International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

Performance Degradation Prediction on Proton Irradiation Effects in 0.35µm SiGe BiCMOS Technology LNA

Lawal Mubashiru Olarewaju, Shuhuan Liu, Li Zuoqi, Aqil Hussain, Yuan Yuan

Abstract— The 0.35µm SiGe BiCMOS LNA was design and simulated by cadence spectre RF design assuming space environment of 63 MeV proton irradiation at the total fluence of 5 x 10^{13} p/cm^2. The current gain degradation was set at 20%, 40%, 60% and 80% in relation with dc electrical measurement to compare pre & post irradiation effects on the LNA. The pre-irradiation LNA, attained a gain of 17.4 to 21.89dB at frequency range of 8 to 12GHz with *NF* below 5.33dB at 12GHz while, post-irradiation LNA, 20% and 40% current gain degradation are able to withstand the tolerance level of proton irradiation whereas, the 60% and 80% current gain degradation gain (*S21*) are reaching negative value. Meanwhile, stability factor (*Kf*>1) was sustained for both pre and post LNA proton irradiation throughout the simulation.

Index Terms— 0.35µm SiGe BiCMOS, Low noise amplifier (LNA), Proton irradiation, Current gain degradation, Cadence spectre RF.

1 Introduction

Silicon–germanium BiCMOS technology has matured into a commercial platform well suited for space and other extreme environment applications [1], [2]. Its excellent low-temperature performance, built-in multi-Mrad (SiO2), total ionizing dose tolerance [3], recent improvements in single event effect performance via radiation hardened by design techniques and seamless integration with best-of-breed CMOS all combines to make SiGe technology attractive. The different SiGe HBT technologies (5HP, 6HP, 7HP and 8HP) adopted over the years has shown an extreme hardness to different kinds of radiation such as proton, neutron and gamma [5]–[11]. Moreover, this bandgap-engineered Silicon–germanium (SiGe) technology is also widely recognized for its low-cost, host of analog, digital, and RF through mm-wave circuit applications [1], [4]. The combination of SiGe HBTs technology with state-of-art Si CMOS with deep-sub-micron CMOS devices, and a variety of passive elements allows for system-on-a-chip (SoC) integration, which is applicable to space-borne electronic systems [12], [4].

The low noise amplifier (LNA) presented in this paper comprises of active components (SiGe technology) and passive components (inductors, resistors, & capacitors) which in turn forms an integral part of the wireless communication systems. According to previous findings, when an amplifier is exposed to radiation, the active components has always being the subject of attacks reported due to their sensitive regions where, the oxide damage in that region eventually resulted into leakage and performance degradation while, the passive components lacks sensitive regions [13]. More so, for an effective LNA performance evaluation; gain, noise figure, linearity, stability factor and power are usually analyzed and they are dependent on one another. The choice of LNA circuit topology depends on the primary objectives of the designer.

The experimental work carried out by other researchers on 63MeV proton irradiation effects reported on the commercially available 5HP SiGe HBT BiCMOS technology incorporated into RF circuit [10] at total fluence of 5 x 10^{13} p/cm^2 indicated that the passive components values are unchanged while; the SiGe HBT indicted a degradation in its performance. Moreso, the 63MeV proton irradiation exposure of 6HP SiGe HBT BiCMOS experimental work performed on Fig. 1 [14], at the total fluence 5 x 10^{13} p/cm^2 showed 80% degradation in the forward-Gummel's dc current gain [15] and also at total fluence of 2 x 10^{13} p/cm^2 showed 60-70% performance degradation in the current gain [11], [16] under similar condition.

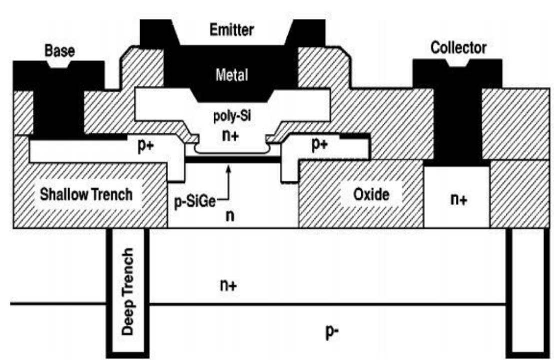

Fig. 1. Schematic cross-section of SiGe HBT BiCMOS technology [14]

