IET Microwaves, Antennas & Propagation

Research Article

Systematic experimental analysis of an optical sensing microwave low-noise amplifier

ISSN 1751-8725
Received on 26th February 2019
Revised 13th August 2019
Accepted on 15th August 2019
E-First on 27th September 2019
doi: 10.1049/iet-map.2019.0163
www.ietdl.org

Alina Caddemi[1], *Emanuele Cardillo*[1] ✉
[1]*Department of Engineering, University of Messina, 98166 Messina, Italy*
✉ *E-mail: ecardillo@unime.it*

Abstract: This study presents a systematic experimental analysis of the noise figure and the gain of an optical sensing low-noise amplifier (LNA) in the X-band region (8.5–10.5 GHz). The study has been carried out with the purpose of analysing the effects of a 635 nm optical radiation on the gain and noise figure of the LNA, by modifying the bias operating points. Upon varying the bias conditions from those suggested into the component datasheet towards the device pinch-off, the role of the light exposure changes from causing degradation of the gain and noise figure into a clear performance enhancement. In the middle, a bias condition is found where the above LNA parameters become unresponsive to light exposure. Whilst the detrimental role played by the strong gate current increase under light exposure on the noise figure degradation is already clear, the experimental results show that close to pinch-off this effect is completely overcome by the drain current and transconductance increases.

1 Introduction

Due to the material bandgap features and the inherent physical properties, the optical sensitivity of III–V compound semiconductor devices has been widely proven and different functions in microwave circuits have been studied, e.g. control of amplifiers gain and tuning of oscillators frequency [1–3]. Furthermore, gallium arsenide (GaAs)-based high electron mobility transistors (HEMTs) are typically employed where demanding high-speed and low-noise requirements are pursued [4–7].

The authors have presented several experimental results regarding the effects of the optical radiation on the dc and microwave behaviour of different HEMT types, and for various optical wavelength [8–12].

Due to a substantial threshold voltage shift caused by the internal photovoltaic effect, the following research findings have been evidenced for all tested devices: increase of transconductance, drain current, the magnitude of the low-frequency transmission coefficient Y_{21}, and of the microwave scattering parameter S_{21} confirming the research findings known to the scientific community.

On the other hand, not too much attention has been paid to accurately study the effects of light exposure on noise performance [13–17]. This might represent a limit when the optical sensing properties of low-noise devices are sought for applications in optoelectronics front-end. In the past experimental investigation, all the devices under test exhibited a marked increase of the minimum noise factor and a decrease of the optimum noise source reflection coefficient, essentially owed to the increase of the noise current under the gate when exposed to a light illumination [8–10]. To examine this aspect within an application-oriented framework, the authors presented a theoretical analysis comparing the dark versus light performance of three low-noise amplifiers (LNAs) tailored for AlGaAs/GaAs HEMT's with 100, 200, and 300 µm scaled gate widths [18].

Apart from a noise figure (NF) degradation due to the light absorption that confirmed the effects observed on the isolated device, a decrease of the LNA gain was also observed.

This result is opposite to the common belief that light exposure of an amplifier might generally improve its performance as a consequence of both the transconductance and the $|S_{21}|$ increase.

To our knowledge, in the scientific literature the gain degradation in an LNA exposed to optical radiation has been treated to a very limited extent with no detailed comment reported on this effect [15]. In this paper, a systematic experimental analysis of the NF and the gain of an optical sensing LNA in the X-band region (8.5–10.5 GHz) is reported.

The observed LNA and device employ different technology and layout from previous papers, so that the reported results can be considered of general validity. The LNA employs a commercial pseudomorphic HEMT (pHEMT) whose package has been opened to allow the interaction with a 635 nm light laser beam.

The experimental study has been carried out by analysing the main effects of the optical radiation on the gain and the noise factor of the LNA at different bias conditions and at a fixed optical power level.

