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Walid Aouimeur, Sylvie Lepilliet, Christophe Gaquière, Estelle Lauga-Larroze, Jean-Daniel Arnould, et al.. A fully in-situ reflectometer in G band in 55 nm SiGe BiCMOS. INMMIC 2018 - International Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits, Jul 2018, Brive La Gaillarde, France. pp.1-3, 10.1109/INMMIC.2018.8430015 . hal-03788144

HAL Id: hal-03788144

<https://hal.science/hal-03788144>

Submitted on 6 Dec 2022

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A Fully *In-Situ* Reflectometer in G band in 55 nm SiGe BiCMOS

W. Aouimeur, S. Lepilliet, C. Gaquière

IEMN, Univ. des Sciences et Technologies de Lille 1
Villeneuve d'Ascq, France

E. Lauga-Larroze, J.-D. Arnould

Univ. Grenoble Alpes, IMEP-LAHC, Grenoble, France

J. Moron-Guerra

ASYGN, Montbonnot-Saint-Martin, France

T. Quemerais, D. Gloria

STMicroelectronics, Crolles and Grenoble, France

A. Serhan

CEA-Leti, Grenoble, France

Abstract—This paper describes an *in-situ* reflectometer for one port VNA in 160 to 200 GHz band (G Band). The proposed system is fabricated in 55 nm SiGe BiCMOS technology from STMicroelectronics. Measured performances of system shown 110 mW of power DC consumption from a 1.2 V supply. A 180 GHz nMOS is measured as the device-under-test (DUT) after an *in-situ* calibration. The results obtained using this fully integrated VNA have been compared to a commercial VNA. A discrepancy of 0.3 dB is noted between the two systems on magnitude over a wide frequency range 172-192 GHz. Without calibration, the "raw" dynamics range of the system is limited by the directivity of the coupler which is 20 dB at 140-220 GHz. This dynamic will be improved after the calibration. The SiGe chip size is 3.3 mm². To our best knowledge, the presented *in-situ* VNA have the first results compared to the recently published and are the first with an *in-situ* calibration integrated in SiGe or CMOS technologies.

Keywords—Built In Self Test, VNA, G Band, S-parameters, Frequency multiplier, Coupler, Mixer, SiGe BiCMOS 55 nm.

I. INTRODUCTION

Microelectronic applications such as wireless communications, radar or space detections require higher data rate resolutions, implying the use of millimeter wave and submillimeter frequencies. Thanks to the silicon technologies improvement, some microelectronic circuits are emerging working in the frequency range of 140-220 GHz (G-band) but they suffer from a lack of complete characterization tools involving costly investment. To date, there are few papers in the literature that deal with the miniaturization of *in-situ* VNA [1]-[3] and even fewer integrated *in-situ* VNAs for Bist application from 1 to 125 GHz. All these papers deal with measuring systems. In the literature we distinguish two types of reflectometer: 6-ports and separation of signal [1]-[3]. [1]-[2] presents the first *in-situ* 6-port reflectometer using for biomedical detector but with narrow-band and with small area. The reflectometer in [3] is fabricated with separation of signal topology and present high bandwidth and huge area (6 mm²).

Therefore, the work developed in this paper aimed to integrate in the die the measurement systems that would measure small signals "S-parameters" of the device under test (DUT). Being closer to the DUT makes it possible to reduce the insertion losses, to reduce the amplitude of the error vectors

and thus the residual errors after calibration. Moreover, it is possible to better control the power of the signal sent and to consider calibration methods using integrated loads, which reduces the time and cost processing.

The solution developed consists on connecting the wafer with some probes and driving it with an external signal that spans the 35-55 GHz band. Once into the die, this signal is then quadrupled in frequency and amplified to reach good power level in G band at the DUT input. *S11* is extracted from the DUT thanks to a very directive coupler designed at the input of the DUT. The outputs of the coupler are then converted to low frequencies ($IF = 0.5-2.4$ GHz) through passive frequency mixers (Fig 1). One of the obvious advantages of this heterodyne integrated test solution is the use of off-chip and low frequency a low cost VNA (<3 GHz) that allow for quick and inexpensive verification of circuits or components. A study of each block standalone have been evaluated (Fig 1).