- *Lawal Mubashiru Olarewaju is currently pursuing PhD in Nuclear science and technology department, School of Power & Energy Engineering, Xi'an Jiao tong University, Xi'an, Shaanxi 710049, China, PH-15529335770. E-mail: lawalolarewaju1@stu.xjtu.edu.cn*
- *Shuhuan Liu, Li Zouqi, Aqil Hussain & Yuan Yuan are currently with Nuclear science and technology department, School of Power & Energy Engineering, Xi'an Jiao tong University, Xi'an, Shaanxi 710049, China, PH-13992843863. E-mail: liushuhuan@xjtu.edu.cn*

International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

Despite, high tolerance level of SiGe HBT BiCMOS technologies, they are still susceptible to proton irradiation. Collector current I_c increases, the current gain β decreases, and the base current I_b increases post irradiation, thus affecting the total functionality of the RF circuits. At present, while it is reported and generally accepted that SiGe HBTs dc electrical measurements are the key agents of change that determines their performance degradation after being set to proton irradiation, little results have been presented particularly on the actual percentage current gain degradation in SiGe BiCMOS LNA by using Cadence spectre RF simulation.

This paper presents cadence spectre RF simulation techniques on the performance degradation prediction on proton irradiation effects in 8 to 12 GHz frequency band SiGe HBT BiCMOS low noise amplifier (LNA) at the total fluence 5 x 10^{13} p/cm^2. It is basically on how the current gain degradation impacts the total functionality of the amplifier's characteristics is simulated.

2 Simulation Details

2.1 SiGe HBT technology

The 100% Si processing compatible SiGe technology implemented into low noise amplifier (LNA) investigated in this research paper is known as SiGe HBT and is a full 0.35µm BiCMOS technology in commercial production [13]. The Taiwan semiconductor manufactory company, TSMC 0.35 µm SiGe HBT BiCMOS is a state-of-the-art BiCMOS process, enabling high performance RF circuitry used with digital circuits and highly compatible to the 0.35µm mixed signal base process. The 0.35µm CMOS process is designed with a thick dielectric and top metal layer, which raises the performance of the intrinsic passive components, such as inductors and capacitors and its provides the designer with high performance SiGe HBT technology having a maximum frequency, f_T at 80 GHz, 3.3V and 5.0V of high driving capabilities and excellent ESD performance. The SiGe HBT emitter area (A_E) of 0.3 x1.04 µm was studied by cadence spectre RF simulation techniques to align with previous experimental findings.

2.2 LNA Circuit Design

The SiGe HBT LNA was designed to cover 8 to 12 GHz band using two– stage common emitter cascoded LNA topology. The topology used is similar to [17] shown Fig. 2. It was considered based on its increased gain and uncommonly used for irradiation. The transistors (Q1, Q2 & Q3) size is (0.3X1.04 µm^2) each of 0.35µm lithography SiGe BiCMOS technology platforms in cadence spectre RF was used for the design inorder to align with previous report on proton irradiation effects in IBM 5HP and 6HP transistors of the same sizes [16]. This circuitry topology was adopted based on its increased gain and improved isolation compared to the single stage. Its drawbacks are higher noise level because of more transistors introduction and lower circuit linearity [17].

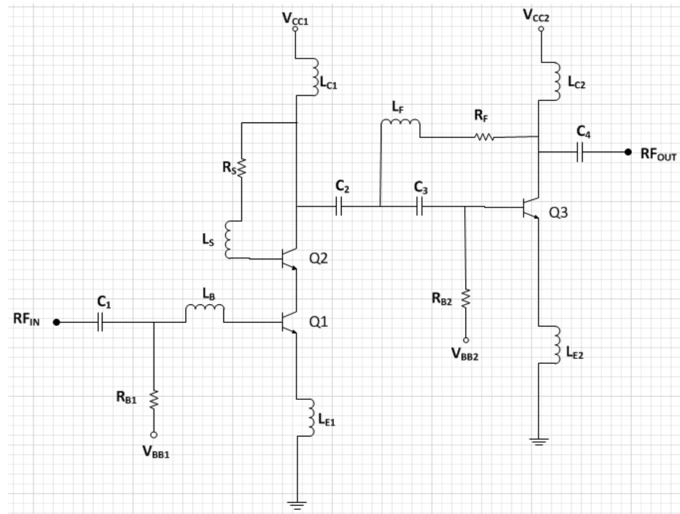

Fig. 2. Schematic circuit of SiGe HBT LNA

The cascoded common emitter (CE) circuit was used as input stage in this amplifier. It is designed to achieve a low noise figure and relatively of high gain. The first stage was optimized to actualize good input matching in the desired frequency band range (8 to 12 GHz) for low noise and high gain while, second stage design is implemented as a CE stage also having a negative feedback loop applied for stabilization.