It has been finally assessed that the consequences of the light exposure on the LNA performance are deeply affected by the bias conditions according to a peculiar trend.

The paper is organised as follows. In Section 2, the experimental set-up and the dc measurements in dark condition and under light exposure are described. The analysis of NF and gain as a function of bias without light exposure and under optical radiation is presented in Section 3. The conclusive remarks are reported in Section 4.

2 Experimental set-up and dc measurements

To perform the dc, NF and gain measurements, two Keithley 2635A and 2611A source meters and an Agilent N8975A (10 MHz–26.5 GHz) NF meter have been used. A properly tailored optical set-up has been used for exposing the device to a laser beam at the wavelength of 635 nm.

The laser source has been calibrated to obtain an optical power of 13.6 mW impinging on the device. This task can be accomplished by means of a neutral step variable optical filter. A rotating mirror installed on a micrometric mount has been finally used to steer the beam direction on the wafer surface.

In Fig. 1, a picture and the block diagram of the measurement set-up have been reported.

The amplifier has been designed and realised on the RO3206 laminate by Rogers Corporation© ($\varepsilon_r = 6.15$, $\tan\delta = 0.0027$) to operate in the low X-band frequency range (8.5–10.5 GHz). The active devices is an InGaAs pHEMT MGF4953A by Mitsubishi Electric Corporation©.