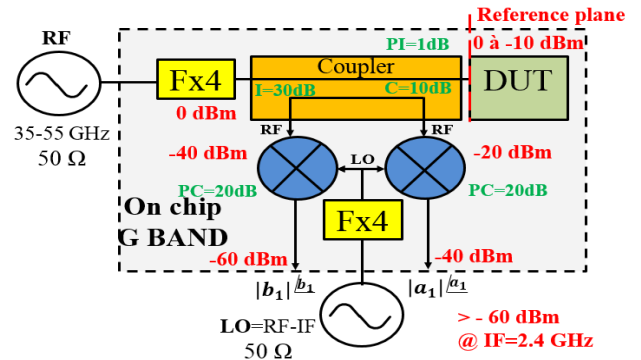


Fig. 1. Block diagram of proposed *in-situ* reflectometer

In this paper, we present a frequency *in-situ* reflectometer in G band frequency based on signal separation technic with a coupler (Fig 1). The design of each blocs and its simulated performances are detailed in Section II, while the experimental results of *in-situ* reflectometer are described and compared at the measured with commercial VNA in Section III. Finally, the conclusion is presented in Section IV

I. DESIGN

This system has been designed in the 55 nm SiGeBiCMOS technology developed by STMicroelectronics for mmW and sub-mmW applications.

This work is supported by the project ANR-14-CE26-0027-BISCIG of the French National Research Agency (ANR) supported by ECSEL TARANTO project toward advanced BiCMOS nanotechnology platforms for RF and THz application

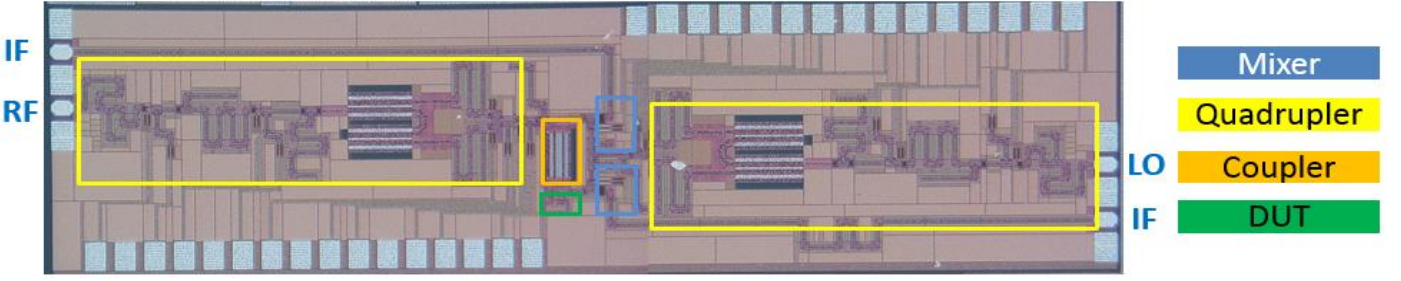


Fig. 2. Chip photo of the fabricated *in-situ* reflectometer in G band

A. G band frequency quadrupler [4]

A solution to generate those high frequencies is to use a lower frequency source and to cascade it with a frequency multipliers chain.

In this part, we present a frequency quadrupler in G band based on single ended doubler fed by a Marchand Balun and balanced frequency doubler [4]. An external frequency source supplies a RF signal at a frequency f_0 between 35 and 55 GHz. This input signal is doubled and amplified to W band thanks to an original Marchand balun based on Slow-wave CPW couplers. Next, the balanced frequency doubler followed by a power amplifier (PA) generates the output signal in the G band. The design of this G band quadrupler and its simulated performances and experimental results are described and compared at the state of art in [4].

B. Coupler

The presented coupler, placed between the quadrupler and the DUT, is used to extract the S_{11} parameters of the DUT (Fig. 1). In order to obtain a compact design with a high isolation, a flat performance, the coupler used a Side Cut Coupled Slow-wave Coplanar Waveguides (SC-CS-CPWs) topology [5].