The bias resistance R_{B1} of the first stage was set in front of the input matching inductor L_B, this resulted in a relatively good input match according to simulation. The first and second stages were designed using inductive emitter degeneration in order to concurrently achieve good noise and impedance matching. The inductor value of L_{E1}, resulted in the best fit performance and the inductor value of L_{E2} was used for emitter degeneration in the second stage also tuned to achieve higher gain. According to the simulations, a slightly higher value for the emitter inductor of the second stage accomplishes a better impedance matching between the two stages. Meanwhile, input impedance matching was also determined by L_B together with C_1 value added to the matching network. RF choke inductors $L_{C1}$and L_{C2} are used for both stages to supply the collectors with best desired bias voltage V_{CC1} and V_{CC2} respectively without losing the signal to the supply. Each RF choke inductors used are two serially connected inductors in order to efficiently block RF signal from leaking to the supply voltage (also AC ground). The positive feedback loop in the first stage was designed to reduce the Q factor and also to increases the bandwidth of the amplifier and the negative feedback loop is for stabilization. The blocking capacitor used was designed for isolation of the base bias from the collector bias, and also for matching. The bias currents and voltages used for this amplifier simulation and other parameters are summarized below in design values of Table. 1.

International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

TABLE 1
DESIGN VALUES FOR THE COMMON-EMITTER SIGE HBT LNA

Symbols	Values	Symbols	Values	Symbols	Values
Q1	0.3x1.04μm^2	L_{C2}	3.10nH	R_S	200Ω
Q2	0.3x1.04μm^2	C_1	903fF	R_f	280Ω
Q3	0.3x1.04μm^2	C_2	3.0pF	R_{B1_1}	5kΩ
L_B	1.47nH	C_3	3.0pF	R_{B2}	5kΩ
L_S	2.2nH	C_4	230fF	I_{C1}	3.3mA
L_f	891pH	V_{CC1}	2.3V	I_{C2}	3.9mA
L_{E1}	132pH	V_{CC2}	2.3V	P_{DC}	16.6mW
L_{E2}	175pH	V_{BB1_1}	1.0V		
L_{C1}	3.10nH	V_{BB2}	1.0V		

response of high frequency transistors. In this work, the transistor's dc electrical value varies from one another indicating different buildup of radiation-induced degradation in the amplifier performances.

TABLE 2
SIMULATED PERCENTAGE DEGRADATION OF SIGE HBT LNA DC ELECTRICAL MEASUREMENT OF PRE AND POST PROTON IRRADIATION AT TOTAL FLUENCE OF 5 X 10^{13} p/cm^2

Transistor	DC	Pre-LNA	Post 20%	Post 40%	Post 60%	Post 80%
Q1	B	181.10	150.4	129.20	111.60	98.09
	I_C (mA)	3.28	7.15	10.35	12.79	14.75
	I_b (μA)	18.11	47.51	80.14	114.70	150.3
Q2	B	180.70	150.30	127.60	109.60	96.94
	I_C (mA)	3.26	7.10	10.27	12.68	14.60
	I_b (μA)	18.04	47.24	80.50	115.70	150.60
Q3	B	242.40	170.40	139.50	120.00	105.50
	I_C (mA)	3.92	7.89	11.01	13.60	15.70
	I_b (μA)	16.16	45.97	78.89	113.40	148.90

3 SIMULATED RESULTS AND DISCUSSION

3.1 Predictive Irradiation Response

The dc electrical agents of changes (current gain β, base current I_b, & collector current I_c) that occurs when SiGe HBT technology are irradiated are closely related mathematically ($\beta = I_c / I_b$). The experimental results reported on the performance degradation of 6HP SiGe HBT BiCMOS when exposed to 63MeV proton irradiation at total fluence of 5 x 10^{13} p/cm^2 on Emitter area A_E, 0.3x1.04μm^2 [11] and 0.44x3μm^2 [16] shows 60-70% and 80% degradation in their dc current gain β respectively. As recorded, the base current I_b, increases with proton irradiation, which is an indicative of radiation-induced damage in SiGe HBT [1], [4] due to the production of generation/recombination (G/R) trapping centers, which causes reduction in the minority carrier lifetime and degrade current gain β of the device located around the periphery of the EB spacer oxide [8]. In addition, it was noted, that both collector-base (CB) and emitter-base (EB) junctions are also used to ascertain the level of radiation damage but, when compared, there is always a slightly less degradation at CB junction than EB junction for proton radiation. In relation to the low noise amplifier if assumed implemented into the 6HP SiGe HBT, the dc electrical measurements changes will affect the total functionality performance of the amplifier.
The SiGe HBT LNA was simulated by assuming space-extreme environment of 63 MeV protons at total fluence of 5 x 10^{13} p/cm^2 and set to have maximum 80% degradation current gain β in accordance with the experimental results reported. The simulated results stated in Table 2 show that, the current gain β values decreases while, base current I_b, & collector current I_c values increases with an increase in the irradiation dosage from 20 to 80% of 5 x 10^{13} p/cm^2. Meanwhile, the S-parameters are commonly used to characterize the electrical

According to the simulation, results of pre and post irradiation LNA were compared and categorized into S-parameter analysis, Noise figure and Stability factor analysis, and Linearity analysis to ascertain their performance degradation.