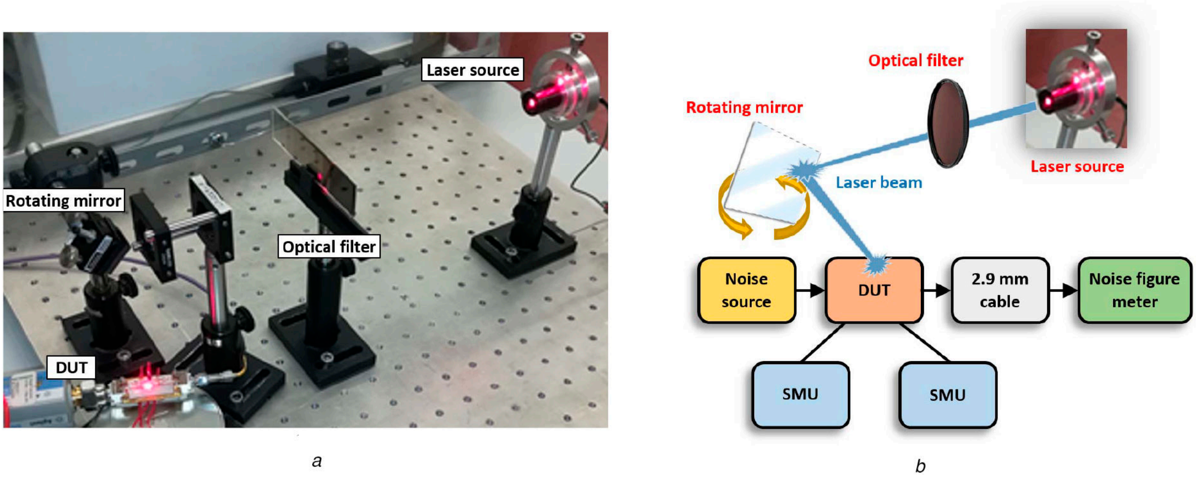


Fig. 1 *The measurement test-bench*
(a) Picture, ***(b)*** Block diagram

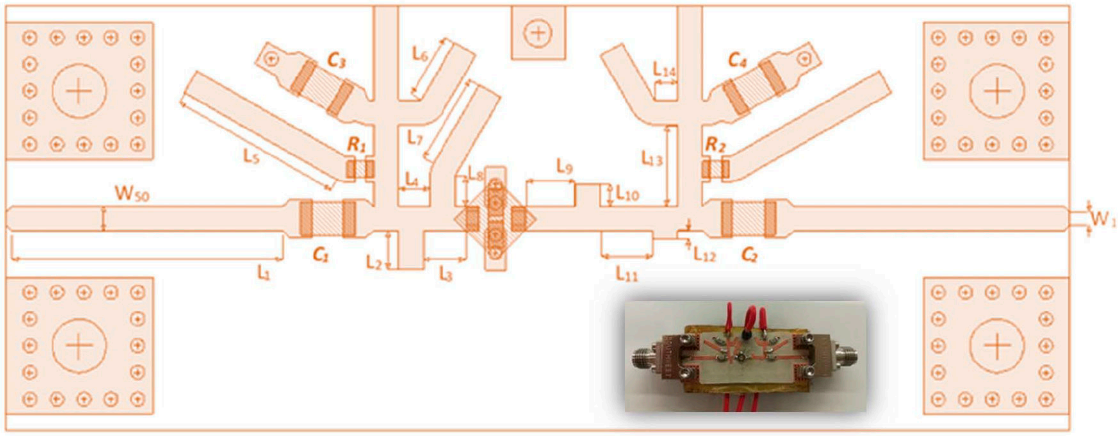


Fig. 2 *Layout and picture of the tested LNA*

Table 1 Values of the amplifier's elements

Symbol	Quantity
W_1, mm	0.5
W_{50}, mm	0.92
L_1, mm	10
L_2, mm	1.45
L_3, mm	1.55
L_4, mm	1.17
L_5, mm	6.4
L_6, mm	2.44
L_7, mm	3.38
L_8, mm	1.125
L_9, mm	1.85
L_{10}, mm	0.8
L_{11}, mm	1.97
L_{12}, mm	0.3
L_{13}, mm	3.05
L_{14}, mm	0.8
C_1–C_2, pF	1
C_3–C_4, pF	1000
R_1–R_2, Ω	100

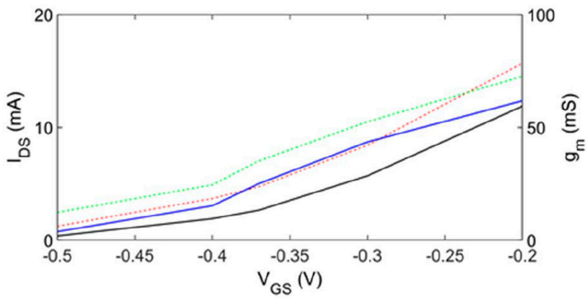
The top side of the device package has been removed to allow the light transmission inside the device. Measured by Mitsubishi Electric Corporation© scattering and noise parameters have been used to design the amplifier ($V_{GS} = 2$ V, $I_{DS} = 10$ mA) [19]. The amplifier has been designed by taking advantage of the microstrip technology to exploit internal laboratory facilities. The design steps have been carried out by employing the electromagnetic simulator within the Microwave Office® software by National Instruments Corp©. In the bias networks, two 100 Ω resistors (R_1 and R_2) in series with a $\lambda/2$ open-circuit stub at the central operating frequency have been employed for improving the amplifier's stability. In the centre part of the bandwidth, the stabilisation network acts as an open circuit without modifying the performance of the amplifier. Far from this frequency sub-band, the resistor stabilisation effect occurs. In Fig. 2, the layout and a picture of the LNA are shown. It encompasses the active device, the dc-blocking, and decoupling capacitors, two double-L matching networks, the stabilisation and bias networks, as well as the connector pads (Table 1).

The gate current I_{GS} and the drain current I_{DS} of the transistor have been measured for different values of V_{GS} at fixed $V_{DS} = 2$ V, both in dark condition and under light exposure, as shown in Fig. 3 together with the dc transconductance g_m.

