV}$  and  $\Gamma_{NS+LNA}$  for each bias condition. Moreover, probe S-parameters are given by probe supplier and output pad is not de-embedded in this study. The first step consists in calculating  $\Gamma_{probe}$  and  $G_{avprobe}$  with the knowledge of  $\Gamma_{NS+LNA}$  and  $\Gamma_{NS}$ , determined during S-parameters measurements. During this development, the noise receiver is assimilated to be a 50  $\Omega$  load termination. This permits to calculate the mismatch factor (M) [13], [14] used to transform effective noise powers into available noise powers, to be able to extract ENR<sub>av</sub> levels. With this knowledge, the transform of relative measured effective noise powers ( $P_{eff}$ ) compared to -174 dBm is done to obtain equivalent available noise temperatures at noise receiver input plane ( $T_{av,B}$ ).

$$T_{av,B} = T_{eff,B} M = \frac{P_{eff,B}}{k_B} M. \quad (4)$$

Then, the equivalent available noise temperatures at probe input plane ( $T_{av,B}$ ) is calculated thanks to the knowledge of  $G_{avprobe}$  as shown in equation (5):

$$T_{av,A} = \frac{T_{av,B} - T_a(1 - G_{avprobe})}{G_{avprobe}} \quad \text{with } T_a = 296 \text{ K}. \quad (5)$$

In this study, several bias states were used for NS and LNA. Extractions of ENR<sub>av</sub> levels at plane A (see Figures 1 and 4) expressed in equation (2) have been done.  $T_{av,A,COLD}$  is a bias state where NS is OFF and LNA is ON,  $T_{av,A,HOT}$  is a bias state where NS is biased with currents varying from 0.25 mA to 25 mA and LNA is ON. It is to be highlighted that unlike conventional ENR definition, for which  $T_{COLD}$  is usually equal to the room temperature, used  $T_{COLD}$  values in our study are varying between 39000 K and 73000 K (see Figure 6).

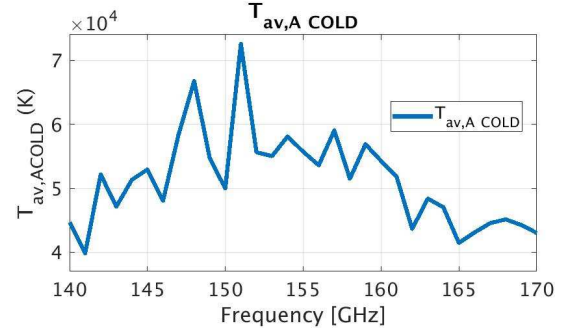


Fig. 6. Used values for  $T_{av,A,COLD}$  (K) in probe input plane (A plane).

#### V. RESULTS

Extracted ENR<sub>av</sub> levels are represented in Figure 7, showing highly monitorable powers up to 37 dB.

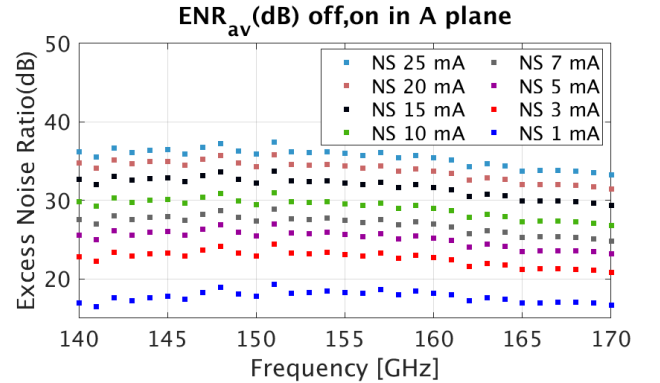


Fig. 7. Extracted ENR<sub>av</sub> (dB) in probe input plane (A plane).

To our knowledge, these are the first results of such monitorable ENR<sub>av</sub> levels at these frequencies using SiGe technology. Considering the MDS aspect, the use of NS in low state and LNA in high state shows a validation of the MDS condition with a 10 dB margin in the 140-170 GHz frequency band. When NS and LNA are set in low state, MDS condition can obviously not be satisfied as depicted in Figure 8.

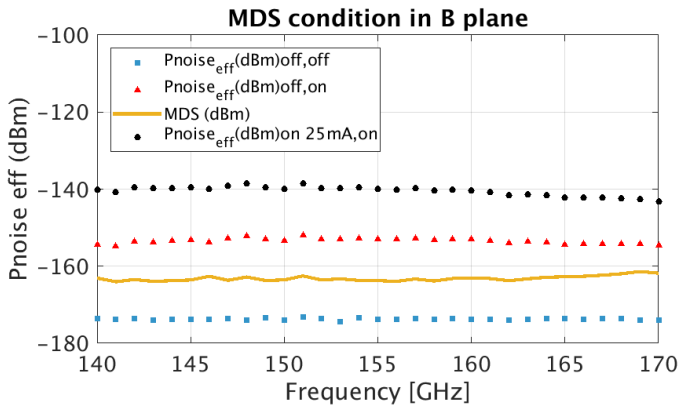


Fig. 8. MDS condition compared to Pnoise eff (dBm) in B plane

A mmW and sub-mmW noise sources state-of-the-art is presented Table 1.

Table 1. mmW and sub-mmW noise sources state-of-the-art

Technology	Frequency range (GHz)	ENR (dB)	Ref.
SiPho PD Ge	75-110	0-40	[7]
UTC-PD	0-20	0-62	[6]
BiCMOS 130 nm	0-40	15-30	[9]
Commercial	110-170	12	[11]
BiCMOS 55 nm	130-260	0-20	[2]
BiCMOS 90 nm	0-30	0-25	[8]
BiCMOS 55 nm	140-170	0-37	This work

## VI. CONCLUSION

A new approach of in-situ active noise source integrated on silicon using a D-band LNA has been described. This way of operating induces higher monitorable ENR levels while respecting the MDS condition. A noise source low biasing LNA high biasing proves to be sufficient to validate this condition with a 10 dB margin. This active noise source shows a constant output matching in both high and low states of biasing. In the case of multi-impedance noise characterization of a DUT, an impedance tuner may be used in source-pull configuration. As a perspective, further studies will bring the noise measurement setup approach of this active noise source followed by an impedance tuner and a DUT in order to evaluate the multi-impedance method.

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