3.2 Pre-Irradiation Performance

The SiGe HBT LNA was simulated at 1.0V for R_{B1} and R_{B2}, and 2.3V for V_{CC1} and V_{CC2} as shown the Fig. 2 schematic. The results overview in Fig. 3 is the S-parameter response of the amplifier pre-irradiation. The S-parameters presented indicated an input and output impedance matching better than -10 dB almost was achieved over the entire X-band and a gain greater than 10 dB was actualized for wider bandwidth. The LNA performance is summarized below;

LNA performance:

Gain (*S21*): > 10 dB in the frequency range: 2.0 to 16.4 GHz

Input Return Loss (*S11*): < -10 dB in the frequency range: 7.5 to 11.0 GHz

Output Return Loss (*S22*): < -10 dB in the frequency range: 8.7 to 18.6 GHz

Reverse gain (*S12*) : < -30 dB throughout the range.

Noise (*NF*): < 5.3 dB in the frequency range: 1.22 to 12.0 GHz

Stability factor (*Kf*): > 1

The stability factor (*Kf*) is greater than one indicating good stability of the amplifier as shown in Fig. 4 of pre-irradiation

International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

NF & *Kf* of LNA. Meanwhile, the linearity of large signal performance of LNA was analyzed using the first single tone test and follow by two-tone test as indicated in Fig. 5 and 6 of P_1dB output compression and IIP_3 of third order respectively. The P_1 dB compression point and third order intercept point was estimated at frequencies f1; 8 GHz and f2; 8.25 GHz. The simulated results show that P_1dB equals -24.4dB at 8GHz in port2 (output) while, the OIP_3 equals 34.96dBm and IIP3 equals –19.95dBm.

Table 3 summarizes the comparison of this work with other research indicating that the results achieved are very good particularly in the area of attaining a gain of 21.89dB at 8GHz with power dissipation of 16.55mW.