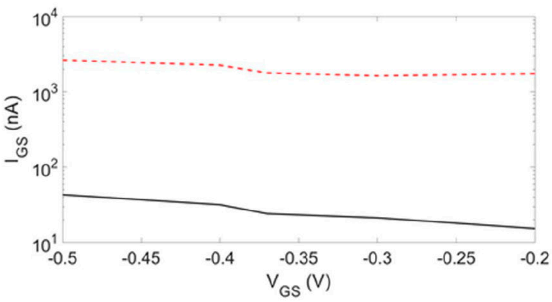
Since the NF and the gain are strongly dependent on the gate current and the dc transconductance, respectively, the monotonic trends reported in Fig. 3 might suggest a similar performance in terms of the amplifier NF and gain as a function of bias. That is not the case, as it will be shown in Section 3.

3 Noise figure and gain measurements

Likewise the case of the dc measurements, the light exposure leads to significant changes also in the behaviour of the NF and the gain. Fig. 4 shows the optical effects on the amplifier performance, when



a



b

Fig. 3 *DC performance of the transistor without and with laser exposure*
(a) Drain current I_{DS} without (black) and with (red-dotted line) light and transconductance g_m without (blue) and with (green dotted line) light, ***(b)*** Gate current I_{GS} without (black) and with (red-dotted line) light versus gate-source voltage (−0.5 ÷ −0.2 V) at $V_{DS} = 2$ V

the gate-source voltage is varied between −0.5 and−0.2 V ($V_{DS} = 2$ V), at the fixed optical power level of 13.6 mW.

By varying the bias point from the design bias conditions (i.e. $V_{GS} = -0.2$ V, $V_{DS} = 2$ V) towards the device pinch-off (i.e. $V_{GS} = -0.5$ V, $V_{DS} = 2$ V), the light effects change from a degradation of the NF and the gain into an evident performance enhancement. In between, a bias condition is found ($V_{GS} = -0.37$ V, $V_{DS} = 2$ V) where no difference is exhibited by the above parameters between dark and light exposure conditions. This case has been evidenced in Fig. 5, where the curve overlapping without laser radiation and under optical exposure is shown.

As far as the NF is concerned, the absence of optical sensitivity might be due to the balance of two simultaneous effects:

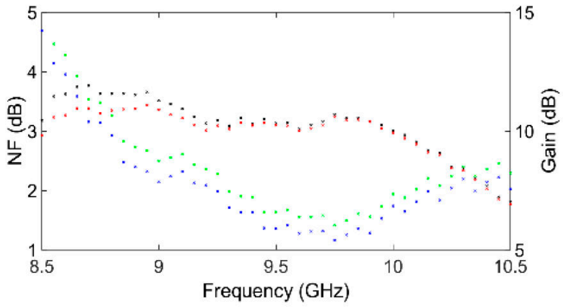
- the NF degradation due to the increase of I_{GS} under illumination;
- the NF improvement due to the increase of I_{DS} and g_m under illumination that approach the design bias condition.

Upon biasing the LNA closer to the pinch-off, the former effect is completely overcome by the increase of I_{DS} and g_m enforced by the optical charge generation. As far as the gain is concerned, the performance degradation due to the light exposure is clearly recognisable by approaching the design bias condition, as predicted in [18]. Once again, the optical sensitivity vanishes at $V_{GS} = -0.37$ V, where the gain degradation is balanced by the positive effects due to the increase of I_{DS} and g_m under light exposure. Close to the pinch-off, the gain degradation caused by light exposure is negligible compared to the remarkable increase of I_{DS} and g_m, leading to a substantial performance enhancement.

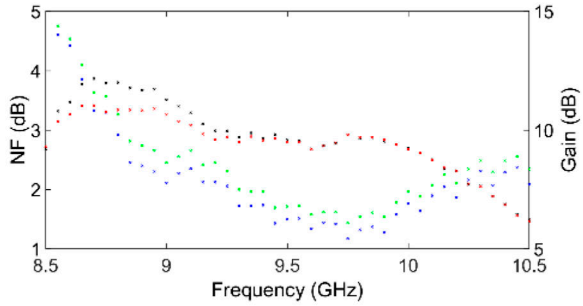
4 Conclusion

In this paper, a systematic experimental analysis of the NF and the gain of an optical sensing LNA in the X-band region (8.5–10.5 GHz) has been presented.