The different parameters of the SC-CS-CPW coupler are determined in order to reach 50 Ohm of impedance in each port, the lowest insertion losses and 10 dB of coupling over the whole frequency bandwidth 140-220 GHz. The top metal strips are composed of a stack of the two top metal levels (M7 and M8). The thin ribbons placed below the strips are fabricated in M5 metal layer (the gap between M5 and M7 is $h=2.1 \mu\text{m}$). The optimum dimensions have been defined following the method in [5] and confirmed by an HFSS EM simulation. The resulting dimensions are $W_s=15 \mu\text{m}$, $W_g=12 \mu\text{m}$, $S=5 \mu\text{m}$, $SL=0.16 \mu\text{m}$, $SS=0.64 \mu\text{m}$, the cuts and the length of SC-CS-CPW lines are $2 \mu\text{m}$ and $160 \mu\text{m}$ respectively. The measured performances of this coupler in standalone after pad and access lines de-embedding are: $\text{Isolation}=30 \text{ dB}$, $\text{Coupling}=10 \text{ dB}$ and $\text{directivity}=20 \text{ dB}$ at 180 GHz.

C. Mixer in G band

In this part, we present a single-ended passive down-conversion mixer in G band. The schematic of this mixer is detailed in (Fig. 3). This mixer is used at the output of the *in-situ* reflectometer like detector (Fig. 1). To reduce the

complexity of the system (Fig.1). a simple passive topology is proposed.

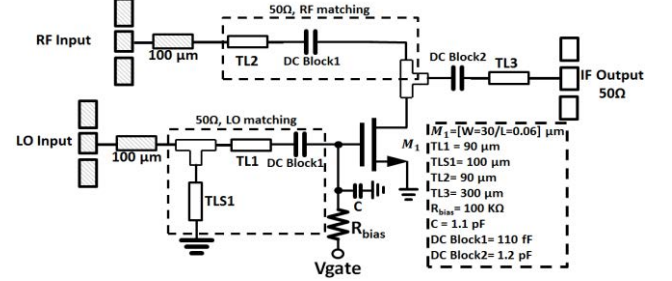


Fig. 3. Schematic of down conversion mixer in G band.

This circuit is optimized to achieve the best compromise between conversion losses, linearity, and the power level required for LO access. When applying the LO to the gate of the nMOS, the sizing of the cold (without V_{ds}) nMOS transistor is done by varying the width, length, and the number of fingers. All of these parameters are set to minimize the ratio Z_{on}/Z_{off} (Z_{on} and Z_{off} are the impedances presented by the nMOS in the ON and OFF states respectively) [6]. The size of the nMOS transistor (width $W=30 \mu\text{m}$, length $L=0.06 \mu\text{m}$) and its bias voltage ($V_{gate}=0.5 \text{ V}$) are set to obtain a good tradeoff between conversion loss and the 1 dB compression point at output $IF=2.4 \text{ GHz}$ (Fig. 3). The measured performances of this mixer in standalone are Conversion loss = 14 dB and $RF-LO$ isolation around 20 dB.

D. DUT in G band

This integrated 50Ω load utilized like DUT is composed of an nMOS transistor M1 and a stub placed at the RF input to suppress the imaginary part of M1 impedance. The real part of the transistor impedance is adjusted with $V_{gate}=0.7 \text{ V}$ to get 50Ω at 180 GHz (Fig. 4).

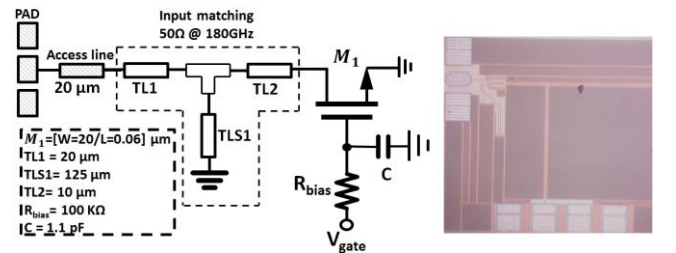


Fig. 4. Schematic (left), Chip photo (right) of the fabricated nMOS used as 50Ω load at 180 GHz.

II. RESULTS AND DISCUSSION

Fig. 5 illustrates the simulated versus measured results of the nMOS load at $V_{gate}=0.7\text{ V}$ from 140 to 220 GHz in standalone. The measured results are compared without (red) and with (blue) pad and access line (AL). The simulated results with Cc extraction are shown without (black) and with (green) pad and access lines.