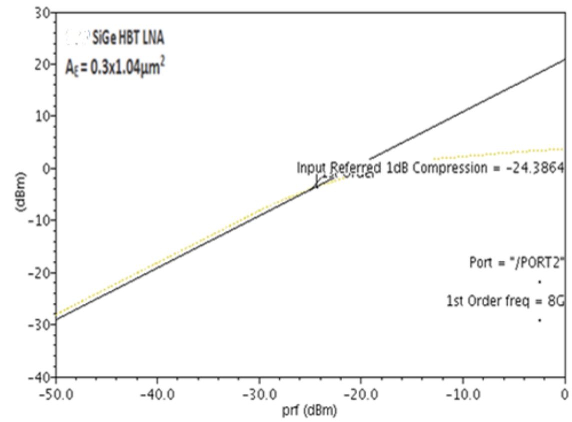

Fig. 5. P_1dB output compressions at 8GHz

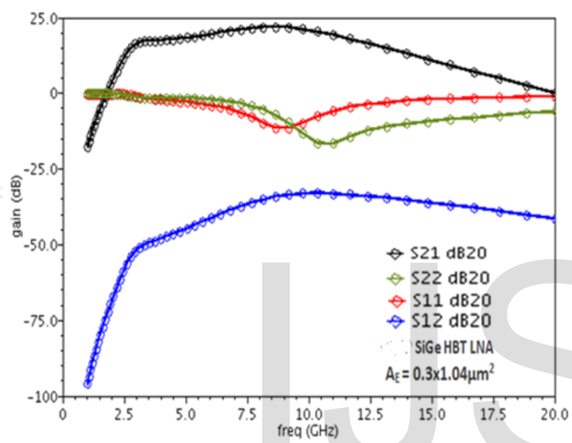

Fig. 3. Pre-irradiation S-parameter response of LNA

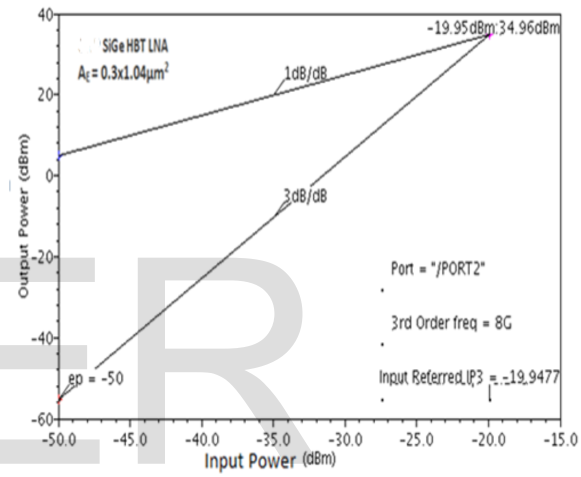

Fig. 6. IIP_3 simulated result at 8 & 8.25GHz

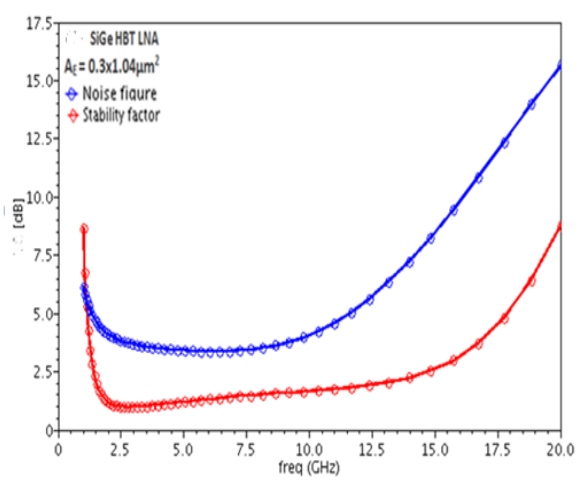

Fig. 4. Pre-irradiation *NF* & *Kf* of LNA

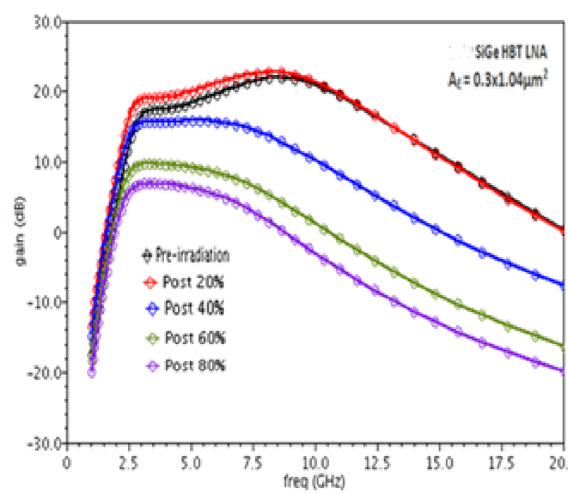

Fig. 7. The pre and post proton irradiation of SiGe HBT LNA gain (*S21*) degradation

International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

TABLE 3

LNA PERFORMANCE COMPARISON WITH OTHER RESEARCH WORK

Process	Topology	Freq (GHz)	NF (dB)	Gain (dB)	IIP_3 (dBm)	Power (mW)	Ref
UTSi SOS 0.5μm CMOS	Single-stage CS	3	1.7	7	10	15	[18]
0.5μm SiGe HBT	Single stage CE+CC feedback	15	4dB up to 15GHz	10dB up to 12GHz	2	24	[19]
0.5μm SiGe HBT	Two stage CE	23	4.1	21	N/A	50	[20]
0.35μm BiCMOS	Single stage cascoded CE	6	2.5	16	-7	13	[21]
0.8μm SiGe HBT	Two- stage CE	16	4	11.5	N/A	8	[22]
0.25μm SiGe HBT	Single-stage CE	8	3.4	9.3	-1.14	7.5	[17]
	Two-stage CE		3.3	18.5	-12.35	15.6	
0.35μm SiGe HBT	Two-stage CE	8	3.5	21.89	-19.95	16.6	This work

3.3 Post-Irradiation Performance

3.3.1 S-parameter analysis

The electrical measurements of LNA were made to quantify their irradiation tolerance level to percentage degradation. Fig. 7 showed the impact of proton exposure on LNA small signal analysis of gain in decibel and frequency response on how current gain potentially affects their circuit behavior. The 20% current gain degradation simulation of post-irradiation LNA gain was still sustainable with an increased value of 22.77dB at 8GHz, 21.41dB at 10GHz, and 17.53dB at 12GHz when compared with the pre-irradiation LNA results of 21.89dB at 8GHz. But, from 40% current gain degradation downwards, the level of gains started dropping drastically with a wider margin stating the tolerance level of the SiGe HBT LNA to proton irradiation. The current gain decrease as function of the total dose in a bipolar transistor is a result of increases in the base current because of oxide trapped charge and recombination rates causing radiation damage in the emitter-base (EB) junction. At 60% current gain degradation, the frequency gain is negative with -3.118dB at 12GHz and for 80% degradation, the only encouraging frequency gain is 1.78dB at 8GHz, while, -2.96dB at 10GHz and -7.46dB at 12GHz are negative value respectively. This shows that, an increase in current gain degradation reduces gain of the amplifier.