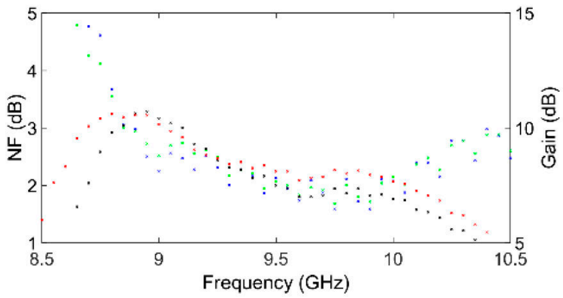
The LNA employs a commercial pHEMT whose package has been opened to allow the interaction with a 635 nm light laser beam.



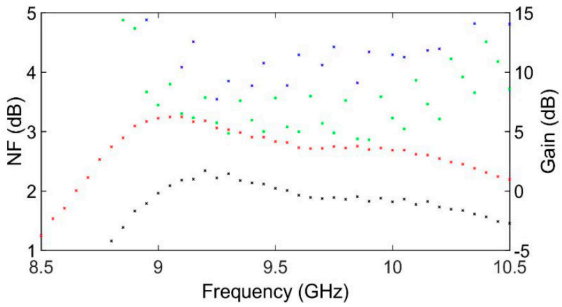
a



b



c



d

Fig. 4 *NF and gain without (blue, black) and with (green, red) light versus frequency (8.5 ÷ 10.5 GHz) at $V_{DS} = 2$ V*
(a) $V_{GS} = -0.2$ V, ***(b)*** $V_{GS} = -0.3$ V, ***(c)*** $V_{GS} = -0.4$ V, ***(d)*** $V_{GS} = -0.5$ V

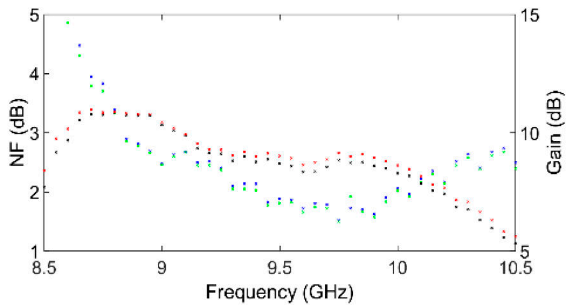


Fig. 5 *NF and gain without (blue, black) and with (green, red) light versus frequency (8.5 ÷ 10.5 GHz) showing the absence of optical sensitivity ($V_{DS} = 2$ V $V_{GS} = -0.37$ V)*

The experimental study has been carried out by analysing the role played by the light exposure on the NF and the gain of the LNA at various bias conditions and at a fixed optical power level. It has been finally assessed that the effects of light exposure on the LNA performance are heavily affected by the bias conditions and exhibit a peculiar trend. This experimental analysis points out quite straightforwardly the role played by an optical control on the microwave performance of a LNA, offering a complete view on the counterbalancing effects taking place within the circuit.

5 References

[1] Sorianello, V., Colace, L., Rajamani, S., *et al.*: 'Design and simulation of optically controlled field effect transistors', *Phys. Status Solidi C*, 2014, **11**, pp. 81–84

[2] Jit, S., Bandhawakar, G., Pal, B.B.: 'Analytical modeling of a DCFL inverter using normally-off GaAs MESFETs under dark and illuminated conditions', *Solid-State Electron.*, 2005, **49**, (4), pp. 628–633

[3] Zamanillo, J.M., Portilla, J., Navarro, C., *et al.*: 'Optical ports: next generation of MMIC control devices?'. 35th European Microwave Conf., Paris, France, October 2005, pp. 1391–1394