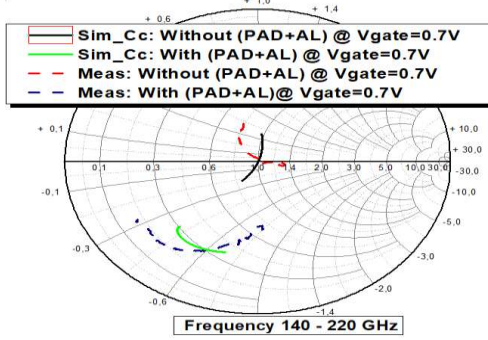


Fig. 5. Comparison between simulated and measured of nMOS load with and without pad and access lines in G band

The experimental setup used to measure the power and phase of output IFs signals ($a1$ and $b1$) is shown in Fig. 6. The setup is composed by two independent signal generators (Agilent E8257D) looking at 10 MHz, two differential probes and cables from DC to 67 GHz for RF-IF1 and LO-IF2 for input-output signal. The commercial two port VNA is first calibrated and used like receiver (or detector) of the output IFs signals ($a1$ and $b1$). The output IF signal power has been checked with spectrum analyzer at 2.4 GHz.

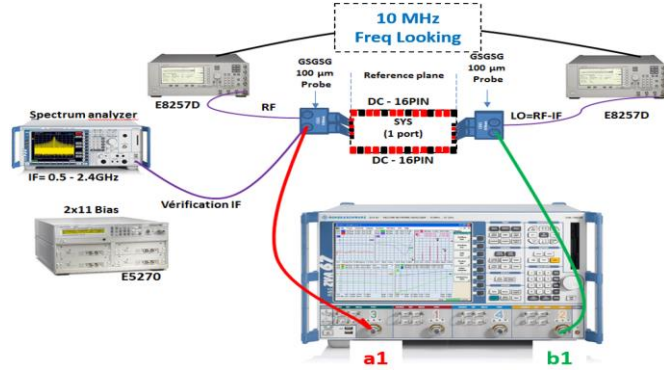


Fig. 6. Setup of measured magnitude of *in-situ* reflectometer

At nominal power supply (1.2 V), the maximum DC power consumption is 110 mW and constitutes the consumption of the two frequency quadruplers in G band. The reflectometer is first calibrated by using a three known impedances $Z1$, $Z2$ and $Z3$ from the DUT in standalone, at the reference plane and calculating the 3-terms errors matrix [7]. Then, $S11$ of *in-situ* DUT are obtained from the corrected $a1$ and $b1$ values.

A very good agreement between measurements with commercial VNA and our *in-situ* reflectometer is noted (Fig. 7). The magnitude measured of $Z4$ (impedance of DUT at ($V_{gate}=0.9\text{ V}$ of nMOS DUT) shown difference is $< 0.3\text{ dB}$ at 172–192 GHz.

Table I presents a comparison with other previous studies in different technologies, frequency range and *in-situ*, *off-situ* DUT. This *in-situ* reflectometer presents good performances in terms of magnitude accuracy and bandwidth frequency.

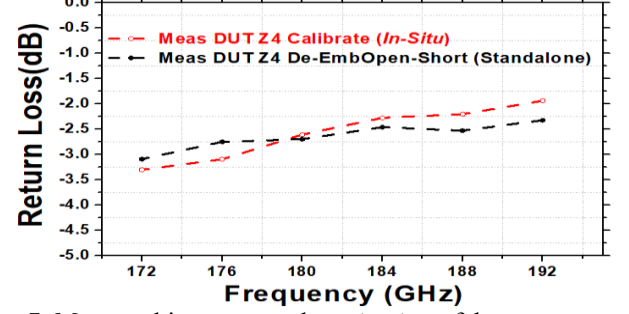


Fig. 7. Measured input return loss: *in-situ* reflectometer versus commercial VNA

TABLE I
PERFORMANCES SUMMARY OF REFLECTOMETER

Ref	Process	Bandwidth [GHz]	Topology	P _{DC} [mW]	Type (DUT)	Area [mm ²]
[3]	BiCMOS	70-110	separation	-	Off-situ	6
This work	55nm BiCMOS	172-192	separation	110	In-situ	3.3

III. CONCLUSION

In this paper, we have presented a fully integrated G band heterodyne *in-situ* reflectometer for one-port vector network analyzers (design and characterization). This reflectometer is composed of a wide band frequency quadrupler made up of two frequency doublers for RF and LO chains, cold downconverters and a very directive coupler based on slow wave topology. First measurements on an *in-situ* DUT show good agreement compare to commercial VNA.

ACKNOWLEDGMENT

The authors wish to acknowledge A. Silligaris from CEA-Leti for his help in design.

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