3.3.2 Noise figure & Stability factor analysis

The rate of noise figure level also increases with the current gain percentage degradation. Just in the same way as the gain level decreases with regard to the radiation damage. The increased base current in the EB junction, raises the level of noise in the LNA as shown in Fig. 8. The noise figure of pre-irradiation LNA which is less than 5.3dB at 12GHz increases as the percentage degradation increases with, 20% at 6.69dB, 40% at 10dB, 60% at 13.94dB, and 80% at 15.69dB all in 12GHz point. Fortunately, the stability factor shown in Fig. 9 for both pre and post proton LNA irradiation throughout the current gain percentage degradation were still able to survive the proton irradiation simulation by maintaining its stability value of more than one (Kf>1). Its confirmed that the LNA is unconditional stable and it is very stable at the total fluence of 5 x 10^{13} p/cm^2 with 80% current gain degradation and also to affirmed that the extrinsic passive components that bring about the stability of the LNA are completely tolerant to proton irradiation.

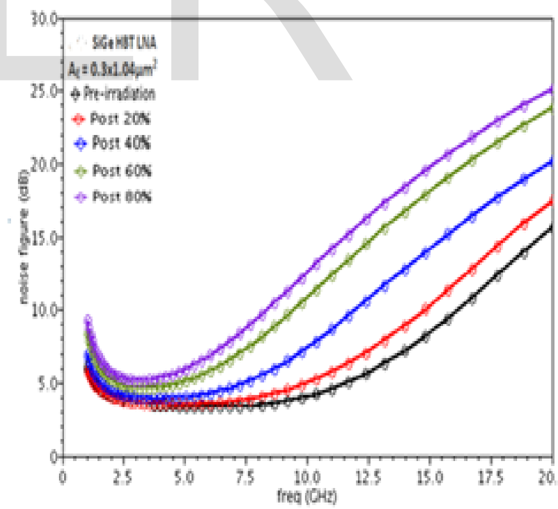

Fig. 8. The pre and post proton irradiation of SiGe HBT LNA NF degradation

International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

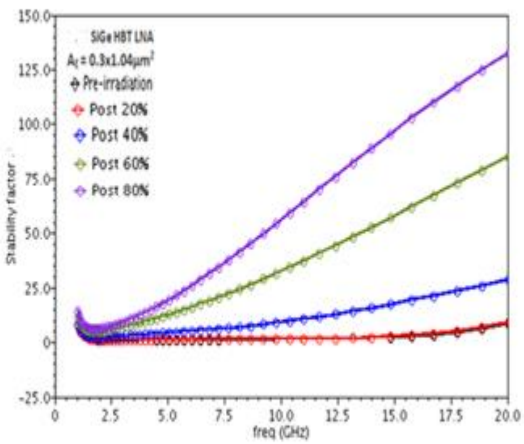

Fig. 9. The pre and post proton irradiation of SiGe HBT LNA *Kf* degradation

3.3.3 Linearity analysis

The ability of the LNA design to recover from short, high power input signals without causing any distortion and damage is very important for it robustness. From the simulated results, the total power consumed by LNA in each of the percentage degradation increases; pre-LNA is 16.6mW, 20% degradation is 34.4mW, 40% degradation is 40.1mW, 60% degradation is 60.7mW, and 80% degradation is 70mW and the 1dB compression point, input referred 3rd order intermodulation point (IIP_3) and output referred intercept point (OIP_3) for the LNA using two input signals with frequencies 8GHz and 8.25GHz respectively are stated in Table 4.

TABLE 4
SIMULATED PERCENTAGE DEGRADATION OF SIGE HBT LNA LINEARITY MEASUREMENT OF PRE AND POST PROTON IRRADIATION AT TOTAL FLUENCE OF 5×10^{13} p/cm²

Linearity	Pre-LNA	Post 20%	Post 40%	Post 60%	Post 80%
P_1dB (dBm)	-24.6	-22.6	-12.6	-95.6	-145.8
IIP_3 (dBm)	-19.9	-19.4	-16.4	-15.8	-15.5
OIP_3 (dBm)	34.9	36.31	39.9	41.9	41.9

With the power increased at every percentage current gain degradation beyond a certain point, the gain of the LNA decreases, and eventually, the output power as described in the Table IV will reach saturation. At that point of input power enabling the LNA reaching saturation, the gain starts to compress leading to nonlinearity.