[4] Cha, E., Moschetti, G., Wadefalk, N., *et al.*: 'Two-finger InP HEMT design for stable cryogenic operation of ultra-low-noise Ka- and Q-band LNAs', *IEEE Trans. Microw. Theory Techn.*, 2017, **65**, (12), pp. 5171–5180

[5] Cuadrado-Calle, D., George, D., Fuller, G., *et al.*: 'Broadband MMIC LNAs for ALMA band 2 + 3 with noise temperature below 28 K', *IEEE Trans. Microw. Theory Tech*, 2017, **65**, (5), pp. 1589–1596

[6] Nguyen, T.T., Riddle, A., Fujii, K., *et al.*: 'Development of wideband and high IIP3 millimeter-wave mixers', *IEEE Trans. Microw. Theory Tech.*, 2016, **65**, (8), pp. 3071–3079

[7] Gavell, M., Angelov, I., Ferndahl, M., *et al.*: 'A V-band stacked HEMT power amplifier with 25-dBm saturated output power in 0.1 μm InGaAs technology', *IEEE Trans. Microw. Theory Tech.*, 2016, **64**, (12), pp. 4232–4240

[8] Caddemi, A., Cardillo, E., Crupi, G.: 'Microwave noise parameter modeling of a GaAs HEMT under optical illumination', *Microw. Opt. Tech. Lett.*, 2016, **58**, (1), pp. 151–154

[9] Caddemi, A., Cardillo, E., Salvo, G., *et al.*: 'Microwave effects of UV light exposure of a GaN HEMT: measurements and model extraction', *Microelectron. Reliab.*, 2016, **65**, pp. 310–317

[10] Caddemi, A., Cardillo, E., Crupi, G.: 'Light activation of noise at microwave frequencies: a study on scaled GaAs HEMT's', *IET Circuits Devices Syst.*, 2018, **12**, (3), pp. 242–248

[11] Caddemi, A., Cardillo, E., Patanè, S., *et al.*: 'Light exposure effects on the dc kink of AlGaN/GaN HEMT's', *Electronics*, 2019, **8**, (6), p. 9

[12] Gautier, J.L., Pasquet, D, Pouvil, P.: 'Optical effect on the static and dynamic characteristics of a GaAs MESFET', *IEEE Trans. Microw. Theory Tech.*, 1985, **33**, (9), pp. 819–822

[13] Thomasian, A., Rezazadeh, A., Everard, J., *et al.*: 'Experimental evidence for trap-induced photoconductive kink in AlGaAs/GaAs HEMT's', *Electron. Lett.*, 1990, **26**, (14), pp. 1094–1095

[14] Escotte, L., Grenier, K., Tartarin, J.G., *et al.*: 'Microwave noise parameters of InGaAs pseudomorphic HEMTs under optical illumination', *IEEE Trans. Microw. Theory Tech.*, 1998, **46**, pp. 1788–1789

[15] de Salles, A.A., Romero, M. A.: 'Al0.3Ga0.7/GaAs HEMT's under optical illumination', *IEEE Trans. Microw. Theory Tech.*, 1991, **39**, pp. 2010–2017

[16] Caddemi, A., Cardillo, E.: 'Optical control of gain amplifiers at microwave frequencies'. Computing and Electromagnetics Int. Workshop, Barcelona, Spain, June 2017, pp. 51–52

[17] Caddemi, A, Cardillo, E, Patanè, S, *et al.*: 'An accurate experimental investigation of an optical sensing microwave amplifier', *IEEE Sens. J.*, 2018, **18**, (22), pp. 9214–9221

[18] Caddemi, A., Cardillo, E., Crupi, G.: 'Comparative analysis of microwave low-noise amplifiers under laser illumination', *Microw. Opt. Tech. Lett.*, 2016, **58**, (10), pp. 2437–2443

[19] Datasheet of MGF4953A Mitsubishi Electric Corporation, Mitsubishi Electric Corporation, April 2011