4 CONCLUSION

To our knowledge, this finding presents the first simulation technique on the performance degradation on proton irradiation effects in 8 to 12GHz frequency band of 0.35µm SiGe HBT BiCMOS Low noise amplifier (LNA) at the total fluence 5 x 10^{13} p/cm². The LNA was designed using common emitter cascoded LNA topology having a gain 21.9dB at 8GHz, noise figure below 5.3dB across the frequency band, and IIP_3 of -19.9dBm. The LNA was simulated with current gain degradation set at 20%, 40%, 60%, and 80% in accordance with the key agent of radiation damage (current gain β, base current I_b & collector current I_b) to predict the actual effects of proton irradiation in the device. It was discovered that only the 20% and 40% current gain degradation are able to withstand the tolerance level of proton irradiation whereas, the 60% and 80% current gain degradation gain (*S21*) are reaching negative value together with high noise figure of higher power 60.7mW and 70.03mW respectively leading to their nonlinearity. Fortunately, stability factor (*Kf*>1) was sustained for both pre and post LNA proton irradiation throughout the simulation confirming its unconditional stability, its reliability at the total dose of 5 x 10^{13} p/cm² of 80% current gain degradation and also to affirmed that the extrinsic passive components are tolerant to proton irradiation.
This paper will help as predicted to check the uncertainty in the actual percentage current gain degradation on proton irradiation effects in SiGe HBT BiCMOS technology LNA.

ACKNOWLEDGMENT

The authors gratefully thank Ministry of Commerce, China (MOC) for their support and also to the entire staff of Nuclear science and technology department, Xian Jiao tong University, Xian, China.

REFERENCES

[1] J. D. Cressler and G. Niu, “Silicon–Germanium Heterojunction Bipolar Transistors,” Artech House: Norwood, MA, 2003

[2] N. H. Vinayakprasanna, K. C. Praveen, N. Pushpa, J. D. Cressler and A. P. Gnana Prakash, "A comparison of 100 MeV oxygen ion and 60Co gamma irradiation effects on advanced 200 GHz SiGe heterojunction bipolar transistors,” *Indian Journal of Physics.*, vol. 89, pp. 789-796, 2015.

[3] K. C. Praveen, "Application of a Pelletron accelerator to study total dose radiation effects on 50GHz SiGe HBTs,” *Nuclear Inst. and Methods in Physics Research.*, B Vol. 273, pp. 43-46, 2012.

[4] B. M. Haugerud, "Proton and gamma radiation effects in a new first-generation SiGe HBT technology,” *Solid State Electronics.*, vol. 50, pp. 181-190, 2006.

[5] A. P. Gnana Prakash, A. K. Sutton, R. M. Diestelhorst, G. Espinel, J. Andrews, B. Jun, J. D. Cressler, P. W. Marshall, and C. J. Marshall, “The effects of irradiation temperature on the proton response of SiGe HBTs,” *IEEE Trans. Nucl. Sci.,* vol. 53(6), pp. 3175–3181, Dec. 2006.

International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017
ISSN 2229-5518

[6] A. K. Sutton, B. M. Haugerud, A. P. Gnana Prakash, B. Jun, J. D. Cressler, C. J. Marshall, P. W. Marshall, R. Ladbury, F. Guarin, and A. J. Joseph, "A Comparison of proton and gamma radiation effects in 200 GHz SiGe HBTs," *IEEE Trans. Nucl. Sci.*, vol. *52*(6), pp. 2358–2365, Dec. 2005.

[7] J. Metcalfe, D. E. Dorfan, A. A. Grillo, A. Jones, F. Martinez-McKinney, P. Mekhedjian, M. Mendoza, H. F. W. Sadrozinski, G. Saffier-Ewing, A. Seiden, E. Spencer, M. Wilder, R. Hackenburg, J. Kierstead, S. Rescia, J. D. Cressler, A. P. Gnana Prakash, A. Sutton, *Nucl. Instrum. Methods A., vol. 579*, pp. 833–838, 2007.

[8] L. Najafizadeh, M. Bellini, A.P. Gnana Prakash, G. A. Espinel, J. D. Cressler, P. W. Marshall, and C. J. Marshall, " Proton tolerance of SiGe precision voltage references for extreme temperature range electronics," *IEEE Trans. Nucl.* Sci., vol. 53(6), 3210–3216, Dec. 2006.

[9] A. K. Sutton, A. P. Gnana Prakash, B. Jun, E. Zhao, M. Bellini, J. Pellish, R. M. Diestelhorst, M. A. Carts, A. Phan, R. Ladbury, J. D. Cressler, P. W. Marshall, C. J. Marshall, R. A. Reed, R. D. Schrimpf, and D. M. Fleetwood, "An investigation of dose rate and source dependent effects in 200GHz SiGe HBTs," *IEEE Trans. Nucl. Sci.*, vol. *53*(6), pp. 3166–3174, 2006.

[10] J. D. Cressler, "On the potential of SiGe HBTs extreme environment electronics," Proc. *IEEE Trans. Nucl. Sci.*, vol. 93(9), 1559–1582, 2005.

[11] J. D. Cressler, R. Krithivasan, G. Zhang, G. Niu, P. Marshall, H. Kim, R. M. Reed, M. J. Palmer, and A. J. Joseph, "An investigation of the origins of the proton tolerance in multiple SiGe HBT BiCMOS technology generations," *IEEE Trans. Nucl. Sci.*, vol. 49(6), pp. 3203–3207, Dec. 2002.

[12] J. D. Cressler, "SiGe HBT technology: a new contender for Si-based RF and microwave circuit applications," *IEEE Trans Microwave Theory Tech.*, vol. 46 pp. 572–89, Nov. 1998.

[13] J. D. Cressler *et al.*, "Proton radiation response of SiGe HBT analog and RF circuits and passives," *IEEE Trans. Nucl. Sci.*, vol. 48, no. 6, pp. 2238–2243, Dec. 2001.

[14] Y. Sun *et al.*, "Degradation differences in the forward and reverse current gain of 25MeV Si ion irradiated SiGe HBT," *Physical B Condensed Matter.*, vol. 449, pp. 186-192, Sept. 2014.

[15] A.P. Gnana Prakasha* and J. D. Cressler, "The effect of 63 MeV hydrogen ion irradiation on 65 GHz UHV/CVD SiGe HBT BiCMOS technology," *Radiation Effects & Defects in Solids* Vol. 166, no. 8–9, pp. 703–709, Aug.–Sept. 2011.

[16] J. D. Cressler, C. H. Michael, S. M. Gregory, Ying Li, G. Niu, J. M. Cheryl, W. M. Paul, S. K. Hak, J. P. Michael, J. J. Alvin, and F. Greg, "The Effects of Proton Irradiation on the Lateral and Vertical Scaling of UHV/CVD SiGe HBT BiCMOS Technology," *IEEE Transactions on Nuclear Science.*, vol. 47, no. 6, Dec. 2000.

[17] Martin Hansson, "Design of microwave low-noise amplifiers in a SiGe BiCMOS process," *Master Thesis, Dept. of Electrical Engineering*, Linköping University, Jan. 2003.

[18] R. Malmqvist, and M. Danestig, "Silicon on Sapphire CMOS LNA's for Future Low Cost S-Band Receivers," *Asia-Pacific Microwave Conference Proceedings*, Kyoto, Japan, pp. 462-465, Nov. 2002.

[19] H. Knapp, D. Zöschg, T. Meister, K. Aufinger, S. Boguth, and L. Treitinger, "15 GHz Wideband Amplifier with 2.8 dB Noise Figure in SiGe Bipolar Technology," *IEEE Radio Frequency Integrated Circuit Symposium*, Phoenix, Arizona, USA, pp. 287-290, May 2001.

[20] G. Schuppener, T Harada, and Y. Li, "A 23-GHz Low-Noise Amplifier in SiGe Heterojunction Bipolar Technology," *IEEE Radio Frequency Integrated Circuit Symposium*, Phoenix, Arizona, USA, pp. 177-180, May 2001.

[21] J. Sadowy, I. Telliez, J. Graffeuil, E. Tournier, L. Escotte and R. Plana, "Low Noise, high linearity, wide bandwidth Amplifier using a 0.35µm SiGe BiCMOS for WLAN applications," *IEEE Radio Frequency Integrated Circuit Symposium*, Seattle, Washington, USA, pp. 217-220, June 2002.

[22] K. B Schad, U. Erben, E. Soenmez, P. Abele, and H. Schumacher, "A Ku Band SiGe Low Noise Amplifier," *Silicon Monolithic Integrated Circuits in RF Systems 2000 Digest of Papers*, Garmisch, Germany, pp. 52-54, April 2000.